

Software and Space: Investigating How a Cosmology Research Group Enacts Infrastructure by
Producing Software

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Abstract

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Producing Software

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Software is a pervasive element of twenty-first century life and an integral element of scientific research. Research in Computer Supported Cooperative Work (CSCW) in recent decades investigates how distributed, collaborative scientific projects take place across different geographical and temporal scales through the enactment of research infrastructures. This dissertation expands upon existing CSCW research with a qualitative, episodic study of a group of cosmologists who are themselves enacting and working among multiple research infrastructures by producing data analysis software as part of a multinational radio telescope project. I describe this cosmology group's software production practices to explain how software is a material for expressing their scientific method. Software operationalizes and encapsulates their cosmology theory, a model of the telescope, observation data, and ongoing analysis decisions. I demonstrate how by using plots (visualizations of observation data, their software, and the physical telescope) they engage in rigorous and thoughtful testing and analysis of infrastructural components in their work. Doing this data-intensive scientific work requires that they collectively develop a deep understanding of multiple infrastructures to isolate and remove

flaws in their data and do a high-precision scientific analysis, interrogating the many embedded relations among conventions of practice that make up their work. My dissertation offers a novel perspective on the production, use, and work of software in science that emphasizes that software in scientific research is not some static product to simply be sustained but a perpetually mutable expression of method to be iterated upon and improved through unfolding research work.

An image presented to us by life brings with it, in a single moment, sensations which are in fact multiple and heterogeneous. The sight, for instance, of the binding of a book once read may weave into the characters of its title the moonlight of a distant summer night. The taste of our breakfast coffee brings with it that vague hope of fine weather which so often long ago, as with the day still intact and full before us, we were drinking it out of a bowl of white porcelain, creamy and fluted and itself looking almost like vitrified milk, suddenly smiled upon us in the pale uncertainty of the dawn. An hour is not merely an hour, it is a vase full of scents and sounds and projects and climates, and what we call reality is a certain connexion between these immediate sensations and the memories which envelop us simultaneously with them—a connexion that is suppressed in a simple cinematographic vision, which just because it professes to confine itself to the truth in fact departs widely from it—a unique connexion which the writer has to rediscover in order to link for ever in his phrase the two sets of phenomena which reality joins together. — Time Regained, Marcel Proust

A Dedication

To my dearest of friends Sarah Jabon and Kaitlyn Crossley née Pisaruk.
You have both been kind enough to see me through the ups and downs of this journey.

I am forever grateful.



Your friends hold the lullabies
They watch the way the night lies
Soft sounds, head's like a radio
Hearts wrapped in blankets, laying low
Hearts wrapped in blankets, laying low

You're cold, maybe you just missed the sun
You fall, feeling like it's just begun
So far, keeping it together's been enough
Look up, rain is falling, looks like love



— Look Up / Heart / Stars

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Images and plots presented in figures throughout this dissertation were provided and reproduced with permission of Magnus and the Radio group.

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I. Contextualizing Software and Infrastructures in Cosmology Research

Can one narrate time — time as such, in and of itself? ... Time is the element of narration, just as it is the element of life—is inextricably bound up with it, as bodies are in space. — The Magic Mountain, Thomas Mann

But the truth, even more, is that life is perpetually weaving fresh threads which link one individual and one event to another, and that these threads are crossed and recrossed, doubled and redoubled to thicken the web, so that between any slightest point of our past and all the others a rich network of memories gives us an almost infinite variety of communicating paths to choose from. — Time Regained, Marcel Proust

Introduction

Software is an intriguing product and an integral element of twenty-first century scientific work. Software is part of how the fresh threads Marcel Proust speaks of above are today perpetually woven in life to link individuals and events across time and space. Software is bound up with life and space, just as time is in Thomas Mann's *The Magic Mountain*. Computer Supported Cooperative Work (CSCW) is an interdisciplinary field that studies the design and use of software and digital computing in support of cooperative work. Research in CSCW investigates how cooperative scientific work unfolds with and through computers. Over the past few decades researchers have studied how distributed, collaborative scientific research takes place across different geographical and temporal scales through the enactment of research infrastructures (Jirotko et al., 2013; Ribes & Lee, 2010). This dissertation contributes to this body of CSCW research with my qualitative, episodic study of a group of cosmologists who are enacting and working among multiple infrastructures by producing data analysis software.

CSCW studies of scientific research commonly adopt Star and Ruhleder's (1996) concept of relational infrastructural where infrastructure emerges "for people in practice, connected to activities and structures" (p.112). Paul Edwards (2010) uses this notion when examining global,

decadal timespan efforts to understand the Earth's weather and climate that results in infrastructure that links numerous systems the world over to sustain knowledge about the Earth. Most CSCW science infrastructure studies instead focus on infrastructure building projects that aim to support scientists doing work as a single project rather than as an all-encompassing global history. This work commonly examines collaborations between domain scientists and software developers building infrastructural systems for scientific use. In the United States these efforts are typically characterized as cyberinfrastructure or research infrastructure projects (Atkins et al., 2003; Borgman, 2015; Edwards et al., 2013; Ribes, 2014). CSCW scholarship examines the human infrastructure of infrastructure (Lee et al., 2006), the different time scales between developing, maintaining, and sustaining infrastructures (Cohn, 2016; Karasti et al., 2010; Ribes & Finholt, 2009), and how products of research (such as data and software) are produced, shared, and reused in different research contexts (Birnholtz & Bietz, 2003; Howison & Herbsleb, 2011; Paine et al., 2015; Ribes, 2014; Rolland & Lee, 2013; Vertesi & Dourish, 2011).

I see a prominent two-part gap in this CSCW scholarship that I address with this dissertation. First, most CSCW studies of infrastructures in science scope their inquiry to investigate one project building an infrastructure. These studies subsume what could be framed as multiple infrastructure projects into one endeavor to focus on how the project is organized and sustained or how different components are built by cooperating arrangements of domain scientists and software developers focused on building systems. My concern on the other hand is with the ways a particular group of cosmologists contributes to and works with a telescope research infrastructure to build their own data analysis research infrastructure on top, see Figure 3. The researchers I studied are both the software developers and the domain scientists in this case. My examination illustrates the conditions in which they can produce their high-precision

data analysis software as they work to deeply understand not only the infrastructure their cooperative work is enacting but also the enacted infrastructures underneath that serve as their scientific instrument.

Second, most prior studies do not take software as the object of their inquiry and do not try to deeply characterize software as a material in scientific infrastructure work. Software is just one of the elements of the projects being studied in these cases. In contrast, software is the object of my inquiry because it is a material for expressing scientific methods in this research group's infrastructural work. It operationalizes and encapsulates their cosmology theory, a model of the telescope, observation data, and ongoing analysis decisions. Software exists as some of the most tangible relations among multiple infrastructures and their stakeholders in this work, whether as pieces of data analysis software or in the digital instantiations of data. To understand the Radio group's scientific practice it is necessary to understand how infrastructures and practices are co-constructed (Fujimura, 1996) through the production of data analysis software. Software is integral to this because producing, using, and assessing software is how the cosmologists I studied create and work through scientific problems. Software is the material they work with to figure out what questions they are asking as well as what questions they can actually ask. I endeavor to unpack software's integral role in this cooperative cosmology work as one case of how software does work in the world.

Cosmologists in Seattle working with a southern hemisphere telescope

In this dissertation I examine the work of one cosmology research group at the University of Washington led by Principal Investigator Magnus, a pseudonym. Magnus is a professor in the Department of Physics engaged in observational cosmology research using innovative radio telescopes. I refer to his research group as the Radio group, also a pseudonym.

The Radio group are contributors to multiple telescope projects. In this dissertation I focus on their work as members of the Widefield Radio Telescope (WRT) project, also a pseudonym. The WRT project is a distributed, cooperative work effort involving researchers from at least three continents, multiple countries, and at least half a dozen different universities—see Chapters Four and Five. I describe the WRT project as a research infrastructure in this work. I study the Radio group because of the central role producing software has in their work. Much of their day-to-day scientific work is cooperatively producing high-precision data analysis software that in practice is becoming an infrastructure layered on top of and bound up with the WRT’s infrastructure—see Chapters Six, Seven, and Eight.

Cosmology is the scientific study of the Universe; it empirically addresses fundamental human questions (e.g., how did the Earth, Solar System, and galaxies get here?), peering back in time to look at the formation of light, stars, and the other wonders of the Universe through telescopes (Loeb, 2006). The Radio group studies the early development of the Universe, specifically the Epoch of Reionization (EoR), using cutting edge radio telescopes. The Epoch of Reionization is a period in cosmic time when galaxies and stars were forming and ionizing the gas present in space—see Appendix A for an overview. This period of cosmic history is not yet well understood, in no small part because the theory underlying this work only solidified in the latter part of the twentieth century and the radio signals that must be probed are exceptionally faint and masked with noise from other phenomena.

The most recent United States National Academies Decadal report for physics and astronomy research prioritizes study of the Epoch of Reionization. Within the United States these decadal reports are influential since they directly affect national funding priorities for the ensuing decade (McCray, 2004). This decadal report describes the EoR as a “key moment in cosmic

history” that lies “largely in the realm of theory today” because previous instruments were not capable of collecting the data to probe this phenomenon (Committee for a Decadal Survey of Astronomy and Astrophysics; National Research Council, 2011, p. 49). To be able to study the EoR effectively scientists have determined that significant quantities of observational data—multiple petabytes amounting to hundreds and thousands of hours—must be processed through high-precision software analyses because the signal being sought is so faint. This is incredibly data-intensive work.

Moving cosmology’s understanding of the Epoch of Reionization out of the realm of theory into the empirical requires designing, building, and using a new generation of radio telescopes and high-precision data analysis software. These activities are the focus of the Radio group’s ongoing cooperative work. Over the course of the three episodes of data collection in my study—described in detail in Chapter Three—I had many conversations about the scientific theory driving this work, the hardware and software of telescopes, and most importantly the Radio group’s high-precision data analysis software. Through this I saw multiple different types of scientific research work being completed.

My earliest data captures pieces of the Radio group’s work helping to build the Widefield Radio Telescope and bring it into an operational state while developing the earliest versions of their own data analysis software (what becomes the infrastructure within and emerging out of this group). This was the work of cooperatively designing, building, and stabilizing a new scientific instrument and systems that make it useable in cooperation with a global scientific collaboration. My second episode follows their work to test and refine their data analysis software once the telescope was operational and they had data to analyze. This was the work of interrogating the operation of this instrument while working through and refining their approach

to high-precision data analyses, inverting multiple infrastructures (Bowker, 1994) as expected and unexpected phenomena were discovered. Finally, my third episode captures reflections on the work of stabilizing their data analysis software, beginning to use it to make knowledge claims about the Epoch of Reionization, and initiating changes to this software as the Widefield Radio Telescope is extended and other telescopes are built to study the EoR. These different types of scientific work all find these individuals discussing and assessing software, data, and hardware. This leads me to my research question and themes of this dissertation.

Research question and themes of the dissertation

Through my episodic, qualitative study of the Radio group I offer a narrative of how twenty-first century cosmology research unfolds. I trace the webs of individuals, organizations, software, data, and hardware systems throughout the multiple infrastructures that create, support, and enable the Radio group's cooperative research work. I address the following research question:

How is a cosmology research group enacting infrastructure through the production of data analysis software?

This question allows me to deeply examine why software matters in the Radio group's work and in relation to their collaborations. I show how software is the material through which their high-precision scientific analysis is able to take place. I unpack how for these scientists to be able to do their work with the Widefield Radio Telescope (an infrastructure project) and their software (another infrastructure layered above and most directly connected through data products, see Figure 3 below) they must continually interrogate the components of these infrastructures, the process of understanding infrastructures in their collective bones. I see these infrastructures as layers in this work due to the chain of dependencies each has. The Radio group's software infrastructure relies upon the existence of data products produced by a telescope research infrastructure underneath. This telescope in turn relies upon a radio

observatory infrastructure below it to provide a radio quiet environment suitable for observations, land to build a device on, and so on. This will not be the case for all scientific endeavors but it is how the work the Radio group engages in is structured.

My analysis examines how the individuals in the Radio group are continually producing materials for creating knowledge while having to interrogate these products and invert the infrastructures they are a part of in order to do their science. Examining how this work unfolds is how I demonstrate how the Radio group's scientific software work results in an infrastructure that is central to not only their own work but over time their collaborators and potentially the larger cosmology community as well. In this dissertation I draw out three primary themes in my analysis of their work to answer my research question. All three themes tie back to a broader idea of understanding an instrument in this group's collective bones. I will explain this idea after describing these themes:

- Software is the expression of the group's scientific method
- Plots are a language
- Working across and among multiple layered infrastructures

Theme 1: Software is the expression of the group's scientific method

Producing data analysis software is the way the Radio group expresses their particular approach to doing cosmology research. Their data analysis software is how they construct a scientific method that produces knowledge outputs for comparison with those from collaborators and others in the cosmology community. This method operationalizes the physics theory, mathematical algorithms, models of the telescope as physical instrument, and the effects of the telescope embedded in the data it creates. Creating software, executing it using data from the Widefield Radio Telescope, and examining the outputs is how the Radio group understands the research questions that they want to ask and how they work out new research questions that they

need to ask but did not yet realize that they needed to ask. Creating their software is not just a task on the pathway to doing science, it is scientific work in and of itself. As Brianna, a post-doctoral researcher in the group, commented to me they do not want to lie to their software analysis, it should be as accurate of a representation of reality as possible.

We fundamentally believe in our group that you want your software analysis to—you don't want to lie to your analysis. You want to have your analysis as close a representation of reality, physical reality as possible. (Brianna, interview)

The Radio group commonly refers to their software as a data analysis pipeline, both in every day interactions and in publications. I refer to their pipeline in this work as the US EoR pipeline, a pseudonym. Referring to data analysis software with a pipeline metaphor is common in science (McCray, 2004) since by design data is input in as a relatively unprocessed product and emerges reduced and shaped according to the analysis approach that is constructed. The US EoR pipeline is the result of the Radio group's cooperative work with different individuals responsible for certain components. No one person could build all of these components and the work must be conducted cooperatively for it to succeed.

In Figure 1 below starting at the top left and moving down and to the right I have traced the idealized flow of data through the Radio group's data analysis software in my analysis. CalibratorImager and ImgPower (produced by post-doctoral researchers Igor and Brianna respectively) are two fully fledged software pipelines for taking in data and outputting different knowledge products. The nuances of each of these pipelines, as well as of Munchy (produced by PhD student Abner), and the RadioCluster computing environment encapsulate much but not all of the Radio group's approach to their data analysis. There are many points where a researcher must make decisions in the operation of the pipeline that affects the resulting scientific analysis. This is a conscious design choice by the Radio group, keeping a human in the loop rather than

automating every operation to proceed without human input. In use all of these components and practices become an infrastructure for this group’s research work.

In Chapter Six I will show how the production of the US EoR pipeline expresses the Radio group’s approach to working with data from telescopes like the WRT (Chapters Four and Five describe how this telescope is constructed and the implications of this for data analysis software). I’ll show how within the group different individuals come to rely upon elements of this software to offer their own scientific contributions, whether that is using data outputs to create products that feed back into this pipeline’s operation or digging into particular facets of one piece of the software to implement new approaches to some element.

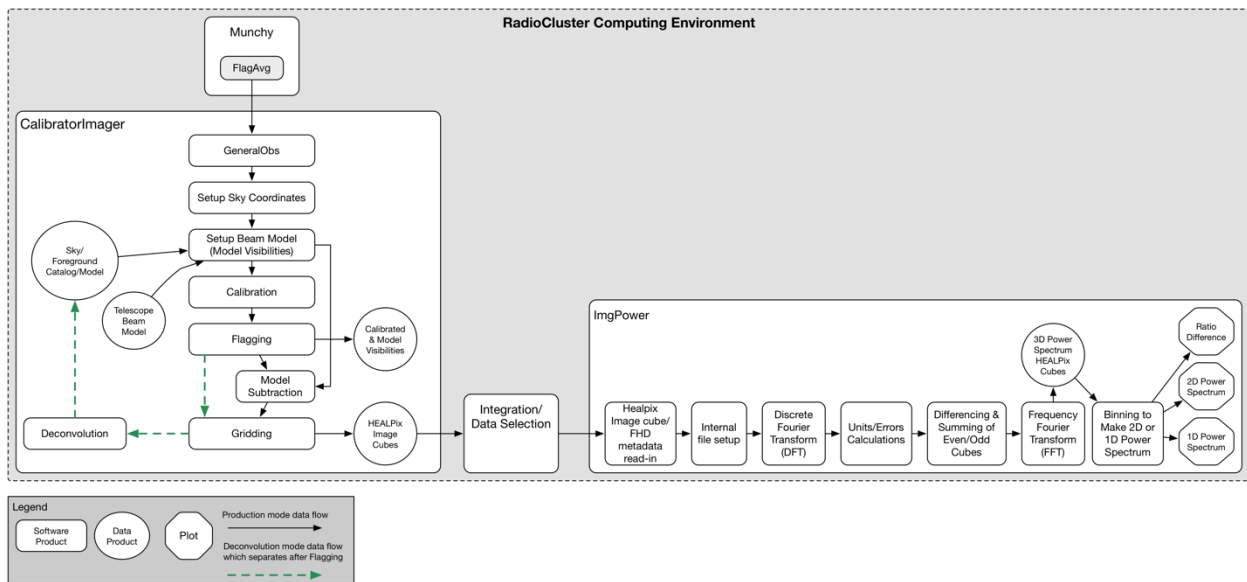


Figure 1. Overview of the US EoR pipeline data analysis software. Munchy, CalibratorImager, and ImgPower are the primary components. CalibratorImager and ImgPower are fully fledged pipelines in and of themselves.

The Radio group’s software captures states of their high-precision analysis that change over time in outputs known as data products. Data product is a term the group takes for granted. I discuss and analyze data products because I came to see in my analysis how these products are coordinative artifacts (Schmidt & Wagner, 2002) that are explicitly designed points of

interchange between both elements of the US EoR pipeline and other software pipelines produced in the WRT project. Data products connect and work across multiple infrastructures. They are the threads between these scientific infrastructures. Previously I defined data products as “datasets that are the output of instruments or of executions of the processing and analysis infrastructure being created” because I wanted to emphasize the “living and in-process nature of these artifacts as products of the research process” in comparison to the rigid, sterile sense afforded by the term dataset (Paine & Lee, 2014, p. 231)¹. I revisit and elaborate upon this definition in Chapter Five based upon further discussion with members of the Radio group and analysis on my part.

Understanding that this data analysis software and these data products are how the Radio group expresses their science is integral to seeing how their work results in infrastructure. Software is how their scientific method is expressed and translated from local into global contexts, becoming taken for granted and black boxed in various individual’s work (Fujimura, 1996; Latour, 1987).

Theme 2: Plots are a language for the Radio group

Intimately connected with the Radio group’s production of software are their plots. Plots are what Magnus (again the principal investigator) calls the language of the group. These artifacts provide a material that visually concretizes the effects of the telescope’s physical design that are inscribed in the data, the natural phenomena that was captured, the operation of different mathematical operations and algorithms written in the software, and the group’s unfolding analysis decisions. Designing, and discussing particular plots is how members of the Radio group convey the scientific questions they are asking to each other. Plots are not only

¹ I will reference papers I co-authored throughout this dissertation but for this narrative will refer to these in the first person. They could not have been completed without the contributions from my co-authors.

visualizations for understanding this science, they are visualizations for understanding and interrogating software and infrastructure. Plots enable the Radio group and their collaborators to have ongoing discussions about their scientific work with a common point of reference by visualizing the data products they are producing. Plots are the focus of the group's weekly meetings and a frequent point of discussion in my conversations with members of the group.

Cosmologists study the Epoch of Reionization by measuring the strength of a radio signal to create a power spectrum. A power spectrum is most commonly visualized in a 1D line chart, but in the Radio group's work a variety of novel 2D power spectrum plots (see Figure 2) are created by the `ImgPower` pipeline to drive their software testing and data analysis work. These complement various plots of calibrated and imaged data output by `CalibratorImager`. Science and technology studies scholarship offers extensive insights into how visualizations of data are created and used by scientists to make knowledge claims (Coopmans et al., 2014; Lynch, 1985; Lynch & Edgerton, 1988; Vertesi, 2015). I am instead interested in the utility of plots for understanding and interrogating infrastructure on the pathway to making knowledge claims about the Epoch of Reionization. I focus on how the Radio group uses plots to understand the operation of their software, the data collected with the Widefield Radio Telescope, and to shape their ongoing analysis by including or excluding pieces of data.

Plots help the Radio group to uncover what they call systematics. Systematics are phenomena or effects captured in data and visualized in plots that result from an instrument being imperfect, a specific category of fault or bug in the infrastructure. They are "anything that is gonna corrupt your signal that is not, like, a thermal noise" as Abner a PhD student in the group describes the idea. Thermal noise does interfere with their signal because the sky is warm at the wavelengths the EoR is being looked for, but it is reducible as larger quantities of data are

integrated together. Systematics instead result from noise introduced by pieces of the telescope’s hardware, whether amplifiers or cables, that will not integrate down as more and more data is added together. The analysis and testing I observed in the Radio group is particularly focused on finding and removing systematics. This is the group’s “whack-a-mole thing” as Brianna the post-doc nicely expresses.

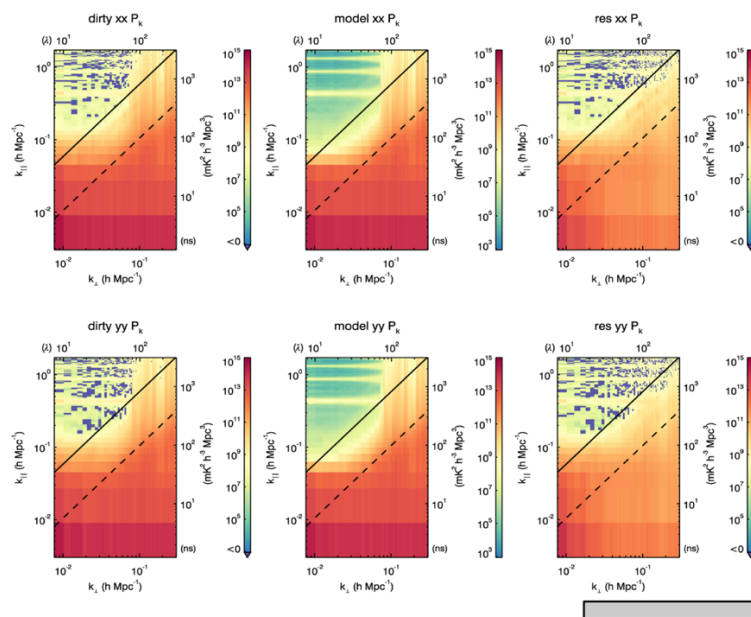


Figure 2. A 2D power spectrum plot.
A variety of these novel visualizations are created by `ImgPower` and used to assess their infrastructures.

One representative systematic that I witnessed the discovery and examination of is what came to be known as the fourth line bug. Briefly, in the 2D power spectrum plot (such as that in Figure 2) there are three horizontal bands (most visible in either of the “model” plots in the center column as the yellow bands breaking up the blue-green coloring) that are harmonically spaced and expected in the output due to the physical design of the WRT. When a fourth, non-harmonically spaced band appeared a flurry of testing and analysis began. Unpacking this example helps me to trace the role of plots among the Radio group and their collaborators as they did their scientific work producing the US EoR pipeline data analysis software while illustrating

connections between my other two themes and showing how the Radio group understands the instrument in their collective bones.

I will show how 2D power spectrum plots are used by the Radio group to perform an infrastructural inversion (Bowker, 1994), working their way through the components of the US EoR pipeline down into the infrastructure of the telescope itself, crossing among these multiple layers in their work. Plots help me as the outside observer as well, enabling me to trace entanglements in this work between software, data, and the telescope—the Radio group’s multiple layered infrastructural components.

Theme 3: Working across and among multiple layered infrastructures

My study of the Radio group’s work foregrounds multiple infrastructures being created and used in their scientific work, see Figure 3. I describe the multinational Widefield Radio Telescope project by examining the Radio group’s positioning and roles within this global endeavor’s human infrastructure as well as their contributions to the various resources the WRT makes available through its kernel (Ribes, 2014). This differs from most of the existing CSCW studies that focused on the building of research infrastructure by following collaborations of software developers and domain scientists.

I draw out how this group contributes to the production of multiple different, entangled scientific infrastructures. The first infrastructure is that of Widefield Radio Telescope, its data collection and storage systems, and the multinational organization that sustains all of these elements as a viable research instrument over time—elements highlighted in green in Figure 3’s middle layer. I analyze the WRT as a research infrastructure with a dynamic human infrastructure in Chapters Four and Five. The WRT is situated atop another infrastructure, that of

a radio observatory in the southern hemisphere. The second infrastructure is that of the Radio group's US EoR pipeline and their practices for doing high-precision cosmology data analysis.

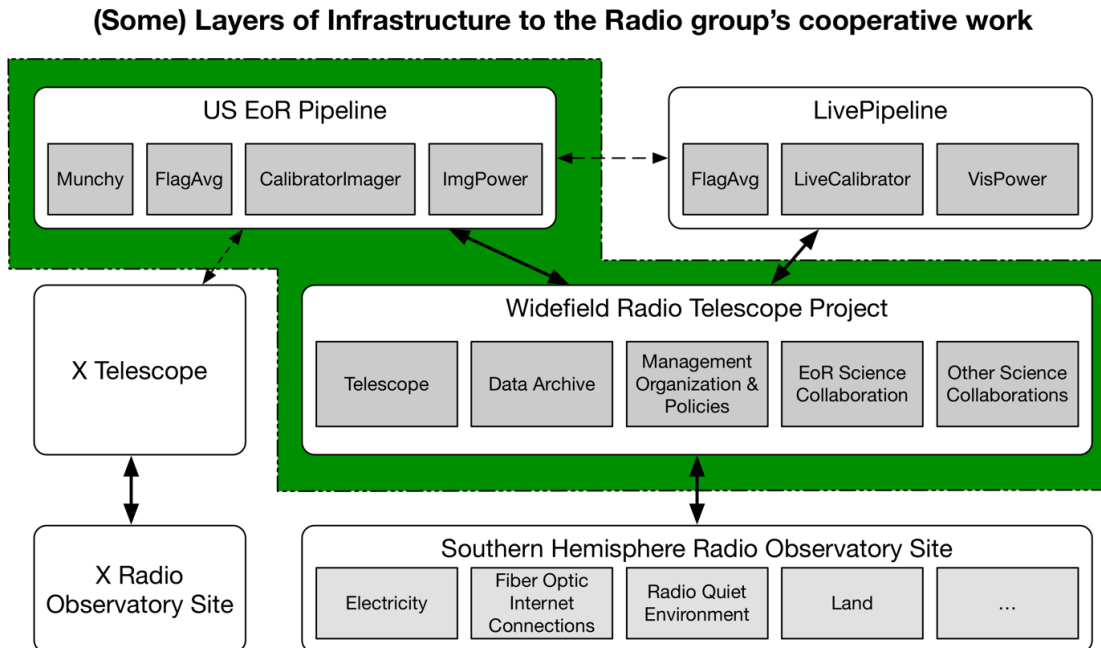


Figure 3. Layers of infrastructure in the Radio group's work. The green shadowed elements are the focus of this dissertation; the Widefield Radio Telescope project that of Chapters Four and Five and the US EoR Pipeline that of Chapters Six and Seven. Resources of each infrastructure are noted in each layer (e.g., the telescope, land, or CalibratorImager software).

This dissertation untangles many, but of course not all, of these overlapping and interacting pieces. For example, I explain how political considerations regarding the radio observatory's land shapes the physical design of the Widefield Radio Telescope, shaping the data it produces and thus influencing the Radio group's data analysis software. Examining components across these three layers of infrastructure helps me to foreground and understand the conditions a single group of researchers can end up encountering and working among to do their work. The Widefield Radio Telescope as an infrastructure exists to create and maintain a scientific instrument and its outputs as resources for creating knowledge. The US EoR pipeline as an infrastructure exists to create and maintain an approach to high-precision cosmology data

analysis, an instrument for creating knowledge that relies upon data products produced by other underlying instruments.

Within the literature on scientific infrastructure there is some focus on how a group of scientists produce and work with multiple infrastructures. Bietz, Baumer, and Lee (2010) describe the concept of synergizing as an analytical lens for examining how stakeholders building infrastructure create and maintain relationships among individuals, organizations, and technologies, all of which may be a part of other infrastructures. Vertesi (2014) develops a vocabulary of seams for examining how actors align multiple, heterogeneous infrastructures to be able to do their work in the moment. Bietz et al.'s concept is useful for seeing how stakeholders ensure infrastructure can be developed at an organizational level. Vertesi's focus on fitting resources together in fleeting moments is very much about individuals getting work done but is not yet developed as a concept for explaining how work is sustained on multiple, layered, and overlapping infrastructures. Instead, in this dissertation I am interested not just in how an infrastructure project's development was sustained or with how individuals do work in fleeting moments. I am interested in how the Radio group sustains their own scientific work across multiple infrastructures over time. They contribute to the development of the Widefield Radio Telescope which is an infrastructure project but they also develop and sustain their own data analysis software infrastructure on top of this. It is the conditions enabling and supporting cooperative work across these layers of infrastructure that help to explain why software matters in this scientific work.

All three of the themes that I just discussed come together when I illustrate how the members of the Radio group need to collectively understand these components in their bones (e.g., develop a deep embodied feeling of the telescope, software, analysis decisions, etc. among

this collective of researchers). This notion conveys the deep connection among different infrastructural components and different individual's knowledge of these components in this scientific work.

Understanding the instrument in your bones

As I concluded my data collection Magnus and I were reflecting on my understanding of his group's work. I was trying to tease out aspects of the relationship between telescopes, the data produced with telescopes, and data analysis software (in other words all of the infrastructures and their components that I was seeing in his group's work). I wanted to understand just how they are entangled and intertwined together in time and space throughout this group's work. This conversation resulted in him explaining how the group needs to understand the instrument in their bones, a notion that foregrounds the need to disentangle the embedded relations among infrastructures and researchers.

By the time of this conversation I had witnessed many of the group's efforts to produce and debug their software. I had seen them trace problems in the plots output by their software backward, down into the machinery of the telescope. I observed them firmly grasping some elements as others behaved in unexpected ways. In this vignette Magnus captures but some of the relationship between telescopes (interferometers in this case), data, and software that I have ended up sifting through to produce the narrative presented in this dissertation.

Drew: ... So during my off and on history here with the group, you know, I come in spurts, right. Um, I have obviously observed many discussions about hardware and software and data. Everything we're talking about here.

Magnus: Yep.

Drew: So one of the things I'm trying to understand, and I would like to hear from your perspective, and we've been teasing around all this, but how are those things all related to each other?

Magnus: [Laughs heartily and pauses for a 10 or so second period] Well, I'm probably not gonna answer your question but, um, so I've said a long time for instruments and I've put my money there, uh, in that in order to do a precision analysis you have to understand the instrument in your bones. So I –

Drew: Instrument in your bones? Sorry.

Magnus: Yeah, the instrument in your bones.

Drew: Wanna make sure that hears it. [Laughs referring to the audio recorder]

Talking with Magnus I was probing how data, software, and hardware are related from his perspective. After uttering that evocative phrase Magnus continued on to explain how doing a high-precision data analysis here requires that the members of the group understand how an interferometer (the type of telescope they work with) actually functions. It is not enough to know what type of instrument produced the data. The group members need to understand how it is designed and built to produce data to be able to analyze this product. As a result, Magnus has intentionally sent the various members of the group to the remote telescope site to work on the device so that they can understand how it is constructed. This has the side benefit of building goodwill in the WRT project since they are helping with its construction.

Magnus: Um, you have to have not just a, oh, there's an interferometer and it kind of works like this. You've got to know how this machine works.

Drew: Mm-hmm.

Magnus: Um, so all the graduate students, I believe this is true, 'cause it was certainly true for most of them, uh, and the postdocs, um, I made sure to send 'em to the field.

Drew: Field being [Z]?

Magnus: Western [Z], in order to work on the hardware.

Drew: Mm-hmm.

Magnus: And part of that was to be a good citizen [to the collaboration] and stuff like that, but a lot of it was you can talk about it until you want—standing there next to it and saying the signal goes here and here and we're having trouble with

this piece and ba-da, yeah, but it's just a qualitatively different understanding of the machine. So when we then see one of these ripples come in, it's kind of like, well, could that be a cable reflection? You know there's a cable. You know the length. You know that not all the cables are the same lengths. You know who to talk to to get the table for which antennas are hooked to which lengths.

Drew: Mm-hmm.

Magnus wants the post-doctoral researchers and students in the Radio group to know how different antennas are connected to each other. Seeing the physical device helps to develop the group's collective understanding of how a radio signal goes from antennas to other pieces of the telescope. When years later a bug appears in their plots—as I noted briefly earlier—they can through cooperative analysis of their data, software, and instrument figure out that is it because of a ripple or reflection in some of the instrument's cables. Having a sense of the instrument's physical wiring turns out to be essential here to understanding their high-precision analysis and debugging their software.

If he did not encourage the development of this understanding of the instrument in the group's collective bones Magnus believes their collective research work would be held back. In contrast, a student in another group who collaborates with the Radio group may only have an abstract understanding of the telescope because they haven't worked on the physical device. No matter how intelligent the student is, how steeped in the physics and mathematics of the research, not knowing how the actual instrument was built and functions in practice limits their understanding of their analyses in software. This type of research requires that scholars deeply understand their instrument and in turn their data analysis software to be able to assess their knowledge products, to ask what is a bug or an unintended feature in the work. Understanding the instrument in their bones is a necessity, the details are critically important as Magnus expresses and I will show with this dissertation.

Magnus: That's the sort of thing that it's been interesting, uh, us-, uh, so like [Josiah] at [X Institution] who is a very bright graduate student finishing up, and very theoretical and mathematically oriented, but I think he's really actually been held back because the instrument's an abstract thing. He can see correlations and try to make magic math to make it go away, but he doesn't understand, y-, you know, he doesn't know why a correlation comes up because he's not 100 percent clear on how it [the instrument] works. I think a very similar argument can be made for the software. In that you can't—the details of how the software works are critically important.

Drew: Mm-hmm.

Magnus: And so you see features, and whether or not they are bugs or – so bugs you worry about 'cause you just want 'em to go away, but a lot of them are unintended features. [Laughs] And so I, I, in that they aren't a bug, per se, and it may even be doing it exactly the way you designed it, but you realize that that's not what you needed.

I had not heard Magnus previously utter the phrase “understand the instrument in your bones,” yet in hindsight this idea does underlie the cooperative work I studied. Doing high-precision scientific analysis work requires unpacking and interrogating a long chain of decisions and elements as uncertainties arise, this is science in action (Latour, 1987). Taking some element for granted is often not possible without leaving some uncertainty about how a result is produced. To do so is to make use of “magic math” where the approach is theoretically derived yet may not fully match with the reality of data produced by an imperfect instrument.

By the time Magnus and I had this conversation it had been almost four years since I had first talked with him about his research. I was now familiar with the members of his group, their collaborators around the United States and world, what an interferometer and interferometric telescope are, the basics of how this type of telescope works, how multiple infrastructures are produced and used in this work, what the software they are producing is and does, and how it has come about through their cooperative research work.

I started studying Magnus and his group intent upon understanding how they produce software and what I learned extends far beyond just software. The idea of understanding the instrument “in your bones” truly extends beyond just the telescope itself. The individuals in the Radio group all wind up having to fathom and continually re-evaluate the details of their software and how to use it as well. They have to understand and discuss many infrastructural components or resources (pieces of software, data, hardware, organizational policies, etc.) that exist among multiple layered and overlapping infrastructures. Continually interrogating these layers and overlapping pieces (with plots being the primary mechanism for doing so) is how these scientists learn what questions to ask in their pursuit of knowledge.

I must stress that any one individual alone cannot deeply understand all of these elements. This notion of understanding the instrument in their bones and the nature of this high-precision work absolutely require the efforts of a group; this work is fundamentally cooperative. The notion of grasping an instrument “in your bones” is a unifying element of the three primary themes that I discussed above that come out of this dissertation because it ties together the reasons software is how the group expresses their scientific method, how they use plots, and how they navigate the different embedded relations of multiple infrastructures. The care in doing this cooperative work is necessary since as Brianna, a post-doctoral researcher in the Radio group, poignantly noted: “*unfortunately, as experimentalists, we all know that often nature conspires against us*” in efforts to better understand it.

As an outsider studying their efforts I had to work to understand their software and cooperative work by digging into and learning about cosmology and fundamental physics, the nuances of telescope design, how scientific analysis can be bound up in both software and printed plots of data, and the ups and downs of distributed cooperative work in a nascent virtual

organization spanning multiple built environments. Doing this allowed me to begin to get a sense of what feeling or understanding the instrument (or really infrastructures) in their bones entails.

Why software is my object of inquiry

Studying the Radio group's cooperative work, I was focused on software as the object of my inquiry. I find there is often not enough effort spent to deeply understand how software does work in the world and is a product of the social worlds producing it. It is a product that is accepted without extensive thought (or perhaps any thought) in people's day-to-day lives and work. Software often appears magical—operating in an ephemeral and intangible realm yet it is wholly bound to the physical world due to the devices it operates on and its construction by humans cooperatively working in different sociotechnical milieus (Berry, 2011; Dourish & Mazmanian, 2013; Kitchin & Dodge, 2011). Nathan Ensmenger in *The Computer Boys Take Over* (2010) captures the beauty and essence of software to me: “Software is perhaps the ultimate heterogeneous technology. It exists simultaneously as an idea, language, technology, and practice. Although intimately associated with the computer, it also clearly transcends it” (p. 8). Software is fundamentally sociotechnical. It is the result of many intertwined technical and social decisions made in particular organizational contexts that act over time across different spaces.

Software originates in part out of the production of scientific knowledge (Ceruzzi, 2003; Ensmenger, 2010). But software has transcended research settings, emerging as a medium and material for conducting cooperative work, producing knowledge, transferring global concerns to one's local context and vice versa (Takhteyev, 2012), and altering our perceptions of time and space (software enables me to converse in real time with someone physically on the other side of the world while reinforcing temporal and spatial gaps every time a hiccup occurs in the digital

link connecting myself and a friend or colleague). Software simultaneously hides under the surface of cooperative work, ignored in everyday tasks, while being the focus of exactly such work in many realms. No matter how subsumed software becomes in anyone's life it quickly sweeps to the forefront when something goes wrong. It is infrastructural just as roads, electricity, waterworks, and various pieces of knowledge are in our day-to-day lives (Bowker & Star, 1999; Star & Ruhleder, 1996). Software matters for cooperative work and life in general.

In my work I purposefully examine software as the object of my inquiry. I could however examine and discuss code or algorithms. Code and algorithms are key elements of software but they are not the only elements that need to be explored—documentation, design plans, organizational arrangements, and outputs from executions of code all need to be understood too. Software studies scholarship makes a distinction between software and code since work in this field typically does a close reading of what is expressed in code, treating it as a text for careful analysis. Berry (2011) nicely states “perhaps the most important point of this distinction is to note that code and software are two sides of the same coin, code is the static textual form of software, and software is the processual operating form” (p.32). It is the processual form and the resulting emergent outputs of the code and algorithms, e.g. the software, that intrigues me. I believe the processual form and emergent outputs are most germane to studying cooperative scientific work since these outputs are what the Radio group examines and interrogates in their unfolding research work.

By using the term software, I am intentionally acknowledging and recognizing the larger milieu that code is a part of; that it is a complex sociotechnical product that results from the intertwined social and technical decisions of its production. In the cooperative cosmology research work I studied software is not a static element. It is a central knowledge product to be

constructed and shaped over time in the ongoing process of creating new knowledge, just as clay is formed and shaped by artisans creating their products. By following software, I am examining phenomena at a meso and macro level rather than at the micro level of code snippets. My analysis does not seek to directly assess and critique the actual code these scientists are producing in their work. I am instead interested in the cooperative work that results in its ongoing production and revision as these researchers work to develop new knowledge. Kitchin and Dodge summarize software as “not an immaterial, stable, and neutral product. Rather, it is a complex, multifaceted, mutable set of relations created through diverse sets of discursive, economic, and material practices” (2011, p. 37). It is exactly these diverse sets of practices I must investigate if I am to explain this cosmology research.

I will end this chapter by outlining the remaining chapters of this dissertation.

Outline of the remainder dissertation

Chapter Two examines relevant literature to explore perspectives on scientific software and data. I explain why software matters by drawing upon software studies scholarship. I discuss computer science research on scientific software development examining (SSD) how software in science is produced from a technical perspective. I look at science and technology studies (STS) explanations of how scientific knowledge is constructed. Finally, I discuss CSCW work studying scientific infrastructure production, as well as a theoretical lens for cooperative work, to elicit a sociotechnical conceptualization of science and software production that shapes how I address my research question.

Chapter Three describes my research site, data collection, and analysis work. I discuss the Radio group’s composition, outline the different periods of time I spent with them, and explain my sources of data for this dissertation. I discuss my iterative process of analyzing this

qualitative data, and how my theoretical concepts influenced this, to not only guide the data collection that took place but also shape the findings presented here.

Chapter Four introduces the multinational Widefield Radio Telescope (WRT) Collaboration and their project building a novel radio telescope. I discuss the Radio group's work on this project in light of CSCW scientific infrastructure research so as to characterize the organization of this project, its various data collection and use policies, and the different cooperative work arrangements and common fields of work that form under the WRT's auspices. I situate the Radio group's software work as part of this multinational endeavor and examine the novel radio telescope here because its design quirks are fundamental to being able to discuss the Radio group's software.

Chapter Five discusses the collection of Epoch of Reionization data with the WRT. I describe Radio group's work as part of the WRT project. I look at how they create components of the WRT to ensure data is reliably produced and the instrument self-documents so that the materials created can be scientifically useful. I end by discussing data products as coordinative artifacts that are the threads between different infrastructures in the Radio group's work.

Chapter Six delves into the Radio group's data analysis software, the US EoR pipeline. I examine how this software is the material through which the Radio group better understands their scientific theory and the data produced by the Widefield Radio Telescope. The Radio group's software is an expression of their scientific analysis approach and following their work producing it allows me to shed light on interesting points of cooperative work engaging data, these researchers and their practices, plots, and infrastructural components.

Chapter Seven examines the Radio group's plot-driven testing practices that illustrate how these scientists analyze data and their infrastructures. I examine what is represented in the

group's plots and ask how they help these researchers to see not only what is in their data but also how the instrument behaved and into the software itself showing how the plots not only support coordination but also shape the scientific work itself. I juxtapose these plot-driven testing practices with software engineering testing methodologies to reframe the conversation on scientific software development and testing. While I do not find that this group of scientists employs strict software engineering methods they do create and use rigorous, reflective practices for their software development and scientific research on the whole.

Finally, Chapter Eight will synthesize what I have learned about the cooperative work of the Radio group to answer my research question, explaining how the Radio group enacts an infrastructure through their software production. I assess just how the Radio group's production of novel cosmology software illustrates how much software matters in cutting-edge, high-precision scientific analyses. Finally, I address limitations of a single site, episodic study and offer thoughts on future research directions in this realm of research.

II. Literature Review

*I think humanity begins where people of no genius think it is already at an end.
— The Magic Mountain, Thomas Mann*

*In reality every reader is, while he is reading, the reader of his own self. The
writer's work is merely a kind of optical instrument which he offers to the reader
to enable him to discern what, without this book, he would perhaps never have
perceived in himself. — Time Regained, Marcel Proust*

Introduction

My examination of software in scientific research is grounded in the interdisciplinary field of Computer Supported Cooperative Work (CSCW). The work of this field is what has offered that kind of optical instrument Proust describes for my studies of work. CSCW scholarship examines cooperative work in a variety of fields as a means for developing theory that supports the design and development of cooperative work arrangements and systems to support these arrangements (Schmidt & Bannon, 1992). Early CSCW research was often oriented around groupware systems and supporting the work of small teams—see (Lee & Paine, 2015) for an overview of early theoretical work in the field and (Schmidt & Bannon, 2013) for an assessment of the state of the field after twenty-five years. CSCW overall draws upon and is influenced by many different disciplines, from psychology and sociology to organizational studies, computer science, human-computer interaction, and science & technology studies. I am furthermore drawing in work from software studies here in this dissertation. In particular, CSCW's research on workplaces relies upon qualitative inquiries, often ethnographic, where actual practice is examined in the place of work. If I am to understand the work of twenty-first century scientists I ought to examine their actual enacted, cooperative work practices.

I fundamentally have to draw from the scholarship of many fields to understand the complex, distributed, and multi-faceted cosmology research work of Magnus and the Radio

group. In the early years of the field Greif (1988), as cited in Schmidt and Bannon (1992), stated that “as a research field, CSCW is distinct from any of the fields on which it draws.” This is a stance I find holds today with CSCW studies of scientific research work and software—CSCW research on these topics is able to and does synthesize elements of many research traditions to produce sociotechnical—intertwined social and technical—narratives of unfolding scientific practices and the development of systems enabling these practices. This dissertation draws upon CSCW, infrastructure studies, science & technology studies, software studies, and some computer science perspectives to try to synthesize a holistic understanding of the cooperative work of this cosmology research group as they produce software and do their science.

Bannon and Schmidt (1989) early in the history of CSCW posit that the field “should be conceived as an endeavor to understand the nature and characteristics of cooperative work with the objective of designing adequate computer-based technologies” (p.360). This dissertation is very much trying to understand the cooperative work of a particular research group. It is however not trying to design computer-based technologies to support the work of this group. Rather it is examining how through the conduct of their cooperative scientific work these cosmologists are designing software, scientific instruments, a virtual organization, and above all else knowledge. This produces implications for designing infrastructural software.

Bannon and Schmidt (1989) explore a variety of forms and definitions of cooperative work. They define cooperative work as “constituted by *work processes that are related as to content*, that is, processes pertaining to the production of a particular product or service” (p.362, emphasis in original). Cooperative work “comprises *indirect* as well as *direct* and *distributed* as well as *collective* modes of interaction” summarized as “the general and neutral designation of multiple persons working together to produce a product or service” (p.362, emphasis in original).

I primarily use the term cooperative to describe the work discussed in this dissertation. I will examine a variety of forms of direct and indirect, distributed and locally-situated cooperative work over the course of this dissertation.

I will come back to cooperative work at the end of this chapter. For the moment I will note that fundamentally in this dissertation I am concerned with cooperative scientific work that is producing software. To understand this scientific work, however, I must explain not only what software is to me as a sociotechnical concept, artifact, and truly material for work (and why it matters) but also how I see infrastructure and cooperative work theorized across multiple literatures. To begin I'll discuss why software matters.

Why software matters

Software and computing are pervasive in twenty-first century life. Individuals encounter software in all manner of contexts in their lives, from financial matters to communicating with friends and family. In recent decades, software has become an inescapable facet of society, a concept known to all that is not always deeply thought about. Software is increasingly important to human endeavors and “matters because it alters the conditions through which society, space, and time, and thus spatiality, are produced” in the course of actions as it is “bound up in, and contributes to, complex discursive and material practices” (Kitchin & Dodge, 2011, p. 13). This dissertation is organized around the examination of software in a cosmology research group because software is a key medium through which scientific knowledge is expressed, created, and ruminated upon in the twenty-first century. Therefore, I first discuss what software is in this dissertation. How is it actually defined in software studies literature? How do I define it for the purposes of this dissertation? Why should anyone care so much about software? Why does software matter?

To address these questions, I turn to the fledgling field of software studies research. Software studies is the research field, along with CSCW, that I am drawn to. First though I'll look to the Oxford English Dictionary for a common technical definition.

The Oxford English Dictionary's (2013) first definition of software is "the programs and procedures required to enable a computer to perform a specific task, as opposed to the physical components of the system." Software is a set of instructions written in code. Code is "any system of symbols and rules for expressing information or instructions in a form usable by a computer or other machine for processing or transmitting information" (Oxford English Dictionary, 2015). Such instructions are necessary to direct digital computing hardware to perform tasks. This is a nice tidy technical definition such that when it comes to computing, software is the digital, non-physical component.

This technical definition of software is probably how most people would immediately think of software. What cannot be forgotten however is that software is much more than just code. In practice software is also documentation, design concepts, data, conceptualizations of society and the world (ontologies), and other artifacts that in concert operate computing hardware for tasks. In this dissertation I frame software as not only the textual code but importantly this larger set of concepts and artifacts. Software studies is the nascent field of research which best accounts for this larger nature of software that also provides perspective on why software matters so much in the twenty-first century—yet much of this realm does often focus a bit too narrowly on code in its studies. I am in particular influenced by the work of Kitchin and Dodge.

Kitchin and Dodge (2011) in *Code/Space* start by defining software as an artifact composed of lines of code—instructions and algorithms that along with inputs produce routines

and programs capable of enacting complex digital functions—for instructing computer hardware—the physical, digital circuitry of a computing system—to complete desired actions (p.3). Code is part and parcel of software, the textual expression of the idea and product. Software studies “focuses on the etiology of code” and how it makes digital technologies “what they are and shapes what they do” while focusing on the role of software in “social formation, organization, and regulation, as if people and things exist in time only, with space a mere neutral backdrop” (p.13). Software is a social and technical artifact that is shaped by the practices of those who create and use it while in turn simultaneously shaping these practices in an endless intertwined, iterative loop. Kitchin and Dodge emphasize how software studies differs from software engineering, computer science, human-computer interaction, information science, and media studies. Rather than focus on the individual cognitive or ergonomic, social communication, or economic transaction actions, software studies “focuses analysis explicitly on the conceptual nature, and productive capacity of software, and its work in the world, from a critical social scientific and cultural perspective” (p.246).

Kitchin and Dodge are geographers and from this orientation posit that software studies does not account for space. They express that “software and the work it does are the products of people and things in time and space” and stress that software thus has consequences for people in time and space:

Software is thus bound up in, and contributes to, complex discursive and material practices, relating to both living and nonliving, which work across geographic scales and times to produce complex spatialities. From this perspective, society, space, and time are co-constitutive—processes that are at once social, spatial, and temporal in nature and produce diverse spatialities. Software matters because it alters the conditions through which society, space, and time, and thus spatiality, are produced. (Kitchin & Dodge, 2011, p. 13)

Kitchin and Dodge's perspective is that software is much more than just code—one I wholly agree with. They stress that software is an actant in the world, that it “augments, supplements, mediates, and regulates our lives and opens up new possibilities—but not in a deterministic way.” Software “is afforded power by a network of contingencies that allows it to do work in the world” such that it can transform and reconfigure the world “in relation to its own systems of thought.” From their perspective this way of thinking about software enables me to begin to think critically about the nature of software and to consider not only how it works but where it works (Kitchin & Dodge, 2011, p. 44).

Mackenzie (2006) in *Cutting Code* also delves into such issues, positing that software undergoes “phases transitions” or changes of states, borrowing a concept from physics, such that it “solidifies at some points, but vaporizes at others” (p.2). Mackenzie's idea is in line with notions of infrastructure to me, as infrastructure becomes visible upon breakdown but merges into the background when it simply functions. He emphasizes the difficulty of representing and interrogating software as he examines code, treating code and coding as a material pathway through which to trace sociality. Enabling me to trace sociality is another reason why software matters to my study of work, and life today, in addition to Kitchin and Dodge's point that software does work in the world.

The characteristics of software as a material object, as a means of production, as a human-technical hybrid, as medium of communication, as terrain of political-economic contestation—in short as sociality—seem hard to represent. Software as a material with specificities, singularities, traits and modes of existence has been displaced by software as mundane application, as infrastructural element in a wider social or technological change (the information revolution, “digital culture,” “new media,” “network society” or “convergence”). (Mackenzie, 2006, p. 2)

Treating software as “mundane application” is exactly what I am attempting *not* to do in this dissertation. Software is not just some ethereal digital tool for accomplishing research goals.

It is the medium for cooperating with colleagues, working through problems, and expressing scientific methods. Furthermore, upending the notion that software as a digital product is not material is a key element of software studies work that is important if software truly shapes and is shaped by physical space as Kitchin and Dodge declare.

Kitchin and Dodge argue that with respect to software “social analyses tend to focus on the consequences of computerization, rather than how software emerges and does work in the world” before stressing again that software is “both a product and a process” (Kitchin & Dodge, 2011, p. 247). I concur overall with this critique having examined literature in software engineering, computer science, human-computer interaction, computer supported cooperative work, and science & technology studies. They stress that:

In designing and writing software, developers make, on the one hand, critical, ontological decisions about what to capture, categorize, and represent in the world. On the other hand, developers make epistemological decisions about the relations between *capta* [data] and how they should be processed to beckon into being actions in the world. Developers often unconsciously place a particular philosophical frame on the world that renders it amenable to the work of code and algorithms, thus realizing a specific system of thought to address a particular relational problem. (Kitchin & Dodge, 2011, p. 247)

In this dissertation I follow software and use this term rather than code because I wish to foreground this much larger milieu that code is a part of and helping to shape. Above and in Chapter One I have noted that software is a mutable set of relations created through diverse sets of practices. Software to me is an expression of beliefs and knowledge held by those who produce it. Quoting Berry (2011) in Chapter One I noted that I study software because it is the processual operating form of code because I am studying the unfolding of cooperative scientific work. The primary takeaway from software studies work for me is that software must not be thought of as a static product of work at one moment in time but rather as an assemblage of the different pieces of knowledge and practices of the particular times and spaces of its production

and use. I'll show how this plays out in this dissertation where the Radio group's particular research practices as individuals and a group are most immediately concretized in the software they are producing. This is a product of the physical spaces and coordinated work in Seattle over a discrete period of time. But at the same time I cannot ignore the larger spatial and temporal dialogues that shape their local work. I had to understand the global context brought in with their collaborators distributed around the Earth, the materiality and spaciality of the telescope they help to build and operate, and the physical structure of the Universe captured in the group's telescope data that is underwritten by the base of knowledge laid down in human history.

Now that I have conceptualized software and its importance to this dissertation I will turn to examine some computer science research on scientific software. This scholarship provides technology-development oriented visions and studies of the role of software in scientific research. Understanding this work is necessary so as to be able to understand what is missing when inquiries are oriented primarily towards technical concerns rather than a more all-encompassing sociotechnical inquiry.

Visions of big data and scientific software development

Software and digital computing are applied technological products of scientific research work. They arise out of, and have long been applied to, cutting-edge experimental scientific research work that requires the processing of numeric data that exceeds the unaided capabilities of humans (Ceruzzi, 2003; Ensmenger, 2010). Interest in pervasive and more powerful applications of software in scientific research has grown since the 1990s. As computing capabilities increased the quantities of data able to be collected, stored, and analyzed by researchers has led to the emergence of new visions for the conduct of twenty-first century science. These visions vary somewhat depending on the particular national context in which they are proposed and the

domain(s) to which they apply. Broadly they fall under the terms eScience, e-Research, Cyberinfrastructure, Data Science, Data-Intensive Science, or Big Data (Atkins et al., 2003; Gray, 2009; Hey et al., 2009; Lohr, 2012). A common theme across these visions are technical focuses on larger quantities of data and the role of computation and software in working with these data. What I see that is missing from all of this work is a connection between the perspectives on software and how scientists actually do their work, for this I will turn to science & technology studies research in a later section.

To many these ideas represent a veritable data revolution (Kitchin, 2014). Why should I care about these visions? How do they influence my study of a single scientific research group and their software? Primarily I simply need to be aware of these broad concepts and the trends associated with them since they are the organizing function under which significant streams of research funding support are being created and allocated (National Science Foundation, 2011, n.d.-a, n.d.-b, n.d.-c). These sociopolitical visions, generally focused on technical interventions, on the whole influence funded scientific research in the United States at this time, including that of the cosmologists who I study.

Each of these terms has many varied, broad definitions (if a coherent one is even offered or remotely agreed upon). Across each term are a couple of common concerns—see (Kitchin, 2014) and (Borgman, 2015) for overviews. First, these endeavors emphasize the application of advancing computing technology that enables faster processing, the transfer and storage of larger and larger quantities of data, and importantly the visualization and analysis of sometimes-disparate datasets. Second, the overarching goal of many of these endeavors is to develop software systems that can be applied across as many domains of scientific research as possible regardless of existing research practices. Overall, each of these terms and the agendas driving

them is rooted in the development and application of advancing computing technology and larger quantities of data. For brevity I use the term eScience to encompass these technology-oriented visions since much of the advocacy for these endeavors has been tied back to this term (although Data Science has become the trendier moniker in 2016).

There are many pursuits as part of eScience work today. Many of these pursuits work to build the generic and widely useful systems of eScience visions. One important stream of research directly connected to this dissertation is different. This is work studying the development of software by scientists themselves. Typically referred to as “scientific software development” and at times “software engineering for science.” This research in computer science is the most germane work from these technical fields for this dissertation.

Scientific software development, the downfall of the scientific method?

What are the impacts of software on the results of scientific research? This is a natural question to me that should be asked if software is so prevalent in science and if software does so much work in the world. Editorials and opinion pieces in a variety of venues raise concerns about the implementation of algorithms influencing results, whether the software used to produce a finding is well-tested or at least openly shared for inspection by other researchers, and provide examples of retractions of erroneous findings traced back to flawed software (Goble, 2014; Ince et al., 2012; Marwick, 2015; Merali, 2010; Miller, 2006; Stodden, 2012, 2013; Stodden et al., 2012). In short, from these perspectives software is potentially invalidating scientific studies when the software scientists create is held up to different unstated standards for quality. These commentaries all call for improvement in scientist’s software development practices by encouraging scientists developing software to draw from the professional practices found in the profession of software engineering. To improve practices, it is necessary to first understand what

scientific software development and software engineering practices are. Only then can a scientist determine whether they are applicable to their research or not.

Computer scientists studying scientific software development generally either investigate scientists developing software on their own or collaborations between domain scientists and professional software developers (Carver et al., 2013; Carver, 2012; Carver et al., 2007; Goble, 2014; Hannay et al., 2009; Heaton & Carver, 2015; Kanewala & Bieman, 2014; Kelly, 2007; Kelly, 2015; Morris & Segal, 2009; Nanthaamornphong & Carver, 2015; Segal, 2008a, 2008b; Segal & Morris, 2011; Wilson, 2006). Scientific software is considered by these scholars to be different from other general purpose software because of its express purpose for use in research work. Kelly (2015) nicely defines scientific software as “application software that includes a large component of knowledge from the scientific application domain and is used to increase the knowledge of science for the purpose of solving real-world problems.” Her definition contextualizes what this realm of scholarship is examining, and the majority of the software investigated in this dissertation, so why then does this scholarship even matter in this dissertation?

Why is scientific software development different from other software development?

Research on scientific software development (SSD) as an organizing, emerging discipline can be found back to the mid 2000s. Through qualitative studies of projects and surveys of practitioners, computer science researchers have created a body of work that juxtaposes the software development practices of scientists with those articulated by software engineers. Out of this work I see a couple of general findings that could apply to this dissertation. First is that scientific software development unfolds differently when compared with formal industrial software development projects, but scientists have often recreated these engineering practices on their

own. Requirements for scientific software—the needs or purposes it is being developed to address—are emergent and thus making use of some software engineering practices is difficult or not possible. Second, the practices of testing scientific software are noted to vary widely; at times notions from software engineering are adopted and adapted while at other times they are not thought about at all.

Research on SSD first and foremost demonstrates that scientist's development practices are not those of formal software engineering. Hannay et al.'s (2009) survey of almost 2,000 scientists is widely cited as evidence for scientist's lack of knowledge regarding software engineering practices. Software engineering work is based upon practices such as requirements elicitation, software architecture and design, design patterns and refactoring, and testing procedures because these activities have contributed to successful software products (Grubb & Takang, 2003; Larman, 2005; Leffingwell & Widrig, 2003; Wysocki, 2006). Finding that scientists are not aware of such practices, let alone employing them, is raised as a cause for concern by Hannay et al. in their paper. The findings of this survey provide an overall context for noting that SSD is not the same as software engineering but the authors do not try to offer a conceptualization of how scientific software development unfolds in practice. Carver (2012) at a later time notes that not only does scientific software development not follow traditional software engineering "best practices" but that in many cases the best practices are not applicable without "significantly tailoring and adapting them." To understand how scientists are developing software, and how this is different from software engineering best practices, I turn to other scholarship.

Judith Segal's extensive work provides some of the earliest field studies of scientific software development (Segal, 2005, 2008a, 2008b, 2009; Segal & Morris, 2008, 2009, 2011).

Her studies of scientists developing software illustrate that this work unfolds in an incremental and iterative manner in a model that runs “counter to any traditional model of software engineering” where a piece of software is produced then some reflection about its functionality takes place (Segal, 2008a)—that traditional software engineering model being a very rigid, one step after another approach with no revisiting of earlier activities in the idealized Waterfall model derived from defense industry approaches to project management (Wysocki, 2006). Segal notes that there is no traditional phase of requirements gathering or much formal testing taking place. Instead, scientists assess their software based on its manipulation of the data and their expectations of the results. Segal summarizes her findings of scientist’s development practice as: 1) produce a piece of software then 2) reflect on its operation. This reflection consists of simply asking “does it do what I want? Can it be improved?” and so on iteratively until scientific results can be produced and published (Segal, 2008a, p. 2).

Segal’s straightforward conceptual model captures the practices of scientific software developers at a high level but leaves me looking for more nuanced examples when examining the work of particular research groups. This model does however align well with the Agile approach to software development that emerged in the early 2000s as a rebuke to traditional models of software engineering work (Agile Manifesto, 2001). The Agile approach emphasizes creating working software rather than formal documentation—since the traditional Waterfall model is derided as overly emphasizing creating documentation—by delivering actual working software rapidly and often with minimal upfront design and documentation, testing as new product is created, and encouraging regular reflection by the team producing the software (Cohn et al., 2009 offer a useful overview in their CSCW study of two Agile projects). Heaton and Carver

(2015) discussing their systematic literature review of SSD research note that scientists have “to a large extent, unconsciously” adopted this Agile approach.

Like Segal’s work other scientific software development research illustrates that requirements are emergent (Heaton & Carver, 2015; Nanthaamornphong & Carver, 2015; Sletholt et al., 2011). Up front requirements gathering and system design work are the traditional hallmarks of a well-organized software development endeavor (Larman, 2005; Leffingwell & Widrig, 2003). Unlike commercial software development, scientific research does not always begin with a clear end point visible. As the scientific software development research illustrates a better idea of the goal and thus how to get there is formed as problems are tackled and mistakes made. Importantly, Segal emphasizes that there are “at least some situations” in which the “full machinery” of software engineering practices shouldn’t be applied to scientific software development (Segal, 2008a). Knowing that requirements are emergent and the work is not the same as traditional software engineering I ask yet again just how should software development work by scientists be viewed? It is surely not just about the technical end product.

Revisiting Kelly (2015) I find a more expansive and reflective consideration of scientific software development. Kelly advocates a shift in understanding scientific software development from a perspective where the product is the software to one where the end product is the scientist’s knowledge. She does this by positing a model of knowledge acquisition used by scientists when developing software. This model delineates five types of knowledge associated with scientific software development work: real world, theory-based, software, execution, and operational. This categorization is explicitly only associated with software although the first two types (real world and theory-based) are the scientific knowledge to be captured and worked with by the software. The specific categorizations are not however what I find important here in this

dissertation. Rather it is the larger shift in viewpoint towards a broader view of scientific software development. This begins to align this type of work closer to the perspective I take on such work—namely one of socially constructed knowledge and infrastructuring where software is a novel product of the cooperative work. Kelly summarizes this well stating:

In our model, the act of developing the software contributes to the scientist's understanding. Developing software is not solely a means of producing an executable. For the scientist, recording the understanding after refinement ultimately takes place not only in the software code, but in scientific reports and other products based on the scientist's acquired understanding. This is a much broader view of "software development" that includes as an end product, the increased knowledge of the scientist, the answer to the scientific question, the reports and products associated with the answer to the scientific question, as well as the software executable. (Kelly, 2015, p. 55)

I have now briefly shown that scientific software development research differentiates this mode of software production from that of traditional, industrial software projects. Requirements and the end goal for a piece of scientific software are known to be fuzzy at the beginning of the project and clarified over time. Shifting to thinking of the end product of this work as knowledge ought to help a scholar move from examining primarily technical concerns to studying the sociotechnical where the social milieu that this work is a vital part of is accounted for.

There is one other key piece to scientific software development scholarship that concerns me in this dissertation. That is the testing of software. These findings are relevant to my examination of the Radio group's use of plots that I introduced in Chapter One and how they test their different pieces of software as they engage in their data analysis.

Developing and testing scientific software

Developing software is fraught with error and testing what is built is a fundamental activity to this work. Much of the scientific software development literature examines the testing practices of scientists and compares them to those espoused in software engineering (SE) as a way to

characterize how SE methods are or are not adopted. Testing is of course necessary to not only confirm that the software produced even runs but is operating and behaving as expected, or when it does something unexpected to help clarify what is taking place. In this dissertation I show the Radio group's rigorous and detailed process of testing their software that is intertwined with their scientific data analysis using plots (the focus of Chapter Seven). I will compare and contrast their plot-driven work with the software engineering and SSD practices that I examine here.

How testing is accomplished is an important point of examination since the scientist needs to understand how their software functioned if they are to be able to assess their scientific results. Understanding how testing is accomplished is vital to not only understanding how software is a product of their local research work but also importantly how their scientific knowledge is rigorously produced and accepted in the larger context of their cooperative work and scientific discipline. One starting point is with Segal's model above where she describes how results are compared against expectations, but I want to look at this issue in more depth starting by asking how do software engineers test their software products?

Software engineers have developed many different types of testing. These include black box and white box, integration, regression, and unit testing among others (Agile Alliance, 2013; Grubb & Takang, 2003). Black box testing provides an input and expected output for a software function and evaluates the result without inspecting the code while in contrast white box testing would inspect the code. Black box testing involves writing tests based on the formal specification of the expected behavior where as white box testing verifies the actual written code. This is necessary since either the specification for the black box test or the actual code tested by the white box test may not be correct for the actual end goal (Grubb & Takang, 2003, p. 190). Integration testing on the other hand tests the functionality of combined elements of the software

since the system's behavior may not be what was expected when different components are brought together. Regression testing in turn evaluates the effect of a change to some part of the code against a previous version of the software and test results. Both of these testing practices enable the software developer to evaluate the functionality and operation of the system over time as changes are made across different components while hopefully not re-introducing old errors (Grubb & Takang, 2003, pp. 191-192). Each of these approaches is predicated upon particular practices for creating and performing tests in conjunction with various software tools to automate this work.

Finally, unit testing is the practice of taking a small segment of a piece of software—a unit—and writing a test that will confirm its functionality based on the expectations for the unit (Agile Alliance, 2013). Different languages for developing software often have their own automated unit testing framework (e.g., JUnit for the Java programming language, <http://junit.org/>) that enables repeated, automated executions of tests so that a developer is quickly and easily made aware of faults. Because of the automated and repeatable design of unit tests software engineering approaches encourage their use for black box, integration, and regression testing. A recent prominent approach to developing software advocates writing unit tests up front before any code is written—known as Test-Driven Development (Beck, 2003)—so that the developer sets the expectation for the software's operation from the beginning. All of these testing approaches allow software engineers to assess how the software that is being produced does or does not meet their expectations as they conduct their work. These approaches all seem beneficial in the production of software. This is why SSD scholarship expends a fair bit of effort assessing how they are or are not used by scientists in their software production.

In recent years there have been multiple literature reviews of scientific software development that discuss testing practices (Heaton & Carver, 2015; Kanewala & Bieman, 2014; Nanthaamornphong & Carver, 2015; Sletholt et al., 2011). First and foremost Nanthaamornphong and Carver (2015) state that if scientific software developers do use a variation of software engineering testing practices then they use unit testing, regression testing, and integration testing. Heaton and Carver also point out that some scientists do not use formalized testing practices. Looking at scientific software developers using any of the three testing practices the question then becomes what challenges or concerns are there with these practices?

These literature reviews point out the mismatches or difficulties of scientific software testing compared with software engineering practices like those discussed above. Sletholt et al. (2011) point out that scientific software is hard to test because of emergent, iterative creation of requirements. This would hinder black box testing approaches since more than likely a specification is not fully formed in advance. Without a clear specification it is hard to write tests to evaluate a piece of software's conformance to that specification. One of Kanewala and Bieman's (2014) research questions in their systematic literature review asks if there are special characteristics to scientific software that makes it difficult to test. They find two main categories of characteristics "(1) Testing challenges that occur due to characteristics of scientific software, and (2) Testing challenges that occur due to cultural differences between scientists and the software engineering community" (Kanewala & Bieman, 2014, p. 1224).

Looking at challenges due to the software itself Kanewala and Bieman identify many issues. These include not knowing what tests to create due to a lack of real data, difficulties creating feasible sets of tests due to the scale of the software, the sheer complexity of the

scientific functions or algorithms implemented in the software make testing difficult or impossible, or perhaps most importantly the fact that the output can't yet be known because the knowledge is at the boundary of what is known so only approximate answers may be possible to produce. If there is not data available or the output has to be approximate then it is hard to write unit tests that will enable black or white box, regression, or integration testing. The authors also note challenges stemming from limited understanding of software engineering testing concepts and associated processes as well as challenges due to not applying known testing approaches (Kanewala & Bieman, 2014, pp. 1224-1226).

Research discussing SSD and how testing is accomplished illustrates broadly that adopting or adapting software engineering practices is not necessarily an easy task. This provides an opportunity to reframe some of the conversation regarding the role of software in scientific research—what I endeavor to do with my discussion in Chapter Seven regarding plots. Examining scientific software testing practices using visualizations is not unprecedented. Easterbrook and Johns (2009), for example, briefly note that in their study of climate modeling software development visualizations are in part how these scientists test their complex software models. SSD scholars recognize that this work is not and cannot be software engineering work exactly yet they still express concern about software's role in science. In a recent editorial Goble (2014) comments on Hannay et al.'s (2009) survey findings about the lack of testing. She finds the expressed lack of understanding or interest in formal software engineering training worrying, commenting: “[t]his is strange because presumably they wouldn't use and trust the results of a microscope or telescope that hadn't been built by qualified engineers or tested. Yet software is the most prevalent of all the instruments used in modern science.” Goble's point is important and reasonable. She advocates for more funding and better training for scientists producing software

since better software would produce better science, and this is not something funders should leave to individuals whose primary training and job responsibilities do not revolve around software development.

I take away from SSD research to date that it is not possible to compare industrial software development to scientific software development. Yet Goble and other scholar's discussions to me minimize their own community's findings that I just examined since they are primarily focused on seemingly deficient technical practices in SSD. I see a gap here in how software production in science is conceptualized. What I am showing through this dissertation's narrative is that producing software is the scientific work. Members of the Radio group cannot do their scientific work creating knowledge about the Universe without creating software. Producing software isn't some secondary activity, it is the scientific work. I think that part of what is missing is a sociotechnical understanding of the social construction of knowledge that recognizes how locally constructed knowledge is adopted in a global context. For this I turn to science & technology studies scholarship.

Social studies of science and technology

Sociological studies of science and technology are active and diverse streams of research. Sociology of science (often referred to as science studies) and sociology of technology are allied in the broad realm of science & technology studies (STS) (Pinch & Bijker, 1984). Such work also often overlaps and connects with research in anthropology, philosophy of science, and history of science and technology. Scholarship in STS unpacks the production of knowledge to surface the different actors engaged in this work and their socially constructed practices that guide and shape scientific facts or the production of technological artifacts. I would expect that software would be one such artifact but interestingly software is not well investigated in STS

studies—one excellent example however being (Ensmenger, 2012). This is a major hole that needs to be rectified given the pervasiveness of software today. Biagioli (1999a) notes that STS work “tends not to ask what science is but rather how science works” while pointing out that the boundary between asking what and how is not clear-cut. It is the how of science that I am concerned with in this dissertation but this boundary is indeed difficult to draw at times.

The vast body of research in STS is too extensive to cover in any one volume, let alone this dissertation, the volumes *The Science Studies Reader* (Biagioli, 1999b), *Ecologies of Knowledge* (Star, 1995b), and *An Introduction to Science and Technology Studies* (Sismondo, 2004) cover the realm extensively. For my purposes here there are a couple of key themes in this field. STS helps when asking questions such as: How is knowledge constructed in science? How do local practices from a laboratory or group extend outward to the global community? What concepts have been examined about physics and astronomy?

STS scholarship helps when examining and revealing the varied cultures and machineries that make up twentieth and twenty-first century scientific practice. In particular, there are threads of work focused on high energy physics and optical astronomy research that I needed to be aware of while studying a cosmology research group since they provide some context for my understanding of the Radio group’s work. Drawing upon this scholarship will help me to be able to better characterize software in scientific research as something more than simply a technical practice or concern. STS scholarship also informs much of the work in computer supported cooperative work that studies scientific collaboration and infrastructure development.

Explaining how scientific knowledge is constructed

Science & technology studies scholarship is focused on science in the making, examining the work practices and artifacts of scientists to ask how is scientific knowledge produced? Pinch

(1985) notes early STS studies examine either “episodes of scientific dispute” or individual laboratories to provide detailed accounts of the “nuts and bolts of scientific activity” to explain how knowledge is produced. This is in contrast to other discipline’s work to explain what knowledge is or that offers realist conceptualizations of facts such that facts are facets of nature just waiting to be uncovered. STS studies of scientific research work examine local research practices using various ethnographic methods and provide thick descriptions of this contextually situated work along with the practices that enable a fact to be produced and acknowledged by a scientific community (Fujimura, 1987, 1996; Garfinkel et al., 1981; Knorr-Cetina, 1999; Knorr-Cetina, 1981; Latour, 1987; Latour & Woolgar, 1986). This work very much informs my orientation to studying scientific research.

The production of a scientific fact is an iterative process of taking the natural or real world and transforming it through a technology—anything from pencil and paper to complex instruments such as telescopes—into a material that can be worked with and transferred across contexts. It is a process of bounding and constraining messy reality into a form that can be reliably evaluated and understood, all while maintaining validity with the messiness. Scientists work to have their local, contextually situated findings translated into a global context through the dissemination of material products (most commonly publications) and engage in different relationships to develop and sustain their power and influence within or across disciplines. Many studies of laboratory work explore these issues, whether to develop accounts of particular contingent research endeavors as the Garfinkel et al. and Knorr-Cetina examples below do or to attempt to develop a generalized framework for understanding science as the work of Latour and Woolgar does.

Garfinkel, Lynch, and Livingston (1981) explain how an optical pulsar was discovered by examining the tapes and logs of an observation session to explain how the scientists “extract a cultural object” from the “local historicity” of their night’s work. This cultural object is the mechanism through which the “apparent” pulse in their data collection becomes an “increasingly definite thing” as worldly objects and embodied practices are intertwined (p.137). Knorr-Cetina (1981) uses a manufacturing metaphor to explain how scientists in the laboratory reason through problems as they sustain the contextuality of their work through resource relationships as products are created, ultimately resulting in the “removable and removed ‘end-product’ of research” the scientific paper. Negotiations among individuals, groups, and organizations are ongoing and necessary for a given laboratory to successfully conduct experiments and produce knowledge from them. Latour and Woolgar (1986) in *Laboratory Life* and Latour (1987) in *Science in Action* describe the documents and other materials of scientific work as “inscriptions,” or “inscription devices” as they define instruments, to explain how researchers go about their work creating chains of evidence that are mobile across contexts over time. Mobilizing allies to one’s inscriptions is necessary to build support for one’s facts so that it can be stabilized to the point that it is black boxed and taken as fact without question. Summarizing these three veins of work and their highly technical skills and complex instruments Lynch (1985) states that “what laboratory scientists perceive and work upon is thus artificial in the extent to which its appearance depends upon such technologies.” Scientific knowledge production is an always locally situated endeavor that must put forth effort to translate knowledge across and among contexts to produce a better understanding of nature through socially constructed representations.

For me and this dissertation what is important is that this work illustrates facets to scientific knowledge production and a fair amount of this research puts forth an ecological

approach to knowledge production. An ecological approach to knowledge production moves past the typical dichotomies of social versus nature or social versus technical and tries not to adopt the perspective of a single actor. The ecologies of knowledge orientation simply means “trying to understand the systemic properties of science by analogy with an ecosystem” such that using the term ecological foregrounds a refusal of the “social/natural or social/technical dichotomies” (Star, 1995a, p. 2)—in essence a sociotechnical orientation. This ecological perspective in turn is a fundamental element of the infrastructure studies work that I draw upon, as I will explore later in this chapter. I will also note that while my data collection was oriented primarily around the work of the Radio group—see Chapter Three—I do endeavor to capture information from the larger telescope collaboration they work with through mailing lists and document repositories in addition to some observations of teleconferences. I also try to represent the perspective of the various individuals of the group who each bring their own backgrounds, concerns, and practices to this milieu.

Fujimura (1996) in *Crafting Science* presents a sociohistory of the development of the oncogene theory in cancer from an ecological perspective that I find provides a coherent way to think about the local to global shift of scientific knowledge across a discipline and into the larger sphere of the public. She examines how a problem becomes “doable” and helps us “understand the processes of constructing, stabilizing, and changing knowledge” through multiple notions that “address how tools, practices, and theories are co-constructed, incorporated, and refashioned in a continual process of negotiation” (p.16). Co-construction in Fujimura’s work is the process of scientists continually “shaping and adjusting materials, instruments, problems, theories and other representations, and social worlds as well as themselves and laboratories” to produce knowledge (p.207). This notion of social worlds “ascribes meanings, commitments, and

perspectives in knowledge-making both to practices and to the people practicing them” (p.12), drawing upon earlier sociological work (Becker, 1982; Gerson, 1983; Strauss, 1978). These elements of science are shaped and adjusted so that they will mesh with one another such that in each situation “a problem is constructed and solved through the interactions that articulate and weave together practices in experiments, laboratory organizations, and multiple social worlds” such as laboratories, fields of research, disciplines, and so on (p.211). Through this work coherence is achieved locally among tools and resources, representations of nature, and the demands of audiences (e.g., those of hiring committees or funding agencies) and extended across contexts through standardized packages that link theory and methods. This theory-method package “represents the flow of resources (concepts, skills, materials, techniques, instruments) along multiple lines of work” (p.222).

Looking at packages in more detail Fujimura (1992) defines the concept as consisting of “a scientific theory and a standardized set of technologies which is adopted by many members of many social worlds to construct a new and at least temporally stable definition” of a phenomenon (p.169). In her case this is the entire notion of cancer and the ensuing line of research. Packages are comparable with another widely adopted STS concept, that of boundary objects offered by Star and Griesemer (1989). Boundary objects are a mechanism for examining cooperation among researchers working together on a shared problem who come from different social worlds. These researchers need to have a shared representation of a phenomenon to accomplish their work, at least temporarily, so that coherence among their different goals can be achieved and the project completed by translating relevant information across boundaries. Star and Griesemer discuss work in a museum of vertebrate zoology to illustrate the necessity of

standardized methods of producing specimens for scientific knowledge to be produced and how the stakeholders accomplished standardization over time.

Fujimura (1992) states that Star and Griesemer argue that cooperation “is necessary to create common understandings, to ensure reliability across domains, and to gather information which retains integrity across time, space, and local contingencies” without presupposing consensus about a fact (p.172). In contrast, her notion of packages is different from a boundary object since a package:

defines a conceptual and technical work space which is less abstract, more structured, less ambiguous, and more concrete. It is a gray box which combines several boundary objects (gene, cancer, oncogene or cancer gene) with standardized methods (in this case, recombinant DNA technologies) in ways which further restrict and define each object. Such codefinition and corestriction narrow the range of possible actions and practices, but also do not entirely define them. ... Simultaneously, however, a standardized package is also similar to a boundary object in that it facilitates interactions and cooperative work between social worlds and increases its opportunities for being transferred into, and enrolling, other worlds; it serves therefore as an interface between multiple social worlds. (Fujimura, 1992, p. 176)

I see the goals of the packages notion as an interesting and broadly useful way of framing the work of a discipline and various researchers within it. The notion of boundary objects has been adopted far more widely, especially in computer supported cooperative work, compared with the packages concept—probably because the boundary object concept is intentionally less restrictive than Fujimura’s. However, if I am trying to understand the larger organizations of a large-scale, distributed, collaborative scientific project and its situation among other research endeavors Fujimura’s packages notion is relevant as I examine how software is a novel product of research work because of this codefinition and corestriction of an overall “work space.” This brings me to the final perspective that I wish to discuss in this section, that of Knorr-Cetina’s epistemic cultures.

Knorr-Cetina's (1999) book *Epistemic Cultures* explores work in a biology laboratory and in high energy physics. Knorr-Cetina foremost states that in contrast to earlier STS studies she is "interested not in the construction of knowledge but in the construction of the machineries of knowledge construction," the epistemic machineries and cultures (p.3). This work instead looks at the enterprise of science through these two cases since the enterprise has a "geography of its own" such that it is not one singular enterprise but many that constitute an entire landscape or market "of independent epistemic monopolies producing vastly different products" (p.4). I find that this is an important point to keep in mind when pondering the scientific software discussed earlier. Researchers in that field already recognize that scientific software development is not the same as software engineering and I believe it is important to remain cognizant that across the different types of scientific research the production of software will also remain varied, as different epistemic commitments manifest as methodological differences that alter the shape that software takes in these social worlds. It is also important not to forget that software is bound up in and contributing to these complex discursive and material practices as Kitchin and Dodge describe.

In her book Knorr-Cetina uses the term culture to refer "to the aggregate patterns and dynamics that are on display in expert practice and that vary in different settings of expertise" such that culture refers back to expertise in a specific way (p.8). Culture in this book is used to foreground the "machineries of knowing composed of practices" that differ vastly between biological laboratory science and that of high energy particle physics. She posits that the notion of culture adds "something" to the idea of practice such that it implies ruptures in any uniformities, and these ruptures are important "because they suggest the existence of different technologies of knowing serving different substantive, technological, and economic ends" (p.10).

Culture also brings to mind “a certain richness of ongoing events” that can be thought of as “a thick growth of variegated patterns piling up on top of one another” (p.10).

Knorr-Cetina’s definition of culture is not all that dissimilar to common conceptualizations of the term. One of many definitions in the Oxford English Dictionary (2008) being “the distinctive ideas, customs, social behaviour, products, or way of life of a particular nation, society, people, or period” for example. The more precise definition offered by Knorr-Cetina is useful when examining scientific research work since the knowledge, expertise, and practices under examination are highly contingent upon different epistemological orientations. Culture of scientific disciplines is also commonly examined, for example Galison (1997) and Traweek (1988) similarly discuss the varied cultures and subcultures of high energy physics although they do not seem to offer as specific of a definition of the term as Knorr-Cetina.

Knorr-Cetina’s notion of culture is useful when considering the Radio group’s work in this dissertation since they are creating practices within their own group, and thus forming a group culture, while being intertwined with the larger multinational telescope collaboration’s emergent practices and culture, let alone those of physics and astronomy broadly. As I will show their software is a particular instantiation of knowing that shapes and is shaped by the larger telescope project’s culture. Knorr-Cetina states that “knowledge systems, in particular, appear like density regions of the social world” and involve multiple “instrumental, linguistic, theoretical, organizational” and other frameworks (p.10). My exploration of the Radio group’s work will focus on the instrumental and organizational framework produced in particular.

Scrutinizing knowledge production in particle physics and optical astronomy

Having examined broadly how STS scholarship explains scientific knowledge production I want to now briefly examine what this field has to say about physics and astronomy. There are many

aspects that could be examined in STS and related fields such as anthropology and history of science. For this dissertation there are a few important connected themes regarding the cultures in these fields when building and using instruments, publishing findings, and crafting images.

Physics and astronomy research are intimately connected yet often focus on phenomena of vastly different physical scales and temporalities. Science & technology studies work studying these fields focuses on either high energy physics (HEP) or particle physics (I use the two terms interchangeably here), or optical astronomy. High energy or particle physics studies miniscule and short-lived phenomena created in the present. Optical and infrared astronomy studies massive and long-lived phenomena that took place long ago. What then does STS scholarship tell me about this research?

High energy physics

Scholarship examining high energy physics (HEP) is wide ranging and draws upon various methodological traditions. Sharon Traweek's (1988) ethnographic volume *Beamtimes and Lifetimes* dives into the world of high energy physics in the United States and Japan throughout the 1970s and 1980s. She eloquently describes what it is like to be a particle physicist working as part of large collaborations, spending years developing an experiment (the lifetimes of careers) to collect data on exceptionally short lived phenomena (the beamtimes of particle accelerators). Peter Galison (1997) in *Image and Logic* provides an extensive historical examination of microphysics in the United States as it emerged and grew from the 1930s onward into the particle physics of post-WWII research by explicitly tracing the development of different instruments. In particular, two competing traditions, the logic and the image traditions of his book's title, through which he explains the material cultures and experimental practices that these different veins of research produced. Karin Knorr-Cetina (1999) in turn examines the high

energy physics (HEP) of the ATLAS experiment at CERN in her volume *Epistemic Cultures*. She explores the large-scale, distributed organizational structures of this project to shift the perspective from individual researchers to that of the communitarian structures creating the epistemic machineries of the project.

Traweek, Galison, and Knorr-Cetina's volumes, let alone other work, all lay out different nuances to the diverse cultures and subcultures in high energy and particle physics. Common across all is the recognition of a shift over decades from individual-driven research programs to conspicuously cooperative work where a variety of different research cultures and subcultures cooperate to accomplish shared goals. Whether focused on temporality of experiments and careers, the material and experimental practices, or the epistemic machineries these volumes illustrate an overall culture of cooperative work to do science in particle physics. Doing experimental HEP research involves contributing to a large project, cooperatively building instruments then collecting and analyzing data. Career paths and academic organizational structures have been crafted to function in this manner in high energy and particle physics. This is visible in the changes to authorship on publications in HEP.

High energy physics began to see norms of authorship change as early as the 1930s. Galison (1997) points out that "only between 1930 and 1945 had predominantly individual research and authorship dwindled, as equipment grew larger, more expensive, and hard enough to handle" such that teams of workers became a necessity in conducting experimental physics work (p.299). As HEP projects grew in size formal rules were crafted governing who was included on papers, in what order, and where and when a member of the collaboration could speak about findings resulting in a "typology of prestige" where the sets of rules "made visible invisible forces that had long governed the intricacies of credit and demonstration" (p.628).

Contributing to the design and development of an instrument was deemed worthy of inclusion on the publication of results, a change in practice from past projects. Credit was given and new career pathways created in recognition of contributions to the large-scale experiment and collaboration.

Knorr-Cetina (1999) describes this gradual shift in HEP as “the erasure of the individual as an epistemic subject” (p.166) such that naming “then, has shifted to the experiment, and so has epistemic agency—the capacity to produce knowledge” (p.167). No longer is it the individual scientist toiling in their laboratory who is recognized as working to produce knowledge. For example, the very recent LIGO gravitational waves finding has as the publication’s first two authors the names of collaborations rather than individuals (Ligo Scientific Collaboration et al., 2016). Instead it is the collective efforts of large teams and groups. Birnholtz (2006) similarly studies a high energy physics project to tease apart what it means to be an author in such “hyperauthored” papers.

The shift from the individual to the collective as instrument building efforts grew in scale is important to note in this dissertation. The Radio group’s work is astronomical in nature—probing the past of the Universe—yet as I will show in Chapters Four and Five the organization of the Widefield Radio Telescope project favors the collective in many ways, rather than traditional astronomy projects favoritism of individual researchers. At first glance it seemed to me as if this project was astronomy-focused but organized like a particle physics endeavor. This was not entirely the case though as I examined literature on optical and infrared astronomy and their cultures.

Optical astronomy

Optical astronomy in contrast to HEP has research cultures and traditions that reward the work of individual scholars, or small teams. Patrick McCray (2000, 2004, 2014) offers extensive historical studies of astronomy in the United States from post-WWII through the 1990s. His volume *Giant Telescopes* (McCray, 2004) traces the development of various high profile optical telescopes with ever larger mirrors that open up more of the sky to investigation. The research culture in post-WWII United States astronomy favors the individual scientist. Universities build telescopes and own the observing time with these instruments, with access to the instruments favoring scholars who are employed by these institutions. Individual researchers could therefore collect and analyze data to be able to publish papers, establishing a career over time. Garfinkel, Lynch, and Livingston (1981) offer an STS study of an observational discovery in this mold, examining the work of individual researchers in the process of using an instrument for their data gathering.

McCray (2004) points out the United States eventually began to fund national optical and radio astronomy observatories that opened up access to instruments to any academic who wrote a successful proposal for observing time (not to say that there was not a significant amount of politics in this work still). These national observatories would end up in competition with different privately funded telescopes—stories that I do not have the space to dig into here but are worth reading. As larger and larger telescopes were built over time they shifted from being single sited instruments to distributed and digitally connected “hyper-telescopes” requiring coordination and central planning of observing sessions. Proposals for observing time had to be submitted and mapped out in detail if scholars wished to use these new giant telescopes, an outgrowth of the operational design of NASA’s space-based instruments and akin to some

particle physics experimental work. Observing time in space-based and hyper-telescopes was still allocated primarily to individual scholars, but a shift took place such that astronomers were no longer at the controls of the instrument. Instead they ceded this responsibility to technicians who took the planned observations and ensured they were conducted in a manner that optimized for the available weather conditions and other factors. This shifted responsibility and authority for the actual observing away from the scientists who would analyze the data.

Overall, McCray (2000) stresses that for optical astronomers “two of the most important assets are access to telescopes and sufficient time allocated on them to make observations and collect data” in the moral economy of this field (p.685). Cooperation to build these instruments is necessary, as it is in high energy physics research. However, the culture of optical astronomy was still primarily to support and reward the efforts of individual scholars collecting and analyzing their own data, rather than a cooperative and collective endeavor like HEP. The differences in culture also surface by comparing the forms of publication authorship between these two disciplines as well.

Above I noted how HEP projects shifted toward a publication model where the collaboration or collective receives primary credit, rather than the individual. McCray (2004) in contrast points out that “most publications of contemporary astronomers, unlike particle physicists, are not written by scores of authors whose individual contributions are difficult to determine” (p.293). He notes that the average number of authors on astronomy papers rose from 1970 onward but by the year 2000 was still just under four. Compare this to HEP papers which may have author lists including more than a thousand individuals.

This difference in authorship vividly illustrates just one piece of the cultural differences between high energy physics and optical astronomy research. This variation is important since it

foregrounds the difference in scope of cooperation and authorship that scholars in these fields expect with regards to data analysis and of course the resulting publication. High energy physics over time has created and accepted a culture where collaborations receive credit and individuals in turn are recognized for their contributions to the collaboration. Astronomy on the other hand is generally rooted in collaboration around instrument building but less so when it comes to data analysis and publication. I see this as an interesting gulf between these two fields with diverging spatial and temporal phenomena of study. Especially in light of how I have seen that the Widefield Radio Telescope project is organized as a scientific collaboration. Before I discuss this gap I need to briefly touch upon the creation of digital data and images in these fields.

Collecting digital astronomical data and creating images

Physics and astronomy instruments have long produced high volume streams of digital data (Djorgovski, 2011; Galison, 1997; McCray, 2004, 2014). In astronomy the digitization and computerization of data (away from physical photographic plates) shifted the practices surrounding the production and use of data. Digital data is far more transportable than that captured on photographic plates while also being amenable to new techniques of processing and analysis, opening up new possibilities for research work long after the data was originally collected. When working at the cutting edge of any experimental work it has long been known that “sophisticated electronics and data analysis have to be employed” to successfully conduct research (Pinch, 1985)—a point that is today still entirely valid regarding the Radio group’s work, although much of the sophistication has shifted from the electronics to the software. The successful collection of data and creation of images is a central component of the scientific work. So how are astronomy images created and standardized?

Lynch and Edgerton (1988) examine digital image processing work in astronomy to assess the extent to which aesthetic decisions are a part of the work of doing this science. The authors examine issues such as correcting instrumental errors with CCDs, the use of color or false color representations to illustrate phenomena not visible to the human eye, and how objectivity in the data is balanced against the transient conditions of the observing situation itself. Lynch and Edgerton posit that the work of expressing the phenomena captured as manipulated through image processing machinery and software requires a “hands-on process” of interpretation. This perceptual process is how, in the words of one of the astronomers, individuals develop a program for “seeing the physics” (p.212).

Vertesi (2015) recently put forward the concept of “drawing as” to explain how researchers working with the NASA Mars rovers craft images using data from the different instruments built and sent millions of miles through space to the Red planet. She emphasizes that in science visualization is “not a question of creating an ever truer or more singular image of an object.” It is instead “a practical activity of *drawing* a natural object *as* an analytical object, inscribing a value into the very composition of what that object is and what makes it interesting” (p.103, emphasis in original). Images or visualizations are specific products of knowledge making practices, the end-product inscriptions of Latour’s (1987) inscription devices.

How images represent phenomena and come to represent the practices of scientific work is an interesting and well covered area of research. In this dissertation this type of concern intersects with the earlier question of how scientists test their software that scientific software development researchers focus on. Chapter Seven examines how the Radio group creates plots and most importantly in my analysis uses them to do scientific analysis and software testing

simultaneously. For the moment there is one other facet of STS scholarship on astronomy images I discuss, that of how astronomers digitize the sky and store data in standardized formats.

Producing digital data with telescopes necessitates some format for it to be stored in. Hoeppe (2014) and McCray (2004, 2014) both examine facets of this issue. Hoeppe specifically examines how astronomers build a consistent dataset from multiple sources of data, “working data together” as he describes the process of calibrating and merging different datasets through a sequential and reflexive process. McCray (2004, 2014) examines the emergence of the Flexible Image Transport System (FITS) file format. Using the metaphor of data friction from Edwards (2010), McCray (2014) discusses how astronomers using digital data faced challenges with interoperability, one instrument’s data was not compatible with that of a second or third instrument. This led in 1976 to a group of astronomers beginning work on what would become the FITS format for storing astronomy data, a format designed to be “‘flexible and self-defining’ yet open to ‘indefinite expansion’ in the future” (McCray, 2014, p. 930). The FITS format has not gone out of fashion and over time has been extended to support different types of data. I have previously discussed the Radio group’s use of UVFITS (Paine & Lee, 2014). UVIFTS is an extension of FITS that is not exactly a standard yet is understood within the radio astronomy community. I will return to this format when discussing data products in later chapters of this dissertation.

Creating standardized file formats seems entirely unimpressive today yet decades ago this was not a common practice in a time when the material nuances of different computing devices shaped the digitized format of data (cf. Dourish, 2014; Dourish & Mazmanian, 2013). Over the 1980s and 1990s as telescopes produced data stored in this common format, software tools were developed to process and analyze such files, and repositories preserved these observations the

data “helped reshape long-accepted research practices” changing the astronomy community’s “beliefs, expectations, and values about how resources for research—scientific data in this case—could and should be shared” which as a result has changed the moral economy of the discipline (McCray, 2014, p. 935). These software tools have been spoken of as “data pipelines” since the early 1990s, a term that “serves partly as a metaphor and partly as a reflection of the underlying physical reality as data flows from, say, an orbiting space telescope to a digital repository” (p.936). This pipeline metaphor is alive and well today as I noted in Chapter One.

Some gaps I see in this STS scholarship

Through this brief and relatively high-level overview of STS work I have laid out a broad realm of inquiry. I have barely scratched the surface of STS examinations of physics and astronomy research, presenting a high level look that notes the different approaches to the use of instruments and work on experiments. This broad difference in culture between physics and astronomy research is important to note because of the organizational structure and culture that is being created with the Widefield Radio Telescope project and in the Radio group.

Chapters Four and Five will examine the structures of this project. For the moment I want to stress that while this cosmology telescope project is rooted in astronomical work many of the individuals contributing come from a physics background with experience working on particle physics style cooperative projects, in particular members of the Radio group. A variety of the project’s policies regarding access to and use of data and in turn publishing findings express a blend of the HEP and optical astronomy cultures I just briefly discussed. These rules and structures setup the expectation of collaboration on data collection, analysis, and publication within the overall project. This is something of a shift from astronomy traditions towards those of particle physics, enacting a project culture that is somewhere in between.

This dissertation also offers a different perspective on the use of imagery or visualizations in physics and astronomy research with my discussion of plots. I illustrate how while enabling the Radio group to see their science, to borrow Lynch and Edgerton's phrase, plots also enable them to see their software and infrastructures. This multiplicity of uses is fascinating and when thinking of software as a material for doing science offers a point for novel inquiry about research practices.

Throughout my discussion of STS studies there is very little mention of software. As I have studied this literature I have come across very little discussion of this artifact and concept. Digital computers are discussed since they are inescapable in the advancement of scientific practices. Yet somehow software has not been an object of explicit focus in explaining how knowledge is socially constructed. Vertesi (2015) and McCray (2004, 2014), for example, do discuss software as part of the milieu of the work they study. But it is not the direct object of their inquiries. This needs to change if STS is to continue to fruitfully examine how scientific research unfolds.

There are studies of software in science being conducted of course. I examined computer science studies of scientific software development earlier. Within computer supported cooperative work there are STS-influenced studies of software as part of infrastructure. These infrastructure studies delve into issues of data standardization and sharing and how digitized instruments shape the collection of data, and how systems are sustained over time.

CSCW studies of cooperative science and infrastructure

Computer supported cooperative work research has spent the last few decades studying scientific collaboration and the building of infrastructures for scientific research informed by STS findings and approaches (Jirotko et al., 2013; Jirotko et al., 2006; Ribes & Lee, 2010). This work falls

under various terms over time as different organizing concepts and emphasizes are applied. These terms include: Collaboratories, Cyberinfrastructure (CI), eScience, e-Research, Data-Intensive Science, Data Science, Big Data, Research Infrastructures, and Knowledge Infrastructures among others. For simplicity I refer to this work as cyberinfrastructure for the moment since it has been the dominant term in the United States since the early 2000s thanks to the National Science Foundation's efforts to fund projects under this auspice. So just what is cyberinfrastructure then? What does CSCW scholarship say about CI?

CSCW studies of cyberinfrastructure adopt a sociotechnical approach where inquiry examines how the social and technical concerns of a project are intertwined and shaping each other, very much influenced by the work of science & technology studies. This differs from the scientific software development literature discussed earlier in the chapter that was focused primarily on technical endeavors. In the United States a National Science Foundation (NSF) Blue-Ribbon Advisory Panel was appointed in the early 2000s to make recommendations on future funding initiatives for infrastructural endeavors to support twenty-first century scientific research. The Blue-Ribbon advisory panel released what is colloquially known as “the Atkins Report” (Atkins et al., 2003) and introduced the term cyberinfrastructure.

The Atkins Report coined the term cyberinfrastructure to describe “infrastructure based upon distributed computer, information and communication technology” that sits between advanced computing resources below and domain-specific tools above (Atkins et al., 2003, p. 5). This report fairly narrowly posits CI as a layer of “enabling hardware, algorithms, software, communications, institutions, and personnel” that is situated below a layer of particular “software programs, services, instruments, data, information, knowledge, and social practices applicable to specific projects, disciplines, and communities of practice” and above a base layer

of advanced computational systems. In effect, cyberinfrastructure is posited as a middleware (Bietz et al., 2013) and domain-specific projects or tools are not within the purview of this concept. In other words, cyberinfrastructure in the vein of the Atkins Report is a generalized resource, a classical infrastructure like a roadway, plumbing system, or the Internet. The definition offered by the Atkins Report is generalized and recognizes the social and organizational elements to any infrastructure. Unfortunately a subsequent National Science Foundation report shifts focus primarily towards the technical products and pushes social and organizational concerns to a rather secondary status (NSF Cyberinfrastructure Council, 2007).

CSCW and information science scholarship extends the Atkins Report CI notion from a primarily technical orientation to a sociotechnical inclination building upon infrastructure studies research. Edwards et al. (2007) in an NSF workshop report define CI as “the set of organizational practices, technical infrastructure, and social norms that collectively provide for the smooth operation of scientific work at a distance” (p.6), noting that infrastructures are composed of many interoperating systems. The report furthermore comments that “the eventual growth of complex infrastructure and the forms it takes are the result of converging histories, path dependencies, serendipity, innovation, and ‘bricolage’ (tinkering)” and that framing CI as a thing to be built or designed “tends to downplay the importance of social, institutional, organizational, legal, cultural, and other non-technical problems developers always face” (p.6-7). Cyberinfrastructure is relational—drawing upon Star and Ruhleder’s (1996) notion that I discuss below—and very importantly results from the ongoing work of stakeholders. CI is not a thing to be designed as a monolithic whole.

The definition in Edwards et al. is broad yet encapsulates much of the agenda taken up by CSCW’s cyberinfrastructure studies. CSCW scholars have studied many different scientific

projects that are framed as cyberinfrastructure—from genomics to ecology, earthquake engineering, earth and environmental sciences, oceanography, and physics, among others (Bietz & Lee, 2009; Cohn, 2013; Faniel & Jacobsen, 2010; Jackson & Barbrow, 2013; Karasti et al., 2010; Kee & Browning, 2010; Lee et al., 2006; Olson et al., 2008; Paine & Lee, 2014; Paine et al., 2015; Ribes, 2014; Ribes & Finholt, 2009; Steinhardt & Jackson, 2014, 2015; Young & Lutters, 2015). I will discuss two key themes to this scholarship below. But first while I examined definitions of cyberinfrastructure I will better define what I mean by infrastructure for the purposes of this dissertation.

What and when is infrastructure?

Infrastructure like software is everywhere so what do I mean when I use the term? Is it a singular thing? In this work it is not. It is a conceptual lens for framing and examining the ecologies of distributed, cooperative knowledge work.

The Oxford English Dictionary (2012) defines infrastructure as “a collective term for the subordinate parts of an undertaking; substructure, foundation.” Popular conceptions of infrastructure evoke images of highway systems, power grids, the telephone network, and today the Internet. Conceptualizations of infrastructure present it as a relatively static entity available as an underlying foundation that simply works when needed. This is assuming infrastructure is even thought about in the first place since it is by default supposed to merge into the background in the world. The everyday perception of infrastructure is primarily as a technical concept. This downplays or ignores the social and relational nature of the concept. Much of the work studying cyberinfrastructure remedies this by employing the relational, ecological infrastructure perspective put forth by Star and Ruhleder (1996)—a concept that is in dialogue with the STS orientations on the social construction of knowledge discussed before.

Star and Ruhleder (1996) introduce eight facets to relational infrastructure by asking not “what is an infrastructure?” but rather “when is an infrastructure?” through their study of the Worm Community System, a proto-CI project in the 1990s. Infrastructure “is something that emerges for people in practice, connected to activities and structures” (p.112). They note that as an analytical lens this shift to a relational property is an “infrastructural inversion” (Bowker, 1994) where changes in infrastructural relations become central to an inquiry of a large-scale system. Bowker and Star (1999) point out that an infrastructural inversion is a gestalt switch to work to keep that which has a tendency to disappear from doing so:

Infrastructural inversion means recognizing the depths of interdependence of technical networks and standards, on the one hand, and the real work of politics and knowledge production on the other. It foregrounds these normally invisible Lilliputian threads and furthermore gives them causal prominence in many areas usually attributed to heroic actors, social movements, or cultural mores. (p.34)

Star and Ruhleder present eight dimensions of infrastructure: 1) embeddedness, 2) transparency, 3) reach or scope, 4) learned as a part of membership, 5) links with conventions of practice, 6) embodiment of standards, 7) built on an installed base, and 8) becomes visible upon breakdown (Star & Ruhleder, 1996, p. 113). Bowker and Star (1999) include a ninth dimension in this list, stating as well that infrastructure is “fixed in modular increments, not all at once or globally” noting that change requires time and negotiation along with adjustment of other aspects of the systems involved (p.35). Together these nine dimensions provide scholars with a language for analytically describing the relations between components in work practices.

Within Star and Ruhleder’s ecological framework they posit that infrastructure is embedded inside of other structures, social arrangements, and technologies. It is transparent to use since it is designed so that it does not have to be reinvented each time an actor attempts to use it, i.e. it invisibly supports such a task. I can turn on the tap and expect water to flow without

having to reinvent plumbing. Infrastructure has reach or scope, both spatial and temporal, since it extends beyond any single event or any one site's practice. It is learned as a part of membership since "the taken-for-grantedness of artifacts and organizational arrangements is a *sine qua non* of membership in a community of practice" (Lave & Wenger, 1991 as cited in Star & Ruhleder 1996, p.113). If I am a software engineer in a large company there will be certain sets of tools and practices that I become accustomed to, they are infrastructural, yet if I change jobs I will more than likely have to adopt a different setup.

Infrastructure has links with conventions of practice since it helps to shape and is shaped by conventions of a community of practice. It is an embodiment of standards since it interacts with other infrastructures and tools in a standardized manner. It is built on an installed base since it does not grow "*de novo*" but rather must contend with existing systems that provide strengths and limitations to the new system. Electricity is infrastructural yet varies globally depending on implementations that took root and over time became the standard in a particular location. Infrastructure becomes visible upon breakdown since the failure of the standardized mechanisms of operation cease to function as designed, foregrounding the missing functionality of the system to those who are reliant upon it. Finally, since infrastructure comes about in fits and starts, rather than all at once, components are created and adjusted over time as negotiations take place. Infrastructure must continually be repaired and maintained as breakdowns, both social and technical, occur in practice.

Importantly "an infrastructure occurs when the tension between local and global is resolved" (Star & Ruhleder, 1996, p. 114). In particular, this resolution occurs when local practices are able to function seamlessly in operation with the larger-scale technology, e.g. when the use of the technology can be accomplished in a "natural" manner. Adopting this relational

infrastructural lens enables scholars to examine the relationships between work practices and technologies, and how they shape each other in use over time and across places. Understanding infrastructure as a relational concept that is composed of not only technological systems and tools but also social arrangements is important for both its designers and users. Star and Bowker (2002) state:

the infrastructure designer must always be aware of the multiple sets of contexts her work impinges on. Frequently a technical innovation must be accompanied by an organizational innovation in order to work: the design of sociotechnical systems engages both the technologist and the organization theorist (p.153)

Making use of their advice a scholar studying work practices and/or designing infrastructure would examine the technological systems *and* the social arrangements in a given context—exactly why I adopt this perspective in this dissertation even though I am not designing myself (and really it is infrastructural components that are designed, not infratructures themselves). With regard to users of infrastructure Star and Bowker state:

the most important thing is for the user of the infrastructure to first become aware of the social and political work that the infrastructure is doing and then seek ways to modify it (locally or globally) as need be. Infrastructures subtend complex ecologies: their design process should always be tentative, flexible and open (Star & Bowker, 2002, p. 160).

Bowker et al. (2010) nicely emphasize that in building infrastructure the “key question is not whether a problem is a ‘social problem or a ‘technical’ one” rather the question is “whether we choose, for any given problem, a primarily social or a primarily technical solution, or some combination” (p.102). It is instead the distribution of solutions that a designer or researcher should be concerned with “as the object of study and as a series of elements that support infrastructure in different ways at different moments” (p.102). Paul Edwards eloquently summarizes the importance and pervasiveness of infrastructure in twenty-first century life:

To be modern is to live within and by means of infrastructures: basic systems and services that are reliable, standardized, and widely accessible, at least within a community. For us, infrastructures reside in a naturalized background, as ordinary and unremarkable as trees, daylight, and dirt. Our civilizations fundamentally depend on them, yet we notice them mainly when they fail. They are the connective tissues and the circulatory systems of modernity. By linking macro, meso, and micro scales of time, space, and social organization, they form the stable foundation of modern social worlds. (Edwards, 2010, pp. 8-9)

Edwards' point reminds me of the perspective on software Kitchin and Dodge (2011) spell out that software is part of and contributes to complex fluid material practices that connect multiple scales of time and space. Furthermore in (Edwards, 2003) he points out, while discussing large technical systems, that for the way he uses infrastructure the notion “invokes possibilities of extension in time, space, and technological linking that go beyond individual systems” (p.200)—in essence he is talking about systems of systems connected across different spatialities and temporalities.

To me software is a product to put through an infrastructural inversion as an observer of cooperative work. Following its production and use in the Radio group as the object of my inquiry I trace out how it becomes embedded in practice, embodies the group's emergent standards for work as well as their conventions of practice, and so on. Simultaneously, through their work I will illustrate how they as scientists are inverting the infrastructure that is settling into place as they do data analysis and assess the functionality of their software and telescope. Developing and maintaining an awareness of the complex work ecology that software helps form is necessary when attempting to design or modify infrastructure that is at least partially composed of software.

As an external viewer I am employing the notion of infrastructure to characterize the Radio group's cooperative work, but I also must account for the perspective of my informants in my analysis. Much of the software work in scientific research is readily examinable as what

Hanseth and Lundberg (2001) describe as work oriented infrastructure where a local group of individuals enact an infrastructure to do their particular tasks on top of larger classical infrastructures like a computer network. Scientists commonly write scripts to complete a small task, link together different pieces of data, or occasionally control an instrument. To these individuals they are not creating infrastructure yet over time as their small pieces (what I would deem to be infrastructural components) come together this is exactly what they are doing. Cohn's (2013, 2016) beautiful description of "Category D" software in a NASA space mission (a category beyond the official categorization of A, B, C) illustrates exactly this point. In the aging and decaying infrastructure of this mission small, very personal pieces of software are not recognized as vital to the mission until one of the lead engineers took away one piece of this project's "glueware" to make members of the team "say ow" and realize the larger infrastructural importance of this element. What begins as software in a work oriented infrastructure meant only for local and seemingly small scale activities becomes a conceptually larger knowledge or information infrastructure within the context of a project, community, or discipline. I see this type of shift in scale and scope in the Radio group's production of software especially.

At this point I want to shift to discuss two themes I see in the overall CSCW cyberinfrastructure literature. The first examines how cyberinfrastructure projects unfold and over time are sustained. Second is work examining one of the primary rationales for cyberinfrastructure: sharing research products, particularly data. I will then discuss what I see as an important gap among these studies, the small amount of work explicitly examining how one group of scientists does work within and among multiple infrastructures.

Creating and sustaining infrastructure in and for cooperative scientific work

I have discussed definitions of cyberinfrastructure and explained what I mean with the term infrastructure. But what does CSCW say about the creation of infrastructure for science? How do these projects grow and how are they sustained over time? Bietz, Baumer, and Lee (2010) state that cyberinfrastructure studies are oriented around infrastructuring work (Karasti & Baker, 2004), concerning themselves with the “process and practices” of CI creation and use. They note that many cyberinfrastructure projects studied in CSCW are in the development phase and thus not yet reaching their infrastructural goals. They are emergent and shifting entities where studies have taken either of two immediate approaches: 1) following a “somewhat bounded subgroup (e.g., one that shares a very particular and already defined set of research or development tasks) for whom to research and design” or 2) to “grapple with messy assemblages of human infrastructure and sociotechnical systems” to tease out patterns of work and cooperation that enable the infrastructure to emerge and stabilize (Bietz et al., 2010, p. 248). These projects span a spectrum from birth and growth to aging and death of infrastructural endeavors.

The human infrastructure of cyberinfrastructure (CI)

Examining the early stages of a CI project Lee, Dourish, and Mark (2006) describe the human infrastructure of cyberinfrastructure to illustrate how stakeholders across a CI project are able to work across different contexts to successfully do their work. These stakeholders work at different institutions, within different streams of research funding, and bring different goals to a project all while working within the confines of an overarching virtual organization. The authors posit that the human infrastructure of CI project is a hybrid of old and new organizational forms, a “vast series of overlapping traditional organizations, consortiums, loosely organized groups, and networks” working to build the infrastructure to accomplish science in a distributed, in-flux

environment. It is not amorphous but rather multimorphous holding more than one shape at any one time while also changing shape over time as the cyberinfrastructure grows.

Examining the human infrastructure of a cyberinfrastructure allows scholars to theorize the messy, changing relationships and relationship work necessary for distributed scientific work. Bietz and Lee in a series of papers with collaborators (Bietz et al., 2010; Bietz et al., 2012; Bietz et al., 2013; Lee et al., 2012; Lee et al., 2010) build upon this notion to describe how CI developers work to sustain their projects across different organizations and funding streams. These stakeholders and their projects often have infrastructural goals that require they be strategic in their work if they hope to reach an infrastructural state.

Bietz, Baumer, and Lee (2010) develop the concepts of synergizing, leveraging, and aligning to explain the processes stakeholders engage in to create and manage relationships to enact cyberinfrastructure. They posit that the two main concerns of synergizing are first ensuring that a common field of work (a notion described at the end of this chapter) exists and in making sure that work can be done in the first place, in contrast to just ensuring work goes well. Aligning is work done by stakeholders to enact a relationship that will be able to produce and then function within a nascent CI. Leveraging on the other hand is using an existing relationship with a resource (a person, artifact, organization, etc.) to create a useful relationship with another resource that will result in synergy for the CI project. Examining CI-projects from a meso, organizational level Bietz et al. state:

Infrastructures can have components that function simultaneously as sub-projects and independent entities. Components may begin to function long before the overall infrastructure is complete, or the same component may be part of multiple infrastructures. Boundaries among projects and sub-projects are likely to be amorphous and in constant flux. Synergizing is a strategy for managing this complexity to create and maintain the common field of work. (Bietz et al., 2010, p. 276)

In contrast, rather than examining a CI project from an organizational level I am following a single group's work. As a result, I see these scientists creating and maintaining multiple common fields of work around different infrastructural components. I can step back and convey the entirety of the Widefield Radio Telescope project as having a singular common field of work, but as I'll elaborate further below the notion of the common field of work is recursive and as I shift and focus on different components they are visible as particular common fields of work within and across the larger project.

Temporal scales of cyberinfrastructure development

Karasti, Baker, and Millerand (2010) foreground temporal concerns in infrastructure development and posit two temporal orientations in this work, project time and infrastructure time. The two temporal orientations shift the developer's focus and concern between short-term novel development tasks and the long-term support and continuity of an infrastructure. In a similar vein Ribes and Finholt (2009) articulate nine tensions faced by stakeholders in CI projects as they try to build something immediately useful yet sustainable into the future. These nine tensions are similar to five "paradoxical challenges" that Lawrence (2006) elicited earlier by studying the midpoint of an atmospheric sciences cyberinfrastructure project.

Steinhardt and Jackson (2014) examine how different temporal rhythms in a CI project unfold at moments of formation and enactment to explore how shared rhythms in local practice and at larger institutional levels are aligned. They argue that plans help to establish shared "baselines of expectation" that local action can be coordinated around. Steinhardt and Jackson (2015) shift to describe the anticipation work of stakeholders engaged in collaborative CI building as their collaborative work enacts a futurist vision. Finally, Steinhardt (2016) examines how a CI project manages the design and development effort as the project is "breaking down"

or “descoped” when funding shifts and the scale or scope must be re-evaluated and priorities shifted if anything usable is to be produced, let alone sustained into the future.

Shifting from studying the early stages of a CI project, Cohn (2013, 2016) delves into the lived temporalities of a NASA mission to describe how change in a project is managed over time as resources decay when the project and its infrastructure are nearing the end of their lifetime. Describing the work of a “geriatric” infrastructure as one that is “in the process of becoming old, with an emergent recognition of aging as a process and an increased appreciation for decline, loss, and finitude of lifetimes” she articulates the processes of convivial decay where stakeholders work with and not against the decay of an infrastructure (Cohn, 2016). Cohn importantly points out that the decay of the spacecraft was very tangible to this NASA mission yet the decay of the various software tools (i.e., infrastructural components) for the project is far harder to make visible. She emphasizes that “what is negotiated in the face of decay is a mutual livability of systems and practices that are running out different lifetimes, aging at different rates, and yet mutually entangled and interdependent” (p.1521)—a type of negotiation that I imagine can probably be found across the different points of a project’s lifetime should someone look and step outside of the easily assumed orientation towards technological progress as the way of our imagined futures (Steinhardt & Jackson, 2015).

Both of these swaths of CSCW literature examines how cyberinfrastructure is cooperatively envisioned, created, and sustained among different stakeholders, organizations, and institutions. The focus on temporality comes down to asking how are components of infrastructures designed and built for different temporal scales that are anticipated and unanticipated to the stakeholders involved. The majority of these studies follow work as it is planned and enacted while that of Cohn studies the decay of a project. From this body of work, I

take away the importance of studying the varying, evolving arrangements of stakeholders in projects as they plan for different time scales. Inherent to the projects of these studies are distributed geographical scales. These notions are in some way connected to one of the major motivations of CI projects that CSCW scholars examine—that of producing and sharing research products.

Producing and sharing research products

Beyond examining how cyberinfrastructure are developed and sustained research focuses on how research products are produced and shared as part of these projects. The most commonly discussed research product is data (typically in association with the instruments used to produce this product). Recently software has emerged as a product receiving some attention, but not enough in my opinion, as well. Both of these products are integral material elements of cyberinfrastructure. What then do CI studies say about the production and sharing of these products?

Producing and sharing data

To begin I'll briefly discuss scholarship on data. Data are the backbone of scientific research and the production of knowledge, described in economic terms as a source of “monopoly rents” in Birnholtz and Bietz (2003) and noted by Jirotko, Lee, and Olson (2013) as the “lifeblood” of science as an enterprise. Star and Ruhleder (1996) in their study spend a fair bit of time discussing data sharing concerns. For any research endeavor what counts as data, how it is produced, and how it is used are key pieces of information for the success of a project. Data are never “raw” they are always “cooked” and constructed based on prior knowledge and the practices of a discipline (Bowker, 2005; Gitelman & Jackson, 2013). Data must be “imagined *as* data to exist and function as such” (Gitelman & Jackson, 2013, p. 3, emphasis in original). Data

are a foundation of scientific research so what then do cyberinfrastructure studies focus on with respect to data?

Cyberinfrastructure efforts are typically closely tied to goals for supporting data sharing in science. Data sharing is a key component of open science initiatives and a requirement of funding agencies and publication venues in the twenty-first century so that research results can not only be reproduced and verified but further built upon (National Science Foundation, 2012; Nature, 2012; Science, 2012; The Royal Society Science Policy Centre, 2012). Furthermore, significant quantities of data are produced in situations that will not be accessible again. Funding agencies expending public tax dollars on this work thus often require sharing a project's data for other reuse by other researchers. As a result, efforts to fund different cyberinfrastructure projects were positioned as a mechanism for facilitating the successful sharing of data between researchers, organizations, and disciplines. Data sharing is central to the data revolution Kitchin examines (Kitchin, 2014). Recalling the editorials that I noted earlier in the chapter about the role of software in science, there is a close connection among open and data science movements to have the open sharing of not only data but also software. But really what does it mean to share data? How does this motivation influence cyberinfrastructure projects or scientific research in general? Having some understanding of these issues will be of use when I start to examine the telescope project that the Radio group works with since they do encounter such concerns.

A mandate or desire to share data raises many questions. How can or should data be shared? Who should data be shared with? What does a researcher gain from sharing their data? Addressing similar questions Zimmerman (2003) defines data sharing broadly in her dissertation. She includes activities ranging from "one-on-one informal interactions" between a data holder and a recipient to "active dissemination or publication via formal mechanisms" (p.6), say by

depositing data into a shared repository. A researcher sharing data with a colleague will have different options available than one who is simply fulfilling a funding agency mandated responsibility since the latter situation may require depositing data into a particular public information infrastructure whereas the first could be as simple as emailing files.

The findings across many CI studies support Zimmerman's broad definition due to the varying social concerns and norms along with different technologies in play (Birnholtz & Bietz, 2003; Borgman et al., 2012; Darch & Sands, 2015; Darch et al., 2015; Faniel & Jacobsen, 2010; Rolland & Lee, 2013; Vertesi & Dourish, 2011; Wallis et al., 2008; Wallis et al., 2013). CSCW research emphasizes the need to understand the context of production for data since this greatly impacts how the data can then be used or reused, whether by the researcher who originally produced it or others whom it may have been shared with. Closely connected with these issues is the design and development of data standards, or guidelines for how data should be collected and stored and thus able to be analyzed or shared.

Birnholtz and Bietz (2003) offer a look through the study of three early cyberinfrastructure efforts. They describe how data help to define boundaries between different communities of practice and in turn can be a gateway into a new community or serve as an indicator of an individual's status within a community. Speaking in particular to the difficulties surrounding the establishment of standards for data sharing, Birnholtz and Bietz state that standards development efforts do not sufficiently pay attention to the different roles data serve in different research communities and that describing metadata—data about the data—for a dataset is not as simple as it is often made out to be. Both of these issues hinder the design of both standards (as abstractions) and systems (as implementations of abstractions) since the context that data is produced and used in varies by researcher. Birnholtz and Bietz emphasize that a

“complete solution” to all needs is not possible or a rational goal since all contexts cannot be captured whether in the present or in the future as a community and its work changes.

Vertesi and Dourish (2011) examine the data sharing cultures and their sociotechnical infrastructures of two different NASA space missions. Each of these space missions has a different culture concerning data production which thus influences how they share this data. Vertesi and Dourish emphasize that the structure and culture of the production of data within a project will influence the parameters for how it can subsequently be shared. In one project for example data is a shared resource because up front it is crafted to be circulated within this open community. In contrast in the second project data is the result of hard work by individuals working as particular science teams towards shared goals often in conflict with other teams who wish to use the spacecraft’s instruments for different scientific purposes.

Vertesi and Dourish propose that data sharing is only one set of practices that are to be found in a larger data economy that is broadly organized around the work of production, use, and circulation of data. Noting that cyberinfrastructure and eScience projects are “traditionally” interested in data circulation, and the ecologies of practices enabling this circulation, Vertesi and Dourish point out that the ecologies of “enmeshed sociotechnical infrastructures for data-sharing are part of this wider economy of data, but attention to other aspects of this data economy is critical for designing data infrastructures” and that CSCW scholars should pay attention to the larger “interactional context” of data (Vertesi & Dourish, 2011, p. 540).

Many other CSCW scholars also raise the issue of the importance of understanding the context of data’s production to the ability of researchers to use or reuse it in their new work (Faniel & Jacobsen, 2010; Faniel & Zimmerman, 2011; Rolland & Lee, 2013). Young and Lutters (2015) describe how the emergent interdisciplinary of land change science is supported by

a CI project that supports the synthesis of different datasets. Faniel and Jacobsen (2010) studied an earthquake engineering CI project to understand how scientists do or do not reuse data depending on how they understand its reliability as a set or trust the researchers who produced the data. Such a focus on trust and reliability concerns is common to much data sharing scholarship. Shifting the conversation Rolland and Lee (2013) look at how researchers actually reuse data once they have determined it is trustworthy or reliable. The authors present a typology of nine question types that cancer epidemiology post-doctoral researchers rely upon to determine how they can reuse existing data that is provided for a new project they are tasked with working on. Through this study Rolland and Lee demonstrate how reconstructing the history of variables in a set of data is vital to its reuse since the lack of a detailed understanding of their construction and derivation could result in an inaccurate analysis of the data when addressing new questions.

Associated with research on the production and sharing of data in CI projects are efforts to outline the lifecycle of a research project, primarily focused on data as the product of research. Wallis et al. (2008) define nine stages to a sensor-system ecology research project. The stages range from experiment design, calibration and setup, data capture or generation, cleaning, integration, derivation, analysis, publication, and finally preservation and sharing. The authors posit that broadly research projects engage in these activities from beginning to end with iteration between and among different stages as problem solving occurs. Darch and Sands (2015) employ this lifecycle model to compare an astronomy cyberinfrastructure project and a deep seafloor biosphere project, “big science” compared with “little science.” They illustrate how the different activities of the Wallis et al. lifecycle model are conducted multiple times and in different arrangements (both temporally and spatially) in these two very different research projects.

In contrast, in Paine et al. (2015) I draw upon the Wallis et al. model and one from a United Kingdom Data Archive (UK Data Archive, 2013) to specifically examine data processing work across four scientific research groups of varying disciplines, including the Radio group. In this paper data processing work is defined as that which bridges the data collection and data analysis work so that I can compare and contrast three practices across the four groups I study. Data processing work is crucial to taking a data product and transforming it from a raw material to one which is analyzable for particular scientific research questions. This takes place over many rounds of iteration by researchers. In the paper I critique the two lifecycle models since they somewhat hide the iteration inherent to scientific work and because the delineation between stages (e.g., data collection, processing, or analysis) can vary not only among disciplines and projects but even among the individuals working on one project. Investigating these work practices is necessary to support the sharing of data or other research products, let alone understand how scientific work is done.

Producing and sharing software

Shifting from focusing on the production and sharing of data to work on software, Howison and Herbsleb (2011, 2013) examine the incentives scientists do or do not have to share the software that they produce. The authors' first paper describes a set of production systems to illustrate how software is created, maintained, and shared in the face of different incentives to motivate researcher's activities (Howison & Herbsleb, 2011). Their later paper in turn then illustrates how fostering an open collaboration approach has successfully supported the production of knowledge in Wikipedia and software in the free and open source software community (Howison & Herbsleb, 2013). Howison and Herbsleb across both papers illustrate how many concerns

surrounding data sharing similarly apply to software sharing, e.g. its value towards reputation or as an economic good for example.

Huang et al. (2013) stress the importance of managing the boundaries surrounding scientific software since different types of software have different meanings to researchers, in this case bioinformaticians, and these meanings thus influence the extent to which a particular piece of software is able to travel beyond the individual or group. Trainer et al. (2015) focus on the “extra work, voluntary or involuntary unpaid labor” necessary to make scientific resources shareable as they must be “generally useful.” Extending CSCW’s work on data sharing, the authors examine four scientific software communities to identify what extra work is necessary to make software generally useful as a shared research product. They describe how sharing is a continuing commitment throughout the lifecycle of development, as work monitoring how the code is used or evaluating new submissions as well as writing documentation all are continually conducted as bugs are fixed or features added. This is work that is not part of just a “sharing event” but rather ongoing cooperative work.

Conceptualizing kernels of infrastructures as an analytical tool

Finally, as an analytical tool Ribes (2014) puts forth the conceptualization of the “kernel” of a research infrastructure as a new unit of analysis for investigating research infrastructures that focuses on the material resources of the infrastructure. He defines the kernel of a research infrastructure as the “core resources and services that an infrastructure makes available *and* the work, techniques and technologies that seek to sustain the availability of those resources over time” (p.574, emphasis in original). The kernel approach to investigating infrastructure “examines resources and services as *entangled* with the work, techniques and technologies used to ensure their availability *as* resources and services” (p.574, emphasis in original). This is an

approach that is fundamentally sociotechnical, drawing upon Bowker's (1994) earlier concept of performing an infrastructural inversion to examine how resources, services, techniques, technologies, and work are shaped by each other. At some level this kernel approach synthesizes many of the streams of research I just discussed around a common language and is oriented towards the sharing of research products.

The kernel of a research infrastructure is composed of two aspects, first that of a "cache" and second of "addressing" activities. The cache is a reference to the resources and services made available by an infrastructure in support of particular scientific investigations. Ribes states that the cache will be different in each infrastructure such that the composition of a cache is specific to the history of a particular infrastructure. He offers examples where some infrastructure caches are created to store and maintain collected data and specimens where as other caches are comprised of data integration and visualization tools without being involved in data collection.

The "addressing" aspect of the kernel is how Ribes refers to the work, techniques, and technologies that strive to ensure that the elements of the cache are available for use in a stable way over time. Addressing, just like a cache, is "highly heterogeneous and specific" to the particular research infrastructure under examination. For example, describing blood samples from an HIV/AIDS infrastructure Ribes notes that an aliquot of blood is only meaningful if it is connected to information about the patient whom it was obtained from, and importantly only if this connection is maintained over time. As soon as the connection is severed the sample reverts to just another bag of blood that is not applicable to the research infrastructure's scientific aims.

The emphasis throughout Ribes' paper is not only on the data in a research infrastructure but more broadly with the materiality of resources in scientific research. The argument is in fact

that CI studies in CSCW have focused on data to the detriment of any concern with the materiality of resources projects create and use. I agree and would extend this to posit that CI studies also gloss over software as a material element of infrastructures in science since the common stance on software is that it is a digital artifact without material basis—something Dourish (2014) poignantly critiques. While software is posited as a key component of cyberinfrastructure and an element of inquiry I find that it is not often interrogated as a resource that is entwined with material practices, even though the software created in and for research infrastructures is fundamentally tied up with the material resources of the scientific project. Ribes closes his article by noting that the methodological reorientation brought about with this kernel approach is to place supporting the examination of “objects of research” at the core of one’s analysis. He emphasizes that “the study of infrastructures must be closely tied to the specific research practices they enable, the materials to do so, and the shifting orientation of investigators to novel phenomena” (p.584). This has echoes of Fujimura’s (1996) explication of how a problem comes to be the phenomena of study in a discipline. By closely studying the Radio group’s software and its production I am surfacing the practices, materials, and shifting orientations to phenomena inherent in their scientific work.

Emphasizing the importance of context to producing and sharing resources

So what do I take away from this discussion about the production and sharing of research products in cyberinfrastructure studies? First, as an observer I must understand the context of data’s production if it is to be usable or shareable. How was an instrument used to produce it? Who was involved in the production process? What practices did they employ to produce, then process and maybe analyze this data? How was software used or produced in this work? I draw upon these findings in this dissertation and unpack how these concerns play out in a different

scientific context, that of observational cosmology. Chapter Five examines how the Radio group produces data with their colleagues who are studying the Epoch of Reionization. I show how these stakeholders are creating a culture around their data as Vertesi and Dourish might describe this work while illustrating the practices central to this stage of the Radio group's engagement with the WRT project (and the WRT's history as well). Subsequently I show how this emergent culture influences how the Radio group analyzes this data. From a cooperative work perspective Birnholtz and Bietz (2003) highlighted the role of standards in data sharing, a facet McCray (2004, 2014) discusses in astronomy specifically, and I see in the case of the Radio group's work how standards for using file formats and exchanging data are central to the work. In the end I will describe how the cooperative work of collecting, processing, and analyzing data is entirely bound up with the Radio group's production and use of software.

A need to studying multiple layered and overlapping infrastructures

I am employing the notion of infrastructure as a lens to study cooperative work in this dissertation. Considering the scope of the data analysis software being produced by Magnus and his group becomes an interesting facet to their work. The larger multinational telescope project Magnus and his group are actively contributing to is very much an infrastructure project. The Widefield Radio Telescope project is an infrastructure undertaking requiring the distributed cooperative work of many individuals, organizations, systems, and so on. I will illustrate this in Chapters Four and Five and refer to it as a research infrastructure. It is the base layer or substrate in Figure 3, that I presented in Chapter One, upon which the Radio group's software is relying. Employing an infrastructural lens to this cooperative work helps me explain how this one research group's participation and contribution unfolds while showing how the WRT as a project is creating a kernel (Ribes, 2014).

At the same time the Radio group's novel software began very much as a work oriented infrastructure and over time has become something larger in scope. I show that the Radio group's local cooperative work is not really contributing to just one infrastructure in the form of their data analysis software. Rather it helps to shape and is shaped (in a co-constructive process as Fujimura describes) by multiple infrastructures associated with this multinational telescope project. In producing their data analysis software and creating an infrastructure Magnus and his group are simultaneously working with and shaping aspects of the Widefield Radio Telescope project as a research infrastructure in its own right. Their work often requires opening the black box, and inverting elements, of the WRT even as they develop their software to work with other telescopes (and thus different underlying infrastructures).

Vertesi (2014) points out that "sociotechnical systems overlap, often messily" and that modern scientific research engages with many infrastructures, with each infrastructure presenting "its own inclusions and exclusions" so that "interactions in multi-infrastructural space present implications for what work is done and how it gets done" (p.266). She puts forward the notion of seams as language for focusing on the work actors do among multiple infrastructures, stitching them together "to achieve fleeting, nonstable, even ephemeral moments of alignment" (p.277). In contrast to her focus I am interested not in ephemeral moments of alignment but the Radio group's ongoing, aligned multi-infrastructural work.

Boyce (2016) draws upon the concept of second-order systems from the large technical system field to examine the "daily practical work of actors who create and maintain" a layered infrastructure on top of and dependent upon another infrastructure. She notes that second-order systems "rely heavily on infrastructures built for other uses" which raises challenges for the actors whose system is dependent on another infrastructure. Boyce explores the concepts of

‘repurposing’ and ‘second-order friction’ to try to improve understanding of these challenges to what amounts to situations of reuse of data and materials in new contexts. Repurposing is “the adaptation of things that were created for one purpose to be used in a different way” (p.53). Second-order friction in turn is a “resistive force, between their system and infrastructures that were built to achieve other goals” (p.53).

Boyce’s concepts are useful when examining the creation and sustainment of new infrastructures built upon other existing infrastructures. At first it seemed to me that these could be salient points in my discussion of the Radio group’s work but the overlapping infrastructures I have studied were co-produced and developed together. The Radio group is not repurposing the materials created by the WRT project nor are they in my experience facing second-order friction. They are helping to produce those materials and using them as they were originally intended, doing science that is one of the primary and largest goals for the WRT project—see Chapter Four. If I were examining how the Radio group were adapting their data analysis software and practices to work with a different existing infrastructure these concepts would come into play—and members of the group do note some work to reuse data from other telescopes and the difficulty of this work but this was not a prominent thread in my data. I am instead examining the production and use of these materials as the telescope is created and stabilized. Following this work lets me see how different fields of work are enacted, overlapping between the WRT as a whole and the Radio group alone. This leads me to turn to discuss what exactly I mean by cooperative work and some key concepts for studying it.

Theorizing arrangements of cooperative work

At the beginning of this chapter I introduced cooperative work by offering Bannon and Schmidt’s (1989) definition from the earliest days of formal CSCW research. Since this field

emerged and began to cohere in the 1980s different streams of scholarship have articulated a vast program of research (Schmidt & Bannon, 2013). What I will use in this dissertation to complement the infrastructural language I just examined are a few key concepts from Schmidt's articulation of the field (Schmidt, 1990, 1991, 1994, 2002; Schmidt & Simone, 1996). These include Cooperative Work Arrangements (CWAs) and the Common Field of Work (CFoW). So what do these terms mean? What again do I mean when we say cooperative work?

To revisit what is cooperative work I'll once again turn to Bannon and Schmidt (1989) since this is the type of work this dissertation is concerned with. Cooperative work is "constituted by *work processes that are related as to content*, that is, processes pertaining to the production of a particular product or service" (p.362, emphasis in original). Cooperative work is goal-directed, aiming to produce a tangible outcome. Cooperative work is also comprised of "*indirect* as well as *direct* and *distributed* as well as *collective* modes of interaction" so that in general it is "multiple persons working together to produce a product or service" (p.362, emphasis in original). The infrastructure work I just discussed is cooperative work, as are the STS examinations of scientific research, the scientific software development work, and the production of any other form of software as well. Working to produce products—whether they are software, knowledge, or instruments—requires cooperative work.

It almost seems that any social interaction is cooperative work. This is not the case in Schmidt's articulation. The definition put forth by Bannon and Schmidt is broad, seemingly too broad. Schmidt (1990) however adds important context to their definition:

Cooperative work, then, is a far more specific concept than social interaction in the system of work in general. The concept pertains to the sphere of production. It does not apply to every social encounter occurring during business hours, nor does it apply to every interaction pertaining to the running of, say, a company. (Schmidt, 1990, p. 10)

This conceptualization of cooperative work does not presuppose any particular organizational form or setting, does not imply regularity of any specific degree, nor that work is done in groups or face-to-face. It does not encapsulate every social encounter an individual has. All work is not cooperative work because “cooperation pertains to production, that is, it stops where consumption begins” and while cooperative work does not presuppose particular organizational forms it does require one of some type because “it requires that the cooperative relations are established deliberately as opposed to accidentally” (Schmidt, 1990, p. 10). Schmidt emphasizes that to examine cooperative work the researcher must have individuals working deliberately on either the same production process or separate but connected processes, citing Marx’s (1867) definition.

Cooperative work matters because “generally speaking, cooperative work relations are formed because of the limited capabilities of single human individuals” to accomplish something that either cannot be completed alone or can be completed at least as quickly or efficiently cooperatively (Schmidt, 1994, p. 8). Schmidt only really implicitly defines cooperative work arrangements and always in relation to the idea of common field of work. Throughout this, and other works, he emphasizes that “actors engaged in cooperative work are *mutually dependent in their work*” and enter into a cooperative work arrangement because of their limited capabilities as individuals to produce a desired product (p.13, emphasis in original). Actors in a cooperative work arrangement “cooperatively and interactively transform a conglomerate of *mutually interacting* objects and processes” that he describes as the field of work or interchangeably the common field of work (p.15, emphasis in original).

Schmidt (2002) states that “conceived of as constituted by a set of interdependent activities” the cooperative work arrangement will in principle be “a transient formation of

interdependent actors, emerging contingently to meet specific requirements, only to dissolve again if and when the need for multiple actors and their concerted effort is no longer present” (p.23). Synthesizing Schmidt’s various discussions, I will define cooperative work arrangements (CWAs) in this dissertation as deliberately organized cooperative relations of interdependent actors who have come together to produce a product. These arrangements are always formed with respect to a particular common field of work, as Schmidt notes repeatedly, and exist to meet those specific requirements before dissolving once the need for effort is no longer present anymore.

Schmidt (1994) articulates five facets to the field of work: 1) the field of work and the cooperative work arrangement mutually constitute and delimit each other, 2) the field of work itself is manifold, comprising the objects and processes, sensors and effectors, and more complex tools and control mechanisms that are inserted between the actors and the objects and processes, 3) the production process takes place in a wider work environment with particular constraints and operational demands present (e.g., commercial, economic, and legal restraints), 4) in this social division of labor the actor-object relationship is recursive with some actor-object relationships being the object of other work processes, and 5) the boundary and character of the field of work changes dynamically as situations change (Schmidt, 1994, p. 15).

The field of work or common field of work is thus a dynamic set of objects and processes upon which a particular cooperative work arrangement is collaborating to produce some thing as part of a wider work environment. In this dissertation the focus is primarily on software as that thing, although there are other important elements that I will discuss. This thing can be tangible or intangible, it can in fact be another CFoW and CWA since these concepts are recursive. Schmidt and Simone (1996) offer an example of an airline booking system where the

arrangements of seats on a plane and the database modeling these arrangements constitute the common field of work for booking agents who change the state of the CFoW in this situation by reserving seats. In this case at some point in the process there is a very tangible airplane with seats and individuals who will sit in them, but simultaneously there is the intangible conceptual model of the data that is employed in the database. The Radio group's production of software offers a similar example as I will show how while the code and data is digital and somewhat ethereal, it is made tangible and physical through their creation and printing of endless plots that surface facets of the data, software, and telescope.

Schmidt (2002) emphasizes that even with the reciprocal definition for the terms they offer a legitimate analytical construct "in so far as cooperating actors in their practices *take and have to take* their *interdependencies* as objectively given and *take for granted and have to take for granted* that their colleagues do so and must do so as well" (p.17, emphasis in original). This point underscores why I find these notions to be important for this dissertation. The Radio group's work is fundamentally interdependent. No one member could do it alone. They take for granted that they have to work together to achieve their different research goals even as the specific goals vary from person to person within the group or among their larger collaborations (these collaborations are explained and assessed in Chapter Four).

The CFoW is an emergent and transient phenomenon, just as its cooperative work arrangement is. Actors, or stakeholders as I prefer to think of these individuals, are interdependent and have a product to create. Schmidt's notions are part of a far larger program for studying cooperative work but in this dissertation I will use these notions to help explain the different arrangements of stakeholders doing different cooperative work within the Radio group and across the Widefield Radio Telescope project. Looking back to the discussion of

infrastructure I'll employ Schmidt's notions to examine how specific infrastructuring work is taking place. The myriad different components of the multiple layered infrastructures are produced by different cooperative work arrangements. Chapter Four explores how many different cooperative work arrangements are organized to enable this telescope to not only be designed and built but in turn used for scientific purposes, stabilizing this scientific instrument for regular data collection. The process of creating different infrastructures requires a multimorphous and flexible human infrastructure and tracing different cooperative work arrangements and common fields of work helps characterize this.

Summary

Over the course of this chapter I have delved into many swaths of literature. I have developed an understanding of how scientific knowledge is socially constructed and what software is in this dissertation. I have expressed that software matters in the world and using analytical perspectives on infrastructure and cooperative work I have the conceptual tools to help convey many aspects of the Radio group's work. Before I dig into the work of Magnus and his group I will first explain a bit more about the group, my time with them, how I collected data, and of course how I analyzed this data to produce this narrative. This is the purpose of Chapter Three.

III. Research Site & Methods

A tale, like the universe, they tell us, expands ceaselessly each time you examine it, until there's finally no telling exactly where it begins, or ends, or where it places you now. — Chang-Rae Lee, On Such A Full Sea

Introduction

This chapter serves two purposes. The first is to describe the observational cosmology research group I study. The second is to explain my qualitative data collection and analysis work, explaining how I came to this tale that expands ceaselessly for me every time I revisit it. The group I studied again is led by Principal Investigator (PI) Magnus, a professor in the Department of Physics at the University of Washington in Seattle, WA. I refer to this research group using the pseudonym “Radio” group. In addition, every individual along with all of their projects and code are referred to with pseudonyms as well to protect each person’s privacy. I will explain the anonymized convention I use to cite the publications, website and wiki pages, and internal memoranda of this group and the cyberinfrastructure collaboration they are a part of in the latter half of the chapter. I collected data across different episodes from June 2011 onward through 2015 for this dissertation. The bulk of this was collected during a focused period between January and May of 2014, a timeline I describe in detail later in this chapter. For the moment, it is not unreasonable to ask why did I study this group?

I began this dissertation study while working on a larger National Science Foundation project—the *Interacting with Cyberinfrastructure in the Face of Changing Science*² study, which I will refer to as the *Interacting with CI* study here for brevity. The *Interacting with CI* study aimed to follow multiple cutting edge scientific research groups over a five-year period to

² See <https://depts.washington.edu/csclab/projects/career-ci-study/> for an overview of the larger study. Magnus and the Radio group have subsequently been enrolled in our follow on study Scientists and Their Software as well <https://depts.washington.edu/csclab/projects/scientists-software/>.

understand how their research practices co-evolve with changes in technology. Details regarding the initial sampling and selection of researchers for this project are available in Paine et al. (2014). Each of the groups enrolled in this larger study were chosen for their situation at the forefront of their respective fields, engagement with large quantities of data (a variable concept depending on the field of research), and development of software within the group and with collaborations. These elements made such groups relevant to CSCW inquiries due to the mixture of these different facets shaping collaborations in advanced scientific research environments.

The Radio group's research is at one of the very edges of their field. They are peering back in time to the long past emergence and growth of the Universe and the reionization of the element hydrogen and the formation of the first stars and galaxies (the "cosmic dawn")—see Appendix A for a brief discussion of this science. They do this research through the use of a novel radio telescope that produces terabytes of data for every night of observation and is of a different design than traditional radio telescopes. This area of physics and astronomy has only recently become a realm that is possible to empirically study thanks to advances in telescopes, the technologies that they are composed of, and the practices of their use. Work in this research area is pushing existing research practices in new directions, pulling from existing research cultures in physics and astronomy that have fairly different histories and approaches to work. Loeb (2006) comments that "cosmologists are addressing some of the fundamental questions that people attempted to resolve over the centuries through philosophical thinking, but we [cosmologists] are doing so based on systematic observation and a quantitative methodology" (p.47). Observational cosmology is in short scientific research that enables humanity to better understand the origin of the Universe while often resulting in applied outcomes due to the work to design and build novel hardware and software.

I ended up choosing the Radio group for this dissertation research for a few key reasons.

First, the Radio group contributes to an international telescope project's work designing a novel instrument, collecting data, and most importantly doing data analysis by producing their own novel software. This facet of the group's work above all else satisfies my primary goal of studying empirical scientists producing their own software while engaged in collecting their own data, rather than following theorists or other researchers who might be assimilating already existing datasets. I did not wish to study scholars who reuse and create assemblages of data since there is wide variety of existing CSCW research on this topic, as I discussed in Chapter Two. Studying theorists was not my goal because I was from the beginning interested in empirical scientific research projects. The Radio group's collection of terabytes of data on a nightly basis also meets my aim of studying research that is data-intensive. The eScience discourse that data-intensive work and big data are heralding a change in research practices offers a fascinating vision and I wished to see how such work is unfolding. I in particular wanted to see how groups producing massive datasets with novel instruments create cutting edge, high-precision techniques for data analysis where prior software no longer works due to fundamental differences in the structure or design of data and the scientific techniques for interrogating it.

Second, I specifically wanted to study researchers developing their own software without any direct support from computer scientists. This contrasts with much of the cyberinfrastructure work in CSCW where collaborations between domain scientists and computer scientists or software engineers are the focus of study. I did not wish to study such collaborations precisely because I wanted to examine the practices researchers without a software engineering background develop to accomplish their work. This is a sorely understudied form of scientific practice in CSCW. Within scientific software development research, as I discussed in Chapter

Two, there is significant discussion regarding the quality of software that domain scientists produce or discussion about how software engineering methods are often not readily adopted or adapted by domain scientists. This motivated my interest in examining how this particular research group develops software and to explore how they do or do not ensure that their research is rigorous and systematic when it comes to the production of software and data analysis.

Third and finally, I wanted to study the Radio group because they are a coherent local research site that had only been formed a few years before I started studying them. CSCW literature already offered many studies of collaborations between domain scientists and software developers as distributed projects but I was interested in a return to studying an individual group to see how their work takes place locally and in concert with distributed collaborators. The Radio group was young when I first met Magnus. They were still developing a group culture and work practices in a new collaborative setting when I first began to interview members. This collaborative setting covers not only the physical spaces of one building in Seattle but also extends to other institutions around the United States and world. Studying their work as they figured out how to work together provides the opportunity to see the messiness of science in action. Importantly, while the local Seattle-based group is the focus of my inquiry they are also working closely with a large distributed group around the United States and internationally through the Widefield Radio Telescope Collaboration. The collaboration is building and using a novel radio telescope which helps to shape the work they need to engage in and how they go about doing that—as I discuss in the remaining chapters of this dissertation. I was able to focus my inquiry on a bounded, local group’s research practices while seeing how these practices interact with a larger collaboration’s work.

The Radio group as a research site

Members of the Radio group

The Radio group is led by Principal Investigator Magnus. Magnus is currently an Associate Professor in the Department of Physics. Over the course of this study Magnus maintained a group with three post-doctoral researchers, three PhD students from the Physics or Astronomy departments, a Masters student for one summer, and a varying cohort of undergraduate research students. Two of the three post-doctoral researchers (Brianna and Igor) and two of the three PhD students (Abner and Peg) were members of the group when data collection began. Jonah (a post-doctoral researcher) and Nima (a PhD student) were first present as members of the group at the beginning of the 2013-2014 academic year during which the bulk of this data collection took place. The particular individuals whom I followed for this dissertation along with their role and relevant project work are listed in Table 1.

Magnus, the post-doctoral researchers, and the PhD students were primarily engaged in working with data from the Widefield Radio Telescope and designing hardware for future evolutions of such instruments during my data collection. The Masters student worked on building a collaborative website for use during data collection one summer. I never met this individual and only heard about their contribution through interviews with PhD students and post-docs. I did not follow Jonah, another post-doc, because he was working primarily with another telescope's data although he was present during meetings. Undergraduate students who joined the Radio group during my data collection were tasked with working on a local, small radio telescope project with guidance from the senior members of the group. The undergraduate students and related small telescope project were kept outside of the scope of my inquiry by

choice since I only wanted to follow the group’s work as part of the WRT project. I’ll now discuss their built and computational environments.

Table 1. Members of the Radio group.

<i>Individual</i>	<i>Group Role</i>	<i>Most Relevant Project Work</i>
<i>Magnus</i>	Principal Investigator	Group leader guiding overall work and advising students
<i>Brianna</i>	Post-doctoral Researcher	Researcher responsible for developing the ImgPower component of the Radio group’s pipeline
<i>Igor</i>	Post-doctoral Researcher	Researcher responsible for developing the CalibratorImager component of the Radio group’s pipeline
<i>Abner</i>	Physics Doctoral Student	Doctoral student responsible for developing the Munchy component of the Radio group’s pipeline and handling the overall execution/management of the Radio group’s pipeline on a shared computing cluster
<i>Peg</i>	Astronomy Doctoral Student	Doctoral student responsible for developing a Sky Catalog data product using CalibratorImager’s Deconvolution mode and a collection of software she designs and develops
<i>Nima</i>	Physics Doctoral Student	Doctoral student responsible for improving the Calibration functionality in CalibratorImager

The Radio group’s built environment

The University of Washington is a large, hilly, urban university campus. The Radio group is housed in the University of Washington’s Physics & Astronomy buildings. This complex on the southwest corner of the main university campus consists of three interconnected buildings. The first building contains auditoriums and lecture spaces where courses are taught in addition to the University of Washington Planetarium and Jacobsen Observatory³. The second and third buildings house offices for faculty, researchers and staff, laboratories and machine shops, various educational spaces, and one of many on-campus coffee shops (cheekily named the H-Bar in a nod to physics theory, as most University of Washington campus cafes are named with a theme related to the department of the building they are located in).

³ <http://www.astro.washington.edu/groups/outreach/tjo/>

Throughout my data collection Magnus and the post-doctoral researchers had offices—shared in the case of the post-docs—on the fifth floor of the Physics and Astronomy tower. Abner, Nima, and the undergraduate students shared an office space in a basement laboratory room, see Figure 4. This laboratory room is shared by Magnus and at least one other faculty member’s students. Peg as an Astronomy student had a shared office on the third floor within the Astronomy area of the building. Peg’s office is physically the most separated from the other spaces that the group is housed within. I asked why she did not move down to the shared laboratory space and she readily commented that she did not want to give up having a window.

The basement laboratory space of the Radio group is filled with multiple desks along with a couch on a platform some 15 to 20 feet off of the ground visible in Figure 4 below. The platform is accessible via a rather steep ladder. Immediately up the ladder hanging on the wall is a small chalkboard that Abner commonly kept a “to do” list on. Placed next to this chalkboard on the floor is a miniature refrigerator with a toaster oven sitting on top. Abner and Nima shared this basement laboratory space with adjacent desks each containing an iMac or Mac Pro computer. Between the opening for the ladder on the platform and Abner’s desk was a tall standing file cabinet. Along the opposite wall are two smaller desk spaces arranged with desktop computers for the undergraduate researchers to use although they were not very often present at the same time as I was. A couch is shoved into another corner along with a table holding coffee and tea brewing equipment. Below this raised platform was another faculty member’s lab space with different equipment for building instruments. Overall this room was cavernous and loud, with conversations and work carrying throughout. Whenever I would arrive and Abner would be working alone I would often enter as he had music playing and echoing throughout the room.

The primary physical space of my meeting observations, and many interviews, was a Physics Department conference room on the fifth floor of the tower. This conference room is open and airy, entered through glass-paned double doors, with two large windows looking west out at the University District neighborhood, the Interstate 5 bridge, and off to the Queen Anne neighborhood, see Figure 5. This view is often quite picturesque and at times distracting when one is lost in thought. At the base of the windows are sturdy ledges that Magnus, myself, and other groups members would commonly lean against or sit on should the group be huddled around plots or a laptop in one corner of the room. Sitting with the doors closed passersby are easily noticeable due to their typically animated discussions, as is the frequent grinding noise from an automated home espresso machine in a kitchenette area. Another professor can often be seen walking up and down the hallways outside this room deep in thought.

The fifth floor conference room is organized with three sturdy wooden tables surrounded by chairs in various states of disrepair in the center of the room. On the southern wall a chalkboard hangs, along with a pull down projection screen. On the northern wall three small bookshelves are overflowing with printed copies of Physics journals and periodicals. A heavy office desk sits in the northeast corner—a place I would regularly frequent as an elevated seat when I was tired of the chairs around the table. Finally, an analog wall clock is mounted on a central pillar between the two windows, regularly making a vibrating or buzzing noise when the hour changes. Now that I have provided a sense of the group's physical spaces I will briefly discuss their computational environments.



Figure 4. Radio group's basement laboratory space.
From the top left going clockwise: the couch and coffee maker; Abner and Nima's desks; the shared whiteboard with Abner's todo list; desks for undergraduate students against the wall.



Figure 5. Physics conference room where Radio group meetings are held.

The Radio group's computational environment

The Radio group's computing environment is primarily Unix based. Computers used by members of the group—with the exception of Igor who uses a Microsoft Windows based machine—are all recent model Apple MacBooks, Power Macs, or iMacs. One of the Radio group's collaborators elsewhere in the United States maintains a Linux cluster at another of the universities—referred to in this dissertation as the RadioCluster. This cluster clones all Widefield Radio Telescope observation data that is captured for EoR science and is connected to the WRT Collaboration archive via a fiber-optic link, described further in Chapter Five. Individuals in the Radio group connect to the RadioCluster via command line interfaces or remote desktop tools to execute the data analysis software they are developing. Additional details regarding the RadioCluster are discussed in Chapter Five.

Throughout my data collection the Radio group would interact virtually using collaborative tools such as Google Chat and Hangouts⁴, WebEx⁵ for teleconferencing, and of course e-mail. The Widefield Radio Telescope project maintains various mailing lists for different projects along with a shared TWiki⁶ for collaboration and a KnowledgeTree⁷ document repository for archiving of memoranda and so on. Now that I have given an overview of the Radio group and the spaces they work in however I'll briefly introduce the Widefield Radio Telescope project.

The Widefield Radio Telescope (WRT) Project

Magnus and his group are key contributors to the Widefield Radio Telescope project. The WRT as a telescope project originated in the mid 2000s as a collaboration between researchers around

⁴ <https://hangouts.google.com/>

⁵ <https://www.webex.com/>

⁶ <http://twiki.org/>

⁷ <https://www.knowledgetree.com/>

the world. The origins of this telescope project, along with the Radio group's role in the design of this instrument, are examined in detail in Chapter Four.

The Widefield Radio Telescope Collaboration is comprised of members from different universities around the world. The WRT Collaboration has member universities, and their faculty and students, from many countries as signatories to a collaboration charter. The WRT Collaboration is organized with a governing board, four different Science Collaborations, and a couple of other advisory groups. The four Science Collaborations were created specifically to use the WRT for a defined set of scientific goals, for example Epoch of Reionization science that the Radio group works on. In addition, there is a group referred to as "Builders" who contributed to the original design and construction of the telescope and a telescope operations team who are responsible for ensuring it is maintained and kept running.

The Radio group contributes primarily to the Epoch of Reionization (EoR) Science Collaboration. The EoR Science Collaboration has members from around the world. Within the EoR Collaboration there is a subset of researchers, including the Radio group, from the United States who makes up what I call the US EoR group. I explain in later chapters how the members of the EoR Science Collaboration are developing and using two data analysis pipelines to process and analyze the EoR data collected with the WRT. One of the two pipelines is the responsibility of the Radio group, and is referred to in this dissertation as the US EoR pipeline. The origins and composition of this pipeline will be described in subsequent chapters.

Describing the Radio group's cooperative work with the US and International EoR groups, and the WRT Collaboration overall, will take place throughout the remaining chapters. For the moment it is sufficient to note that the Radio group's work that I studied is very much not isolated but rather intensely cooperative and interconnected with work around the globe.

Research Methods

This dissertation uses qualitative methods. I rely upon a longitudinal series of semi-structured interviews bolstered with observations of workspaces and group meetings and the collection and analysis of different artifacts produced by the Radio group to develop the findings offered in this manuscript. Many of these artifacts are produced by the WRT Collaboration and in the end provide me with primary sources with which to produce a recent history of the project. Just as the work of researchers in the Radio group unfolds through a reflective process of evaluating data so does my data and my interpretation of this data. I'll first describe the three sources of data that I use to capture the work of the Radio group. Following this I will discuss the timeline that my data collection followed before ultimately discussing my iterative data analysis.

Semi-Structured Interviews

Interviews are the backbone of my qualitative data collection. Weiss (1995) notes that “interviewing gives us access to the observations of others” and posits that interviewing “can inform us about the nature of social life” (p.1). Interviews enable a researcher to open a window on the past and to learn about settings that would otherwise be closed to a researcher’s inquiry. Interviews enable me to learn about project work that took place not only before my data collection began but also when I was not present in a workspace. Interviews most importantly enabled me to engage in deep, guided conversations with the researchers working in the Radio group. Over time interviews provided insight into each researcher’s successes, troubles, goals, travails, and so on.

As with any method of data collection the risk of bias is not escapable with interviews. Over the course of each interview I had to consciously work to listen rather than speak, constantly ask interviewees to define terms or elaborate on their meaning, and to allow their

perspectives to come across rather than my own pre-formed perception of a situation or artifact. Furthermore, the risk of a biased account from an individual is always present as Weiss (1995, pp. 149-150) observes that respondents will tend to try to portray themselves in a positive light and this can be countered through interviews regarding the same event with other respondents or examination of other records. It is also crucial that as with all sources of data I remember that everything is context dependent. My interviews with the Radio group took place at particular moments in their experience with the project and larger group that they are members of. The trust and frankness with which each respondent and myself could engage in conversation thus differed between my earliest and latest interviews, as can be seen through the gradual increase in the length of my interviews as they opened up to me.

All of my interviews are semi-structured as opposed to fully structured and rigid. Semi-structured interviews use an “interview guide,” or protocol as I more commonly refer to such guides, which outlines the topics to be covered in the interview and helps to keep the conversation flowing in a direction that produces desirable data (Weiss, 1995, p. 48). At the same time, a semi-structured interview protocol leaves room for exploration of the interviewee’s experience as the interviewer learns about the individual’s experiences and thoughts. A fully structured and rigid protocol on the other hand would not leave room for this exploration of concepts and would provide survey-like data instead.

Semi-structured interviews also provided me with the opportunity to inquire about artifacts or events that I collected or observed through my other data collection methods. Inquiring about artifacts and events is important for obtaining respondent’s perspectives and ensuring my understanding of these things is correct. For example, I encouraged my interviewees to draw

diagrams of the software they are responsible for developing or to explain how the Widefield Radio Telescope functions, Figure 6 being an example from an interview with Brianna.

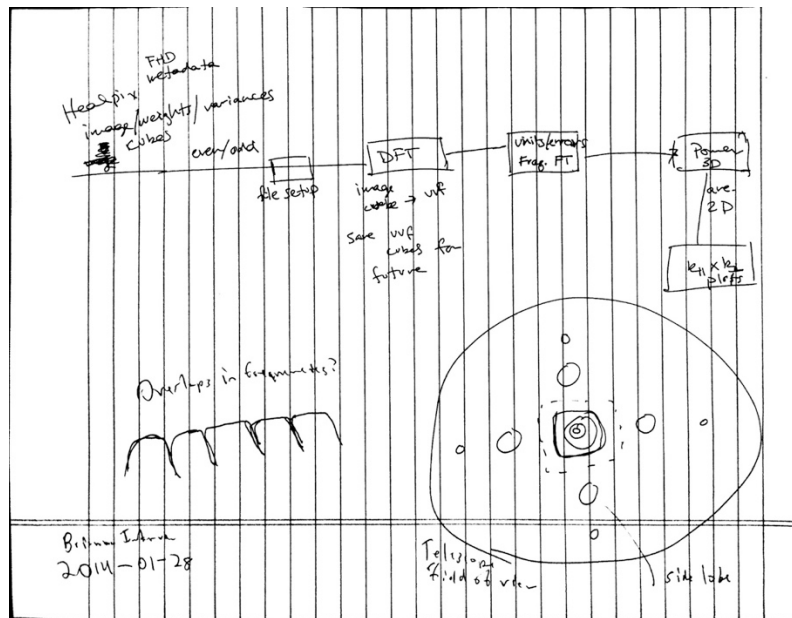


Figure 6. Diagrams drawn during an interview with Brianna in January 2014.

Each round of interviews that I conducted was designed to draw out the work each member of the group is engaged in, both at the time of the interview and in the past. All of my interviews were digitally recorded then professionally transcribed. Transcripts returned to me were then manually cleaned through a process of listening to the original audio recording and reading the returned text file. This cleaning process is necessary to not only ensure consistency in style but also accuracy regarding the often highly technical terms and concepts mentioned by the interviewee and myself as the interviewer. Looking back even now to earlier interviews I am able to recognize flaws in even my own recognition of terms since they were not known to me at that time. This is an unfortunate but realistic component to any form of data produced. Finally, interviewees were always consented before each interview took place according to the human

subjects protocol governing either the *Interacting with CI* or the Scientists & Their Software projects—see footnote at the beginning of this chapter.

Observations of group meetings

Observations of group meetings and workspaces are my second data collection method. Emerson, Fretz, and Shaw (1995) assert that ethnographic research “involves both being with other people to see how they respond to events as they happen and experiencing for oneself these events and the circumstances that give rise to them” and that an ethnographer seeks to immerse themselves in others’ worlds to be able to grasp what they experience as meaningful and important (p.2). Observations enable me as the outsider to enter my field site and begin to develop rapport with the individuals in the group while seeing what their concerns are, how their work unfolds on a day-to-day basis, and perhaps most importantly developing their respect and trust as a person who is genuinely interested in understanding their work and the challenges they face. Furthermore, being present during discussions of problems being addressed or updates on the status of a project added context to interviews I had already completed while providing fodder for future lines of inquiry as I followed threads in the Radio group’s work. Observation of work spaces is a fundamental approach to much of the scholarship in science & technology studies and CSCW.

My observations primarily focused on attending the Radio group’s regularly scheduled meetings. The Radio group held weekly “all hands” meetings lasting one to two hours where every individual offers an update on their project work. During these roundtable updates Magnus was kind enough to always ask me for an update about my work, whether related to the group or not, truly welcoming me into the group. As all of the post-doctoral researchers and graduate students were working on the WRT project these meetings usually turned into in-depth data

analysis and software debugging sessions as they continued ongoing discussions regarding issues currently being faced. On a few occasions there would also be discussion of a journal article, although this was rare during my time with the group due to the amount of analysis work to be discussed. In addition, there were a series of different teleconferences for the various WRT Collaboration groups, including one for the US EoR group and another for the International EoR group. I attended many US EoR group teleconferences where I was made aware of issues regarding the operation of the RadioCluster computing system along with overall data analysis concerns. I did not attend any of the International EoR teleconferences.

Throughout my observations of the Radio group I recorded field note jottings that I would then transcribe into narrative descriptions of my time with the group. Writing up field notes is not a simple passive act where “facts” are written about what I witnessed. Instead, “such writing involves active processes of interpretation and sense-making” where some things are captured as significant and others dismissed or entirely unobserved by me as the observer as insignificant (Emerson et al., 1995, p. 8). My earliest jottings in the field and resulting descriptions are fairly dry as I attempted to even capture the interactions between individuals in the groups and the vast landscape of project work taking place. As I slowly increased the amount of time spent in the field, and as I completed interviews and analyzed different artifacts, I came to focus my observations on particular tasks or practices I was observing. I worked to capture “thick descriptions” as Geertz (1973) describes results of the process of capturing and interpreting the “webs of significance” that make up culture. For example, my earliest field notes make note of the importance of plots and visualizing data without capturing great detail typically since I was not yet aware of their significance to the software and culture of the Radio group. Today, my time spent in the Radio group’s meetings is highly attuned to the plots they share and

how they interact with them, especially when these interactions or artifacts are new to the group's practice.

My field notes were written in Microsoft Word and when able images or diagrams are embedded in the document. For every group meeting I attended I would sketch the layout of the room and note where each individual was seated. Diagrams of these layouts are included at the beginning of most of my field note documents. When an individual or multiple individuals presented slides or some sort of formal presentation I would strive to obtain a copy of the slides so that I have them to refer to in my field notes. Each of my field note documents was dated and stored in my dissertation data archive.

Artifacts

The third and final method of data collection was to collect and interpret artifacts from the group. Artifacts for this dissertation include publicly accessible websites, internal Wikis, published papers from the group's work, emails to group mailing lists, pictures taken during my time with the groups or by the groups themselves, diagrams drawn for me by individuals, emails between myself and a group member, and perhaps most importantly the myriad different plots produced by members of the Radio group. My collection of these artifacts creates an archive of different material elements of the Radio group's work.

Artifacts serve a two-fold purpose for this work. First they are vital to my ability to grasp much of the science and past work of the group since they concretize not only the many specialized terms but also a perspective on the different practices engaged in for each project. Documentation of policies by the WRT Collaboration, design decisions, and past teleconferences or data analysis tasks has provided me with valuable primary sources for analysis. Second, during later rounds of interviews artifacts served as especially important conversation pieces,

enabling the interviewees to illustrate a concept or element of their work while providing me with a tangible reference point during my later analysis of the conversation.

Artifacts were collected throughout the course of my dissertation work. I first asked to be added to email lists of the group around November of 2013 prior to starting my focused fieldwork during January through May 2014. Being added to the mailing list provided me with a passive source of information on the group's activities. Mailing lists for the Radio group were primarily used to discuss major issues facing the different EoR groups or the status of publications submitted to review. I stored all of the emails sent to these lists on occasion have downloaded an archive to store with my other data. As messages were sent I read through each and archived those directly related to project work I was studying as PDFs.

Beyond emails, I collected information from archival publications of the project along with internal Wiki and public web pages maintained by the Widefield Radio Telescope Collaboration and saved them as PDFs for a static record. These publications and web pages detail the design and build out of the telescope, procedures for governing the project such as rights to data collected, and procedures for allocating observation time with the telescope. These were opportunistically gathered as I was analyzing interview and observation data so that I could solidify my understanding of concepts discussed or the context of information I was gathering.

Finally, during interviews and my time spent with the group I collected diagrams and endless plots as individuals or the group worked on their projects. Plots are such an integral portion of Magnus and the Radio group's work that they are a focal point of meetings, distributed regularly over mailing lists, and perpetually being added to a shared Dropbox that was created at some point during my data collection in 2014—and that I was added to as a member in early 2015—that contained over 900 megabytes of different plots (close to 2,000

individual files) by spring of 2015. I especially made sure to insert plots and diagrams discussed during later interviews into the transcript so that I would immediately be able to reference them while reading the discussion that prompted me to store them. Plots are integral because they are the material that the Radio group uses to understand and discuss the telescope, their software, and their data with each other. In Chapter One I introduced the idea that plots are the language of the group. The sheer volume produced by the group and the fact that almost everyone one of my interactions with these individuals brought up plots can only begin to underscore their importance to my ability to understand their scientific work.

My collection and use of all of these types of artifacts has been crucial to illustrating the context of my other sources of data. As I have already noted plots and diagrams are key discussion points during my interviews and allow me to better understand information that was being conveyed. Being a recipient of messages on the email lists enabled me to maintain awareness of general events in between my observation visits and also made me aware of concerns that I might want to discuss in person with an individual, for example the Fourth line bug in the Radio group that I elaborate upon in detail in later chapters.

My citation convention for anonymized documents

Many of the artifacts that I collected from the Radio group and Widefield Radio Telescope Consortium are publicly available but identifiable. To protect the anonymity of my informants I cannot directly cite them in this manuscript. However, for traceability and accountability I do use an anonymized citation convention that provides me with a link back to the original document. These citations appear as a footnote entry throughout the text with comments as appropriate to the context. They are prefixed with WRT- followed by a document type, a date, and finally a unique identifier. For example, WRT-Memo-2012-05-10-EoRDataAccess would refer to a

memorandum on Epoch of Reionization data access published by the WRT Collaboration on May 10, 2012. Using this convention enables me to refer back to my personal data archive to find the original document.

A longitudinal, episodic data collection timeline

This dissertation project's first piece of data is from the Summer of 2011 when I first interviewed Magnus, see Figure 7 below for a visual timeline. At this point in time my interview of Magnus was simply one of the twenty researchers interviewed for the larger *Interacting with CI* study. I would first meet the members of the Radio group in the Spring of 2012 resulting in my first interviews of group members the following year in the Spring of 2013. I would subsequently interview members of the group again during Winter 2014 while engaged in the bulk of my observation data collection for this dissertation. Finally, I interviewed members of the Radio group a third time during Winter 2015 after I solidified my understanding of their work and wished to develop deeper data regarding particular elements of their practices that make up the bulk of my findings. In total I have conducted over 19 hours of interviews, 30 hours of observations, and collected hundreds of plots along with over 500 email threads and parsed multiple publications and Wiki pages from the Radio group. Interviews provide me with the most succinct understanding of the software production in the group but conducting observations and collecting artifacts was integral to my ability to really comprehend this group's changing scientific work.

What the scientific work really was constituted of shifted over time throughout my data collection. In what I frame as the first episode (my early observations and interviews between 2011-2013) the group was doing the scientific work of helping build a novel telescope as a new scientific instrument and bring it into an operational state. They were simultaneously building

their software and preparing it as a new approach to data analysis, working with limited quantities of provisional data. During this time period the Radio group and WRT collaborators were publishing articles about their new data analysis techniques, the technical design of this instrument, the instrument's expected performance, and findings from data taken with the pre-operational telescope.

The second episode (my interviews and observations in 2014) finds the group digging into their analysis approach by continually testing and assessing the software they are producing using some of the data from the Widefield Radio Telescope's first operational semester (this started in July 2013). Finally, the third episode (my interviews and observations in 2015) captured an inflection point in the group as their analysis approach stabilized, initial work to offer new findings about the Epoch of Reionization took place, and the group began to contribute to expansions to the WRT while simultaneously planning a new generation of telescope and changes to their software.

In the remainder of this section I discuss in detail the types of questions I was asking during each of these episodes of data collection. On occasion during my data analysis throughout 2015-2016 I have asked for clarification on findings from group members as appropriate to ensure accuracy.

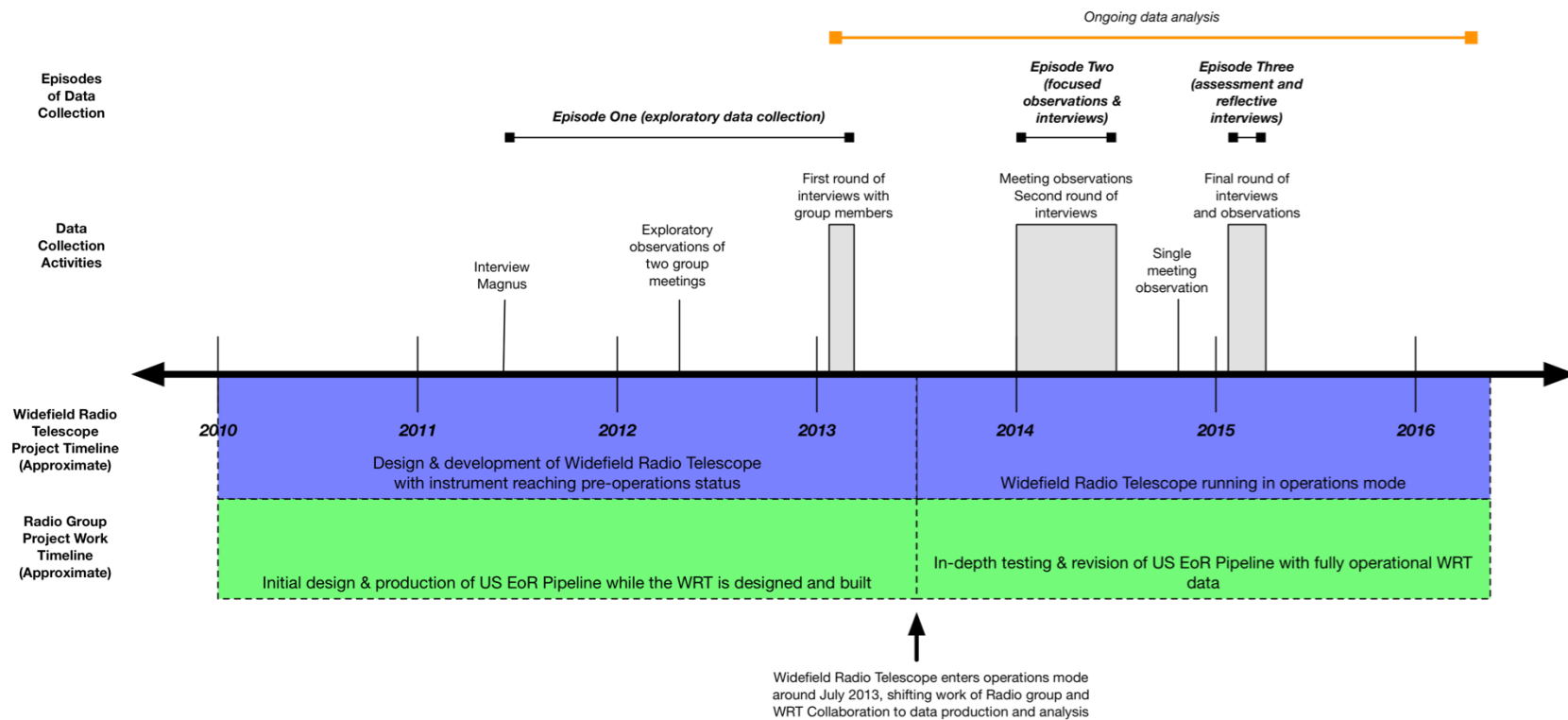


Figure 7. Data collection timeline.

Below the timeline two broad phases of the WRT project are captured in blue. The Radio group’s software production work is visible in green. Above the timeline my data collection activities are listed with each episode noted. Project history prior to 2010 is not included in this timeline.

Episode one: exploratory data collection

My first interaction with the Radio group took place in the Summer of 2011 when I first met Magnus while working on the *Interacting with CI* study. This interview was scheduled for one hour and lasted 72 minutes. It was designed as a semi-structured interview to elicit information regarding each of the interviewed Principal Investigator's (PI's):

- Current research projects and overall research agenda
- How their research is interdisciplinary
- Their research methods and the skill sets of members of their groups
- The software being used and/or developed in their research
- Where they are obtaining and sending data to/from along with examples

The initial interviews for the *Interacting with CI* project introduced me to the work of the Radio group from the perspective of Magnus. As I analyzed the transcripts from the twenty interviews the project collected I noted the degree to which each interviewee illustrated a sense of reflection about their work to guide my choice of future inquiries. Magnus's interview illustrated his group's working with significant and increasing quantities of data while their technological practice shifted as they develop their own software. The Radio group's increasing quantities of data and their development of their own software aligned them with my research interests and that of the *Interacting with CI* study overall. This led to the enrollment of Magnus and his group in the longitudinal portion of the study.

The following Spring (2012) I met the research group for the first time. This took place during one of each group's regularly scheduled all hands meetings where I introduced myself and my laboratory, the *Interacting with CI* project, and consented every member in accordance with our human subjects protocol. I then attended another meeting of the group the following week to begin to learn something about their work and to become known to the various individuals. In the Winter of 2013, working with the other members of the *Interacting with CI*

study, an interview protocol was developed and then employed during Spring 2013. This semi-structured interview protocol was designed to gather information about each interviewee's:

- Educational background and position with the research group
- The projects they were working on along with who they worked with
- Detailed walkthroughs of their work on their two primary projects (as applicable) including:
 - where the data is obtained from, the process for obtaining it, the software used to obtain it, and who was involved in obtaining it
 - the data analysis process for the project including what is completed to prepare data for analysis and who is involved
 - what software is used for the data analysis along with how it was acquired and who develops it along with the reason that software is used
- How the data analysis for the project may have evolved since the project started
- Who outside of the group uses a project's data and how it is shared
- How any software that is developed by the group is shared with persons outside of the group and who might be using it

These interviews were semi-structured and scheduled to be one hour. I requested time with members of the group who appeared to be central to the focal projects based on my initial, brief observations of the group. This led to four interviews with individuals—two PhD students and two post-doctoral researchers. The four interviews lasted between 34 and 65 minutes (average 50 minutes). Summaries of the interview lengths and each interviewee's role in the group (reiterated from earlier in this chapter) are summarized in Table 2.

Table 2. Spring 2013 interviews.

<i>Interviewee</i>	<i>Role in Group</i>	<i>Interview Length (minutes)</i>
<i>Brianna</i>	Post-doctoral Researcher	65
<i>Abner</i>	PhD Student	59
<i>Igor</i>	Post-doctoral Researcher	34
<i>Peg</i>	PhD Student	40

Episode two: studying a period of intensive software testing and analysis

Following my first round of interviews with the four group members and my initial analysis I officially discussed following the Radio group as the site of study for this dissertation with Magnus in November of 2013. This led to my addition to the International EoR group's mailing list and subsequently in January of 2014 I began a five-month stretch of observations of group meetings and a second round of group member interviews. My observations during this period were aimed at helping me to grasp the group's culture while deepening my understanding of the work of developing data analysis pipelines across the WRT project.

I was able to see the concentrated work of developing and debugging the US EoR pipeline in preparation for a "run" using a larger quantity of data than had been completed up until this point. I also witnessed the emergence of a fairly major and somewhat unexpected bug in the analyzing of data—the Fourth Line bug—whose thread across the US EoR pipeline and the larger WRT project became a focus of not only my inquiry but also the Radio group's research efforts. This time observing meetings also emphasized the importance of cooperative analysis of plots in the Radio group's work. My two exploratory observations of the group's meetings exposed me to their use of plots but it was not until I attended meetings over a period of months that I learned just how central these artifacts are in their work.

Early in my period of focused observations I engaged in a second round of interviews with group members. These interviews took place in January and February of 2014 with the same four members of the group, summarized in Table 3. This round of interviews was designed so that the interviewee would walk me through the different stages of work involved in the pipeline development project I was studying. I wanted these individuals to not only tell me but to

show me how their software works and their analysis is conducted. In particular, I asked each interviewee to:

- Update me on the current status of the project and their responsibilities
- Show me how they collect data
- Show me how they process data
- Show me how they analyze data
- Show me how they archive data
- Show me how they release data outside of the group

Each of these questions was designed to elicit a discussion around different stages of research lifecycles that my research group and I were examining. Overall models of this “lifecycle” were posited in the literature (UK Data Archive, 2013; Wallis et al., 2008) from either a policy perspective in the case of a UK Data Archive initiative or from the study of a single domain science in the case of Wallis et al. with an ecology sensor network. This lifecycle concept guided the overall inquiry of these interviews yet as I found through the process of talking with these four researchers the concept does not hold up from the day-to-day perspective of this group’s work.

At this point in time Brianna and Igor were in the depths of developing and testing their pipeline components (ImgPower and CalibratorImager as I will explore in Chapter Six). Abner had been drawn in to developing the controller components (Munchy) of the US EoR pipeline and managing the many and constant executions to test changes to the code and new “cuts” on the data as the group analyzed this stream of data coming in. Peg was working on developing a catalog of radio sources in the WRT’s field of view, what ultimately was her dissertation work.

Conducting a round of interviews while increasing the amount of time I spent observing the group rapidly strengthened my awareness of different ongoing concerns and practices in their day-to-day work. The Radio group’s single overarching project led to a constant dialog among

the group members and with their collaborators around the United States and the rest of the world while I was present. Regular meetings were heavily oriented around the latest plots of data, with Magnus regularly asking everyone at the beginning of meetings to put their plots on the table before he would declare the person with the most to have “won the meeting.” By May of 2014 I had been collecting and analyzing data to the point that I was not seeing new phenomena. I stepped back to focus on analysis and to write two publications using this data with my colleagues (Paine & Lee, 2014; Paine et al., 2015).

Table 3. Winter 2014 interviews.

<i>Interviewee</i>	<i>Role in Group</i>	<i>Interview Length (minutes)</i>
<i>Brianna</i>	Post-doctoral Researcher	125
<i>Abner</i>	PhD Student	78
<i>Igor</i>	Post-doctoral Researcher	67
<i>Peg</i>	PhD Student	56

Episode three: reflecting on my understanding of the group’s work

Stepping back and analyzing my interview, observation, and artifact data through May of 2014 left me with questions about the state of the Radio group’s ongoing work. By January 2015 this led me to design a final round of interviews with members of this group. This round—the third time I interviewed three of the members, the second time Magnus, and the first with one of the new PhD students (Nima)—focused on having members of the group react to and reflect upon how I captured elements of their work. In particular I structured much of these interviews around a printout of a diagram I produced of their pipeline and asked them to mark up in red ink what was incorrect and/or missing—see Figure 8 for a photograph of four of the marked up diagrams.

I also designed this round of interviews to solidify my understanding of various key terms and concepts in their practice along with various coordinative systems that support their work.

These final five interviews rounded out my data collection. Interviewing Magnus for a second time, my first since that initial interview in 2011, truly helped me to reflect upon my understanding of his group's years of work while building up my depth of understanding regarding the WRT project's origins and future. In total, this resulted in over 19 hours of semi-structured interviews, over 30 hours of observations, and hundreds of artifacts collected. My final interviews with members of the radio group are summarized in Table 4.

Table 4. Winter 2015 interviews.

<i>Interviewee</i>	<i>Role in Group</i>	<i>Interview Length (minutes)</i>
<i>Abner</i>	PhD Student	96
<i>Brianna</i>	Post-doctoral Researcher	178
<i>Igor</i>	Post-doctoral Researcher	76
<i>Nima</i>	PhD Student	78
<i>Magnus</i>	Principal Investigator	141

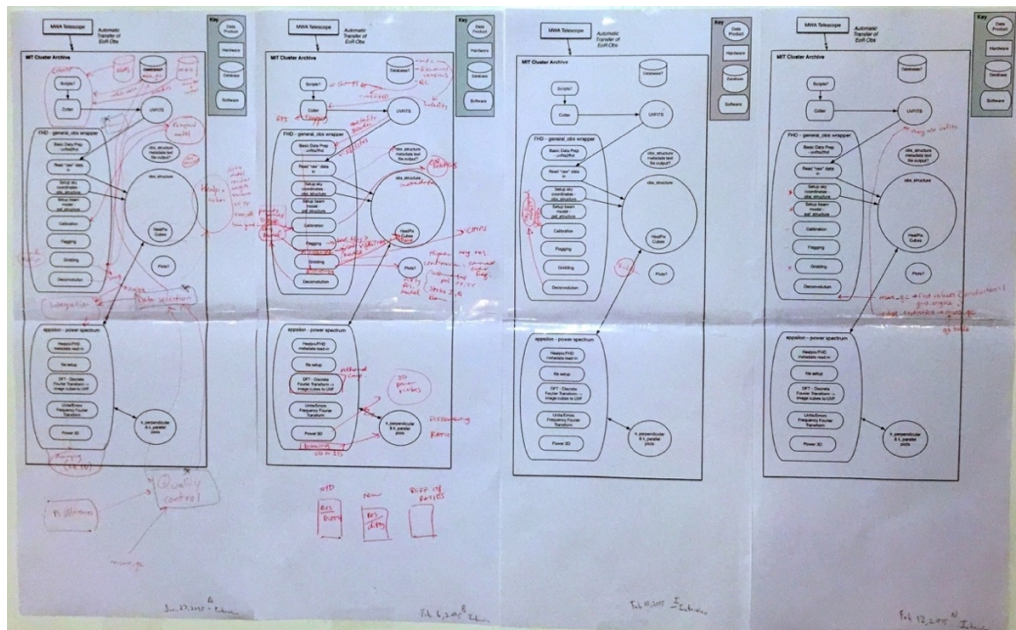


Figure 8. Pipeline diagrams from final round of interviews.

As a way to obtain feedback on my understanding of their work I asked Abner, Brianna, Igor, and Nima to mark up my abstraction of their software using a red pen. Not pictured is a fifth copy that was completed by Magnus.

Data analysis

My data analysis took place over multiple years, iterating as I collected new data so that earlier findings guided my ongoing inquiry. Throughout the course of my data collection I was constantly analyzing and reflecting upon the different pieces I was gathering, creating my understanding of cosmology while working to not let software engineering perspectives from my earlier training entirely color what I was seeing. Qualitative research is inherently a reflective process and the researcher must continually position themselves in relation to their data and analysis. I had to work to bound my thoughts on software engineering and consciously question how they were influencing my data and analysis. Data that I collected was placed into the ATLAS.ti⁸ qualitative data analysis software package and archived in a folder that was organized with transcripts, field notes, and artifacts stored in dated folders. When provided with a physical artifact, such as a print out of a plot or a hand drawn diagram during a meeting or interview, I kept this in addition to scanning it and storing a PDF in a Dropbox folder.

My analysis was guided by the notion of tracing the relationships between individuals, organizations, software, data, and hardware across the Radio group's work. Software was the artifact I used to trace these relationships, akin to Harper's (2000) tracing of a document's career at the International Monetary Fund. Collecting and analyzing data on this group for the *Interacting with CI and Scientists & Their Software* projects influenced this exploratory data by probing about the disciplinary backgrounds of the scientists, where they are obtaining data from, how they're working with it, and especially who they're collaborating with to do different aspects of their work. Simultaneously having an interest in studying software I pushed to foreground inquiries about this topic. I have revisited this early data countless times as I

⁸ <http://atlasti.com/>

collected and analyzed newer data, foregrounding misperceptions and misunderstandings I had early on about specific terms or what the Radio group was trying to achieve.

I continually open coded data that I collected, whether it was physically printed on paper or stored digitally in ATLAS.ti (see Figure 9 for pictures of this concept), for emerging concepts (Emerson et al., 1995; Miles & Huberman, 1994; Weiss, 1995). Emerson et al. (1995) state that coding “is a way of opening up avenues of inquiry” where the researcher identifies and develops concepts resulting in analytic insights by closely examining their data. Qualitative coding identifies, elaborates, and refines analytic insights “from and for the interpretation of data” (p.151). Weiss (1995) in addition emphasizes that when coding the researcher brings some categories with them to their studies before ever knowing what the interviews will produce. In my case this would most readily be ideas of types of software for example (i.e., applications, scripts, operating systems, etc.). In addition to open coding, for every interview I closed coded for each protocol question and any issues with the transcription. Closed coding for the protocol questions helped me to verify that the protocol was covered and to foreground differences in the lengths of different individual’s answers to particular questions depending on the type of work they are involved in.

Open coding helped me capture emergent and unexpected phenomena in the data. Early in my data collection my codes would often be simple mentions of a piece of software, a source of data, or an individual or organization involved in the work. For example, my first round of group member interviews produced codes such as “defining/explaining a common term in their work” to help me generate a dictionary of the scientific concepts guiding the individual’s work or codes specifically regarding software such as “developing confidence in software used/developed” as I was noticing how my interviewees discussed how they must examine the

software being used in their work to understand how it is affecting their analysis. I also always used the code “juicy”⁹ to capture and recall especially interesting points. Over time my coding evolved to capture discussions about specific scientific concepts, their connection to the Radio group’s software, the use of plots to develop software and analyze data, and facets to the telescope as an instrument. I continually reflected upon how I was coding, asking if I was imposing Software Engineering or CSCW perspectives too heavily on my data. I also consciously thought about my position as an outsider coming and going in the group, thinking about what these individuals were eager to tell me and what this could be hiding about their work. I have also worked to theorize terms and concepts continually used by these individuals, giving them meaning in a CSCW context by relating them to existing CSCW, STS, software engineering, or software studies terms.

Analysis of my exploratory data

As my coding progressed I began to group codes together to surface themes. Themes are structures or patterns that help me as a researcher begin to categorize and compare aspects of the data I am analyzing. Two early themes in my analysis especially shaped my subsequent data collection. The first surfaced a divide between work within the Radio group and work engaging their collaborators. The second pointed to a variety of connections between their data and their software. This led me to start Episode Two (the point where I was explicitly studying the group for this dissertation) of my data collection with a research question asking how radio astronomers use internally and externally developed software to work with their data.

I was interested at this point in first examining how software was used by this group of scientists to work with their data. Second I wanted to untangle the software that was actually

⁹ I picked up this name from Matt Bietz over the course of many rounds of coding another project’s data.

being produced in the group versus software created by stakeholders outside of their group as my exploratory findings were surfacing a division in the Radio group's work. At this point in time I was immersing myself in CSCW and scientific software development literature in addition to analyzing this exploratory data. This scholarship, on top of my prior training as a software engineer, made me less interested in seeing how collaborations between software developers and domain scientists transpired. I wanted to see how scientists themselves, trained or not in software engineering methodologies, created this product and resource in their own work. Software engineering training provided me with multiple ideas of how to build software but seeing the variety of approaches in that profession alone I was more curious to see how a group of scientists figured out an approach to building software on their own in conjunction with the work to do their science. As I read more and more science & technology studies and CSCW literature I began to see the social construction of knowledge and work practices, whether related to software or not, more than I did software engineering conceptualizations. I was always skeptical of editorials and publications on scientific software development bemoaning the state of scientist's software production and its lack of software engineering rigor, and studying STS and CSCW literature only solidified this skepticism. From my perspective looking for software engineering practices was simply imposing external ideas of validity to work practices and scientific software development scholarship was already beginning to recognize that scientific software development is not the same as commercial software development.

My coding and analysis of my exploratory data helped me to constrain my continued inquiry around the software that I have come to describe as the US EoR pipeline. Over time as my understanding of the Radio group's project work grew I was able to refine codes into themes which lead to memos on the work taking place, asking who, what, when, where, why questions

about the Radio group’s data collection, software production, use of plots, and contributions to the WRT project—all elements I explore in the empirical chapters of this dissertation.

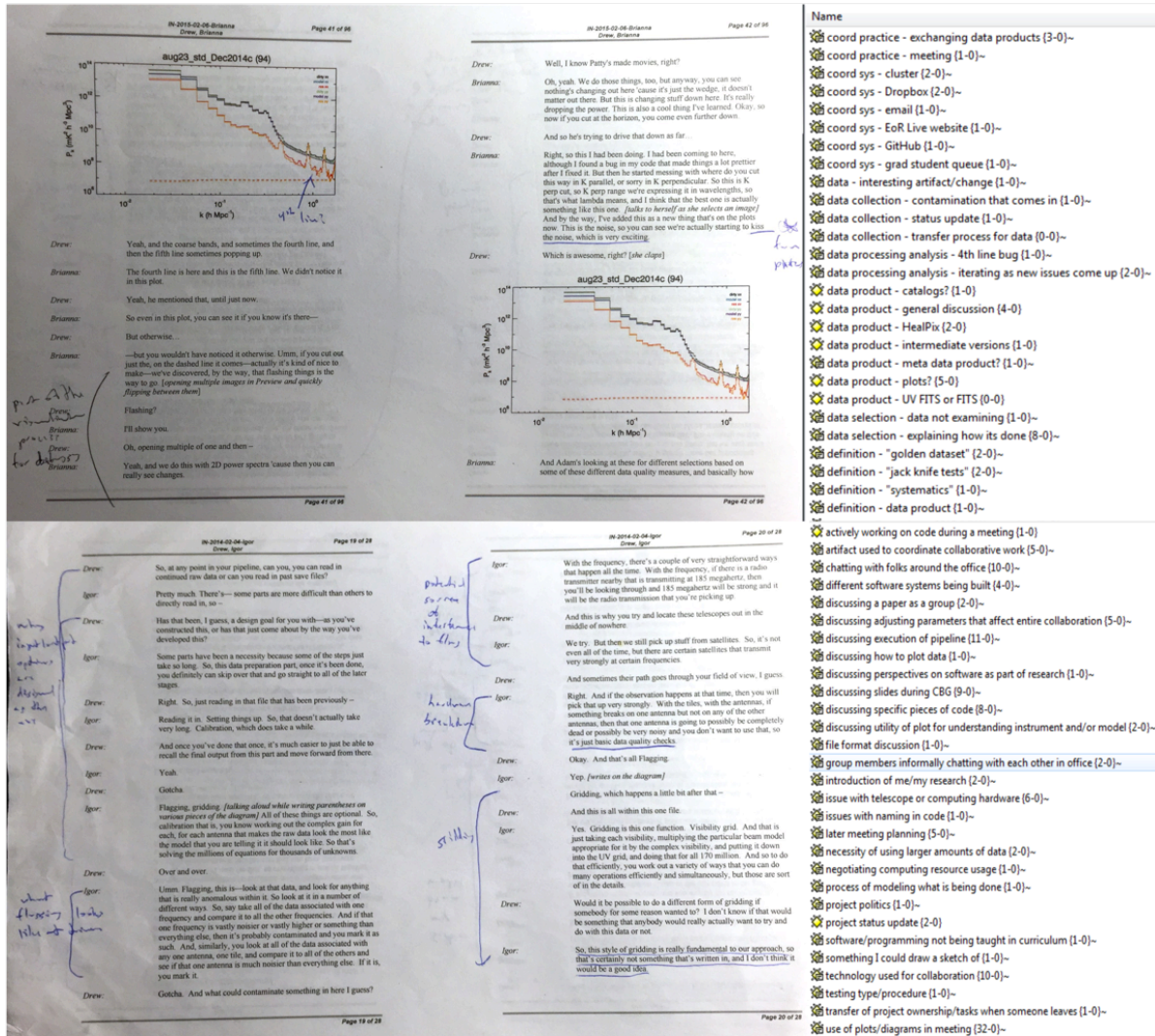


Figure 9. Coding from my data analysis. I iterated between coding physical printouts of interviews and digitally coding in atlas.TI. In the top right codes have been organized into themes around coordinative systems, data collection, data products, and definitions of scientific terms for example.

Memo writing is the process where a qualitative researcher writes to “elaborate ideas and begin to link or tie codes and bits of data together” (Emerson et al., 1995, p. 162). Emerson et al. note that the central task of memo writing is “to develop theoretical connections between”

(p.164) different pieces of data, figuring out what to foreground and background in the analysis so that the researcher can present a meaningful narrative. For example, my code regarding developing confidence in the software along with similar expressions of concern regarding the origin of data led to a theme asking how researchers do or do not interrogate the resources or artifacts that comprise their work. Themes about the origins of data and the connection to the Widefield Radio Telescope as a project and instrument led me to write memos on the Radio group's efforts helping to commission the WRT instrument, their place within this virtual organization, and the development of software pipelines for Epoch of Reionization data analysis.

An integral part of my development of themes and memos was my creation of diagrams of the Radio group's software. These diagrams drew upon artifacts created or obtained during interviews of observations as well as archival items that I stored. To help me sort out the Radio group's approach to analysis and their software I iterated upon diagrams Igor and Brianna drew for me during interviews. I took my coding and drew the relations between pieces of software, data, the instrument, and individuals doing work. As a check on my analysis I employed my own diagram of the US EoR pipeline during my final round of interviews. This helped me assess not only my own analysis up until that point but prompted discussions of change in the software since I had last collected data. I also diagrammed the organization of the Widefield Radio Telescope project to help me sort out the situation of the Radio group within and relationship to this infrastructural endeavor. My efforts diagramming my data are present in this dissertation through many of the figures I offer (Figure 1, Figure 3, Figure 11, and Figure 14).

Developing the themes of the dissertation with my theoretical commitments

Out of my memo writing and diagramming at this point I wrote one publication unpacking the Radio group's US EoR pipeline development (Paine & Lee, 2014) and another examining their

practices for data processing work as compared with three other scientific groups (Paine et al., 2015). This memo and publication writing highlighted an emergent point that over time solidified into my understanding that the data analysis work in high-precision empirical research is deeply connected to the different hardware and software systems and work practices in data production work. The deep connection between data production and its analysis runs through this dissertation, that notion of needing to understand the instrument in your bones Magnus expresses and that unifies my findings. Through this writing process my guiding research question developed from being about using internally and externally developed software to work with data to focusing on how the Radio group is enacting infrastructure by producing software.

In (Paine & Lee, 2014) I noted little research had explored in detail the conditions in which infrastructural software is produced by scientists. This idea is present in this dissertation as I frame both the WRT project as a research infrastructure and the Radio group's data analysis software as another research infrastructure layered above, see Figure 3, and show how they are intimately connected and co-produced from the perspective of the Radio group's work. Drawing upon the notion of relational infrastructure (Star & Ruhleder, 1996) and the idea of performing an infrastructural inversion (Bowker, 1994; Bowker & Star, 1999) I organized my memos and the themes within them to explain the multiple infrastructures that I see in the Radio group's work. The idea of the kernel of a research infrastructure (Ribes, 2014) helps me explain how the WRT and Radio group stabilized a novel telescope so that it can usefully be employed in scientific studies by entangling data, the instrument, and software in particular ways. I use the notions of cooperative work arrangements and common field of work to frame how individuals cooperate to create particular infrastructural components.

The theme of software as the expression of the Radio group's scientific method is framed by perspectives on the social construction of knowledge from STS and cooperative work from CSCW. These concepts help me illustrate how the Radio group's software production enables them to enact an infrastructure. Fujimura (1996) discusses how scientists co-construct materials, instruments, theories, representations, and so on in their work to produce knowledge. All of the various elements shape each other to get to the point where a fact can be black boxed as Latour (1987) describes the closing up of the messiness of knowledge production into the tidy representation of complex work that is a scientific fact. Viewing software as a multifaceted and mutable set of relations created through the discursive and material practices (Kitchin & Dodge, 2011) of science helps me explain how the Radio group does high-precision scientific work.

In my analysis the notion of data products surfaced as a key facet connecting the multiple infrastructures in the Radio group's work as well as being a material that supports coordination among the pieces of their software and these individual's different practices. Tracing the flow of data products in my analysis by visualizing the software components, data, and points where humans do work helped me solidify my understanding of the Radio group's work while guiding further data collection (e.g., as in Figure 8). Data products connect my themes of software as the expression of the Radio group's scientific method and that of plots being their language because plots visualize information captured in data products as created by the software. I have also come to realize that data products capture states of the scientific analysis, since various intermediate versions encapsulate data that has been processed through some version of the software that is I realized expressing the Radio group's approach to cosmology. Data products and plots of them (as well as plots of other aspects of the science or instrument) become representations of the common fields of work being created in the Radio group's infrastructural work.

Summary

I collected and analyzed data over three episodes. Analyzing this corpus gives me the ability to illustrate many aspects of Magnus and his group's work. I learned about the Widefield Radio Telescope project from my informants during interviews and their discussions during observations, but I had to bolster this understanding using the variety of artifacts I collected. I primarily focused on the Radio group's software production during my data collection and in my analysis have come to see how it is their ongoing expression of a scientific method, as well as their extensive use of plots in their enactment of infrastructure. I will turn over the next four chapters to develop the ideas underlying the themes I have introduced in this chapter and Chapter One. I will return in Chapter Eight to discussion limitations to my study and analysis.

IV. Framing a Cosmology Research Infrastructure

Order and classification are the beginning of mastery, whereas the truly dreadful enemy is the unknown. — The Magic Mountain, Thomas Mann

It is the explanation that opens our eyes; the dispelling of an error gives us an additional sense. — Marcel Proust, Sodom & Gomorrah

Introduction

From our very first interactions Magnus merrily described the unfolding vision of the Widefield Radio Telescope project. At this time earth was being moved on the telescope's southern hemisphere radio observatory site, hardware built and installed in this remote radio quiet area, and tests of the instrument and systems conducted. In the middle of our first conversation he ushered me over to the door of his office to show me a picture of antennas being constructed in this remote desert location. His excitement was palpable.

Conversations with Magnus and everyone in the group about their software invariably referenced the work of collaborators across the United States and world. I quickly realized that I needed to understand the infrastructure of the Widefield Radio Telescope project to begin to remotely understand the Radio group's software work. In addition, I needed to bring some order and classification to my own data analysis to explain how this group of individuals in Seattle recognizes their position in this multinational project, to grasp how their dialogue with this project's policies and resources shapes their local work, even as they help to shape the larger project itself. It is the overarching conditions of this project that in part shape the Radio group's software. I have previously (Paine & Lee, 2014) noted that these conditions are understudied. This chapter starts to untangle and explain this project as a research infrastructure with a kernel that must create and sustain a cache (Ribes, 2014). In this chapter, I discuss some of the

infrastructural elements highlighted in green in Figure 10 (additional elements are discussed in Chapter Five).

(Some) Layers of Infrastructure to the Radio group’s cooperative work

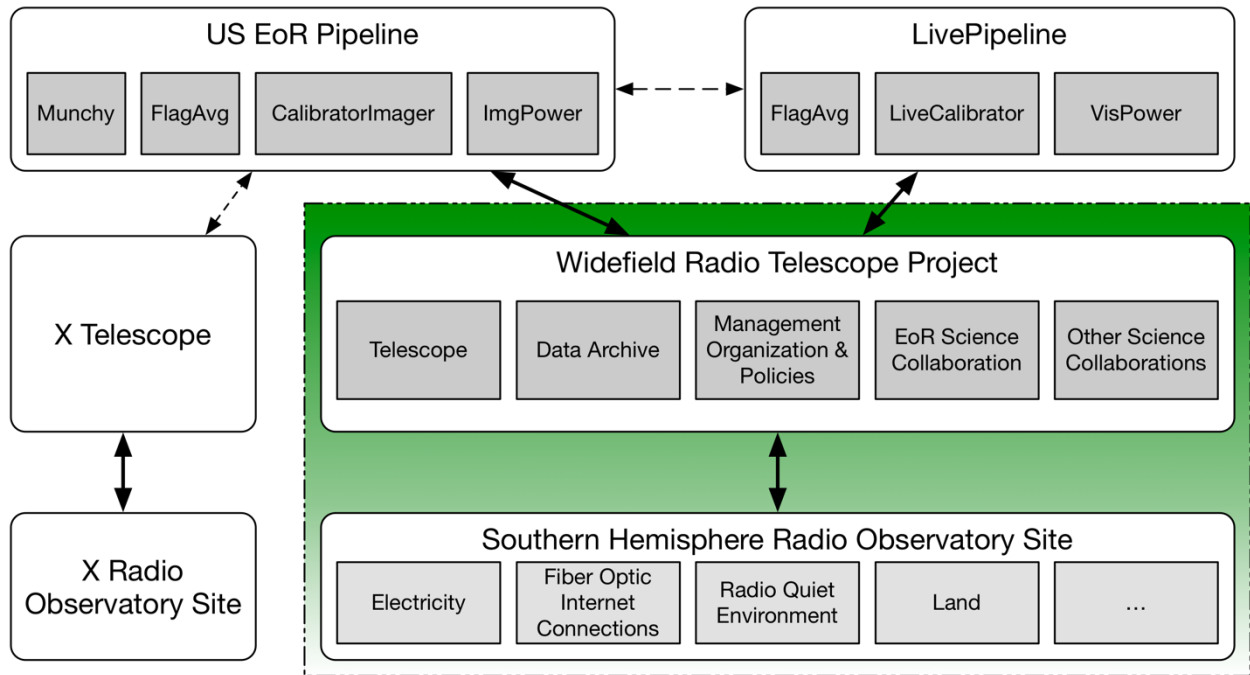


Figure 10. Infrastructures examined in Chapter Four. The focus of this chapter is the Widefield Radio Telescope project. Discussing this will require touching on points about the radio observatory site and a bit about the US EoR pipeline as part of the Radio group’s contribution to the WRT and EoR Science Collaboration. Grey boxes are resources of the infrastructures.

I examine how the Widefield Radio Telescope is organized as a coherent project, how its human infrastructure is arranged. I draw out the different cooperative work arrangements and common fields of work that the Radio group is a central part of in this project. I frame the Widefield Radio Telescope project as a research infrastructure where the cooperative work arrangements are part of the cache in the infrastructure’s kernel (Ribes, 2014). These heterogeneous experts develop and sustain the rest of the cache’s resources for use in answering different cosmology science goals.

The WRT is a virtual organization with cooperative work arrangements for the management of the project and instrument as well as four specific Science Collaborations. I refer to the organization in this dissertation as the WRT Collaboration and use the word collaboration primarily to refer to this entity or its defined scientific groups (discussing cooperative work for activities instead). Each of these Science Collaborations is designed to avail itself of the resources of the infrastructure yet simultaneously help to sustain the kernel itself. The Radio group is part of the EoR Science Collaboration which has significant sway over the entire project as I will explain throughout this chapter.

Examining these elements of the project's human infrastructure enables me to understand this particular project's emergent epistemic machinery (Knorr-Cetina, 1999) that is but one within the larger cosmology research community. This project is a research infrastructure upon which the Radio group can produce their own infrastructure in the form of their data analysis software. The WRT organization and its policies, along with other resources, produce the conditions underlying the Radio group's software development work.

Organizing the human infrastructure of this research infrastructure

From the beginning of my study I knew that the Widefield Radio Telescope project is a multinational undertaking. Magnus and his group made it clear that they are one of many who are contributing to the Widefield Radio Telescope. He and the members of his group readily explained that they contribute to this project's study of the Epoch of Reionization. Brianna, among others, informed me that studying the Epoch of Reionization is the largest scientific goal of this project and as a result wields considerable influence over the design and operation of the instrument. Looking at how this project has organized itself is necessary to understand in part

how it is able to support knowledge production work. This organization creates policies, the telescope, and data that are the resources in the cache of this infrastructure.

When I began my study I did not really know how the WRT project might be organized. I was familiar with high profile particle physics projects like the Large Hadron Collider and knew that it was a large multinational organization. I was also familiar with different telescopes, but I knew nothing about this novel telescope. The members of the Radio group explained to me that the WRT project is organized formally as the WRT Collaboration with scholars contributing from around the world. In time I learned that the project charter defines the WRT as “the collaborative project of the Parties signatory to this SOC [Statement of Collaboration] and the respective member organizations in [Country X] or the U.S. whom the Parties represent”¹⁰. I have therefore chosen to refer to the WRT Collaboration in this dissertation when writing specifically about the established multinational organization of scholars who are party to this Statement of Collaboration document. How then have the parties to this SOC organized the project in the time since this document was written?

Broadly the WRT Collaboration has created an organization with a couple of management groups and four specific Science Collaborations to create and sustain resources for doing cosmology—the telescope and resulting data, see Figure 11 below. The WRT Collaboration consists of different institutions, e.g. universities, as partners to the collaboration and individuals from these institutions as members. The WRT Collaboration created two types of membership for researchers that provide a well-defined pathway for these scholars to have access to the infrastructure’s resources. The first is “Individual Member” and the second is “Associate Member.” Researchers from an institution that is partner to the SOC are eligible to be

¹⁰ WRT-Memo-2012-12-02-IndividualMemberPolicy referencing material from the 2009 Statement of Collaboration, p. 3-4.

an “Individual Member” of the WRT Collaboration. Researchers whose institution is not a partner to the WRT Collaboration agreement can be voted into the project as an Associate Member by the WRT Board. Undergraduate, graduate, and post-graduate students can be Individual Members so long as they’re enrolled in a degree program and one or more of their supervisors is an Individual Member of the WRT Collaboration¹¹. Membership provides access to WRT Collaboration resources such as raw data, results, publications, software, and so on. It does however require that the member contribute to the project and complete tasks which they commit to. The WRT Collaboration’s policy on individual membership lays out these rules¹¹.

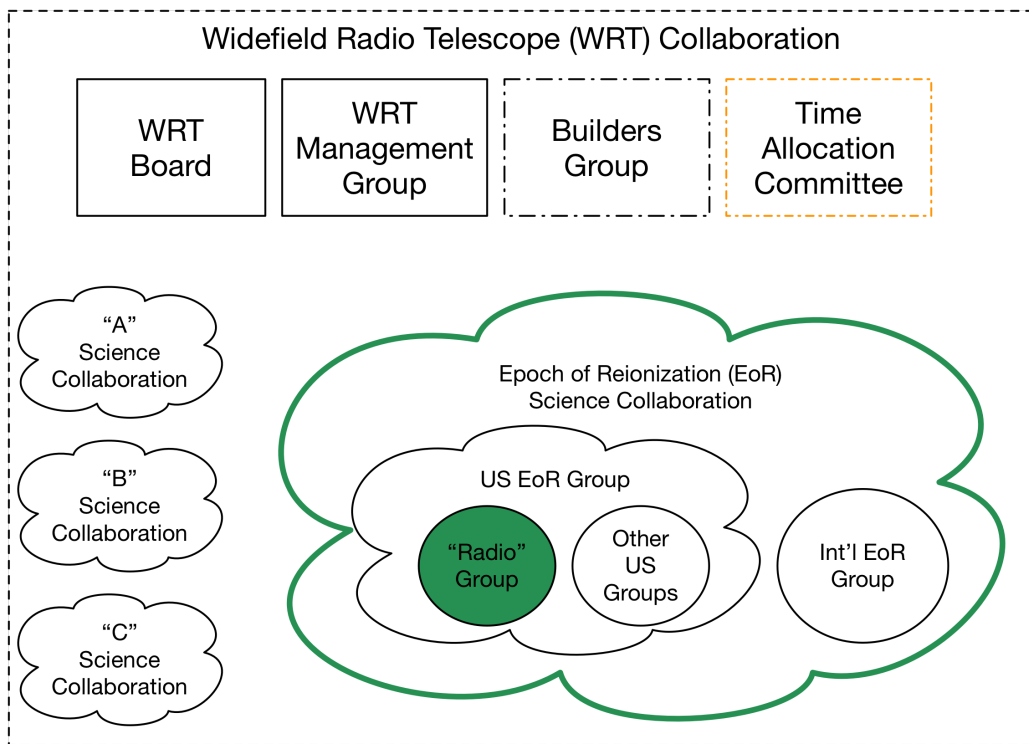


Figure 11. Organization of the WRT Collaboration. This abstraction has the Radio group highlighted in green. The size of the science collaborations is not meant to imply a judgment regarding their size or contributions to the WRT, rather I did not collect data on A, B, and C. Members of the Board, Management Group, Time Allocation Committee (composed out scientists from outside the WRT Collaboration), and Builders Group all also belong to at least one science collaboration under which they do their scientific work. The Builder Group existed to design and build the telescope systems but dissolved once the instrument became operational.

¹¹ WRT-Memo-2012-12-02-IndividualMemberPolicy, p. 1-2.

Creating and defining the types of membership is the first step towards the WRT Collaboration creating and setting identifiable and visible expectations for individuals who wish to use this infrastructure's resources, for being part of the human infrastructure of this research infrastructure. The collaboration's expectations are constructed and codified through written WRT Collaboration policies that are publicly available on the project's website. These policies are part of the Radio group's cooperative work with this infrastructure project. They are learned as part of membership (Star & Ruhleder, 1996) in the project and shift into the background of the Radio group's day-to-day work but emerge at certain key points such as the preparation of publications, a point I'll elaborate on later in the chapter.

The Associate Member role turns out to be important for supporting and sustaining the WRT Collaboration's ongoing human infrastructure. As post-doctoral researchers working on the WRT project advance in their careers they take jobs at different universities. These universities may or may not already be partner to, or willing to partner to, the WRT Collaboration. This situation impacted Magnus when he became a faculty member at the University of Washington. He noted that when he accepted his faculty job "UW [University of Washington] was worried about requirements for future money so refused to buy in" to the WRT Collaboration. Being voted in as an Associate Member enabled Magnus to continue to contribute to the project as he had since its inception. As a result of his Associate Membership, his own post-doctoral researchers and students could contribute to the WRT as well. This type of situation arose for other researchers as well. For example, one researcher who transitioned from being a post-doc to faculty elsewhere in the United States at an institution that also would not buy in to the WRT Collaboration. This took place even as he at one point held a key management position in the project.

As an organization the WRT Collaboration sets project goals, pulls together resources for building and maintaining a telescope, and socially mediates the production and use of data with this instrument. This contrasts with traditional astronomy observatories McCray (2004) describes which are standalone entities which primarily exist to manage the telescope itself but don't take responsibility for the data produced long-term. From McCray's description if I were to characterize these traditional astronomy observatories as a research infrastructure then I would say their kernel is designed to maintain an instrument as a resource but not its data products. The WRT Collaboration on the other hand is organized in the vein of particle physics projects (cf. Knorr-Cetina, 1999) where the work is that of a collective who build the instrument, collect and maintain data, and engage in analysis with some amount of cooperation.

Ribes (2014) stresses that every research infrastructure's kernel is highly specific and just with a simple comparison to past astronomy endeavors I can see that the WRT project is a departure from most astronomy endeavors and is more akin to particle physics undertakings, at least in terms of the overall organization of the project. Understanding this basic difference turns out to underlie many of the facets to the cooperative work I see in the Radio group, from their constant dialogue with collaborators around the world to their lack of concern about data being shared widely, since the expectation of the work is that it will be a cooperative, collective undertaking. The epistemic culture of this project is somewhere on a spectrum in between that of the collective in high energy physics projects that Knorr-Cetina (1999) describes and the individual investigator's group in astronomy that McCray (2004) illustrates. For the moment though, there is another key organizing aspect to the WRT Collaboration I must describe, its Science Collaborations.

WRT Science Collaborations

The Widefield Radio Telescope as a project was created to “demonstrate technologies and techniques suitable for future application on larger scales” as well as to “pursue targeted high-value science objectives.”¹² It is a stepping stone technologically and scientifically to future larger telescopes (and possibly collaborations for such telescopes). The high-value science objectives of the WRT project fall into four areas of science inquiry, organized as Science Collaborations. Epoch of Reionization science is one of the four and the only one I am concerned with in this dissertation since it is the one Science Collaboration the Radio group is a part of. I refer to the other three Science Collaborations by letters A, B, and C since I did not examine any of the research happening in these areas, see Figure 11 above. The four Science Collaborations are the mechanism through which the WRT Collaboration collectively shares the telescope to collect and analyze data to produce new scientific knowledge.

Each of the four Science Collaborations is free to create its own internal organizational structure and policies in relation to those guiding the WRT Collaboration as a whole for its cooperative work (subject to the WRT Board’s approval). Each of the Science Collaborations is a part of the kernel of the WRT Collaboration, working in concert with the management and governance groups to sustain the infrastructure. During my study the Epoch of Reionization Science Collaboration was broadly organized into what I refer to as US EoR group and the International (Int’l.) EoR group, see Figure 11. The Int’l. EoR group encompasses all WRT project members who work on this area of science. I define the US EoR group as the subset of individuals from universities in the United States contributing to the WRT project’s EoR science efforts. I furthermore distinguish between Magnus and the Radio group and other researchers at

¹² WRT-Memo-2012-12-02-IndividualMemberPolicy, p. 3 referencing the WRT Statement of Collaboration.

institutions around the United States within the US EoR Group since my focus was on this group alone. Throughout my data collection it became apparent that the EoR Science Collaboration is the primary “science user” of the telescope. It collects the most data and is the only one with specific addendums defined in WRT Collaboration policy documents. The effect of these addendums and influence become apparent in the different addressing activities, such as observing time allocations, that I discuss below.

The WRT Collaboration’s creation of Science Collaboration’s produces an organizing mechanism for the Associate and Individual members based on scientific interest who are contributing to the overall project. This structure provides the project’s human infrastructure with specific allegiances to cohere with. Science Collaborations are a known group of individuals with shared research goals. They are able to form different cooperative work arrangements to enable the production and sustainment of particular mutually beneficial research products. These products are necessary to advance the research goals of the particular Science Collaboration and in turn the WRT project overall. Membership in one of the four Science Collaborations ensures access to resources such as data since each is guaranteed some amount of data collection time and its use for scientific analysis related to the particular collaboration’s research. For example, the EoR Science Collaboration is provided with exclusive rights to use the data it collects to offer knowledge claims about the Epoch of Reionization, as laid out in the WRT Collaboration’s operations phase data access policy¹³.

At first glance the WRT Science Collaborations seemed similar to the working groups Lee et al. (2006) describe in a bioinformatics research infrastructure. Working groups in Lee et al’s study were formed “to focus on specific areas of development or application” and were the

¹³ WRT-Memo-2012-08-15-OperationsDataAccessPolicy, p.2

primary site of “collective action” (p.485). They existed alongside task forces that were responsible for project wide “cross-test bed concerns” such as data sharing. In practice Lee et al. found that individuals were fuzzy as to what working groups and task forces meant, whether they were a part of one or another, and how membership in one entirely even affected their research work in practice. The individuals had a limited, partial view of the organizational structure and their membership but were still able to successfully do scientific work because they developed “selective knowledge for those aspects of the human infrastructure that they need to interact with in order to coordinate” (p.486).

In contrast, I’ve seen in my interviews and observations that the members of the Radio group are cognizant of their membership in the EoR Science Collaboration and its US EoR Group. They know where in this overall structure of the WRT Collaboration they are situated. Being members of this Science Collaboration is what affords them the right to use EoR data collected with the Widefield Radio Telescope due to the WRT Collaboration’s data policies. In the course of day-to-day work, the Radio group is able to take a partial view of the entire collaboration like the participants in Lee et al.’s study. They can focus on working within their local Seattle group to analyze data, or with collaborators elsewhere in the US or International EoR groups, without needing to think about the entire structure of the WRT Collaboration.

When necessary though they figure out where within the project some element of their work fits. For example, Brianna and Magnus contributed to the development of the telescope itself. Members of the WRT Collaboration who did this were part of the early stage Builders group. The Builders group was situated outside of the Science Collaborations, cutting across the entirety of the project. Work to implement systems for the telescope was clearly defined as being the focus of this cooperative work arrangement within the whole of the Widefield Radio

Telescope project. Similarly, Igor discussed work by a group of individuals outside of any specific Science Collaboration to accurately model the beam of the telescope so that the different data analysis software pipelines being created in the WRT Collaboration could all be improved. This cooperative work arrangement existed to work on the common field of work that is this software model of the telescope beam. Igor explained that he was not directly contributing to this work but he nonetheless maintained awareness so that he could update his own software to be able to use this product of the WRT Collaboration.

Seeing how the WRT Collaboration is structured with Science Collaborations as well as other management or task-oriented groups illustrates that the human infrastructure of this research infrastructure is overall well-defined through the specification of groups as part of the project's original charter, and the successful formation and sustainment of these groups. The Radio group's role in this human infrastructure is easily visible from the data I collected. Just knowing that they see themselves as part of a specific Science Collaboration or other groups does not explain how this structure produces the conditions for their software production. To understand how the conditions for the Radio group's work in this project come about I needed to examine the work of managing and governing the WRT Collaboration. This management and governance work is part of the addressing activities that the kernel of the WRT Collaboration does to ensure that resources are available for use and stable over time.

Managing and governing the WRT collaboration

The WRT Collaboration was created to build a novel telescope to study the Epoch of Reionization. Creating a research infrastructure that is scientifically useful requires putting in place a system for managing the resources. Obtaining suitable land in which to build a radio telescope, designing an instrument that can be scientifically useful, building the instrument, then

over time operating and maintaining the instrument is a large endeavor. Within the kernel of the Widefield Radio Telescope Collaboration are its management and governance groups, see the top of Figure 11. This includes the WRT Board, WRT Management Group, an external Time Allocation Committee, and during the pre-operations phase of the project the Builders Group I mentioned Brianna and Magnus were a part of. Each of these groups is a cooperative work arrangement that produces and maintains different resources for the infrastructure. Three of the addressing activities that these groups do as part of the kernel are allocating instrument time, setting and enforcing policies for data access, and writing and enforcing policies for publishing results produced with WRT resources. Each of these addressing activities and the resources they concern are entangled with other products, especially the data collected with the telescope but also software produced within the collaboration and in time publications. Setting and enforcing policies creates the conditions for these infrastructural components to be created and used.

Addressing Activity 1: Allocating instrument time

One governance task of the WRT Board is forming a Time Allocation Committee (composed of scientists who do not work on the WRT project) to fairly disperse observation time with the telescope. The Time Allocation Committee is responsible for issuing requests for observing time then dispersing allocations on a semester basis every year. This process is guided by policies and guarantees made to different science collaborations in accordance to different agreements made based on funding and in-kind contributions to the project¹⁴. This activity is an ongoing addressing activity that the Time Allocation Committee engages in as part of the WRT project's cache.

¹⁴ WRT-Memo-2012-08-06-TimeAllocationPolicy

A collaboratively developed instrument necessitates the creation of policies for sharing it as a finite resource and its products, especially data. The WRT Collaboration allocates time primarily as part of either of two main categories¹⁴, Guaranteed Time or Open Access Time. Guaranteed time is the bulk of observing time (60% of a semester's total time) applicable to observation proposals made by the four Science Collaborations. Guaranteed Time proposals must be submitted by teams that are at least 50% comprised of Individual members in the WRT Collaboration. Open Access Time (20% of a semester's total time) on the other hand affords researchers who are not Individual or Associate members of the WRT Collaboration or teams comprised of less than 50% Individual members to have a chance to use the telescope for their scientific aims. Finally, the remaining 20% of time in each semester is allocated at the discretion of the WRT Director. All four collaborations submit a request for particular slots of time during each semester and the Time Allocation Committee disperses time in accordance with the written policies. Once a Science Collaboration is awarded time an individual within the collaboration will be responsible for determining how to configure the telescope for that collaboration's time allocation and scientific aims.

Distributing observing time is not so simple as allocating the gross number of hours that have been divvied up across the different requests each observing semester. Certain times of day and points in the year will be better for one science collaboration or another. Members of the Radio group pointed out that for EoR data collection the EoR Science Collaboration needs the galaxy to be down and out of the instrument's field of view since its radio emissions introduce large quantities of noise in their data. In addition, there must be time for an operations team at the radio observatory to perform any necessary maintenance on the instrument.

The Time Allocation Committee must over time continue to manage the availability of the telescope as a finite resource to the various groups of researchers who are part of the WRT Collaboration. Most interestingly perhaps though is that there is a discrepancy between allocations of observing time and the amount of usable data produced in an observation due to the hardware and software design of the telescope itself. This technical design decision has in turn had to be accommodated in the sociotechnical practice of the WRT Collaboration's observation time allocation process.

Policy flexibility in light of technical outcomes

When the Time Allocation Committee assigns some block of time to a Science Collaboration they allocate a chunk in hours. In the 2013B semester—each calendar year has an A and B semester—there were a total of around 600 hours to allocate and the EoR Science Collaboration received 353 hours according to a public list on the WRT website for example. Observation time is allocated in blocks of hours across an observing semester yet exists for the Radio group and their collaborators in chunks of differing units when doing analysis depending on the particular work they are engaged in and how much data they integrate together (e.g., a single two-minute observation to 3 hours of observations and so on). A single observation is constructed by the telescope's systems as a two-minute chunk. Over time I became used to members of the Radio group referring informally to each observation in two minute chunks. The individuals would quickly note however that the amount of usable data in each observation is actually only 112 seconds. This leaves a gap of 8 seconds between the idealized, abstract length of an observation and the collected, usable data. I inquired further about this discrepancy during a conversation with Igor. He immediately explained that the reason is partially political and partially technical:

Well, it's that we set everything up as two minutes. And for a variety of reasons that are partially political, it's actually 112 seconds. So, we are guaranteed 350

hours of observing. And within each observation, the first few seconds are often not useful data, and so a person setting all of this up just cropped off those first 8 seconds making it 112 seconds. And, politically, only the seconds that are recorded count towards our time. So only the 112 useful seconds that we save actually count towards our 350 hours. (Igor, interview)

The Widefield Radio Telescope is configured with two-minute observation cadences. Between observations the telescope hardware may be electronically shifting between ‘pointings’ on the sky. Doing this requires sending signals to change the path of an electromagnetic signal through the instrument, a point I’ll discuss more later in the chapter. Inherent in this process are delays since signals of course physically take time to propagate throughout the entire device. Due to the delays in shifts of the telescope hardware between each individual observation’s pointing results in “not useful data” at the beginning of each two-minute observation period. This not useful data is a spurious and noise-filled 8 seconds resulting in just 112 seconds of desired data for each 2-minute observation.

This 8 second gap is entangled with many aspects of the Widefield Radio Telescope. Over time it has become an inherent part of every observation collected, the software for working with the data, and of course the infrastructure for collecting the data. The Time Allocation Committee’s addressing work to distribute observation time ended up needing to account for the amount of actually usable data when the instrument’s observations are scheduled. Taking a semester’s allocation and counting observations that take place using the 2-minute interval will over the course of the dozens to hundreds of hours allotted to a Science Collaboration result in each being short changed valuable actual data due to this known 8 seconds of bad data. For purposes of counting allocated time the shorter 112 second observation length is employed even though the instrument itself is operating on a two-minute cadence.

Through use the manifested technical reality of the device has entangled itself into the sociopolitical operational policies governing the instrument's operation. The enactment of the WRT's time allocation policies had to be flexible to account for technical issues in the design of the telescope and the social demands of the different researchers who form this collaboration. Observing time with a telescope is a precious resource (McCray, 2000, 2004) just as beamtime is in high energy physics projects (Traweek, 1988). Lobbying to ensure the correct allocations are received and used is not surprising. For the EoR Science Collaboration the 8 second gaps could indeed result in significant quantities of missing data over time, as this cooperative work arrangement receives a very large allocation of telescope observing time in the WRT Collaboration.

The significant allocations of instrument time for EoR science

The EoR Science Collaboration is noteworthy within the overall WRT Collaboration in part due to the significant quantities of guaranteed observing time it wields, as well as its role in founding this telescope project and shaping the design of the instrument. This outsized allocation influences WRT Collaboration policies as well as the design of the actual instrument itself. This latter issue is a point I'll examine later in this chapter when I discuss the telescope's design. I first learned about the division into different Science Collaborations and a bit about the amounts of data collection necessary for each collaboration's science goals from Brianna.

Brianna describes the EoR Science Collaboration as the biggest user of telescope time among the four Science Collaborations, using perhaps 90% of the instrument's observing time, a point reiterated by other members of the group during interviews. I was surprised since this is a large allocation of time for just one of the four Science Collaborations to receive. Formally however, this outsized allocation is indeed codified in the WRT time allocation policy, although

it is really around 50% of any given observing semester's time¹⁵. This large quantity of observing time has also been consistently made visible and reinforced by emailed distribution of observation call for proposals as well as their publication on the WRT project's website where awarded observation time for each semester is publicly listed¹⁶.

We're the biggest. We're like 90% of the instrument. There's [Science Group A] and [Science Group B] stuff that can look at the sun. [Science Group C]. Basically, all the normal things you do with astronomy, except our telescope isn't that well optimized for many of them. And so it's really optimized for EoR, and we are the most – the power user here. ... it turns out that the EoR just needs a lot more data to do our science than the other people do because you can see bright points versus quite quickly. You don't have to integrate [data] that long to see the [phenomena of interest to these groups] – what we're looking for, it's so faint that you have to integrate a lot longer, which means you have more data. (Brianna, interview)

The WRT Science Collaborations each end up with different allocations of observing time every semester under the Guaranteed Time category. During the 2013B semester EoR science received 353 hours out of around 600, during the 2014A semester 350 out of a possible 800 or so hours, and in the 2014B semester 880 hours out of approximately 1600 hours¹⁷. The notable usage by the EoR collaboration is necessary because the Epoch of Reionization as a physical phenomenon requires significant volumes of data to examine. This is due to the phenomena being observable at this point in the Universe's history as a very faint radio signal that is heavily dominated by noise. The signal is so faint that it can easily be masked by spurious effects of the instrument and other sources in the sky as will become clear throughout later chapters on the Radio group's software. To create a scientifically investigable cultural object

¹⁵ WRT-Memo-2012-08-06-TimeAllocationPolicy.

¹⁶ WRT-Memo-2012-12-19-1stAnnouncementofObsOp, WRT-CFPMemo-2013-03-04-2013BSemesterObsCFP, WRT-CFPMemo-2013-07-26-2014ASemesterObsCFP, WRT-Memo-2014-03-17-2ndAnnouncementofObsOp, WRT-CFPMemo-2014-03-17-2014BSemesterObsCFP, WRT-Memo-2014-09-11-2ndAnnouncementofObsOpAdd, WRT-CFPMemo-2014-09-11-2015ASemesterObsCFP, WRT-CFPMemo-2015-09-10-2016ASemesterObsCFP

¹⁷ All listed publicly on the WRT project website.

(Garfinkel et al., 1981) or inscription (Latour, 1987) the Radio group and the others in the EoR Science Collaboration must wield hundreds of hours of their instrument's time.

The necessity of collecting so much data as well as EoR science being a main objective for the WRT provides the EoR Science Collaboration with significant influence across the project. The large Guaranteed Time allocations of observing time ensures this one science collaboration receives a large quantity of the valuable resource that is data (Birnholtz & Bietz, 2003), albeit in exchange for a large amount of work on the part of the many researchers allied in this one Science Collaboration. Ensuring that allotments of observing time are calculated using the actual usable amount of data rather than the abstracted quantity is just one element to the political concerns of sharing a telescope and the entanglement of EoR science goals with the data produced.

Throughout my time with the Radio group they expressed little concern with obtaining data. As members of the EoR Science Collaboration and its guaranteed large amounts of telescope time obtaining data was not an issue, they had hundreds of hours to begin working with once the telescope went online. This guarantee is part of why some of the organizational aspects of the WRT Collaboration can merge into the background for the members of the Radio group, becoming part of the infrastructural conditions enabling these scientists to focus on the work of producing their data analysis software. The data access, use, and publication policies of the WRT Collaboration also create the conditions for the Radio group's work though, and the EoR Science Collaboration's sway within the WRT project is also codified here.

Addressing Activity 2: Managing policies for data access and use

Another crucial task of the WRT Board and Management Group is the creation and enforcement of WRT Collaboration policies regarding data collection and use. This ranges from who within a

project can access which data at what time to ultimately when and how data will be made publicly available to any cosmology researcher¹⁸. Making data publicly available is often a requirement of funding agencies, as noted in Chapter Two, but interestingly the how is often left up to the particular projects to determine, which is the case here. The kernel of the WRT Collaboration regardless is responsible for working to keep data collected with the telescope available and scientifically usable (at least perhaps until it one day dissolves as a virtual organization). Creating and enforcing data access and use policies is the second addressing activity of the kernel in the WRT Collaboration that I examine.

Above I noted that WRT observing time is categorized as either Guaranteed Time or Open Access Time. Associated with these categories are policies for access to and use of the collected data¹⁹. The policies regarding data collected from Guaranteed Time and Open Access Time specifically apply to the “raw data” which is defined by the WRT Collaboration as that data that comes out of the telescope’s base processing systems that is not yet processed for specific scientific work. Gitelman and Jackson (2013) emphasize that data are never really raw and always cooked but the WRT Collaboration’s definition in this policy is rational as the data output by the telescope is an inscription but it has not been polished or transformed into a product from which knowledge claims can be made. Raw data from Guaranteed Time observations are to be made available to all WRT Individual members immediately, regardless of whether they are part of the specific Science Collaboration that made the proposal. Raw data collected under Open Access Time will be made available first to the individuals who proposed the observations for an 18-month proprietary period that starts from the date of collection. This

¹⁸ There are a series of policy documents related to data access and sharing. WRT-Memo-2012-07-25-PreOpDataAccessPolicy, WRT-Memo-2012-08-15-OperationsDataAccessPolicy, and WRT-Memo-2015-06-11-PublicDataReleaseStatement.

¹⁹ WRT-Memo-2012-08-15-OperationsDataAccessPolicy

data will subsequently fall under the WRT Collaboration's open access policies¹⁹. The "higher-order data products" that are produced through the work of the different members and science collaborations in contrast can be subject to different policies as defined by the individual science collaborations and approved by the WRT governing board¹⁹.

Importantly, across all of the WRT Collaboration's data access policies there is a specific addendum for Epoch of Reionization data. This addendum supersedes the normal access rights such that only members of the EoR Science Collaboration have access to this raw observation data for an 18-month period that begins at the end of each observing semester, with the exception of appealing to the WRT Director for access to analyze this data for non-EoR science. This contrasts to the overall policy where raw data is accessible to any member of the WRT Collaboration immediately after it is collected, and the wider scientific community 18 months after the date of the individual observation. Data specifically collected for EoR uses is privileged in contrast to other uses of the telescope. This policy addendum illustrates special privileges that EoR science has in the overall WRT project.

The WRT Collaboration as a whole must enforce these data access policies. They are not the entire story though as the EoR Science Collaboration has its own charter document that spells out further rules for this cooperative work arrangement²⁰. I noted above that all four of the Science Collaborations are free to set rules and policies internally so long as the WRT Board approves of the written policies and procedures. Regarding data access and use the EoR charter references the WRT Collaboration policy on data access but it does note that an "inactive" EoR collaborator loses the right to access data. This Science Collaboration's charter becomes most relevant when publishing papers using EoR data, as I examine below.

²⁰ WRT-Memo-2013-12-16-EoRCollabRevisedCharter

Working with these policies in place the Radio group and the other EoR scientists in the WRT Collaboration have a baseline expectation for the access to and use of EoR data. If a researcher joins the WRT Collaboration and is interested in EoR science but for some reason did not join the EoR Science Collaboration then they should not have access to this data and therefore should not be able to subvert the cooperative work that the EoR Science Collaboration is engaged in. Once raw data is collected the EoR Science Collaboration's charter also spells out policies for the scientific use of this product in relation to the WRT Collaboration's publication policy. Managing these policies is again an addressing activity.

Addressing Activity 3: Managing policies for publishing WRT products

The WRT Board also creates publication policies mandating lists of individuals who must be included on papers published using WRT resources. The policy explicitly defines a "WRT Publication" as "any journal/proceedings paper, popular article, or other publicly available document that has been derived from proprietary data, algorithms, software or hardware associated with the [WRT]" while also laying out a detailed submissions and review process for authors to adhere to²¹. I find it interesting that there is the explicit recognition of software work in this publication policy rather than its omission as might be expected when one thinks about scientific publications. The WRT Collaboration at least expresses some of the importance of software to this project through this policy. Creating and enforcing publication policy is a third addressing activity of the WRT Collaboration's kernel.

The publication policy created and enforced by the WRT Board mandates proposals be circulated within the collaboration. Proposals must have a primary contact, a proposed author list, and a proposed ordering for the authors. This policy and the circulation of a proposal

²¹ WRT-Memo-2013-07-23-PublicationPolicy

provides any WRT Individual member with the opportunity to request to be an author if they are not already included. Proposals must meet any requirements set forth by one of the four Science Collaborations when using data collected by that cooperative work arrangement for its scientific use. The EoR Science Collaboration as an example mandates that all of its members be included on publications related to the “detection of 21cm EoR signatures”²². Before a publication can be submitted to a journal or other venue it must undergo Collaboration Review. This process ensures that anyone who is a member of the WRT Collaboration has a minimum of two weeks to provide feedback on the draft of the paper before it is submitted. The EoR Science Collaboration has supplemented this requirement with an internal collaboration review period and the assignment of one member who did not help write the paper to be the internal reviewer who provides feedback throughout the writing process. For publications submitted to venues that provide feedback and revisions this entire internal review process must be repeated once the authors make changes. If there is a dispute regarding a publication the WRT Project Scientist is to make a recommendation to the WRT Board who will issue a final decision.

Publications approved by the WRT Collaboration and accepted in a journal or other venue are encouraged to be publicly disseminated at the appropriate point (e.g., when the article is accepted for publication). Publications are also encouraged to include two citations related to the project, an overview article and an instrument design article, and must include the standard WRT Collaboration acknowledgements. These acknowledgements include not only the many funding agencies and specific grants to individuals but importantly recognition of the native community whose land the telescope sits on. Acknowledging the rights of the native persons who traditionally owned the land of the radio observatory illustrates one point where the WRT as

²² WRT-Memo-2013-12-16-EoRCollabRevisedCharter

a research infrastructure is entangled with a layer of infrastructure underneath. There are many more visible connections when discussing the telescope itself below, but I find that this simple publication acknowledgement is an interesting inversion of the observatory infrastructure. It continually reinforces the WRT's entanglement with a physical place and this place's human history reaching back millennia as the telescope project works to collect data reaching back billions of years in cosmic history.

As part of the publication policy the WRT Collaboration maintains author lists. These lists included the names of members who must be included on publications related to certain topics or using data produced during a particular period of time. Over time as individuals have joined and left the WRT project author lists have varied. One interesting example is the "Builders" list. The Builders list refers to the group of individuals who contributed to the design and development of the Widefield Radio Telescope and must be included on all publications using project resources from a specified time period. The Builders group of WRT members was a cooperative work arrangement formed to create the telescope, the common field of work for this work. Once the instrument was operational and being managed by an operations team from the radio observatory this cooperative work arrangement dissolved yet the list of individuals to be included on publications remained.

Throughout my data collection I witnessed publication proposals and reviews work their way through the EoR Science Collaboration and the overall WRT Collaboration. This process makes visible different facets of the WRT as an infrastructure depending on the individuals involved in the publication and those who choose to comment on it. Creating and enforcing these policies ensures that the WRT Collaboration as a whole has a voice in the results produced using its products. Publications represent the collaboration to the larger scientific community. They

make claims about the operation of the instrument, the data it produces, and the software created to develop this knowledge. Ensuring the publication policies are adhered to and working for the collaboration falls both to the WRT Board and also the individual Science Collaborations (assuming they define specific additions as the EoR Science Collaboration does).

The addressing work related to publication policies (let alone for allocating instrument time and data access and use) is only some of the work necessary to making the WRT project function successfully as a scientific endeavor, but it does provide a tangible point in which to see products shifted out of the depths of the infrastructure and out into the larger scientific world. I have stated that these policies are all part of the infrastructural conditions in which the Radio group's work takes place. Brianna and Magnus being part of the builders list provides them with recognition over time for their work on the telescope itself. No one in the Radio group expressed worry about having access to data, it was guaranteed by virtue of their membership in the EoR Science Collaboration. Interestingly they also expressed little concern with sharing EoR data publicly.

Worries, or the lack thereof, about sharing EoR data products

Probing the Epoch of Reionization requires significant quantities of data and that the WRT Collaboration has created its various policies in a way that offers concessions to this area of exploration. This ensures the researchers engaged in this work have entitlements regarding EoR data that protect this currency (Birnholtz & Bietz, 2003) such that they have the time to transform raw material into a scientific product that is publishable and shareable within the EoR Science Collaboration, the larger WRT collaboration, and in the end the greater cosmology community. Proprietary periods or embargoes are not uncommon in astronomy research (McCray, 2004) and here they provide scientists in the WRT Collaboration with the necessary

time after the data is collected to be able to process and analyze this material before it is shared with the wider cosmology community.

When I inquired about sharing data during interviews with the Radio group these individuals did not express much concern about the raw data being made available to researchers outside of the EoR Science Collaboration. Given the exceptional amount of work involved in transforming the raw data into a valid scientific finding Brianna, Magnus, and the rest of the group expressed little worry about researchers outside the EoR Science Collaboration being able to use this data in its raw state, at least not without requesting help from someone in the WRT Collaboration for which there is a process outlined as part of the policies I just discussed. I ended up discussing the uselessness or futility of sharing data in many situations with Magnus. Magnus posited that data sharing is worse than useless for research that is working so close to the instrument like that of the EoR Science Collaboration. This is in contrast to many famous astronomy telescopes (Hubble being one, see <http://hla.stsci.edu/>) where data is publicly shared as a data product and analyses are intentionally abstracted away from the nuances of the instrument. EoR data produced with the Widefield Radio Telescope is so bound up and entangled with the design and operation of the instrument and the collaboration that to Magnus not even everyone who is working in the WRT Collaboration itself may be able to do anything scientifically useful with it. The work of making a scientifically valid object is not simple here.

Oh, it's even, it's even worse than that. So, w-, well, s-, so it's actu-, so there's this mandate to share data, and it has been very powerful for something like Hubble or other instruments which produce things where the instrument is not visible at the level at which you desire to work. It really is a star, a galaxy, a thing you can ignore, you have to kinda know where the filter bands are but you can more or less ignore instrumental effects. If you're working close to the instrument's capabilities, if you're down at that precision limit, all of a sudden the instrument is in all your data. And you have to understand the instrument, and so releasing it free to someone who doesn't know the instrument is useless, and I actually see it at a much better degree. Two-thirds of the people who work in the [WRT] do not

understand the data enough to analyze the EoR data, the instrument enough to analyze the EoR data. They don't. So even within the people who've built it, they don't have enough understanding of the instrument. Forget the analysis, uh, because the analysis is reflecting the instrument in a, in a lot of ways. Um, so you end up with these things, you get these just mind-numbingly dull conversations. Oh, are we gonna make it public? Are we not? Oh, da, da, da. Sure, make it public. It's pointless. (Magnus, interview)

The WRT policies regarding EoR data carve out special privileges for this particular science collaboration's work. And yet from Magnus's point of view due to the intricacy of the analysis required to work with this data most researchers will be unable to do so without expending significant quantities of effort to learn in depth how the instrument works and really to create their own software as well. Brianna also expressed little concern with publicly sharing EoR data since the WRT policies would require that anyone using the data end up including many key WRT members on any publications. From her perspective other researchers are welcome to try and do a better job of analysis, once again knowing how much work would be required to push analyses further than what is already being accomplished by members of the EoR Science Collaboration. Without doing the work to effectively understand the instrument in their bones researchers probably cannot make effective scientific use of the EoR data.

As a result of the policies created, and in no small part due to the difficulty of the analysis work, the valuable currency that is EoR data collected with the Widefield Radio Telescope is a material that is shareable but not readily useful to outside researchers, and perhaps even other WRT researchers depending on their depth of experience with the instrument. The WRT Collaboration and EoR Science Collaboration policies I've just described provide much of the context in which the Radio group's cooperative production of software takes place. As members they are provided with resources for their work, in particular EoR data. Their work also contributes back to these two intertwined and overlapping collaborations.

Magnus's point that releasing this data free to anyone when its analysis requires detailed understanding of the instrument leads me to the other purposes of this chapter. That is to explain how the Radio group's software is situated in the EoR Science Collaboration and the design of the Widefield Radio Telescope. I did not follow the work of designing and building this complex device. I did however have to learn a significant amount about it because like the WRT Collaboration as an organization of researchers this instrument influences the context of the Radio group's cooperative software production. The emphasized points in that quote from Magnus above foreshadow what I will show throughout Chapters Six and Seven, analyzing this EoR data is entirely bound up with developing a deep understanding of the telescope itself. Before I discuss the design of the telescope though I first want to examine how the Radio group's data analysis software fits as part of this structure that I just described.

Situating the Radio group's US EoR pipeline software in the WRT Collaboration

In Chapter One I briefly introduced the Radio group's US EoR pipeline. What I did not explain is that their pipeline is one of two official EoR Science Collaboration data analysis pipelines. The two official pipelines are the EoR Science Collaboration's default mechanisms for analyzing data for publication (other collaboration members can implement their own approaches but they must compare findings with those output by either of the official pipelines), see Figure 12 below. The US EoR pipeline was not even originally part of the WRT project's plans and yet by the time of my second episode of data collection the Radio group's software was positioned as one of two official pipelines and was the one only fully functioning.

A shift in scope for a real-time data processing pipeline

The Widefield Radio Telescope that was built is a scaled back version of the original design, it was de-scoped early in its history to borrow Steinhardt's (2016) term. The physical telescope is

composed of 128 antenna tiles (discussed later in this chapter). This is a fourfold reduction from the original design's 512 antenna tiles. The volumes of data that would have been created with a 512 antenna tile telescope would have been significantly greater than the already high volumes coming out of the built telescope today (a single "reduced" 2-minute observation file is around 7 gigabytes alone). To handle this volume of data the WRT Collaboration's plan was to implement a real-time data processing pipeline that would calibrate and image data into a reduced form. This is what I refer to in this dissertation as the LivePipeline.

The LivePipeline was intended to then take the telescope system's output and run this data through some processing steps. It would do an initial calibration of the data and output imaged data products for later analysis. This would be done rather than store the traditional interferometric telescope output of visibilities. Visibilities are simply the raw measured electromagnetic signal captured by a telescope. Images in contrast are products of multiple mathematical operations that in some circumstances can be visualized through plots. Multiple members of the Radio group emphasized that visibilities are considered to be the "real" data in the astronomy community, pure and uncontaminated by the effects of analysis techniques, whereas images are contaminated by researcher's efforts analyzing the data. Outputting visibilities would not have been technologically feasible in the late 2000s for a 512 antenna tile telescope (computing power was not expected to be fast enough). With the downsizing of the telescope the LivePipeline shifted from being used in real-time to processing data after it is collected, just as I saw the Radio group doing with their US EoR pipeline.

The development of the Radio group's US EoR pipeline began before the Widefield Radio Telescope was fully built. Igor noted that various groups within the EoR Science Collaboration were planning on developing multiple different software analysis approaches to

complement the planned LivePipeline. I asked Magnus about the origins of the US EoR pipeline and the variety of originally planned analysis approaches I had heard about. Magnus stated that the EoR Science Collaboration had many planned approaches for engaging in data analysis work. Many of these plans entailed individual research groups taking the data produced with the telescope and having a graduate student or two work with it. He characterizes this as “partly astronomy culture” compared with the particle physics groups he did his own PhD with where teams collaborate on analysis work. This echoes the points of McCray (2000, 2004) who describes how even as optical telescopes came to be built by large collaborations the data analysis was still the purview of individual scientists. Magnus noted that these various approaches would rely upon the images produced by the LivePipeline.

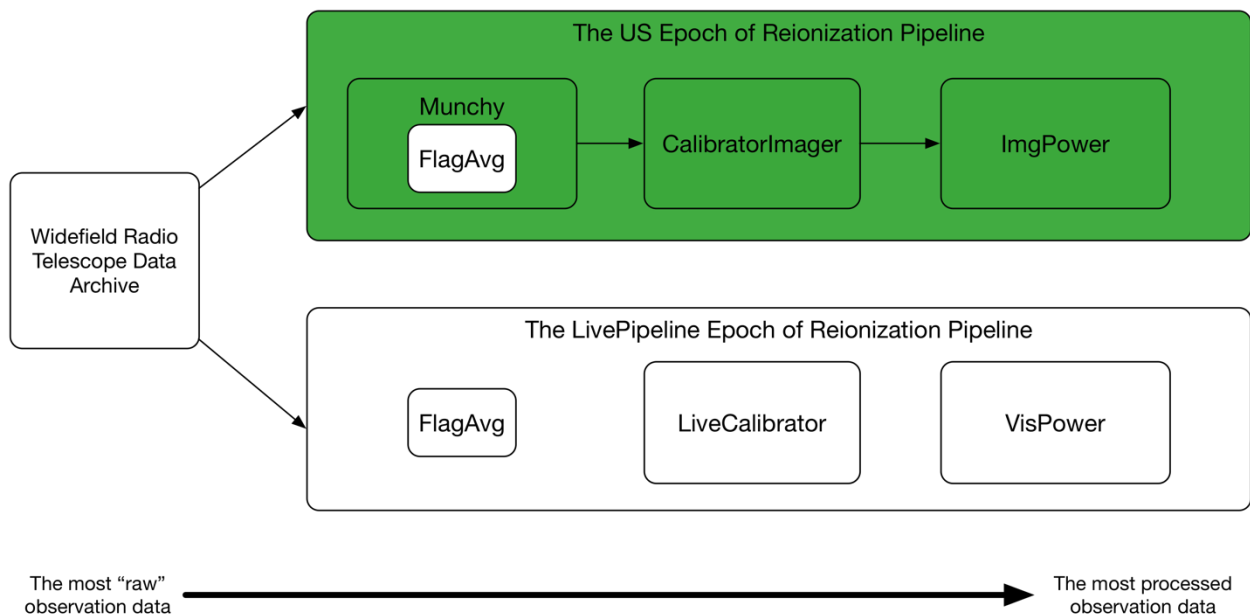


Figure 12. Overview of the US EoR pipeline and the LivePipeline.

Data from the telescope goes from raw to most processed from left to right. The Radio group’s software is highlighted in green and has the general, idealized flow of data indicated with arrows. The flow of data internally through the LivePipeline is not noted because I did not examine its operation.

Magnus recounts that Igor’s CalibratorImager pipeline originally “was a way of measuring antenna beams” that over time “started doing better at actually analyzing the data” so

the group, with Igor being responsible for this piece, pressed ahead with development. In parallel, Brianna's approach to producing power spectrum was being developed along with a similar solution elsewhere in the EoR Science Collaboration (VisPower, see Figure 12). Each of these components was being developed as one of multiple possible pipelines for processing data within the EoR Science Collaboration. In December 2013 the Radio group's pipeline went from being one of around five potential EoR analysis pipelines to one of two official pipelines—the LivePipeline remaining the other and originally planned pipeline. The other potential pipelines could still be developed by different groups but they would not be the direct focus of the EoR Science Collaboration.

Becoming an official EoR Science Collaboration product

During the first all hands meeting of that year in early January 2014, after reintroducing me to the existing and new members of the group, Magnus offered a recap of the recent WRT meeting in December 2013—the meeting where the diagram in Figure 13 was presented with the design outline for the US EoR pipeline and the LivePipeline. This meeting was one of the WRT Collaboration's twice yearly in-person meetings where the WRT Board meets to discuss the latest concerns that the project faces and talks on different research tasks are given. In addition, the four different Science Collaborations are able to have in-person time working together while also sharing updates on the progress of their research with the collaboration as a whole. These are known as “busy days.”

During this January all hands meeting of the Radio group Magnus first recapped that the LivePipeline and the Radio group's US EoR pipeline—which until this meeting known as the “UW Pipeline”—were now the two official EoR processing pipelines for the EoR Science Collaboration. The UW Pipeline was now the US Pipeline, a simple but important change in the

name. Brianna and Igor immediately commented to everyone present at this all hands meeting that this is down from three or so pipelines that were somewhat the focus of the EoR Science Collaboration before the meeting. Igor in the past had even expressed some annoyance to me that the Radio group's pipeline had not received more focus from the EoR Science Collaboration in previous years. This annoyance was in part because the LivePipeline at this point in time did not really function at all whereas the Radio group's US EoR pipeline was at least partially operational.

During this Radio group meeting the members were happy that their work was being recognized across the EoR Science Collaboration as a valid approach to analyzing EoR data. They were still somewhat exasperated at some reactions they had received at the WRT meeting, although they quickly shrugged off this discontent. Over the course of the WRT meeting in December it turns out they were referring to this software as the "UW Pipeline" since the abstracts they had submitted in advance for talks were framed around the pipeline with this name. This software had always just been a product of the Radio group without necessarily having significant importance to the larger EoR Science Collaboration. It was their common field of work as a local arrangement of individuals, a product that expressed their approach to doing EoR data analysis. Yes, it was entangled with the design of the Widefield Radio Telescope and their membership in the EoR Science Collaboration, but this software was not yet as entangled as it would end up being with this shift in status to being one of two official pipelines.

While at the December WRT meeting Brianna, Igor, Abner, and Peg continued to describe their software as the UW pipeline and this apparently ruffled some EoR collaborator's feathers since the name was formally changed early on at the meeting. This name change for the Radio group's software shifted it from the margins of the collaboration to the center as a

common field of work shared by a suddenly larger cooperative work arrangement yet they were still habitually referring to it with the more narrowly scoped name. The WRT board’s discussion during this December 2013 meeting of the Radio group’s pipeline led to the renaming to as the “US EoR pipeline” to represent its shift to being key to much of the WRT’s EoR work yet geographically produced in the United States. This was seemingly not made entirely clear to all of the members of the Radio group immediately though based on the reactions at the beginning of this January meeting that I attended, and our subsequent conversations in the next few weeks.

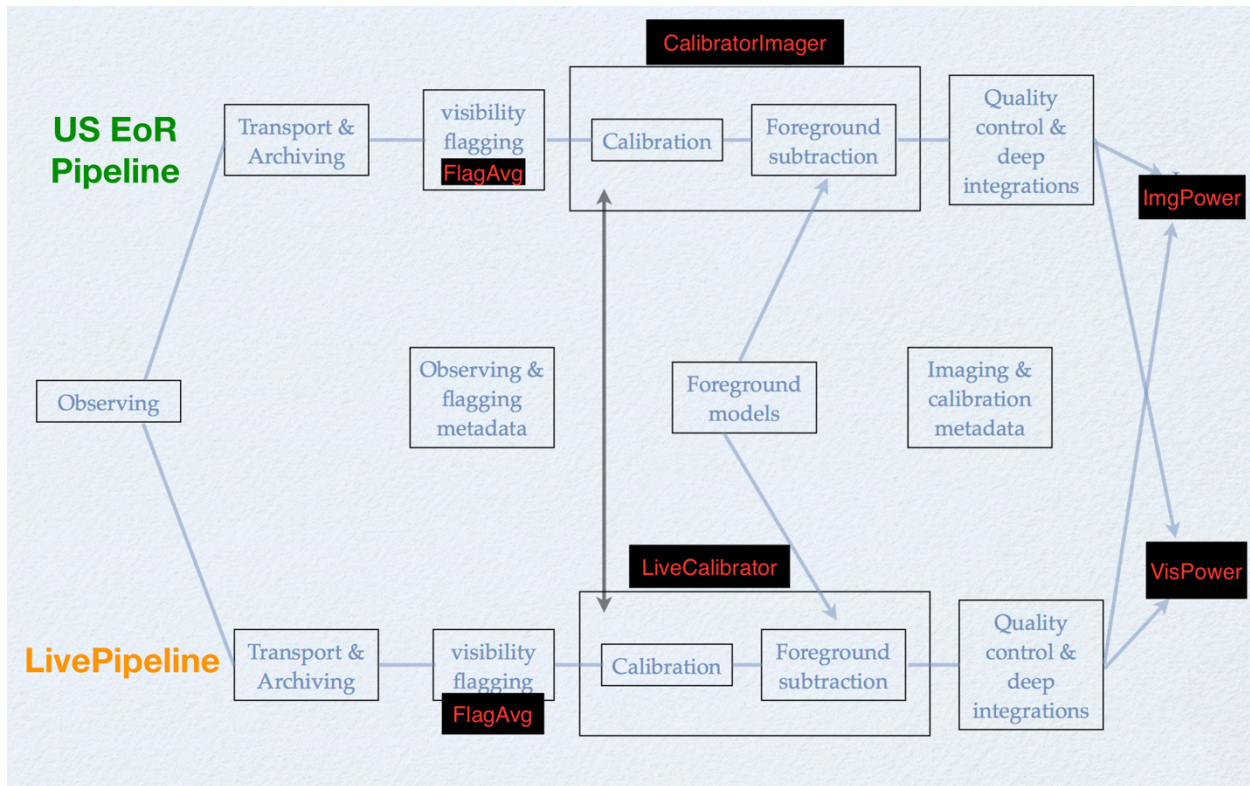


Figure 13. EoR pipelines design diagram from Magnus. Pseudonyms in red are added to match those used in this dissertation. This early design diagram represents the general, abstract approach to EoR analysis across both the LivePipeline and US EoR pipeline. By design data products are meant to be exchanged at multiple stages of each pipeline to enable evaluation of each scientific approach.

Even with the shift in name and status the Radio group’s software was still their responsibility to produce. CalibratorImager is primarily Igor’s responsibility. ImgPower is

Brianna's. But other members of the US EoR group instead came to rely on the data products output by this pipeline to do their own work—data products being encapsulations of observation data with analyses. Through this shift in status the Radio group's software is becoming an infrastructure to this part of the EoR Science Collaboration. It became embedded in the US EoR group's work. Interestingly, as the US EoR pipeline transitioned from being mostly just the interest of the Radio group to being a focal endeavor of the EoR Science Collaboration it was functioning more stably and fully than the LivePipeline. While the LivePipeline was originally envisioned and designed to handle the large volumes of data in real-time from the WRT instrument, the situation had shifted such that it could not yet reliably process large quantities of already captured data. In contrast, the US EoR pipeline could handle hours and hours of observations from end-to-end. As an infrastructure being built on top of the WRT it was to some extent stabilizing. In the course of testing and analyzing data though, the EoR Science Collaboration needed to be able to compare and evaluate the two approaches, data products are key to ensuring the parallel pipelines are interoperable.

Ensuring parallel, interoperable data analysis approaches to avert 'beauty contests'

Perhaps the most interesting part of the origins of the US EoR pipeline and LivePipeline is how they were designed to exchange data products. As one of the senior members of the EoR Science Collaboration Magnus expressed to me that he pushed for the ability to share data products between the multiple approaches to data processing and analysis. Recall from my brief introduction in Chapter One that data products are datasets output by instruments or data analysis software. The key to creating two parallel, interoperable data analysis approaches for EoR science in the WRT Collaboration are exchangeable data products. These artifacts encapsulate

the different approaches to analysis the Radio group and their collaborators create. They also thread these infrastructures together and back to the WRT.

Magnus describes how he advocated for transferability of these outputs from different pipeline components so that contrasting approaches to analyzing data could be evaluated and interrogated across the EoR collaboration in a “bake-off.” Taking a particular observation then exchanging the data products created as each pipeline transforms that observation from its raw, original state to an end product enables the different groups within the EoR Science Collaboration to interrogate and compare each approach to a high-precision scientific analysis. This is a bake off, but it is only possible if common types of data products are agreed upon and created by the two software pipelines. The arrows throughout, and items listed in the middle, of Figure 13 illustrate the points of interchange between the US EoR pipeline and the LivePipeline.

Magnus’s desire for the ability to “have a bake-off” between different pipelines and their components by exchanging the many data products, especially the intermediate versions, was his strategy intended to help keep the results of any one pipeline from being opaque and black boxed to all but their creator(s). If these different data products are produced and shared then the efficacy of each approach to analysis can be examined and debated, either improving each group’s approach or at the very least foregrounding the different techniques being applied. This strategy keeps each cooperative work arrangement (the individuals creating the LivePipeline or the Radio group) from being able to advocate for its product without offering evidence for inspection by all.

... one of the things I was very adamant about is that we needed multiple approaches and that we needed to be able to share between the approaches to figure out what was really working. I didn't want different p-, completely isolated pipelines that came up with different answers and then having y-, y-, y-, [sic] you know, beauty contests. I wanted to be able to test between them 'cause I felt that

was the way to have them learn, uh, people learn is to be able to take – calibrate it one way, transfer the calibration to the other, and really have a bake-off between different pieces to [sic] what worked better. (Magnus, interview)

I'll show in Chapter Six just how complex the US EoR pipeline is. The complexity of just the US EoR pipeline's components alone will illustrate the ease with which a component might become a black box where very few people deeply understand its design and operation. The EoR Science Collaboration's decision to be able to exchange and shine a spotlight into each other's data products thus can help to head off any potential "beauty contests" between the results produced by the different research groups within the collaboration where someone might seek to advocate for their own findings as the "correct" results. If one group or individual wishes to assert that their approach is better than another then they can put forth their data products so that they can be analyzed with another software pipeline and the results compared through plots or numeric outputs. The EoR Science Collaboration has subsequently prepared publications comparing the US EoR pipeline and the LivePipeline analysis approaches. This strengthens the arguments for these analysis approaches within the cosmology community precisely because they can show how neither is black boxing away its results while pointing out the strengths and weaknesses of the two pipelines. It probably does not hurt as well that at least the Radio group's software is publicly available through a GitHub version control account on the internet for anyone to inspect.

From its origins as a "way to measure antennas beams" to becoming one of the central components of the Widefield Radio Telescope's EoR data analysis approach the US EoR pipeline has shifted to become a product and scientific analysis approach that is valuable to not only the EoR Science Collaboration, and the WRT Collaboration as a whole, but hopefully other interferometric radio telescope projects. I'll return to this pipeline in Chapter Six to illustrate

how it embodies the analysis techniques and approaches of Magnus and the Radio group while being produced in dialogue with the work of their collaborators in the EoR Science Collaboration.

So far in this chapter I have explained how the WRT Collaboration is organized and some of the ongoing addressing activities that this infrastructure's cache is engaged in. Seeing how the US EoR pipeline is situated as part of the EoR Science Collaboration starts to give a sense of the conditions the Radio group is producing this software in. Part of their software production will require that they produce data products to exchange with another pipeline. Publishing findings with their software will require adhering to the WRT Collaboration's publications policy. These simple examples start to show how their software is entangled with the WRT as an underlying infrastructure, how their cooperative work here at the University of Washington is entangled with the cooperative work of the EoR Science Collaboration. At this point I want to turn to discuss the actual Widefield Radio Telescope as a physical scientific instrument. Understanding the organization is pointless if I don't understand the device at its core. This will setup my discussion of its use by the EoR Science Collaboration in Chapter Five to produce useful data.

Explaining the basics of the Widefield Radio Telescope's design

Traditional radio telescopes that most commonly come to mind use a large dish that can be physically pointed at locations on the sky to examine phenomena. Advances in telescope design have led to new designs using arrays of multiple antennas that are pointed electronically at different phenomena of interest and the signals correlated together—this is the basic design of the Widefield Radio Telescope. It is an interferometric telescope, a type of device where signals are added together so information can be extracted. The WRT is designed to gather radio signals

from a wide swath of the sky at once, a wide field of view—hence my pseudonym. A principle design goal for this instrument is to be able to measure the power of the Epoch of Reionization signal over the sky by capturing and integrating large quantities of data. This is in contrast to traditional telescopes that are designed with narrow fields of view to peer at particular phenomena, e.g. a star, nebula, or galaxy. The concept of correlation underlying the WRT and a detailed discussion of the telescope’s components can be found in Appendix B. I’ll provide a brief overview here.

The Widefield Radio Telescope is composed of 128 Antenna Tiles that are arranged at the radio observatory in a pseudo-random manner (Abner and Magnus developed a simulation to optimize placement within a set of constraints and scientific goals). Each Antenna Tile has 16 dipole antennas on a mesh screen. These antennas will capture electromagnetic signals from the sky. Every Antenna Tile is connected to an Analog Beamformer. The Analog Beamformer adds the signal from all 16 antennas on a tile together and sends them to the Receiver. It can point the telescope at different areas of the sky by delaying signals, hence the name. A WRT Receiver is connected to eight Antenna Tiles and performs an analog to digital conversion of the signal being captured. Receivers filter the signal collected and constrain it into narrower channels of interest to the Science Collaboration collecting data. The constrained signals from the Receivers will pass into the bespoke Correlators which further process the radio signal. The WRT’s Correlator is unique and the concept of correlation is the “soul of interferometry” as Brianna told me—see Appendix B for more discussion on this. The Correlator will output the transformed signals into the WRT’s Data Capture system where it is stored in the Online Archive. From the Online Archive this raw Correlator data will be sent to different WRT Data Archives for use by scientists. The Radio group works with a clone of EoR data that is located in the United States.

This basic overview of the WRT simplifies many important details but most are not necessary to understanding the work in this dissertation. There are three aspects that I do need to discuss. First I will explain how the influence of the EoR Science Collaboration extends beyond just the use of the WRT, this cooperative work arrangement physically shaped the layout of the telescope in a way that is beneficial to EoR science. Second, I will discuss how the instrument is pointed on the sky. Third, I will discuss the cables that connect Antenna Tiles to Analog Beamformers. These three details shape the EoR data and in turn the Radio group’s US EoR pipeline software work.

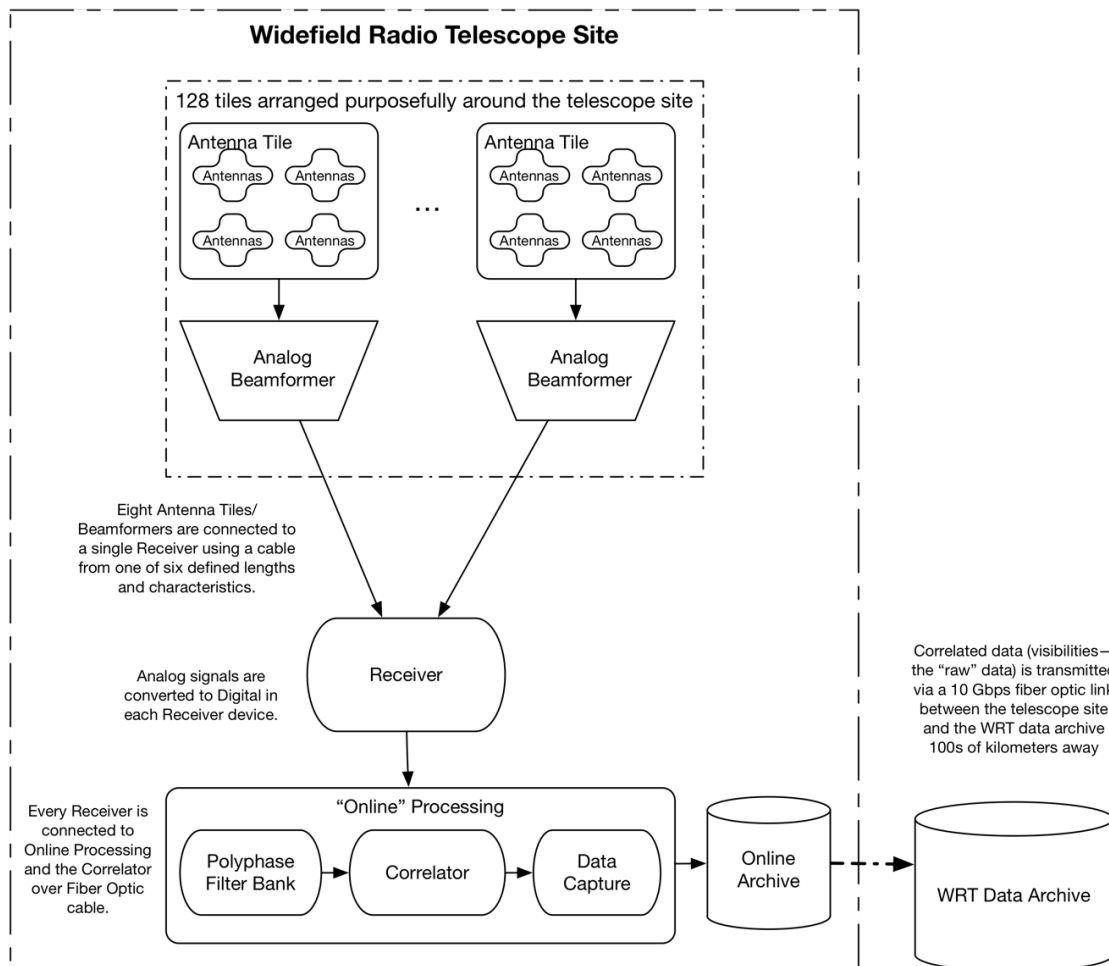


Figure 14. The Widefield Radio Telescope’s components. The telescope is physically located at a southern hemisphere radio observatory. The 128 antenna tiles are arranged in a pseudo-random order on this site to account for different scientific goals.

Physically optimizing the WRT for EoR science

I mentioned that the 128 Antenna Tiles of the WRT are laid out in a pseudo-random manner around the radio observatory site. The layout of the Antenna Tiles directly shapes the data that is collected since the physical placement of these components changes the signal that is captured and correlated, directly influencing the shape of the telescope’s primary beam that is modeled in Igor’s CalibratorImager software. I explained above how the EoR Science Collaboration is a “power user” by sheer volume of observing time allocated. This Science Collaboration’s scientific aims have however much more interestingly been inscribed in the design of the telescope as a physical, hardware device. This is due to the Radio group’s contributions to the layout of the WRT’s Antenna Tiles.

Exactly where each Antenna Tile is placed physically on the ground directly influences the characteristics of the electromagnetic signal that is captured. A common field of work that emerged in the WRT Collaboration was designing the Antenna Tile layouts. Magnus and Abner both formed part of the cooperative work arrangement that contributed to the current instrument’s layout as well as future potential layouts through their work modeling different layout designs in software. This design task, like all others for the telescope, is a complex sociotechnical process. The layout of the Antenna Tiles is a design problem rooted in the mathematics and physics of the electromagnetic signals that are to be captured by the telescope, the science underlying interferometry. The technical aspects to the design problem are further changed and constrained by details of the physical environment—such as roads, buildings, how flat the land is, different vegetation present, and different land ownership concerns—along with the project’s financial state. This modeling and design work produced multiple papers from the WRT Collaboration, including one lead by Abner early in his doctoral career.

Designing the WRT itself requires working with the multiple infrastructural constraints and conditions of the radio observatory it sits on. I explained earlier that one required acknowledgement in publications is to the native population who traditionally own the land the telescope is placed on. Their rights and concerns in fact had to be accounted for in the placement of Antenna Tiles. Brianna explained that when Abner was tasked with figuring out options for an extended, future layout of the telescope he had a variety of constraints to work with. One of these constraints was to try and limit where things are physically placed on the ground to areas that had previously been “walked over” and approved by the native group who traditionally owned this radio observatory’s land. Obtaining walk over approval requires paying the tribe to perform this task regardless of whether they approve a use or not. This sociopolitical facet to the radio observatory as the underlying infrastructure for the WRT project feeds into the design choices of Abner and the rest of the WRT Collaboration.

Anytime you want to put anything down, it has to have been walked over in the past at some point by a tribal group and decided whether it was okay to put anything there. It turns out if you want to do a new space, you have to pay them a certain amount of money to go out and do it and then either they say it's okay or they don't, but you have to pay them either way. So there's a big bias toward using spaces that have already been walked over, and there's some area that has, and then also minimizing the area of new stuff just because it's really expensive and you don't know what they're going to find. We do know certain types of terrain that they're more likely to be bothered by, the water flow areas and the things that look like mesas. They're actually much shorter than that. They're called breakaways, are generally off limits, but there can be other things, too. (Brianna, interview)

The goal for Magnus and other Epoch of Reionization researchers when working on the Antenna Tile layout common field of work was to distribute antennas so that the instrument is as sensitive to the EoR signal as possible. In an entirely idealized scenario with a perfectly functioning hardware system Magnus notes that it is desirable to have the antennas be centrally

condensed, e.g. placed closely together in a circular pattern. In practice such a layout is undesirable from both a technical standpoint and a political standpoint.

Entirely centrally condensed antennas are a technical problem since an instrument is never perfect and thus must be calibrated. Central to interferometric telescopes is the concept of “baselines” or the distance between antennas. An entirely centrally condensed design will result in short baselines which produces data that is difficult to calibrate. An interferometric telescope benefits from having some long baselines, e.g. having some antennas dispersed at a distance to provide longer distances between antennas. From a political standpoint having only a centrally condensed core of antennas would compromise scientific goals of the WRT Collaboration beyond studying the EoR. The built layout of Antenna Tiles must be balanced such that it will serve the scientific needs of each Science Collaboration as well as to ensure data is not too difficult to calibrate lest data processing and analysis be even more labor intensive.

When the WRT was originally being designed Magnus, as a post-doc, and a student collaborator were tasked with designing the Antenna Tile layout. Magnus and his collaborator were able to define the design conversation that took place within the WRT Collaboration. They socially shaped the initial technical design that was the focus of this common field of work, setting the stage for future discussions. Magnus mirthfully described that this design effort led to “THE” starting specification for the potential layouts of the antennas such that no one questioned that this must be the starting point.

... but for the EoR being centrally condensed, it, it, the answer is you wanna put 'em all next to each other. But, one, we, we didn't think that was really quite the answer 'cause to calibrate you want longer baselines and stuff, and that would mean you couldn't do any other science ... And so we tried r^0 , r^{-1} , r^{-2} , r^{-3} , um, as distributions, and they got more and more sensitive in order. r^{-3} is so centrally condensed they're basically almost no long baselines, so we thought no one would

buy that, so we backed it off to r^{-2} . That then gets written in as THE spec.
[Laughs] Nobody questions it. (Magnus, interview)

Magnus and his collaborator's layout modeling work and the resulting conversation starter they produced very literally shapes the data taken with the Widefield Radio Telescope since the primary beam of an interferometric device is shaped by the antenna layout, just as the details of the mirror in an optical telescope influences the data captured in that type of instrument (cf. McCray, 2004). Originally the Widefield Radio Telescope was meant to have 512 tiles of antennas. Due to budget constraints the WRT Collaboration was forced to downsize the project's scale and ended up with the final 128 tiles. This descopeing and downsizing of the WRT as an instrument not only decreased the amount of data being captured in every observation but required adjusting the physical placement of the antennas since there are now fewer than originally intended, a task Magnus and Abner worked on by creating simulations early in Abner's doctoral career. The layout of the antennas, both originally and for the downsized version of the telescope, in the end had to be constructed to balance the data collection capabilities of the instrument for the four different scientific uses of the instrument.

The built layout of the WRT antenna tiles ended up being quite optimized for EoR data collection while also being of use to other scientific goals and accounting for the realities of a flawed physical instrument where raw data is not perfectly captured but rather must be calibrated and interrogated to be of scientific use. The layout meets the needs of the different scientific stakeholders while fitting within the allotted budget. The WRT Collaboration had to work with and respect the rights and wishes of a native population to whom the land the telescope is placed on originally belonged. This population's rights add another facet to the sociotechnical milieu of the WRT as an infrastructure where the individuals working on the instrument design had to align the seams between their nascent infrastructure and that of the radio observatory it was

being built on. This was not a fleeting moment of alignment between multiple infrastructures like Vertesi (2014) examines, rather it is one infrastructure permanently constraining and entangling one another. This entanglement extends into the Radio group's infrastructure through their software's encapsulation of a model of the telescope.

Steering a stationary telescope on the sky

The name Analog Beamformer suggests that the signal (and therefore the data) collected by the telescope is shaped by this hardware component. This is indeed the case, as I mentioned above this device enables the telescope that is physically fixed in one spot to be pointed at different regions of the sky. The WRT's Analog Beamformers are composed of delay switches. Delay switches simply cause a signal coming in to not continue through the circuit until some amount of time later. The Analog Beamformers delay switches are used to point each antenna of the telescope at a different area of the sky by altering the time at which a signal arrives. This is setting the pointing of the instrument for an observation. The WRT may not physically move but with these delays it can point in 256 different beam directions²³. The Analog Beamformers will be controlled by the telescope's control and monitoring system that I discuss in Chapter Five based on the configuration a Science Collaboration chooses for their data observations.

The beam directions for every two-minute observation's pointing create what is known as the telescope's primary beam. The primary beam is a central element in accurately analyzing data taken with the WRT. Igor explained to me how in commonly available, standard radio astronomy software "instead of using the actual beam pattern, which is fundamentally different for every single antenna pair, it just uses one just single, simple shape that's the same for all of" the different beams (Igor, interview). This single, simple shape is okay for narrow field of view

²³ WRT-Pub-2013-WRTSystemOverview

telescopes where something bright is right in the center of the telescope’s beam and analyses can be setup appropriately. This is everything that the Widefield Radio Telescope and its EoR data are not. The WRT is capturing most of the sky at once and looking for faint, diffuse phenomena and as a result Igor cannot black box the shape of the WRT’s primary beam.

Igor’s CalibratorImager software is the point in the US EoR pipeline where the beam must be accurately modeled for their overall technique to work, the “lobster” like beam in Figure 15 being one example shape of the instrument’s primary beam. I will examine this further in Chapter Six. Using the Analog Beamformers to steer the WRT on the sky is a conceptually simple task yet doing so is integral to producing data that is scientifically useful for studying the Epoch of Reionization since the EoR Science Collaboration wants to point the telescope at areas on the sky it can expect to find this signal. This is just one example of the importance of understanding the design of this telescope for the Radio group to be able to successfully produce their software. Another is the cables connecting the Antenna Tiles and Analog Beamformers.

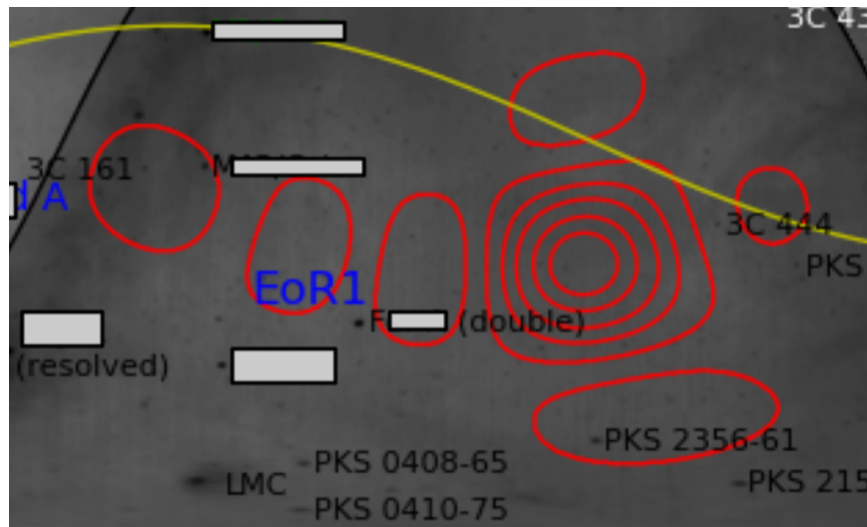


Figure 15. An example WRT beam shape.
The shape of the beam is represented in red in this visualization. The central core of concentric circles is the primary beam while the individual circles around the core are known as side lobes.

Six seemingly simple cables and their signal reflection properties

Above I mentioned that sets of eight Antenna Tiles/Analog Beamformers are wired to one WRT Receiver. The selection of cables with which to connect these components turns out to be unexpectedly important for the Radio group's software production. The distances from different Antenna Tiles and their Analog Beamformers to one of the eight Receivers varies due to the placement of the tiles in the radio observatory's physical environment. Instead of using cables cut to length for each Analog Beamformer to Receiver connection the WRT Collaboration intentionally wired these components together with only one of six possible cables—specifically in lengths of 90, 150, 230, 320, 400 and 524 meters. This has ended up being a wise design decision.

The restriction to six cable options was a specific design decision chosen to try to mitigate potential data processing issues should signals end up being delayed in varying amounts across different cables. This is important since the physical properties of a particular cable directly influences how fast and clearly an electromagnetic signal travels from one end to another. By using only six particular cables the telescope will have consistent characteristics for signals traveling between the Analog Beamformers and Receivers. If the signals between each of the Analog Beamformers and Receivers did arrive with different delays this would add even more to the processing burden of the various software analysis packages developed by researchers in the WRT Collaboration. Knowing about this design decision and where to find the details about it becomes important knowledge in data analysis and software production.

Even with only six particular cables in use the connection between Analog Beamformers and Receivers has in practice been subject to a flaw. In later chapters I unpack the example of the “fourth line bug” that I introduced in Chapter One. Looking back at Figure 2 I explained that

there are three expected horizontal bands in the Radio group's 2D power spectrum plots. These horizontal bands are artifacts of the coarse filtering in the telescope's chain of hardware. The 4th line bug came up unexpectedly during my second episode of data collection as a fourth, non-harmonically spaced horizontal band. This bug and the group's cooperative work to understand it directly illustrates the impact of these six cables on the data processing and analysis. The 2D power spectrum plot displayed an unexpected artifact leading the group to ponder its potential cause. In their work to build an infrastructure for doing data analysis they ended up having to invert that of the WRT, an infrastructure in a layer below their own infrastructure. The use of six standardized cables to connect hardware devices becomes an interestingly important design decision that at first glance would not seem to matter all that much, as almost any such decision might appear to the unaware observer.

Summary

In this chapter I examined the WRT Collaboration as an organization creating an infrastructure. I discussed the collaboration's structure with management groups as well as four Science Collaborations. There are a variety of different cooperative work arrangements in the WRT Collaboration focused on many different products for research work, yet above all they are all part of the overarching cooperative work arrangement of the project. I explained the EoR Science Collaboration that the Radio group is a part of, unpacking multiple facets to this Science Collaboration's role and influence across this infrastructure project. I opened up part of the black box that is the Widefield Radio Telescope as a physical instrument built by the stakeholders of this infrastructure and foreshadowed elements of it that will influence the Radio group's data analysis software. I also looked at the origins of the Radio group's US EoR pipeline as part of the EoR Science Collaboration to set the stage for untangling its production.

Paul Edwards (2003) argues that “infrastructures simultaneously shape and are shaped by—in other words, co-construct—the condition of modernity” linking macro, meso, and micro scales of “time, space, and social organization” to form the stable foundation of modern social worlds (p.186), remarking that “the notion of infrastructure invokes possibilities of extension in time, space, and technological linking that go beyond individual systems” (p.200). Examining the WRT Collaboration as a research infrastructure does exactly this. The WRT Collaboration has created an infrastructure linking multiple continents with an instrument that is able to peer back in time all while creating a virtual organization. The kernel of this infrastructure is creating different resources to enable scientific work, this infrastructure “operates upon its resources” (Ribes, 2014) by setting policies for their creation and use. The policies regarding observation time, data access and use, and publications all touch upon parts of the entangled resources of the cache of this infrastructure. This is not all of the story though. I introduced the telescope’s hardware components and in the next chapter I will turn to look at the systems that enable its use as a data collection device. To understand how, for example, EoR data is produced and sustained as a resource by the kernel I will examine the EoR Science Collaboration’s data collection process that relies upon the stability of these systems in the next chapter.

The WRT project is working at the edge of what is possible scientifically to study the Epoch of Reionization. One of the founding goals for the WRT project was to demonstrate technologies and techniques to examine the potential for future even larger telescopes. The novel telescope design partially addresses that goal. The Radio group’s software does this as a novel approach to data analysis as well. From the perspective of the Radio group and their colleagues in the WRT Collaboration they have come together to create an instrument and are using it to accomplish their research goals. Doing this requires creating different arrangements of

individuals to work together cooperatively on some shared common field of work. This can be as expansive as the project itself, any of the four science goals of a Science Collaboration, or much more narrowly by allocating telescope time. Examining the deliberately created arrangements of interdependent stakeholders trying to produce a product enables me to foreground particular points of interest over time.

As the outside observer studying infrastructure I have begun to invert this cosmology research infrastructure by teasing apart its constituent components and their relations to each other. The policies for enabling and supporting distributed collaborative work and this interferometric telescope, become a significant part of the installed based upon which Individual WRT members and their groups are able to do their scientific work. Knowing the procedure for authoring and publishing papers using this infrastructure's data is part of the community of practice that has to be learned as part of membership. The Widefield Radio Telescope is built upon the infrastructure of an existing radio observatory site. Embedding this telescope on to this site requires working with the resources it is providing and sustaining while also extending and adapting them to the scientific needs of this project. Future work to study the entanglements of the WRT and its radio observatory would provide the ability to explain these entanglements in more depth, beyond a simple example of working with constraints stemming from the rights of a native population to this physical land.

Looking at the origins of the Radio group's US EoR pipeline software illustrates how it shifted from being a product of a single local group and shifted to resulting in an infrastructure for the larger EoR Science Collaboration. In light of the overall WRT's fourfold downsizing the planned real-time data analysis software was not created as expected. At the same time the Radio group's efforts started to cohere and function as the instrument came about and data was

produced. The emphasis on the ability to exchange data products between the US EoR pipeline and the LivePipeline leads me to some of the key aspects of the production of data and in turn this analysis software that comes out of my remaining chapters.

Describing the WRT's components and the constructed device shows the influence of the Radio group and the larger EoR Science Collaboration in the physical layout of the telescope's antennas. Magnus, Abner, and their colleagues work modeling and designing potential arrangements for the antenna tiles setup the common field of work for this design task. What started as a cooperative work arrangement primarily between a few individuals set the stage for ensuing conversations and over time the entire project's scientific work. This chapter has explored just part of the first layer of conditions necessary for the Radio group's infrastructural work. These conditions—the policies and organization of the project, the design of the instrument, etc.—in and of themselves are infrastructural. What I need to examine now is the use of the Widefield Radio Telescope to actually collect EoR data. What are some of the addressing activities that the EoR Science Collaboration must engage in as part of the WRT's kernel if it is to obtain data? Data is after all the raw material necessary for this cooperative work.

V. Employing an Infrastructure to Create Data Products

... it seemed to me to extend also into the past by virtue of the memory which had been superimposed upon it ... — Marcel Proust, The Fugitive

Introduction

Having introduced the Widefield Radio Telescope project, the Radio group's role in it producing software, and the telescope itself I can now turn to discuss how this telescope is actually used to collect data, creating inscriptions of the Universe's past from the signals in the background of the sky. At the beginning of Chapter Four, in Figure 10, I illustrated that the Widefield Radio Telescope is one layer of infrastructure that I am discussing in this dissertation. This chapter continues to look at that layer, shifting focus to how the EoR Science Collaboration works with two of the resources produced by this layer, the telescope and data archive, to produce another resource, observation data. The argument of this chapter is that producing Epoch of Reionization data with the Widefield Radio Telescope creates scientifically usable materials (data products). The different cooperative work arrangements within the EoR Science Collaboration can do their research with this material because of the work done in the WRT infrastructure's cache. Producing data and the infrastructural components necessary to do so is part of the work of enacting and sustaining the WRT as a research infrastructure.

In this process the Radio group and their collaborators in the EoR Science Collaboration are working as part of the WRT's cache. For the Radio group understanding how the telescope creates data products becomes essential knowledge in their work producing data analysis software. Data products are the encapsulations of data, software, and the telescope that I see connecting the WRT as a research infrastructure and the Radio group's US EoR pipeline

software as another infrastructure above (the EoR Science Collaboration's LivePipeline would be another infrastructure similar to the US EoR pipeline).

Much of the work that I examine in this chapter is that of creating infrastructural components that support the ongoing activity of collecting data and documenting how this is done. This is work to make the telescope a resource for scientific inquiries, creating and embedding conventions of practice that become part of the infrastructure's cache. The examples I discuss in this chapter extend back into the telescope development and pre-operations phase forward into the instrument's early operational phase. I investigate how the WRT designed the telescope to "self-document" its operation through monitor and control systems and its data archive so that the data products created will be scientifically usable. I then turn to the Radio group and EoR Science Collaboration's cooperative work monitoring data collection and the transfer of EoR data around the globe to the United States for the US EoR group to work with. Data collection and transfer are automated activities yet cooperative work among the various arrangements of individuals is necessary to monitor and understand these processes. This leads me to my discussion of data products, what they are and how they are a thread among multiple infrastructures in the Radio group's work, serving as coordinative artifacts among different infrastructures and cooperative work arrangements.

My explanation looks at how the data collection process not only produces the raw material for the Radio group's use producing software and analyzing data but also helps to imbue these individuals with an understanding of the WRT as an instrument in their bones. Brianna, Igor, Abner, Peg, and Nima as post-docs and PhD students all have their different research interests. Yet none can do their work alone and together they, along with Magnus (and other collaborators), develop a feeling for how the Widefield Radio Telescope operates in practice.

Their early engagement in the data collection process helps them understand its operational behavior when effects from the instrument or its data collection systems appear in their plots. This work is how the Radio group probes the Universe's past all while interrogating the accretions of their own project's ongoing decisions that coalesce as metadata embedded in their many different data products. When the Radio group eventually shifts modes to using the observation data as a resource for producing their software and making scientific claims they shift roles, engaging in activities of scientific investigation that uses the kernel's resources. This work is not part of the WRT's kernel as Ribes (2014) emphasizes that one activity that is not part of a kernel is "an investigation conducted using the resources and services of that infrastructure" (p.585). The group's work embedded in both infrastructures results in them working as part of each kernel simultaneously. Their data collection work is part of the WRT kernel while their software production is part of another kernel.

An automated process for collecting data

Collecting data with the Widefield Radio Telescope is a cooperative process that requires proposals for observation time by Science Collaborations, configuration of the telescope to appropriately capture the desired data, and monitoring of the telescope as it operates to attempt to catch any noticeable faults in the data collection before it is transferred to different archives around the world. The actual operation of the telescope is automated and requires little direct input from a researcher in the lived moment of collecting data. It is the design of the systems that make this process automated that I end up being interested in since these systems influence the Radio group's ability to untangle the instrument in their analysis work. To be able to use data they need to be able to trust and understand its production, a point raised in many CSCW studies about data sharing and reuse (Faniel & Jacobsen, 2010; Rolland & Lee, 2013; Zimmerman,

2003). The observation data and metadata created in this automated process are the resources that the WRT kernel must continually engage in addressing activities with to keep the cache of this infrastructure relevant scientifically over time.

In Chapter Four I explained that the WRT's Time Allocation Committee disperses instrument observing time. When I asked about the process of operating the instrument, once time is allocated for a semester, Brianna conveyed that a member of the telescope operations team is tasked with laying out the overall observing schedule for the instrument on typically what is a per-night basis. Each awarded observing proposal (e.g., the EoR Science Collaboration's award) is given windows of nights that it will be allowed to observe during. Once windows of time are assigned an individual must setup the observations in the telescope's monitor and control systems. For the EoR Science Collaboration this responsibility fell to Darcy, a post-doc at another university in the United States. How Darcy goes about doing this was outside of the scope of my data collection and remains a point for potential future investigation.

The WRT as an instrument has settings that can be changed to support the different scientific goals. The settings a particular cooperative work arrangement wants for their observation data must be determined beforehand so that the individual programming the system can properly configure the WRT's control systems to shape the form of the data being collected. One example is the selection of frequency channels to take as output from the filter banks in the Receivers to send into the Correlator since this point in the instrument's hardware-software chain narrows the scope of the data that is collected. Once the instrument is configured and observing is happening the EoR Science Collaboration has a distributed, cooperative monitoring process. This monitoring process is known as serving as the "on-duty astronomer" in a harkening back to the early days of astronomy observing where the scientist collecting data would spend all night

inside the cold, frigid telescope working (McCray, 2004). An on-duty astronomer monitors the state of data collection through a purpose-built website called “EoRLive,” detailed in Appendix C, during this process. Whether the other three Science Collaborations have any similar sort of process is outside the scope of my inquiry.

The cooperative work monitoring observations is designed to produce logs about the behavior of the instrument as it collects data. These logs become metadata about the collected observations. The metadata produced through this process can be referenced later when particular data is being selected for analysis. This is in addition to metadata produced by the different infrastructures of the telescope itself. The creation and storage of this metadata is part of how the cache of the WRT’s infrastructure works to make observations available and stable over time as a resource.

Building infrastructural components for collecting and archiving data

The Widefield Radio Telescope is not simply a collection of components placed in the desert. It exists as an assemblage of infrastructural components; the hardware, software, data, and policies the different cooperative work arrangements of the WRT create. The telescope produces significant volumes of data that must be captured and reduced for archiving. One of the ways it is able to create data that are usable as scientific objects is by self-documenting its operation, recording a variety of metadata that preserves context for the resulting observations. This self-documentation is possible because of infrastructural components that the WRT Builders group created. The data and metadata from this self-documented state of the instrument are then made available through a series of data archives to the members of the WRT Collaboration around the world.

The telescope described in Chapter Four is an amalgamation of hardware and software components that in use is a scientific instrument. The telescope will store data from its Online Processing system into an archive system that takes the output of the instrument, raw data, and makes it available for researchers around the world. Wielding the telescope to collect useful data however requires engaging with its control and monitoring system. This is a purpose-built management system that I refer to as ControlMonitor. ControlMonitor is software that monitors the state of the entire instrument while also taking a schedule of observations and operating the instrument autonomously for the Science Collaborations according to the configuration they agreed upon. ControlMonitor is designed to make the instrument self-documenting so that over time the parameters and characteristics of the telescope during an observation can be recalled and interrogated as necessary when different scientific analyses are undertaken. This self-documenting approach is key to making this digital observation data a scientific object and not just a meaningless artifact. Individuals do not have to sustain this information when it is built into the infrastructure's resources, the infrastructure's cache instead needs to sustain the archive.

The self-documenting design of this telescope's control and monitoring systems contributes to the WRT kernel's addressing activities by creating the information necessary to make observation data retrievable and usable over time. Ribes (2014) points out that bags of blood are only useful as scientific specimens so long as an infrastructure's kernel ensures they are labeled and stored properly in the event a researcher wishes to retrieve and use them. The metadata created by ControlMonitor is akin to the labels put on bags of blood, helping to transform this artifact into a potential scientific object. The WRT's work ensuring the database and computing systems this information is stored in are maintained and accessible to the appropriate individuals is akin to the ongoing work ensuring blood samples are stored in the

proper conditions. Both of these very different activities keep materials available and potentially amenable to scientific questions. Creating these entanglements fell to the Builders group when developing the telescope control software.

Building ControlMonitor to create a self-documenting scientific instrument

Building ControlMonitor was a cooperative endeavor of a subset of the WRT's Builders group. Brianna is one member of the WRT Collaboration's builders group that created ControlMonitor. She commented that Magnus originally signed up to contribute to this effort but did not have time to work directly on it. He then happily volunteered her for the task.

ControlMonitor is designed with a database as the point of coordination between the different software and hardware systems of the WRT. Brianna explained that this design decision is motivated by the diversity of software languages being employed across the WRT project. Everything being built formed a "mesh" of different components. Her contribution to ControlMonitor is written in the Java programming language whereas some other components are in Python, C, or other languages. The members of the cooperative work arrangement developing ControlMonitor all brought different software backgrounds, research interests, and amounts of time available to this effort. The diversity of funding streams in the WRT project also made it difficult to mandate any one language when the individuals building something were volunteering their time.

The solution to this variety of programming backgrounds and languages was designing ControlMonitor around a central database. This resolution was pragmatic and sociotechnical. As long as a given programming language can interact with the database then a component can theoretically be written in that language, providing technical flexibility. At the same time, the different individuals who end up volunteering and contributing can complete their work in a

software language they are comfortable with, or perhaps at least interested in learning. They can work on their own research goals while supporting the overall WRT project's goals as well. The centralization around a database also helps to somewhat ameliorate the coming and going of different individuals to this part of the project as they are not full time and may shift their focus to other tasks. This addresses the social aspects of the issue and demonstrates a pragmatic case of flexibility in designing and enacting infrastructural components when contributions are voluntary and managing such a task comes with little power over these volunteers.

And the way that the [ControlMonitor] software is organized is around a database. And so we have – and part – this was – there were several reasons for this. Partly, it was because everybody writes a different language. So we've got Python, C, Java, and then some various things that make websites and stuff. So it's all a mesh. We have a lot of people who have worked on it in the past and some of them are still working on it and some of 'em are not. They come and go. Nobody is full-time on the project. They're spread over three countries. So it's been a challenge. But the database has worked really well. (Brianna, interview)

Brianna built the piece of ControlMonitor that manages the telescope as it is capturing observations. I refer to this as SystemController. Chapter Four discusses how the WRT Collaboration's Time Allocation Committee is responsible for allocating observing time. I noted that a member of each science collaboration is then responsible for entering their schedule and desired configuration into the telescope's control and monitor system. The schedule is stored in ControlMonitor's central database. Brianna's SystemController software is in charge of autonomously executing this schedule and ensuring that all of the different hardware components are configured correctly for a given observation. Her software is responsible for accurately and reliably translating an abstract command into actions in the physical world.

I also briefly described in Chapter Four how the telescope is pointed at different places on the sky by switching among different delay switches in the Analog Beamformers. ControlMonitor is responsible for ensuring that each Analog Beamformer's delay is set

appropriately for each of the Antenna Tiles, all while keeping every device synchronized to a central clock so that data collected from all 128 tiles is in sync and therefore usable. This is crucial for the viability of the captured data since synchronization issues or lag would introduce errors, perhaps seemingly random, in the data. These would then have to be traced down during analysis work on top of the many other issues that can arise since the instrument is perpetually visible in the data when something goes wrong. Brianna describes how every command and operation given to ControlMonitor, and in turn SystemController, is logged in the central database. This is necessary not only for coordinating the operation of the instrument but to provide a historical record of every operation: “*so it’s keeping track of every command that was ever sent, all of the temperatures, all of the voltages, all of that stuff*” (Brianna, interview). The telescope is “self-documenting” when creating this historical, operational record. This operational record in turn must be sustained by the kernel of the WRT so that a scientist using this operation data can properly transform these digital artifacts into a scientific object for asking questions about the Universe.

Brianna stresses that ControlMonitor takes the very high level observing schedule from the database—i.e., “collect data at these times”—and determines what this means in the context of the telescope’s actual, real world in the moment configuration. This is the low level, concrete answer of how is the telescope actually wired together at that particular moment. Brianna’s SystemController software is translating an abstract desired action from a Science Collaboration into tangible, enacted actions. This translation is crucial since some components of the telescope are wired together in particular physical arrangements to allow for different types of observations to be completed. These arrangements can be changed should there be a particular scientific need. During the build out of the telescope configurations were changed as various tests were

conducted. However, now that the instrument is in an operational “real” state the physical wiring is not often changed. The primary physical changes being completed to the operational instrument were replacing components hit by lightning during a thunderstorm, a pretty regular occurrence as various members of the Radio group mentioned it happening throughout the various episodes of my data collection.

And yeah, if you want to physically change something, you have to go move a cable and then you have to tell the database you moved the cable in order for things to work. [Laughter] So there is a little bit there. But that doesn't change too frequently, especially now that we're settling into a real instrument. When we were working with a prototype, it was changing fairly quickly. We're in the commissioning stage now, so we've got all the hardware on the ground and we're working on getting everything working. And also which systems are live. And so some of that comes out of the database and some of that is who calls into [SystemController] and says, “Hey, I'm here, I'm ready.” (Brianna, interview)

Other than the database and SystemController, ControlMonitor is also composed of a website interface and other control systems. The web interface enables a member of the WRT Collaboration to examine the current state of any given component of the telescope. This interface is linked to from the “EoRLive” website that the EoR Science Collaboration uses when monitoring observations. The web interface enables any member of the WRT Collaboration (and to some extent the general public since even I could load some pages without authentication) to open up the black box of the telescope from anywhere in the world at any point in time. The instrument of this research infrastructure remains physically remote yet is digitally accessible. Software is doing work in the world through and with these components to bring phenomena captured from the sky visible in the southern hemisphere elsewhere to many other countries.

The self-documenting instrument and the infrastructure cache

By creating this “self-documenting” instrument the WRT Collaboration is ensuring this telescope's operational state is able to be recreated over time. This information is stored as part

of ControlMonitor and ends up being encapsulated in data products produced by a Science Collaboration. Self-documenting the instrument's operation is necessary to be able to do high-precision data analysis work where any of the at first glance insignificant details can quickly become significant. I've noted many times that the EoR signal is incredibly faint and easily covered up by noise from the instrument or some other flaw introduced in the data. The Radio group needs to be able to know what the real world conditions at the instrument were, to recall how the EoR Science Collaboration collectively decided to configure this device when analyzing data.

For example, the telescope is in a desert environment where temperatures fluctuate across a wide range over the day and night. The WRT Builders group included temperature monitoring as a feature in ControlMonitor. Brianna explained that these researchers expected that perhaps some hardware might overheat. This would produce data that is not scientifically valid. Brianna continued on to note that during the build out and very early operations they discovered through this temperature monitoring feature that some components were at times operating in too cold of an environment and therefore producing bad data. This turn of events was not expected but became understandable serendipitously thanks to the implementation of a feature for the exact opposite purpose. Enabling the black box of the device to always be opened up and interrogated if an individual is interested, or it becomes necessary to do so, and sustaining this ability is an example of the kernel having to not only create this resource in its cache but to ensure it is not lost as a component of this infrastructure's set of relations.

This concept of having the instrument self-document and produce metadata necessary to successfully use observation data is enabling some of the tasks CSCW researchers point out are necessary when data is reused for later studies, although this is a case of use rather than reuse

(and really reuse is just a special case of use that may or may not involve the researchers who created a resource). Rolland and Lee (2013) describe the work cancer epidemiologists undertake to reuse data from prior studies. The epidemiologists studied open up the black box of the dataset they are handed by a senior colleague, working to disentangle the variations in how the dataset's variables were constructed. This was achievable by these researchers because they reached out to the individuals who originally did the work, probing the history of this artifact to construct the metadata required to reuse the original dataset. The scholars Rolland and Lee studied did not have an infrastructure supporting and sustaining knowledge about the study instrument.

In contrast, my example with the WRT is illustrating how an infrastructure's kernel through well placed design decisions is capturing and sustaining the entanglements between observation data and the instrument that produced them so that they are reproducible. The metadata that captures operational quirks and design details across the telescope in ControlMonitor becomes important knowledge in the Radio group's data analysis. They use this and other metadata to assess which observations should be processed through their software. In the US EoR pipeline by design a researcher executing the software selects observations for analysis rather than automatically expending significant computational time on all data, both good and bad. Because ControlMonitor was built to self-document the telescope as an instrument it remains open to being interrogated for both expected and unexpected quirks and flaws days, months, or even years later when the Radio group's data analysis is happening. Key to keeping all of this information available and accessible to the different scholars in the WRT are its series of data archives that the kernel must sustain.

Data archives in the WRT’s kernel

To sustain the data it produces, the WRT Collaboration built and maintains a three tier (zero, one, and two) data archive. The data archive is another resource of the infrastructure’s kernel that I visualized in Figure 10. The three tier archive captures the flow of data out of the telescope’s Online Processing and storage system, making sure they are accessible to the different Science Collaborations²⁴ as data products. This system is necessary for the WRT Collaboration to be able to support the varied scientific goals of the project over time—most pressingly for an immediate time span of the next five to ten years, but ostensibly for the decades beyond as well.

Tier Zero of the data archive is the site of data production, the Online Processing component including the Correlator and Online Archive noted in Chapter Four and Appendix B. This initial tier is described by the collaboration as “online” since this tier operates directly with the telescope hardware. It is part of the process of digitizing the analog radio signals, inscribing phenomena into an object that can be continually manipulated over time as different research questions arise. The settings a Science Collaboration chooses shape the data that is collected, trimming radio signals down to a desired range.

Tier One, the second, is the long-term archive of the data produced in Tier Zero and an offline-processing system that different Science Collaborations may use to work with this observation data. The Tier One archive is connected to the Tier Zero online system via a 10 gigabit per second fiber optic link running through the vast expanse of this remote desert since these two archives are physically separated by hundreds of kilometers. The nearest city to the radio observatory site is intentionally quite far away to reduce the amount of human produced radio frequency interference which would keep this instrument from producing usable data. This

²⁴ WRT-Pub-2013-WRTSystemOverview

radio quiet environment is another resource of the radio observatory as an infrastructure that its kernel must work to maintain.

Tier Two, the third and final, consists of cloned archives of subsets of the data for particular Science Collaborations. The RadioCluster is a computing cluster located in the United States that is a Tier Two archive that stores the subset of data produced by the EoR Science Collaboration. The RadioCluster is the shared computing environment for all members of the US EoR Group, including the Radio group. It is a site of negotiated use in this cooperative work because it is a finite, shared resource, as I examine below. The RadioCluster is a point where the layering of the Radio group's data analysis software as an infrastructure on top of that of the WRT Collaboration is visible. The RadioCluster is a resource of part of the EoR Science Collaboration, funding and maintained by members in the United States and filled with EoR data from the WRT. As a result, it is where the executions of the Radio group's software using large quantities of data takes place. Talking with Abner, Brianna, Nima, or Peg they would frequently pull up a remote access window to this machine to show me part the software they were working on or a new plot. Their own work producing and sustaining infrastructural components relies upon the RadioCluster existing and functioning. This top layer is entangled and partially embedded in an extended resource of the layer below.

The different tiers of data archives create contexts in which the WRT project's data will be stored and supported for time spans beyond the immediate five to ten-year span of the immediate WRT project in an ideal situation. How the different archives age and are or are not sustained as a lived infrastructure by the WRT Collaboration, perhaps turning into a geriatric infrastructure (Cohn, 2013, 2016), remains to be seen at this time. It was also unclear to the members of the Radio group what data from these archives would end up being shared publicly.

Raw observation data is easily shareable, if somewhat useless from Magnus's perspective, but it was unclear whether the different funding mandates the WRT Collaboration operates under would require any of the higher-order data products produced by Science Collaborations be made public. Since this was outside of the day-to-day tasks of the members of the Radio group it was never conveyed to me as a pressing concern.

Having explained how observation data as a resource of the WRT infrastructure is created and documented I am going to shift my focus to examine work the EoR Science Collaboration engaged in to make this resource useful in their work. This is the work of monitoring EoR data collection, a task that began when the telescope came online and that broke down fairly quickly as the instrument met this Science Collaboration's behavioral expectations.

Monitoring the telescope to watch for breakdowns by serving as on-duty astronomer

On a night where EoR data is collected there is not necessarily a need for anyone in the EoR Science Collaboration to monitor the telescope. The WRT was after all designed to be configured in software then left to operate on its own. The telescope is a new instrument though, and at the beginning of its operations phase it was not necessarily an entirely stable device. There are only so many issues that can be uncovered in testing. Some bugs will not arise until an instrument is wielded for scientific studies. The EoR Science Collaboration therefore developed an online and offline data monitoring process, the on-duty astronomer process.

The on-duty astronomer process serves multiple purposes. Primarily it is to create logs of metadata for observations where the instrument seems to have had a fault in some way. A second purpose is to help foster membership in the EoR Science Collaboration. As a part of the WRT infrastructure's kernel this process is an example of addressing work that is entangled with observation data, part of the process of ensuring the instrument is scientifically usable. Yet it

turns out that this activity will not be sustained as the telescope is determined to be a stable enough, “point and forget” device such that the limited time individuals in the EoR Science Collaboration have is better spent working with the observation data and potentially throwing out or ignoring any not useful data.

I first became aware of the EoR collaboration’s on-duty astronomer practice during an interview with Abner in my second episode of data collection. This conversation was only at the beginning of the telescope’s second operational semester (rather than the pre-operational testing phase) and the Radio group as well as their collaborators around the world were not yet sure that this device was a stable instrument. At this point in time he was in the thick of getting the Radio group’s US EoR pipeline software running reliably on the RadioCluster and I wanted to know how the Radio group collects their data. Abner proceeded to explain that data is automatically transferred from the WRT’s Tier One data archive to the RadioCluster as a Tier Two archive, which becomes a primary computational site of work for members of the Radio group. I followed up by asking if he or other members were involved with the actual operation of the telescope. This led Abner to show me the EoRLive website. The EoRLive website is an assemblage of embedded information widgets on a few purpose-built webpages that also directly links to key webpages of the WRT’s ControlMonitor system along with different shared Google spreadsheets (see Appendix C). These publicly accessible information displays show information about the Widefield Radio Telescope’s operation and the transfer of data to the RadioCluster. When Abner walked me through the second version of the website it was organized into three webpages. Organizing all of this information into this one website enables any member of the EoR Science Collaboration to easily examine the state of data collection.

As he loaded the EoRLive website Abner began by explaining that for every day the EoR Science Collaboration is observing there will be someone designated as the “observer” or “on-duty astronomer.” The on-duty astronomer will keep the EoRLive website pulled up on their computer while completing their day-to-day tasks. They will check the status of the instrument every half an hour to an hour as Brianna would eventually tell me. The on-duty astronomer creates a log entry if they notice an anomaly with the telescope or even just to note that all of the systems look to be functioning as expected. Abner explained that if the information looks “really bad” the observer should contact either a member of the operations team or someone else in the collaboration to discuss the issue. All of this work is the “online” monitoring of the instrument during an observation period.

every day that we are observing if somebody designated as the observer, you know, the on duty astronomer if you will, and you’re supposed to monitor it and make sure things are happening when they’re supposed to happen. It’s very minimal as far as there is not a lot of actually going in to fix anything; it’s just sort of going in to check it. Do things look right? If they don’t, just make a log entry. If it looks really bad tell somebody else. I like to say “get an adult.” (Abner, interview)

Abner and Brianna both explained that members of the US EoR group are the individuals responsible for the real-time, online monitoring of observations. This is the result of geography since the telescope collects data at night in its physical location. This happens to correspond to daytime for the various members of the US EoR group. In turn, during the daytime following a night’s observations the members of the International EoR group who are in the same geographic realm as the telescope are supposed to revisit the night’s data. These individuals are supposed to quickly check the night’s observations, looking for any further anomalies that might be detected and verifying that the observation data is transferred to the different archives successfully. This second part of the practice is the “offline” work.

The split of the on-duty astronomer practice into online and offline work divides the labor within this cooperative work arrangement based upon the member's geographic location and the natural daytime and nighttime these individuals live under. This practice is not especially labor intensive, but it is important for the EoR Science Collaboration as they try to develop an understanding of the telescope's quirks that can influence their subsequent data analysis. The process is a type of addressing activity that this Science Collaboration created early on in the telescope's operational phase as a part of the WRT's kernel to make sure the resource being created is available as expected.

Magnus commented to me that he thinks the on-duty astronomer practice "was important both in making sure we were getting good data and as a collaboration builder in terms of people feeling like they were part of the team" in this early operational phase of the telescope. An individual participating in this activity is developing some understanding of how the instrument operates, making use of the different webpages of the ControlMonitor system as well as the bespoke EoRLive website to obtain a feeling for the telescope that can be recalled and shared with other individuals during data analysis. Being the on-duty astronomer and logging anomalies during data collection, perhaps noting that a tile of antennas is broken or when the galaxy is up and present in the sky, helps to give these scientists awareness of what is happening in the world when their data is collected, insight into how an artifact for scientific analysis is produced.

The logs created through the on-duty astronomer practice are metadata that is part of the EoR collaboration's historical record of the observation process while enrolling the various members of the EoR Science Collaboration in the data gathering process over time. The on-duty astronomer work supplements the telescope's designed self-documenting features to surface in the moment how the device is functioning. This metadata can be important during the Radio

group's data analysis when someone is determining whether to use a particular two-minute observation's data or not. I initially imagined that this metadata would in turn be incorporated somehow computationally into either the Radio group's US EoR pipeline or the LivePipeline. It does require at least some effort to produce after all. In practice the logs and resulting metadata were always manually assessed by the collaboration, never being computationally integrated into the US EoR pipeline's operation.

When I asked about this Magnus, and other members of this group, emphasized that it had not been worth the effort to connect this metadata computationally to any of the points where data is selected in their pipeline. Instead the Radio group has intentionally kept these key points in their software where a human must select which data to work with. From Magnus's perspective they have not made an effort to use this metadata computationally partially because "there wasn't enough value of what humans were able to put in the metadata in order to make integrating it worthwhile" since the WRT as an instrument in conjunction with its monitor and control infrastructure became a "point and forget" system. This perspective is interesting to me given that while the on-duty astronomer process and EoRLive website are fairly simple they do require effort on the part of the members of the collaboration. I expected that the log data produced might be prioritized somewhat in the automated computational elements of the data analysis but this was not the case. Coming around to not necessarily using this metadata for analysis does unsurprisingly align with the breakdown and dissolution of this on-duty astronomer observation activity it turns out.

Breakdown and dissolution of the on-duty astronomer practice

The practice of being the on-duty astronomer is designed to be relatively uncomplicated and not burdensome for the members of the EoR Science Collaboration. It is not a task that was brought

up negatively in my discussions with the members of the Radio group. The only times I discussed this practice with anyone in the group were when I explicitly inquired about it after Abner first mentioned it to me, or when I saw the EoRLive site loaded in an individual's browser while we were talking and made an inquiry. Serving as on-duty astronomer became just part of being a member in this collaboration for a period of time, just another aspect of the conventions of practice in this infrastructure as they focused on their software production work.

As I noted above, over the course of my data collection I learned that the metadata logged in EoRLive is not computationally incorporated into their data analysis software to help prune bad observation data, nor were there plans to integrate this metadata. Furthermore, as observation sessions carried on and the telescope operated stably multiple members commented that individuals often failed to really keep up with assigned observation monitoring duties. Instead as the instrument proved to be stable and “point and forget,” breakdown and dissolution of the on-duty astronomer practice and the EoRLive website came to be the norm. This in spite of the explicit inclusion of this practice as an activity necessary to maintain one's membership in the EoR Science Collaboration²⁵. This wholesale shift in the span of six months to a year intrigued me since the practice did not remain even as a peripheral activity.

Creating the on-duty astronomer practice served a practical need in the EoR Science Collaboration during the early stages of the instrument's operational phase. It was unknown how stable the device would be or the exact quality of the data produced. New devices are expected to have bugs and unexpected behaviors in practice. Calibrating instruments is a common, ongoing activity in the kernel of infrastructures (Darch & Sands, 2015; Ribes, 2014) and something the

²⁵ WRT-Memo-2013-12-16-EoRCollabRevisedCharter, p. 6.

WRT Collaboration worked on not only during the telescope's development but on into the operations phase as different data analysis efforts began.

I asked Magnus to reflect on how this practice and the EoRLive website have been used in the EoR Science Collaboration. He noted that early on there was a technical need since the instrument did have faults appearing regularly and the EoR Science Collaboration needed to ensure both that it obtained good data and understood how the telescope functioned. From his perspective as a project leader the practice also was a “collaboration builder” by bringing people into the team and giving them further investment in the creation of this material for their subsequent research work. And yet as the instrument stabilized the practice has “largely gone away” as Magnus and other members of the group commented by early 2015. Abner reflected that the collaboration laid out observing schedules that spread the task among the members, but in reality only a handful of the members completed this work.

so we have in the past scheduled people to keep track of this every day. There would be somebody who's supposed to take a look at this, make sure the telescope's working. ... Found that nobody actually does it, so it's been pretty poor, yeah. If you look at the logs, there's like four or five people that make all of the log entries, and there's you know like 20 people that are scheduled, so. (Abner, interview)

Serving as on-duty astronomer was primarily about understanding the instrument as a new telescope, how stably it performed and what faults commonly arise. The Widefield Radio Telescope stabilized, shifting from an object of research and design to be studied and improved to an object to do research with. Members across the EoR Science Collaboration turned to work on their various data analysis activities. Over time as this data analysis work became all-consuming the observation monitoring process dissolved. Brianna reflected that while the log metadata was not directly integrated into the data processing and analysis pipelines being built, it was useful in the process of analyzing data when “something funky” appears since it is possible

to turn to the EoRLive logs and find a note to ameliorate concerns. Of course this is only possible if a member of the EoR Science Collaboration did take the time to log information in the first place.

While I was analyzing my own data I discovered that the EoRLive had fallen offline sometime during 2015. I queried Abner via email as I was curious if any changes were being made to the website or if the breakdown was temporary. After consultation with Darcy he responded that either the hosting for the website or the backend database connection had failed. Abner explained that “unfortunately it sounds like because no one really uses the site, if it goes down it stays down until someone needs it.” He ended the email mentioning that Darcy said I might find this “philosophy [of maintenance] interesting from the perspective of studying how we deal with our data...” since this website and practice were created to help ensure quality data yet are in fact not being actively used within the EoR Science Collaboration or even all that easily accessible. It is not even possible for someone from this cooperative work arrangement to try and engage in this work since the website remains down and inaccessible until an individual decides to do the work to fix the breakdown of this system or manually finds and connects to the relevant database. This process and associated website were only a year or two old yet they have already aged to the point that they have, at least for now, expired.

Magnus reinforces how the original motivation behind the on-duty astronomer practice and EoRLive site fell by the wayside as the members of the Science Collaboration shifted their focus once they were used to working with the instrument. He posits that “nobody ever really finds anything” outside of a major operational issue that would be noticed by the operations team because the bugs are so “subtle” and not noticeable until an individual is deep into data analysis. This foreshadows the complexity of the work to produce data analysis software for this scientific

experiment that has such low signal to noise data and where the work is living incredibly closely to the instrument rather than at a detached point. The subtlety of bugs furthermore suggests that for such data intensive, high-precision work it is simpler to just throw out spurious data rather than invest the effort of humans to document even more about the data's collection.

Magnus: Well, that's kind of fascinating 'cause it's gone up and down and things like that, and I think early on it was important because pe-, with people having sort of s-, you know, shifts, and they would take it and stuff like that, and seeing how the instrument would run, and I think it was important both in making sure we were getting good data and as a collaboration builder in terms of people feeling like they were part of the team.

Drew: Right.

Magnus: It's largely gone away as well. I mean the web page is there. [this conversation took place before the website broke down]

Drew: Right.

Magnus: 'Cause it, the instrument has gotten so robust at taking data on its own, it really is tedious. [Laughs]

Drew: Uh –

Magnus: Nobody ever really finds anything. The bugs that it, if it has problems, they're so bloody subtle that you don't find 'em until – but, uh, or most of the instrument just doesn't fall over. You ask it to take data. It takes data. (Magnus, interview)

Magnus's reflection that the EoRLive site and the on-duty astronomer practice originated both to ensure quality data and to build the collaboration as a coherent arrangement of individuals working on connected tasks illustrates multiple roles that this work served within the EoR Science Collaboration. The WRT Collaboration as a scientific instrument building project required the work and buy-in of stakeholders to build this instrument as a physical device, software for collecting data and managing this infrastructure's hardware components, and a diverse human infrastructure. Shifting into an operational phase and wielding the instrument to create the resource (observation data) useful for the particular scientific aims of the EoR Science

Collaboration—probing the early stages of the Universe—led to new cooperative work arrangements as the common fields of work shifted. One arrangement’s common field of work was the monitoring of data collection to produce metadata. This cooperative work arrangement needed to be fostered through the engagement of the members in this new shared work where the instrument is at least somewhat understood in its instantiated and operational state. In a relatively quick amount of time (six months to a year), however, the on-duty astronomer practice has broken down due to individual stakeholders not always acting as the on-duty astronomer and the EoRLive website actually ceasing to be available in a functioning form. The practice may have been designed to be simple to do yet has perhaps become “tedious” or a burden as the instrument simply functions as a point and forget device in the moment of data collection.

At this point though, now that the Radio group has EoR data collected they need to get it halfway around the world to the computing cluster they operate the US EoR pipeline on. This is again an activity that is designed to be automated, yet there is still cooperative work to be engaged in continually to successfully share this computing resource.

Shifting EoR data halfway across the globe to a local shared computing resource

Throughout my time with the Radio group I was constantly discussing or being shown work taking place on the US EoR group’s shared computing system. I refer to this system here as the “RadioCluster.” As a subset of the EoR Science Collaboration the US EoR group maintains a cloned archive of EoR observation data on this shared computing cluster here in the United States. This archive exists so that the members of the US EoR group have a locally available copy of the data. The RadioCluster is an integral component of the US EoR group’s infrastructure for conducting their research as Abner’s Munchy software in the US EoR pipeline is explicitly bound up with the configuration and operation of the RadioCluster. The US EoR

pipeline as the Radio group's primary infrastructural endeavor and the RadioCluster as a resource maintained in by part of the WRT Collaboration kernel are entangled through the ongoing work to produce data products as resources for EoR science.

The RadioCluster is a Linux-based computing system that can store petabytes of data. It is hosted by a university in the United States. Members of the US EoR group work on the cluster by using various remote desktop tools—software with both graphical and command line interfaces—to login and not only execute software they are using but also to work on developing various pieces of code and to produce plots. The RadioCluster is a resource for, and site where, cooperative work is conducted. It is a common field of work for the US EoR group to maintain (the product of the cooperative work here being a functioning shared computer system) that has become embedded in their routines while providing one local site where researchers from around the United States can exchange resources. Conversations among members of the Radio and US EoR groups, both informal discussions and those during teleconferences, regularly reference different locations of files on the RadioCluster as data analyses are carried out. Working as part of this cooperative work arrangement ends up requiring learning how this system works and understanding the conventions of practice this arrangement of researchers has socially constructed.

The RadioCluster is configured with a clone of the WRT Collaboration's EoR data and its relevant metadata. EoR Observations collected by the telescope are automatically copied from the WRT data archive (the Tier One archive) to the RadioCluster (a Tier Two archive). During my study this was functioning well enough that within an hour of a night's observations finishing the entirety of the night's data would have been copied to the RadioCluster. Copying this data to the United States from the southern hemisphere shifts it to a local location. Local here meaning

being in the same country and on the same continent as the US EoR group as opposed to on another continent separated by an ocean, thousands of miles, and subject to the latencies inherent in communications networks operating across such distances. Shifting contexts from the telescope and primary WRT Collaboration data archives to this local, US-based site really results in a shift in the infrastructural work being done as well. This is the point where I see my focus shift from the Radio group's work in the WRT Collaboration's kernel to that of producing data analysis software and as a result an infrastructure layered upon that of the WRT Collaboration.

The cloned raw observation data takes up significant amounts of storage space so it is automatically processed by the first stage of the US EoR pipeline, Munchy. Munchy is built by Abner, one of the PhD students, and through a series of bespoke scripts feeds EoR data to a piece of software developed by an individual elsewhere in the WRT Collaboration, FlagAvg. FlagAvg will algorithmically flag bad data and reduce the remainder through a series of mathematical operations. Folders upon folders of the raw data files are spread across the cluster, managed by the data archive software and Munchy processes them so that a new data product (UVFITS files in this case) is produced and the even larger raw files can be deleted (since they are always transferable from the WRT's Tier One archive again if needed). This is beginning the process of creating a variety of data products that the US EoR pipeline and the Radio group work with in their data analysis.

Working on the RadioCluster is necessary since the quantity of data typically being analyzed necessitates the use of an advanced computing resource and not just individual stakeholder's laptops or desktops since there is not enough memory or storage space on these devices (a single 2-minute reduced observation file that comes out of FlagAvg is many gigabytes and there is often not enough memory in such machines to process observations). Simple tests of

software being produced can be and are completed using single 2-minute observations, but anything truly computationally intensive takes place in the context of the RadioCluster as the Radio group continually reaches the point where new bugs or phenomena cannot be seen in small quantities of data. The RadioCluster as a resource in the US EoR group is vital to the different scientific investigations being conducted to analyze the data it stores.

Throughout my study the RadioCluster was a point of discussion among the US EoR group. Its ongoing configuration, operation and maintenance directly affects the completion of different research tasks within both the Radio group and the larger US EoR group. Ideally the RadioCluster would merge into the background for Abner, Nima, and the other members of the Radio and US EoR groups. In reality this does not entirely work out. Within the Radio group itself Abner and subsequently Nima were responsible for conducting much of the group's work on the cluster. These graduate students were responsible for running different jobs to complete various tests for other members of the group, completing tasks so that resources are created for Magnus, Brianna, Igor, and the Radio group as a whole to examine. Abner and Nima often do this work in conjunction with Darcy the post-doctoral researcher at another university since he is in charge of the RadioCluster's operation for the US EoR group. Managing the system and running analyses on it are both part of the cooperative work of sharing this finite computing resource. This is not always a frictionless process.

Implementing a sociotechnical solution to stem breakdowns of a finite resource

The RadioCluster is a shared resource among the entirety of the US EoR group. It is housed at one of the collaboration's member universities and as a result is physically maintained by an information technology (IT) group there. This in and of itself has been problematic for the US EoR group as they are dependent upon this IT group for fixing any hardware failures, responding

to major configuration changes, or even simply physically rebooting a device. Every time such a breakdown happens the US EoR group as a cooperative work arrangement needs to enroll an IT person to fix this system. Throughout my study I heard various expressions of grief about the need to do this but it was not a point that I inquired about extensively. Instead what came to the foreground for me was the actual operation and management of the RadioCluster as a computing resource by and for the US EoR group. The work of sharing this finite computing resource in and among this arrangement of researchers.

The operation, management, and ultimately sharing of the RadioCluster is the responsibility of the US EoR group itself. Allocating computing time and managing its use is an ongoing task for the members of the US EoR group. Sharing the finite amount of computing time available requires not only that every researcher be a considerate user of the machine but work with the rest of the cooperative work arrangement to negotiate how it is shared so that every individual's software can be successfully run as needed. A balancing act between different social and technical needs. The system is only so large and there is not funding to expand it significantly. It is finite.

Prior to January of 2014 the RadioCluster was simply available to members of the US EoR group as a resource that users could access by remotely logging in. Individuals could then execute different computing jobs by starting as many tasks as they desired. There was not yet a significant quantity of observation data to work with. The telescope only went into full operation during July 2013 so data analysis was not as intensive as it would be by the time I was spending time with the group in Winter of 2014. By 2014 due to the quantity of data being processed and the computational intensity of some tasks the free and open access approach easily and frequently brought the cluster to a halt, entirely freezing up particular nodes of the system. Abner

amusedly described how he and another researcher were sometimes crashing one of the computing nodes of the cluster, leading to an IT person having to bring the computer back online followed by a researcher restarting any tasks that were also running. When a crash occurred the US EoR group was dependent upon the IT staff physically managing the systems to reboot the affected machine. How long this took was entirely dependent on how long the request took to work its way to the appropriate people as various members of the Radio group explained. This was problematic since it would slow down the completion of data analysis tasks. The US EoR group therefore had to find a way to fix this problem and share the system efficiently and reliably.

Abner was the first individual to inform me of the group's effort to tackle this problem by installing Grid Scheduler/Grid Engine on the cluster computers (I will refer to Grid Engine alone since this is how group members discuss this software). At this point in time he was the member of the Radio group responsible for running tasks on the RadioCluster for everyone. Grid Engine is a piece of open source software for taking a user-provided list of tasks and ensuring they are executed across an array of computing hardware according to a set of user-defined rules (Open Grid Scheduler Project, N.d.). Grid Engine was presented within the US EoR group as a necessary addition to the RadioCluster's setup so that this limited computing resource could be managed with a negotiated set of rules rather than simply being provided for use as is without much governance.

The adoption of Grid Engine was a technical intervention that forced a shift in the conventions of practice for the members of the US EoR group, neither a purely social or purely technical solution but a sociotechnical solution in the management of this infrastructure (Bowker et al., 2010). Until this time members of the US EoR group could readily just login remotely and

run jobs. With Grid Engine installed the US EoR group had to develop a policy for the explicit allocation of RadioCluster computing time as a finite resource since this software is designed to allocate computing time based on particular codified rules.

Negotiating how to nicely share a computing cluster

During the February 28, 2014 US EoR teleconference the process for configuring the scheduler and resource allocations was an extended piece of the discussion, working to figure out how to manage and ameliorate these recurring breakdowns. This conversation in fact followed a brief discussion regarding the corruption of stored data due to a hardware fault (another breakdown of this infrastructural component in its own right). This was a moment of inversion of this infrastructural component by the US EoR group, opening up the black box of the resource to discuss its structure and flexibility and to negotiate new conventions of practice for sharing it.

The shift in operation to use Grid Engine required not only the technical configuration of the system with the agreed upon rules but also the reinforcement of the practice among the members of the collaboration by those adhering to the designed process. While attending this teleconference in February 2014 I noted how the post-doctoral researcher partially responsible for cluster management (Darcy) had to urge one of the other PhD students in the US EoR group (Josiah) to start running their work using Grid Engine rather than just logging into the system directly.

My field notes record that Darcy began the discussion by pointing out that most members had successfully shifted to using the Grid Engine scheduler to run their jobs over the preceding week. He then commented that they as a group now needed to figure out how to share nicely. Darcy had asked Josiah to begin using Grid Engine a few weeks prior but Josiah noted that at this point he was unable to successfully use the Grid Engine setup for his analysis tasks. Josiah

explained that his software requires a high amount of memory usage for a short period of time when it is run. This conflicts with the US EoR group's initial Grid Engine configuration where each user's job is allocated a particular amount of memory and processing power for a longer period of time. Josiah's software design and its operational characteristics are clashing with the initial social configuration of the system. To ensure that Josiah begins using Grid Engine and adhering to the collaboration's desired setup the attendees of this teleconference engage in a troubleshooting discussion to brainstorm potential changes to support both the group's and individual's needs.

This troubleshooting discussion began with Abner offering a suggestion by asking Josiah if he could perhaps split his code up so that it can be run in batches that use smaller amounts of memory. This would require that Josiah revise his software to hopefully better work within the Grid Engine scheme that has been setup. Darcy follows this suggestion by offering to create a special queue in Grid Engine that lets tasks think they have more memory available than they actually do, at least for a short period. He also notes that he has configured the system so that a user can only have 100 out of 300 possible slots available in the queue at a time in an attempt to prevent any one individual from monopolizing the resource. Darcy supports this configuration choice by noting that on another project's cluster that he works with the system is also configured to place a hard limit on the amount of time an individual user's jobs can be executing. The example Darcy offers illustrates that this choice is not just him and some of the members of the US EoR group being unreasonable. This tactic on the part of Darcy of appealing to his experience working on a different scientific project facing the same issue was interesting as part of this conversation since he, along with the other individuals active on this teleconference, were working hard to be tactful and politic towards Josiah's particular research needs. The

conversation continues for another five to ten minutes with potential solutions being raised and discussed among the different individuals present at the different sites around the United States who have called into the teleconference.

Overall, the tone throughout this discussion is that members across the US EoR group do not find Josiah's use of the RadioCluster to date to be very considerate, but they attempt to be diplomatic with various solutions. In the end, Darcy requests that for now that everyone please try to track how long their jobs take to run over the next week so that they can use this data to adjust the resource allocations in a few weeks as he is going to limit how long an individual user's jobs can run. Nima offers one final suggestion of perhaps creating a "debug" queue for testing since from her perspective this is how Grid Engine is designed to really be used.

The installation and initial configuration of Grid Engine puts in place a set of rules for sharing a finite computing resource among many different researchers within the US EoR group. GridEngine is flexible in its configuration options, yet requires the social negotiations of the different stakeholders using the system it runs on and manages. The US EoR group enrolled this outside software solution to help handle the ongoing use of their finite computing resource as one mechanism for handling a type of the inevitable breakdowns of their infrastructure.

Overall, the RadioCluster is a key component of the Widefield Radio Telescope project for both the Radio group and the US EoR group. It is a local site where they can operate and debug their various pieces of data analysis software that turns into a common field of work when the arrangement of individuals has to determine how to keep it operational. As a resource the RadioCluster is a system where technical and social concerns co-exist, shaping each other as the different stakeholders negotiate how to share and use this resource for their different particular group's research goals. The RadioCluster requires continual care by the US EoR group in the

face of breakdowns. For some members, however, it is able to somewhat fade into the background as just another component of their working environment. It is simply part of the infrastructure for conducting their work. It is the WRT resources available on the RadioCluster that these individuals are primarily focused on, the EoR observation data captured in various data products. Data products are the threads connecting the infrastructure of the WRT Collaboration to that of the Radio group's data analysis software and their software to that of the LivePipeline elsewhere in the International EoR group.

Data products as a thread between multiple cosmology infrastructures

I have now examined the WRT Collaboration as a research infrastructure and begun to examine points where the Radio group's US EoR pipeline is connected to this underlying layer. Data products are the thread I see connecting the three layers of cosmology infrastructures investigated throughout this dissertation. The different cooperative work arrangements of the EoR Science Collaboration create and share data products as coordinative artifacts among their different infrastructural components. Data products entangle the instrument, the work of using it to produce data, the radio observatory underlying the instrument, and approaches to data analysis in a digital artifact that is easily transferrable between contexts. They are resources in an infrastructure's cache that the kernel will have to address for investigators wishing to ask specific scientific questions. Tracing data products in the Radio group's software production helps to surface the connections among the multiple infrastructures they are creating and working with as well as to examine the cooperative work they engage in doing science.

The notion of referring to the outputs of research work as data products is common yet curiously they are not defined when discussed. My exposure to the term came from an interview with Igor and over time I discovered that it appears throughout papers published by the WRT

Collaboration as well as other cosmology researchers. Documents produced by NASA commonly use the term —*but interestingly do not define*—to frame the datasets that they provide to researchers from satellite sensor systems (Borgman, 2007; National Aeronautics and Space Administration (NASA), 2011). These are often satellite datasets for climate science that inform different model or reanalysis products (Edwards, 2010). Through my study I came to see how data products serve many roles. They capture the states of the instrument and ensuing scientific analysis while serving as coordinative artifacts among the different researchers in the Radio group and EoR Science Collaboration. They are a thread between the different infrastructural components that the Radio group works with and creates.

Data products, in particular intermediate versions, are central outputs of this ongoing scientific work. They provide a tangible, traceable partial record of the data processing and analysis being completed. Following the software and data products of the Radio group for example enables me to follow the translation of their raw telescope observation data into an output that expresses their scientific approach and knowledge. In my earlier work examining the Radio group I defined the terms data products and intermediate data products as the notion's prominence was apparent in my data (Paine & Lee, 2014). I defined data products as “the datasets that are the output of instruments or of executions of the processing and analysis infrastructure being created” within a research group's work. Intermediate data products in turn were defined to refer to “data outputs that have been processed by a stage of a pipeline that must be further processed to be useful to the scientific goal” (p.1). These definitions apply here in this dissertation but I explain four facets to these artifacts that help to further characterize the notion.

I defined these two terms earlier in this prior publication as part of an early analysis of the Radio group's software development to emphasize the “living and in-process nature of these

artifacts as products of the research process” in contrast to the impression afforded by existing scholarship that the term dataset implies a finished artifact that is “less subject to the vagaries of an emerging and evolving” research infrastructure. Here I can lay out seven types of data products created or used by the US EoR pipeline, all of which in the practices of the Radio group’s cooperative work are coordinative artifacts (Schmidt & Wagner, 2004) that thread and link together multiple infrastructural components continually.

Seven data products produced by the Radio group

Through my analysis I can define and trace out seven different data products in the Radio group’s data analysis software. The seven data products surface points of coordination between different components of the US EoR pipeline, the members of the Radio group, and even the LivePipeline produced by the EoR Science Collaboration. By tracing data products and their myriad intermediate versions, I am able to examine how these outputs are designed, produced, changed, and ultimately shared as part of an on-going and reproducible research practice. Intermediate data products in particular enable me to follow science in the making (Latour, 1987), providing a window into the states of the analysis at singular points in time.

In my earlier paper defining data products (Paine & Lee, 2014) I identified three data products in the Radio group’s US EoR pipeline: 1) UVFITS files, 2) IDL Save files, and 3) plots. Subsequently in my third data collection episode I asked members of the Radio group what were the data products in their work when working through the diagram I constructed of their software—see Chapter Three. I knew by this point that there were many different types of data products in their work, and that the term is one used in in their work. However, I was not fully aware of the variety of products across the entire pipeline. I also did not yet quite understand that plots were not a data product in and of themselves, or that IDL Save files are just a file format

for storing certain data products. Rather, plots are visual representations of the various data products, a human interpretable form of these complex artifacts that enables them to become physical materials that can be cooperatively studied—see Chapter Seven.

Out of my discussions the variety of data products that emerge as outputs of the US EoR pipeline were made clear to me. Briefly the different types of data products include: 1) FITS and UVFITS files, 2) an Intermediate Calibration Product, 3) a Telescope Beam Model 4) HEALPix Cubes, 5) Calibrated Visibilities, 6) Model Visibilities, and 7) a Sky Catalog. FITS or UVFITS data products are the starting output from the Widefield Radio Telescope that the US EoR pipeline will take in. HEALPix Cubes are the data product that is exchanged between Igor's CalibratorImager pipeline and Brianna's ImgPower pipeline. Calibrated and Model Visibilities will be exchange between CalibratorImager and components of the LivePipeline per the design mandate of the EoR Science Collaboration to share outputs between their two official data analysis pipelines. All seven data products capture some socially constructed facet to the WRT, the data analysis software, and natural phenomena. Data products for me are a way to see how data and knowledge is transferred and translated through and among different pieces of software and different cooperative work arrangements.

The definition of data products in my prior publication is broad, intentionally so at the time as the notion was only just emerging in my data. Through further data collection and analysis, I came to understand that there are four key tangible aspects to data products in the Radio group's work that I studied. These facets illustrate what the concept is to the Radio group in their work, and after I explain them I can discuss how I see data products as coordinative artifacts supporting cooperative work across infrastructures. These four facets illustrate the ways data products support the Radio group's enactment of infrastructures by producing data analysis software:

- Information that is written to some form of storage
- Realizations of the data from a telescope and of the data analysis software
- A mechanism for marketing an instrument and data analysis approach to members of the cosmology community
- A mechanism for extending the self-documentation of the instrument to also self-document aspects of a group's data analysis

The information that is written to a storage disc

First, for the Radio group data products at their simplest are “anything one writes to disk” as Magnus and others summarized the notion. Data products are the inscriptions created through the chain of telescope hardware and its archive systems that end up being shared and moved around the different cooperative work arrangements of the WRT project as resources. In the Radio group's work these objects can be anything from the initial, raw data output and stored in UVFITS files by the telescope infrastructure to the fully processed and analyzable HEALPix cubes of data output at the end of the US EoR pipeline. The degree to which a data product has been processed influences its utility to different pieces of software and the state of the data analysis at that point. Raw data products are not yet analyzed. The HEALPix cubes produced by the end of the ImgPower pipeline are at the end point of the Radio group's analysis.

Data products are stored in a variety of file formats on different computing systems. File formats are standardized storage mechanisms for storing data, such as FITS, UVFITS or IDL Save files in the US EoR pipeline. Data products in the Radio group's work are frequently associated with file formats (FITS or UVFITS) or data representation schemes (HEALPix cubes) but the format alone is not the data product in this work. It is the combination of the data and the specific use of the file format as part of a piece of data analysis software that creates a data product in the Radio group's infrastructure work. As a result, the manner in which data products are stored in different file formats can vary. Understanding these variations becomes necessary

knowledge for an individual to work within these multiple infrastructures. The conventions of practice regarding the use of a data product's file format must be shared.

For example, I described in Paine and Lee (2014) how Igor readily noted that FITS is a standardized file format in astronomy—McCray (2004, 2014) details its origins—and UVFITS is “something that people hacked to make it kind of work” for a different type of data. This social constructed, hacked use is necessary because FITS (Flexible Image Transport System)²⁶ is an image-oriented file format. UVFITS in contrast is storing uv plane visibilities—where the uv plane is the mathematical space of the data that is different from the image plane's X and Y coordinates. They are composed in an entirely different mathematical manner requiring data be inserted into this format in a common, community known and socially constructed manner that is nonetheless not an official standard. Documentation for CASA, a general purpose radio astronomy analysis package produced by the National Radio Astronomy Observatory, notes “the UVFITS format is not exactly a standard, but is a popular archive and transport format nonetheless” (National Radio Astronomy Observatory, 2010b).

Files formats are a mechanism for storing data products in structures that are readily readable and shareable among different pieces of software so long as the software supports their interchange using conventions of practice that are shared but perhaps not formally standardized. Data products being the inscription that is written to disc means that the Radio group has a mechanism for sharing their data among the different cooperative work arrangements of the WRT project. They become an artifact to be shared in the course of enacting infrastructures and cooperatively analyzing data.

²⁶ See <http://fits.gsfc.nasa.gov/> for details.

Enacting a realization of the entangled data and software

Second, data products by design are points of coordination and exchange of data between different pieces of software that are a realization or encapsulation of the scientific analysis at that point in time. Magnus emphasized that data products are a “realization of the data” and/or a “realization of the software” at particular points in time. I do not see these as separable issues, data and software are always intertwined in this work from the point at which an analog signal is converted to a digital signal in the WRT. Magnus commented that data products serve as “a transition between one piece of the system and another. It’s an ICD [interface control document].” Data products are first an abstract concept for what information should be interchanged that in practice then become the particular instantiation of actual collected and processed data.

As the design of the data analysis software changes Magnus points out the “strongly iterative boundary” of what is put into data products in their analysis. This occurs since over time the group learns what information needs to be exchanged among pieces of the analysis that they were not necessarily aware of up front. Up front the design of data products is not an entirely simple or readily apparent process. This strongly iterative boundary, between what is put into a data product and what the researchers discover needs to be in the data products, foregrounds the necessity of understanding that it is the countless intermediate versions produced by the group as they engage in their scientific analysis that are important to trace among the different arrangements of individuals and software doing work among these multiple infrastructures.

I witnessed this iterative boundary change within the Radio group at the interchange between CalibratorImager and ImgPower. Originally, Igor was processing data and creating image HEALPix cubes, weights cubes, and a variance cube to pass to Brianna’s ImgPower

pipeline. Internally Igor was creating Dirty, Model, and Residual image cubes that each encapsulate different aspects of the data and points in CalibratorImager's processing but he was only outputting one of the three image cubes into a data product for ImgPower to use since her software can work with just one. Through their unfolding analysis work the group realized that having Igor pass all three image cubes plus the weights and variance cubes (i.e. giving Brianna's software more aspects of the data and analysis to work with) was beneficial to their software debugging. The boundary of what was being shared shifted as the group collectively realized the benefits of sharing more of the information that is in the software analysis that can be put into the data products easily.

Magnus also notes that the data products being realizations of the data and software in turn leads to "the lovely situation of the same data has been sent through two different versions of the analysis [software] to create two data products." Externally the two data products appear to be the same but if they are opened up and peered into these scientists can see that because they were produced by different versions of the software they are now different inscriptions. If data product A is sent through versions X and Y of the US EoR pipeline, then the data products output could be labeled A.X and A.Y. If versions X and Y of the software are different implementations of even just part of one algorithm the resulting data products are not the same even though they started with the same product and are attempting to do the same analysis. The change in implementation of the software's algorithm changes the data analysis. This would be common as the Radio group identifies and fixes bugs and comparing versions A.X and A.Y through visualization in plots is a frequent task. Data products are therefore inherently an entanglement of some phenomena inscribed by an instrument at a particular point in time and space with that of software from another time and place.

Marketing an instrument and data analysis approach

Third, data products are a way of demonstrating the array of functionality and quality of the data analysis software, both to the Radio group and to other researchers. This is done through their visualization in plots. Data products are a way of enrolling stakeholders from outside the Radio group to their approach to data analysis. Plots visualizing data products are human interpretable representations that can serve as “marketing” in Igor’s words. He emphasizes that illustrating the different types of data products created by their software is a way “to convey that we know what we’re talking about” to researchers inside and outside of the WRT Collaboration.

For example, one of Igor’s presentations at the primary American Astronomy conference had an entire slide devoted to foregrounding CalibratorImager’s different data products to convey the complexity of his analysis software to the community. Abner described this to me by noting that what the group “found is that it’s really hard to convince people that we have a lot of data products. They tend to think that we have like one thing that comes out, but we really have all of this different stuff.” Explaining what data products are produced when using the Radio group’s data analysis software is part of demonstrating the functionality and utility of this software to researchers outside of the WRT Collaboration’s cooperative work arrangements. A researcher outside of the EoR Science Collaboration may be interested in CalibratorImager’s Sky Catalog data product but may not be interested in the imaged data stored in HEALPix cubes. Conveying the variety of data products to the larger cosmology research community illustrates the scale of the WRT project and in particular the Radio group’s approach to this type of scientific work. Doing this is part of the group’s work to translate their approach to different contexts by enrolling allies (Latour, 1987) in their field to their methodological approach.

Extending the self-documenting notion and enfolding history of the analysis

Finally, a fourth facet of data products is their role in storing and extending telescope metadata. The data products do this by capturing their own metadata or header information that characterizes and contextualizes the observation data within. Earlier in this chapter I explained how the WRT Collaboration designed the telescope to be self-documenting, storing all of the operational characteristics and performance data (e.g., the temperatures during observations, what antenna tiles were or were not working, and so on). All of this information about the actual observation data needs to be stored in the data product and accessible to any researcher who may try to use the data product at a later point in time. Without this information the data is like the bags of blood missing labels about its production that Ribes (2014) describes. Scientifically it is not useful.

Since a data product is produced using a particular version of the software, which may implement particular algorithms in different ways, it is important for the Radio group's data analysis process that the version of the software and data is recorded and accessible for inspection at a later time. Igor and Brianna both keep their software's code in GitHub²⁷ version control repositories. GitHub provides a unique identifier known as a hash for every piece of code and change stored in the repository. The data products created by the US EoR pipeline end up including this GitHub version hash to help document what version of the software produced this resource. This enables the members of the Radio group to go back and interrogate the particular version of the software should some sort of bug be found.

Taking metadata from the self-documentation that the Widefield Radio Telescope creates as an instrument, and embedding and extending it with information about the data analysis

²⁷ <https://github.com/>

software, and storing all of this information in data products is part of how the Radio group's software becomes self-documenting as well. Storing this information as part of producing their own data analysis infrastructure helps the Radio group sustain it by ensuring resources they create are scientifically usable. Self-documenting is part of the addressing work of the different infrastructure kernels I see in the Radio group's work.

Data products supporting coordination among infrastructural components

In this dissertation data products are the threads among the various infrastructural components in the Radio group's work that encapsulate their data. For the production of knowledge, data products encapsulate telescope observations and provide a mechanism for using and sharing these inscriptions among different pieces of software. Within the Radio group and among their different cooperative work arrangements in the EoR Science Collaboration data products are a coordinative artifact, material artifacts that are central to coordinative practices and cooperative work (Schmidt & Wagner, 2002). Data products enable the different stakeholders in the Radio group, US EoR group, and EoR Science Collaboration to exchange data in the process of being analyzed and transfer their different research practices across contexts.

Data products fulfill a variety of roles simultaneously in the Radio group's work through the four facets I just discussed. In Chapter Four I described how the LivePipeline and the US EoR pipeline were designed to exchange data products from various points in their respective analyses. Data products are intentionally meant to be passed through the boundaries of these different infrastructures, exchanging and mixing the two approaches to data analysis each represents. As objects to be designed data products specify what information is to be included and how they should be structured, at least within the conventions of practice in the cooperative work arrangement that is the EoR Science Collaboration. When the Radio group or the EoR

Science Collaboration chooses to share EoR data publicly it will be in some form of data product (although exactly what form was unclear to the members of the group when I asked and there is the question of whether there's any utility in this if I recall Magnus's point that the data is useless to most researchers).

In practice I find that most data products in the Radio group's work meet my definition of intermediate data products. The various outputs of the US EoR pipeline often need to be further processed for analysis through more stages of the software. It is only when examining who is using a data product and why they are using it that the question of whether the data product needs to be further processed to be scientifically useful is answerable. `ImgPower` and `CalibratorImager` are designed to regularly output intermediate data products. A data product saved in the middle of executing Igor's `CalibratorImager` software would be an intermediate version. It can be called up and used in a later execution of `CalibratorImager` but it is not yet analyzable in Brianna's `ImgPower` software. Saving intermediate data products is done for a few reasons. First off having these intermediate outputs enables an individual to interrogate how particular elements of the software transformed the data. The data can be interrogated throughout many different stages, it is not entirely black boxed by design as is visible in Figure 13. Second, from a practical standpoint computational time on the `RadioCluster` is limited and having intermediate data products output saves time while debugging the software.

The real utility of intermediate data products is in saving the state of analysis at some point in these software pipelines to reduce the amount of future computational time needed by an individual when analyzing some element in this work. If an intermediately processed data product is available and meets a researcher's needs they can simply call upon it instead of starting from some rawer product and expending time to get to a product useful to their analysis.

This comes to the forefront in the Radio group's continual software testing work. In *ImgPower* one operation takes hours to complete while others only take minutes. Brianna therefore saves intermediate data products after that computationally intensive operation and uses them when testing and debugging mathematical operations that follow in her pipeline. Producing intermediate data products throughout *CalibratorImager* and *ImgPower* allows a member of the Radio group or US EoR group to not only save computation time but really to iterate on different pieces of the software's implementation while holding some elements of the analysis static for the time being. The debugging and analysis work relies upon and transforms a variety of these intermediate products as different tests are conducted and *CalibratorImager* or *ImgPower* undergo rewrites of their code.

My definition of data products and intermediate data products is intentionally bound up with the software (and underlying instruments) that uses and produces these artifacts. Borgman (2007) also notes the intertwining of data with software, hardware, and knowledge. She comments that separating data from software is difficult and that the ability to trace the creation and transformation of pieces of data requires understanding the instrumentation involved.

Data are difficult to separate from the software, equipment, documentation, and knowledge required to use them. For example, if data are produced by an instrument such as a sensor network, interpreting those data requires an understanding of the instrument—for example, what do the sensors detect, under what conditions, at what frequency of observation, and with what type of calibration? Similarly, a data set may be uninterpretable without the software used to create or analyze it (and perhaps the same version or release of that software). (Borgman, 2007, p. 183)

The data products in the Radio group affirm and bolster Borgman's point that data are often "uninterpretable without the software used to create or analyze it" since these artifacts in the Radio group's work are very much encapsulations of the different versions of software used to produce them. Intermediate data products output by *CalibratorImager* or *ImgPower* not only

encapsulate some data captured with the Widefield Radio Telescope but also the state of Igor or Brianna's software.

Fundamentally the Radio group's software and data products are entangled representations of the different evolving states of their scientific understanding of the operation of the Widefield Radio Telescope, the radio signal they are probing, and their current scientific goals. They are threads connecting the different components of the US EoR pipeline software to each other, to the WRT Collaboration's infrastructure with an instrument and archives, and to the radio observatory with its radio quiet environment in the skies above.

Summary

The process of collecting and producing Epoch of Reionization data with the Widefield Radio Telescope conveyed during my discussions with members of the Radio group comes across as not altogether that complex. After all, much of the telescope's operation is automated and "point and forget." Yet how the telescope operates while data is collected is quite important since the characteristics of that operation will be permanently inscribed in the observations that are encapsulated in data products. The telescope's characteristics that result from its socially constructed design and operation are why these individuals as scientists must feel the instrument in their bones in the first place.

The WRT's ControlMonitor software and data archives are how this set of hardware devices out in the desert transform into a scientific instrument in action. This telescope is what McCray (2004) would describe as a "hyper-telescope," geographically and temporally distributed but connected through digital telecommunications systems, but is from my CSCW perspective a research infrastructure. The software shapes and configures this instrument so that it is a chain of devices able to capture the sought after radio signal from the sky. Brianna and

other WRT members who built ControlMonitor's myriad components formed a cooperative work arrangement that itself was part of the larger WRT Builders group. They wrote this software around a central database since this affords flexibility to their volunteer work building different infrastructural components. Researchers need incentives to make completing tasks that benefit the collaboration worth their time and effort (Howison & Herbsleb, 2011). The design flexibility the WRT Builders group exhibited provides different members of the cooperative work arrangement with the opportunity to contribute to the infrastructure. These contributions take place in a situation where individuals are not directly funded to complete these tasks and flexibility helps motivate them to do so, for example by letting them advance their personal research goals.

The cooperative work of the WRT Collaboration spans multiple continents, time zones, universities, and research practices. This distributed, global collaboration and its policies (discussed in Chapter Four) create the sociotechnical context for how this novel interferometric instrument was built and is now used. The on-duty astronomer practice and EoRLive website helped to reduce this span within the EoR Science Collaboration yet they have broken down over time since the value of what an individual could observe about the infrastructure through its monitoring systems did not exceed the amount of time that must be invested in the work. Magnus describes the operational telescope as "point and forget" where you can ask it to "take data" and it will do so. At the same time, he emphasizes that for any instrument there is a period of time where it must be "dialed in" to "have it be reliable, and you never know how reliable it's going to get." The EoR Science Collaboration's dialing in of the instrument to the point where it can become just a tool for use rather than an object of design and construction makes visible an inflection point in this cooperative work. The telescope began to become embedded in these

scholar's research as they shifted to analyzing the material it is used to create. The Radio group's efforts shifted to directly working on their data analysis software primarily.

Once the instrument is dialed in the kernel of the WRT must maintain that state and ensure that the resources created, in this case data products, continue to be useful to the different Science Collaborations. This is in large part a fairly simple task since the components of the infrastructure were designed to self-document. Capturing all of the operational parameters during observations and storing this in conjunction with the captured radio signals produces a material with which to ask scientific questions. I see this notion extending from the telescope's management and control systems into the data products created and used by the Radio group. Their data products encapsulate metadata about the data analysis software and the self-documentation from the instrument. This accretion of information into the data products ensures that these objects can be opened up and examined if necessary. So long as the resources of the kernel are designed this way I see the addressing work that the Radio group or their collaborators have to engage in being simplified. They can shift their efforts to using these materials in the enactment of their own infrastructure as they produce their software.

The RadioCluster archive of EoR data in the United States further brings the remote and distributed instrument into the local context of the US EoR group. This system becomes the computational site where work is done day-to-day since the data stored here is what will be processed and analyzed in the Radio group and their colleague's work. It is a finite resource subject to breakdowns, both social and technical. To be able to use this resource the US EoR group must cooperate to prescribe how it is to be shared. These rules shape how the software being produced by different individuals can function. Josiah's software is an example of a disconnect between the configuration of the RadioCluster's Grid Engine management software

and the analysis approach of one member of this cooperative work arrangement. Furthermore, Abner's Munchy software is wedded to this computing cluster and the configuration the US EoR group has created. This begins to demonstrate how components of two the WRT and US EoR pipeline infrastructures are tangled up with each other, something I will continue to examine in the remaining chapters.

Finally, the example of the on-duty astronomer idea illustrates a case of addressing work that was created in the WRT's kernel then relatively quickly shed as it was decided the instrument functions reliably. Ribes (2014) notes that there are always actors in an infrastructure's kernel tasked with shedding features. In the case of the on-duty astronomer practice it has been shed from the kernel in practice but seemingly not by willful action. Instead it was inaction and a lack of maintenance by the cooperative work arrangement on either the resource (EoRLive website and logs) or themselves as a collective since the activity just dissolved. In future work it would be interesting to probe this further. Was there a formal discussion about dissolving the practice even though it remains in the EoR Science Collaboration's policies and the database of metadata produced is out there on some computing system waiting to be accessed again? On further reflection it is also possible to ask if the vast quantities of data that the EoR Science Collaboration is collecting obviates the necessity of rigorously monitoring all observations since data can be thrown out if it is found to be bad down the road during data analysis. Perhaps this practice was shed in part because if data is lost more could presumably just be collected. In my time with the Radio group they were not yet to the point of using even the entire first semester's collection of data. When working with big data it is worth asking how much does actually need to be sustained by a research infrastructure over time.

The telescope itself is seemingly fading into the background of this work, yet as I will show in the next two chapters continually thrusts back into view during data analysis. The Radio group's cooperative production of software to analyze EoR data is an ongoing process of poking and prodding the instrument and the data it inscribes, unearthing and interrogating the "bloody subtle" effects that are perpetually living within. This cooperative work is a fascinating and exciting dialogue between these scientists, software, the data, and of course this interferometric telescope that is mediated through the software being produced.

VI. Producing Software as Scientific Practice

I felt that there lay open before him—before me, had not habit made me a prisoner—all the routes in space, in life itself; he flew on, let himself glide for a few moments over the sea, then quickly making up his mind, seeming to yield to some attraction that was the reverse of gravity, as though returning to his native element, with a slight adjustment of his golden wings he headed straight up into the sky. — Sodom and Gomorrah, Marcel Proust

Introduction

I witnessed the Radio group laboring over their high-precision data analysis software, the US EoR pipeline, throughout my multiple episodes of data collection. Their work figuring out what paths this pipeline should provide (and take in operation) requires continual care and reflection. I've discussed aspects of the Radio group's work contributing to the WRT project and how they and the EoR Science Collaboration collect data to study the Epoch of Reionization. This chapter shifts the focus of this dissertation to the US EoR pipeline. This is the top layer of the multiple infrastructures that the Radio group creates and works with, see Figure 16.

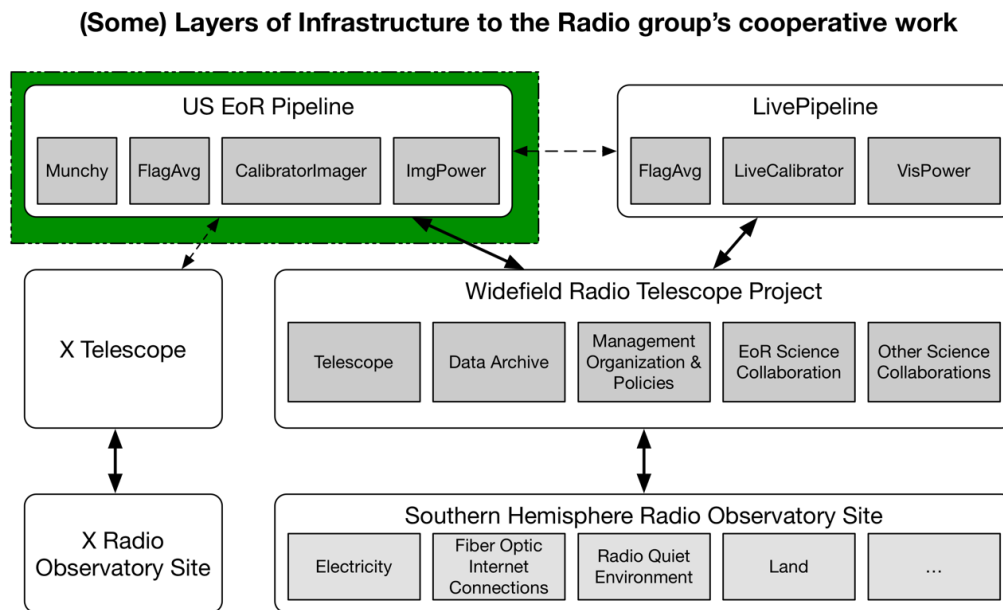


Figure 16. Infrastructure examined in Chapter Six.

This is the Radio group's software, the US EoR pipeline. The focus of this chapter is on this top layer but it is not possible to ignore the underlying layers of infrastructure in this work.

The software being produced by Abner, Brianna, Igor, Peg, and Nima is the medium through which this group's approach to a high-precision scientific analysis is expressed and how they are enacting a new knowledge infrastructure. It is their work of creating the complex, multifaceted, mutable set of relations Kitchin and Dodge (2011) describe. Characterizing software production as an expression of science practice is a shift in understanding how scientists produce software and infrastructure in their cooperative work from prior STS and CSCW studies. For the Radio group their research practice producing software is not only about creating a pipeline for analyzing data. Software is the material that enables them to ask and understand scientific questions that they care about as the pipeline entangles different layers of infrastructure together in their day-to-day work. They are learning how to ask the questions necessary to better understand the Epoch of Reionization, interferometric telescopes, and their own scientific method. Producing software is how Magnus, Brianna, Igor, Abner, Peg, and Nima create chains of relations that can extend among different contexts and scientific problems over time, embedding their conventions of practice into a resource that they will have to sustain over time.

Central to understanding how software expresses their scientific method is the inseparability of this software and data—and as a consequence the telescope as an amalgamation of hardware, software, and practices—emerged as a recurring and central theme in my own data. I find that the software work of the group unfolds as part of a complex dialogue between these researchers, their data products, their scientific theory, the Widefield Radio Telescope infrastructure, and their globally distributed collaborators. Successfully doing this requires that they work among multiple layers of infrastructure and figure out how to interrogate and disentangle the effects particular components have on the emergent whole. Data products connect and encapsulate information about each of these infrastructures, they are a thread

between them. Producing this software requires that the Radio group invert multiple infrastructures and open endless black boxes as questions change and issues arise.

Cooperatively producing new infrastructural software components

The Radio group is producing multiple pieces of software that all together take interferometric data, image and synthesize it, and create power spectrum as a way to measure the power or intensity of the sought out EoR signal. Producing and using this software is how the Radio group is enacting and sustaining an infrastructure for doing high-precision cosmology data analyses. As I noted in Chapters One and Four I call this the US EoR pipeline, see Figure 17 for an overview.

During my study the US EoR pipeline was the product of Abner creating Munchy, Igor building CalibratorImager, and Brianna developing ImgPower. Peg, a PhD student in the group, produces a separate set of software to create new Sky Catalog data products for use in CalibratorImager. Doing so she relies upon Munchy and CalibratorImager to produce data products for her work. Nima, a new PhD student towards the end of my data collection, was tasked with improving facets of CalibratorImager's approach to calibrating data. Collectively these different interconnected components and approach to data analysis are a common field of work for this arrangement of individuals as they work to enact a stable approach to analyzing data. In addition, elsewhere in the US EoR group other PhD students and researchers came to rely upon the US EoR pipeline as they conducted their own research. One PhD student was creating their own approach to producing power spectrum while relying upon data products output by CalibratorImager to be able to do their research.

The various software components each of these individuals is responsible for together enact a knowledge infrastructure within the Radio group, and for their US EoR group collaborators, with different elements becoming embedded in the routines of daily work for some

individuals while simultaneously being the object of work for others. I witnessed how their infrastructure is being enacted through software, using the materials created and sustained by the WRT infrastructure, primarily data products, and the RadioCluster. The US EoR pipeline works with the different data products stored on the RadioCluster, the computational site where all of these individuals operate their software (discussed in Chapter Five). Within the EoR Science Collaboration the US EoR pipeline is one of two official data analysis pipelines along with the LivePipeline (as I explained in Chapter Four).

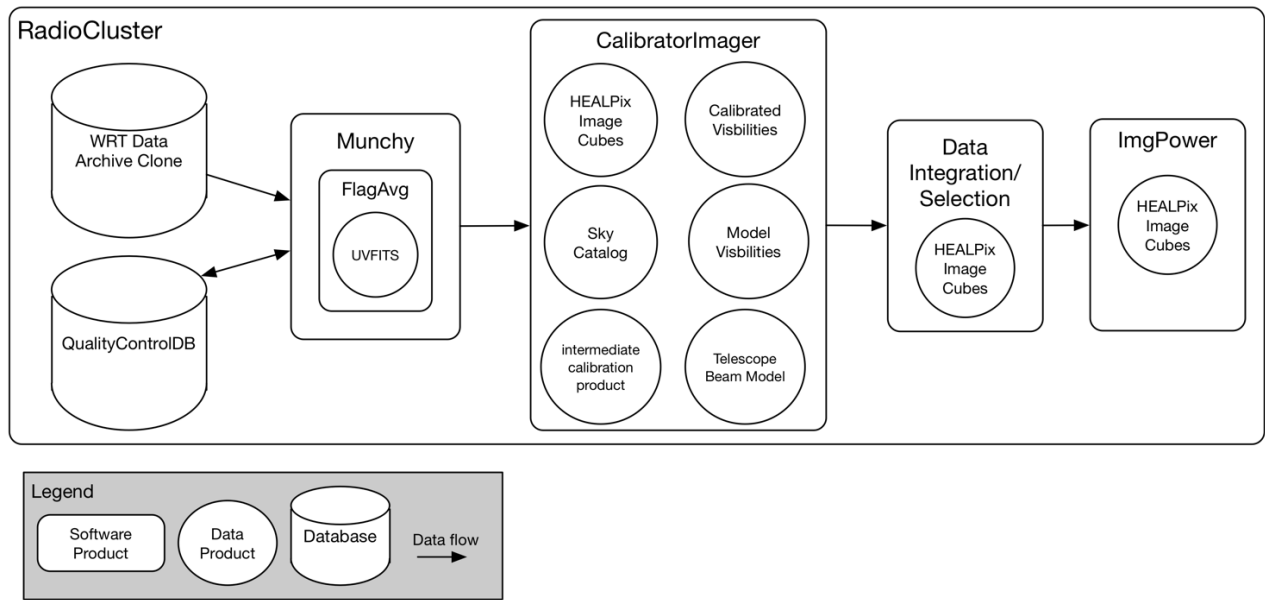


Figure 17. Abstraction of the US EoR pipeline components. In this simplification data flows left to right from raw to a fully processed state. Munchy, CalibratorImager, and ImgPower are the primary components. The Data Integration/Selection step is distinct but exists in a space between CalibratorImager and ImgPower, a point where a human must manually determine what data they wish to integrate together for the creation of power spectrum.

If I were still focused on the work of the WRT’s kernel the Radio group’s software production would fall outside of the scope of inquiry as it is an investigation using the resources of the infrastructure. Instead I have to shift perspectives and move up a layer to a different infrastructure. Focusing on this top layer, the cooperative work of the Radio group is creating the resources they will have to sustain over time. They are creating a separate, but entangled kernel

and cache with its own resources. The investigations using these resources to make new claims about the EoR were only just beginning as I completed my own study. Successfully doing this requires working among multiple infrastructures to address multiple scientific goals, navigating among the different embedded relations and practices.

Working among multiple infrastructures and multiple scientific goals

The Radio group's production of software has unfolded in concert with their work designing, building, and now operating the WRT as a research infrastructure. Each infrastructure's history is entangled with the other when I examine the work Magnus, Brianna, Igor, Abner, Peg, and Nima engage in. They have purpose-built the US EoR pipeline to take Widefield Radio Telescope data and conduct a high-precision analysis to produce power spectrum. This is the underlying motivation driving the extensive work on all of their software, and yet there are many other scientific goals and contributions emerging from this cooperative work.

The primary goal in the Radio group's work, along with the work of the EoR Science Collaboration and WRT Collaboration overall, is to produce power spectrum of the 21-cm EoR signal. Power spectrum are a statistical measurement of the amount power in a signal over different frequencies. Abner's dissertation emphasizes that the expected brightness or power of the 21-cm Epoch of Reionization signal is extremely faint, especially when compared to the thermal noise that is the background throughout the sky. Instruments like the WRT don't yet have the fidelity to produce maps outlining the structure of this phenomenon throughout the Universe and therefore can only produce an averaged statistical measurement. Once more powerful telescopes are built the driving idea is to be able to map out and probe the structure of reionizing Hydrogen gas in the Universe during this distant period of time. For now, though, this

is not possible so an improved statistical measurement is being sought out. This is why the power spectrum is the primary end product for Magnus and the Radio group.

A second significant scientific output of the US EoR pipeline can be a catalog of different sources in the sky (e.g., galaxies). The area of the sky that the WRT is pointed at is not well studied in the frequencies this instrument captures its data. Peg's use of data products produced by CalibratorImager is key to her work producing software that can create an improved catalog of sources in the sky. As a scientific contribution Peg's work not only helps to improve the US EoR pipeline (by feeding a new catalog in) but also by helping cosmologists better understand the area of the Universe that the WRT is looking at. She relies upon the software produced by the other members of the group to be stable so as to be able to focus on her own research goals. CalibratorImager is part of the infrastructure of doing her science as part of this group.

Finally, working on the US EoR pipeline also creates scientific knowledge about the operational state and functionality of both the telescope as an instrument and the pipeline software itself as an approach and scientific method for doing data analysis. This knowledge is that which is created as the group develops a feeling of the instrument in their bones. All of this information is scientifically useful for assessing the design of this telescope and potentially informing future interferometric telescopes. Understanding how physical hardware design decisions (such as the selection of six lengths of cable to connect antennas and receivers or how frequency channels are selected and filtered, as I noted in Chapter Four) unfolds in the implementation and use of data analysis software provides the Radio group and the WRT Collaboration with opportunities for learning how to improve future scientific instruments. To cooperatively work on each of these scientific goals the Radio group produces the US EoR pipeline software in parallel with their ongoing efforts as part of the WRT infrastructure kernel.

Expressing an approach to high-precision scientific data analysis through software

The production of the Radio group's software is not just the creation and use of a simple tool along the way to later analysis work. Rather, the ongoing, iterative production and use of this pipeline is how the Radio group is able to go from an abstract "model of the instrument" as an idealized device to "translate data into a model of the science" that enables them to better understand the Epoch of Reionization as Magnus opined. The software of the US EoR pipeline as a complex, changing expression of the group's knowledge is "the translator" and means of enacting their scientific method because "the data is a realization [of nature]. The other two [models of the instrument and science] are kind of abstract ideas, but you actually saw the sky on Tuesday" (Magnus, interview). Magnus and his group are taking inscriptions or tracings of nature and making them into investigable objects through their production of software.

Part of why this is fascinating is how mutable software is. The Radio group can iterate on and on looking for problems, fixing bugs, and re-evaluating how their scientific methods operate as they work with different amounts of data and an instrument that they grasp better and better. This takes place across varying temporal scales, separated from the in-the-moment work of the telescope collecting data yet extending this point in time infinitely as they work with and revisit particular observations trying to better understand what was in the sky that night. Yet through this work the Radio group still maintains a rigorous and reproducible scientific practice with this mutability and temporal flexibility, in part because they can capture and trace many details and changes perpetually so long as they craft these systems to be self-documenting (as the telescope was designed to be) and imbue their data products with the metadata necessary to let them trace the chains of relations between their software, the telescope, and data.

Igor and Brianna store CalibratorImager and ImgPower’s code in a publicly available GitHub version control repository. This enables traceability since every version of the software stored here is able to be explored and tracked since a unique record is associated with what is known as a Git hash. The Radio group over time has grown to take advantage of this GitHub functionality by incorporating the unique hash of a version of the software in the data products and printing this as part of a string of metadata on their plots. Using this publicly available software engineering tool with the mutable material through which they express their scientific method helps them in their effort to maintain a reproducible and traceable scientific practice. I’ll explain how their practice using GitHub concretized in other ways in Chapter Seven.

The Radio group’s ongoing production of software and data products is the expression of their continually refined high-precision scientific analysis. Producing this software is how the Radio group learns and creates new knowledge, figuring out what they “didn’t know in the process of just writing it and working on it [the software]” (Brianna, interview). Software is the material they use to convey their scientific method. They enroll existing pieces of software from other contexts and shape and adjust (Fujimura, 1996) it to meet the needs of the pipeline they are constructing, whether it is the FlagAvg software produced elsewhere in the WRT Collaboration or code for storing and working with data in a particular socially constructed cosmology coordinate systems such as HEALPix²⁸ software. Reflecting on the construction of the US EoR pipeline Brianna emphasized how all of the Radio group’s software is rooted in fundamental physics, math, and statistics. The software is the instantiation and expression of the Radio group’s interpretation of how to do this science.

... all of our algorithms are really based on some fundamental physics, and math, and statistics thinking. So [CalibratorImager] is based on something called

²⁸ <http://healpix.sourceforge.net/>

optimal map making, which is something that was developed for CMB [Cosmic Microwave Background], and the major breakthrough there was going from visibilities to a map can be information lossless if you grid with the beam shape. And that's math that's been shown by—actually [US researcher]. And [CalibratorImager] was built on that concept. It's also called software holography. (Brianna, interview)

The US EoR pipeline is constructed to perform many operations to transform data output from the telescope into an end data product that is visualizable in power spectrum plots (such as Figure 2 that I introduced in Chapter One). Central to this are CalibratorImager and ImgPower. These pieces of software are pipelines in and of themselves that become common fields of work for the Radio group. Looking at both of these pieces of software I see not only how data flows through the overall US EoR pipeline (at least in an idealized manner) but importantly many points where the idea of the group feeling the instrument in their bones surfaces.

Constructing a novel approach to calibrating and imaging interferometric data

CalibratorImager is a complex piece of data analysis software with many data management steps and algorithms, see Figure 18. Igor designed it to be a general purpose method of calibrating and imaging interferometric radio telescope data. CalibratorImager expresses a novel approach to high-precision analysis of interferometric data by translating key theoretical and mathematical concepts into working software. Rather than replicate previous approaches, Igor in cooperation with his colleagues has worked out a different method. As a result, CalibratorImager is employed by the Radio group to analyze WRT EoR data but it is by design applicable to different interferometric telescopes, both past and present.

So, what I'm primarily working on is developing the core of the software that we use for reducing and analyzing the data from the [WRT]. In our field, it is called the calibration and imaging pipeline, so this is the software that takes the raw, but not really quite as raw as it could be data, and reformats it and calibrates it and turns it into something that we can either just make images of or send to [Brianna's] power spectrum code. (Igor, interview)

Igor has constructed CalibratorImager to execute many different functions. Executing this litany of functions is necessary to place the Epoch of Reionization data into the correct mathematical frame of reference that has been constructed within cosmology through theory development and prior experimental efforts. The exact functions to be executed in any given run of CalibratorImager depend on the analysis goals of the individual running the software and the state of the data products passed in. In the software's Production mode raw WRT data will need to go through almost every function to be usable in Brianna's ImgPower pipeline. If the Production mode starts with a data product saved from some intermediate state of a prior execution of CalibratorImager then some functions can be skipped, for example if data has already been run through the Setup Sky Coordinates function, saved, then read back into the software then it does not necessarily need to work through this function again. Igor creates intermediate data products throughout CalibratorImager to save on computational time in future executions of the US EoR pipeline.

The functions CalibratorImager executes (visualized in Figure 18 above) include: basic data management operations including reading in files, setting up sky coordinates that have been collectively decided upon to work with the data, setting up a model of the telescope beam drawn in as a resource from the infrastructure of the telescope being used, calibration algorithms, data flagging algorithms, the output of calibrated visibility data products for other software pipelines (in this case VisPower elsewhere in the EoR Science Collaboration), gridding of data to create imaged data products, foreground subtraction to remove unwanted sources in the captured signals, and deconvolution to develop a model of sources in the sky that the telescope looks at.

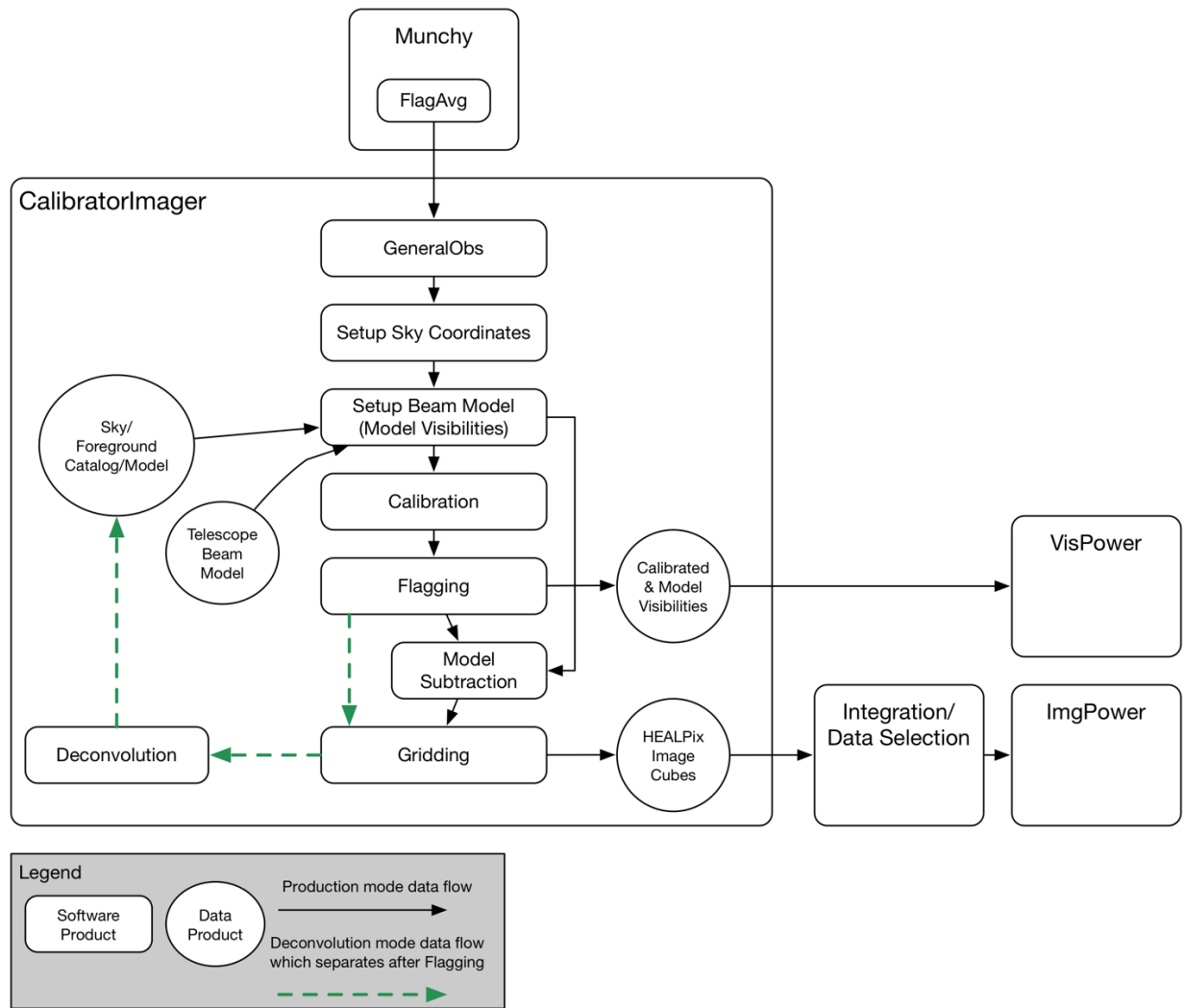


Figure 18. Analysis steps of the CalibratorImager software.

CalibratorImager has two modes of operation: Production and Deconvolution. Production takes raw data and results in HEALPix Image Cubes to pass to ImgPower for further analysis. Deconvolution creates a new sky model for improving future runs of the analysis.

Igor’s work producing CalibratorImager for high-precision data analysis took place over many years, beginning before the Widefield Radio Telescope was even fully constructed. Even so, developing his software requires Igor (and the rest of the Radio group) to understand the particulars of the WRT and conform to the policies of this project. Publishing a paper on CalibratorImager’s scientific approach is subject to the WRT paper policies that I discussed in Chapter Four. Igor’s publication in 2012 about this software includes not only himself and members of the Radio group as co-authors but many other individuals in the WRT Collaboration

in accordance with these rules. When the unexpected fourth line appears in Brianna's 2D power spectrum plots all of the individuals in the Radio group, the US EoR group, and even the EoR Science Collaboration need to be able to discuss possible causes and discuss how CalibratorImager or any other software component might be playing a part. Igor has to be able to convey the different implementation decisions he makes and how they relate to the WRT (or another telescope) and the physical, mathematical theory underlying interferometry to other members of the Radio group or the US EoR group as bugs are probed or new techniques discussed.

CalibratorImager is different from pre-existing, commonly available radio astronomy software in part because it incorporates a precision model of the telescope's beam, see Figure 20. This differentiates CalibratorImager from these general-purpose radio astronomy analysis packages that model a telescope beam using more basic shapes regardless of the particulars of the telescope that was the source of the data. This beam model is also a product of coordinated development by a cooperative work arrangement enacted among the whole WRT Collaboration. The beam model is a product of a cross-cutting set of individuals since it impacts all four Scientific Collaboration's analyses. The four Science Collaborations are sharing the same instrument and thus modeling its operation precisely is of mutual benefit.

Igor has designed CalibratorImager to work with and produce a variety of data products that I introduced in Chapter Five (visible in Figure 18). The telescope beam model is in and of itself a data product for this software because it captures information about the physical instrument as it is operating. Various expressions of the EoR data being worked with are also stored in data products, both visibilities and HEALPix cubes for example, that can be exchanged by design between the US EoR pipeline and the LivePipeline so that both groups producing

software can compare their data analysis approaches—that bake off idea of Magnus’s that I noted in Chapter Four. I’ll revisit the beam model later when examining some of the ways that the US EoR pipeline is entangled with the infrastructure of the WRT project. I’ll also examine in greater detail CalibratorImager’s two operational modes and how they relate to two of the scientific goals I discussed above. For the moment I am going to discuss Brianna’s ImgPower software that relies on data products output by CalibratorImager.

Balancing statistical rigor and computational efficiency when producing power spectrum

ImgPower, like CalibratorImager, is also a fully-fledged pipeline with many functions to be performed to create power spectrum, see Figure 19. Power spectrum can be created in different ways and ImgPower represents the particular method the Radio group has chosen to construct. Brianna created her approach to be an efficient and rigorous-enough method for producing power spectrum that is scientifically valid so long as assumptions are clearly and explicitly explained. By design Brianna’s ImgPower software is useful for interrogating the Radio group’s overall data analysis approach and the data produced by the WRT in a time efficient manner, rather than being more rigorous and taking longer to run.

Brianna’s ImgPower software handles various file management tasks, performs multiple different Fourier transform mathematical operations, calculates statistical measures about the data being analyzed, and bins and averages cubes of data down into one or two dimensions so that they can be visualized through plots. By design, so long as ImgPower is provided HEALPix image cubes it is able to analyze interferometric data to produce a variety of different power spectrum plots. Crafting this software to perform all of these operations is the result of Brianna and the Radio group’s desired approach to doing cosmology data analysis while accounting for the design of the WRT and the design of the data it produces.

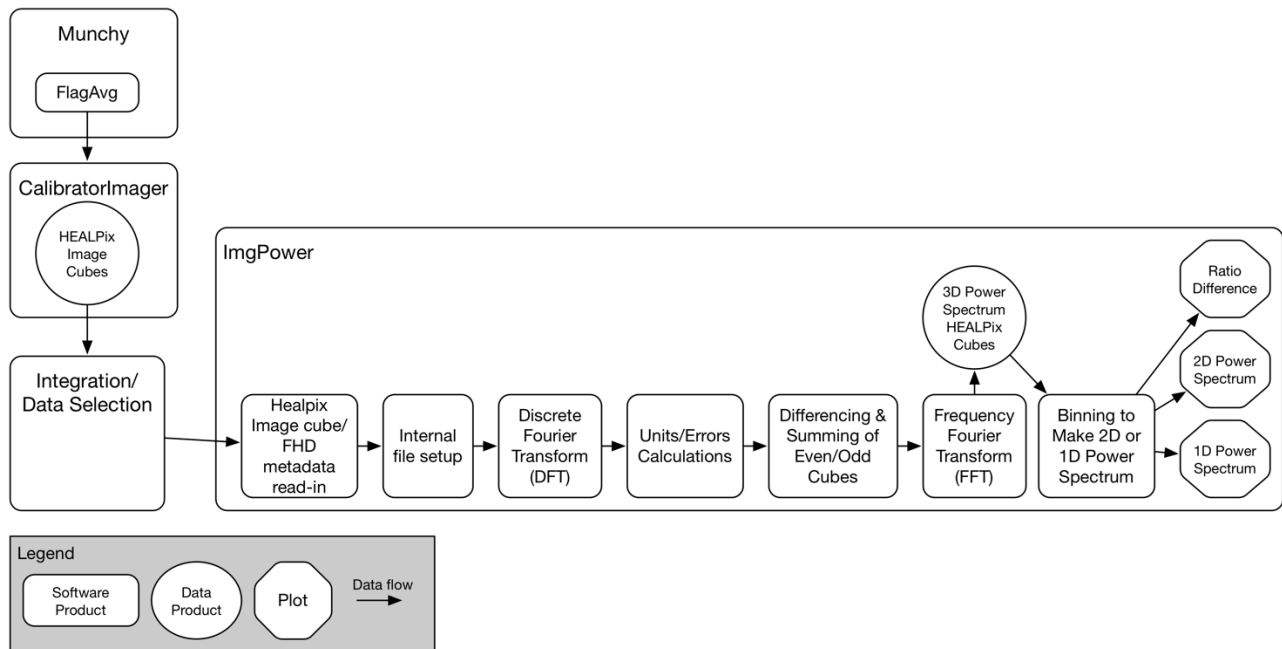


Figure 19. Analysis steps of the ImgPower software. HEALPix image cubes output by CalibratorImager must be selected and integrated to be processed through ImgPower. Three common plots that are its end products are listed on the right side.

One way I came to see this was in learning why Brianna constructed the particular order of mathematical operations completed in ImgPower and that this is important because her design affects how complex or easy certain operations will be to complete. Brianna emphasizes that how she constructed the Frequency Fourier Transform (a common mathematical operation in many fields) is “not totally straightforward” because the error values necessary for proper statistical calculations with the data are variable depending on the frequency of the observation being analyzed. Detailing this process and the mathematics driving the different steps completed Brianna illustrates the importance of understanding how statistical error is being calculated and tracked in the ImgPower pipeline. Since the observation data is a series of different frequencies and different Fourier modes the software must be designed to propagate error values in appropriate manners if the Radio group and their collaborators are to have any ability to offer valid findings. She is constructing a particular approach by drawing upon physical and

mathematical theory and calculations that she worked out and discussed with the rest of this group while making some important assumptions that influence how statistically rigorous her output is. These assumptions must be conveyed in publications using this software to produce findings and to individuals elsewhere in the EoR Science Collaboration using ImgPower.

Because after you do your Fourier transform, you had N frequencies and now you have N Fourier modes, and you want to know what the error bar in each of those Fourier modes is. And if your error bars are flat, that's trivial. If they're not flat, it's not trivial. And you can kind of imagine that, you know, if your error bar happens to line up with your mode so that you have, you know, smaller error bars where your mode is small and bigger error bars where your mode is big, that's a different situation than if they were shifted 90 degrees so that you had big error bars where your mode was small and small error bars where your mode was big. And then, of course, you have all the modes, all the different frequencies, and how those error bars propagate is complicated. So what I do is that I assume, in the uvf stage, that my error bars in each voxel are independent. Another way to say that is that the covariance matrix is diagonal, in this uvf space. And that is the big assumption that I make that makes my code not totally rigorous. (Brianna, interview)

In contrast to ImgPower, the VisPower power spectrum pipeline created by colleagues in the EoR Science Collaboration is designed to be more rigorous in its approach. VisPower sacrifices computational speed and efficiency for a more statistically meticulous output. It expresses a different construction for creating power spectrum. Brianna's ImgPower pipeline makes this design trade off so that her software is more readily available to be used for understanding the Widefield Radio Telescope as an instrument and debugging the different pipelines since changes can be rapidly tested since it is less computationally intensive.

ImgPower will produce different HEALPix cube data products as it analyzes data. Brianna intentionally outputs some intermediate data products at key points to save on computational time in future runs of the pipeline. She explained to me that the Discrete Fourier Transform (DFT) step is the most computationally intensive element of the ImgPower pipeline. The DFT operations take hours to run in the ImgPower pipeline where as the other steps are only

a matter of seconds or minutes each. To keep from having to perform the DFT every time she tests a change to ImgPower (typically in an operation that follows this step) Brianna designed ImgPower to save intermediate data products after the DFT operations are completed. The DFT-processed intermediate data products can then be read in during later executions of the ImgPower pipeline so that this computationally intensive element in the software does not have to be re-executed unnecessarily. Brianna notes that this works out since most bug hunting that she will undertake with the ImgPower component is in the operations completed after the DFT. She can save computational time to facilitate her ongoing analysis and bug hunting.

So then we have – at this point, I save these uvf cubes, for future [writing on diagram]. And the reason I do this is that it's very rare [laughter] that I ever have to redo this DFT. I might – in bug hunting. When I do bug hunting, it's typically after this. (Brianna, interview)

Intentionally involving a human in the pipeline between CalibratorImager and ImgPower

Brianna's ImgPower pipeline is designed to take in HEALPix cube data products output by either Igor's CalibratorImager pipeline or the LivePipeline. But in between CalibratorImager and ImgPower there is one crucial step to be completed, that of selecting and adding together the HEALPix cube data products that an individual wants to use to create power spectrum. This inflection point between CalibratorImager and ImgPower is designed by the Radio group to intentionally keep a human involved in the data analysis process.

The selection of data to add together for further processing into a power spectrum is what in a previous publication I have framed as a type of data processing work (Paine et al., 2015). In the context of this dissertation I consider this an analysis activity (as I do the other items I framed in that publication as processing work). I subsume all of the thought and reflection necessary to do this scientific work here as analysis work as I am not trying to tease apart and compare different models of a research lifecycle. Brianna, Abner, Igor, or whomever else is running the

US EoR pipeline will have to choose which data products output from CalibratorImager they wish to continue working with. Integrating data that has been transformed into HEALPix cubes is how the Radio group takes a collection of 2-minute observation data products and assembles enough together to reduce the amount of noise present—whether 30 minutes, 3 hours, or even larger quantities—so that there is the possibility of probing the EoR signal. This step between CalibratorImager and ImgPower is in fact the last point in the pipeline where the researchers can exclude individual 2-minute observations from the analysis.

Abner describes this integration as “a trivial step” in a technical sense since it is simply just adding together the desired image cubes. However, this integration point in between CalibratorImager and ImgPower is a key moment of serious thought on the part of the researchers operating the pipeline since the choice of data to be integrated informs the phenomena that are or are not visible in power spectrum plots. It is intentionally designed as a moment in the analysis where the researcher running the pipeline must determine what to include or exclude rather than simply being an automated task. Including or excluding particular observations fundamentally shapes the power spectrum produced since these observations add and subtract power in the integrated data products. Not taking the opportunity to evaluate the HEALPix cubes output by CalibratorImager, in particular metadata that contextualizes the quality, would be a lost moment for excluding particularly troublesome observations. Those that are filled with signal from foregrounds or other noise.

Brianna’s ImgPower software turns out to be central to tracing effects between the different layers of infrastructure in the Radio group because it produces the plots that make concrete different pieces of the software, data, and hardware. Trading some scientific statistical rigor for the utility of this implementation of ImgPower (and by saving data products that have

already had the DFT step completed) has been deemed worthwhile by Brianna and the rest of the Radio group in their work. Intentionally keeping a human in the pipeline is likewise a conscious choice in the group's expression of their approach to data analysis. Throughout my time with these individuals there was continual effort to better understand how CalibratorImager and ImgPower function in practice (as well as the telescope itself). Crafting ImgPower as Brianna did helps the group in their ongoing process of developing and improving their feeling of these different instruments or infrastructures in their bones.

Developing a feeling of the software and instrument in their bones

The more time I spent with the group the more I grew to realize that the software is the expression of their approach to analysis. This was not at all obvious when I began my study. I imagined software was important but I did not yet conceptualize how producing this pipeline is the way the Radio group can convey their scientific method to each other and their collaborators. Really software here is the articulation of the Radio group's scientific methods and techniques that is repeatable perpetually, as the examples I just discussed begin to illustrate. The US EoR pipeline software is not just a tool for doing work. It is one of the materials that Igor, Brianna, Abner, and so on use to think through and address scientific problems as well as the mechanism for producing the other important material for their analysis (plots which I'll discuss in the next chapter).

In Chapter One I presented a vignette of one of my discussion's with Magnus. He emphasized his belief that "in order to do a precision analysis you have to understand the instrument in your bones." For Igor, Brianna, Abner, and the rest of the Radio group to be able to produce their different pieces of software and assess how it is working they must deeply understand the telescope. Producing this software is not just about learning to write code. It is a

process of doing scientific analysis work, thinking through problems, and trying to understand what the problems even are. In practice they need to come to understand and feel their software as an instrument as well, it is every bit as complex and nuanced as the telescope itself. Brianna expressed this back and forth dialogue between the software, data, and science during one of our conversations. The context of production for these different elements cannot be disassociated from the analysis effort. Learning to do this analysis is a process of learning about their enacted infrastructures with some elements surfacing while others become embedded in their day-to-day practice. To produce this software requires knowing the science, knowing the instrument, and how data is designed and created.

But I really think that when you start getting into detailed statistical analyses and when you actually get into really writing the code, you have got to understand science. You have to understand where the data's coming from, the instrument. Now in social science, that might be Twitter, but the instrument you have to understand in detail in order to be able to really understand what your data's telling you because you just get crap out of it if you don't know what it is. You have to understand your science because you have to understand what you're going after. So there's these interconnected things and you cannot disassociate those. (Brianna, interview)

Magnus expresses that the software in their work lives between the instrument and its data and their analysis. Calling it the product of these elements he remarked “I don’t think the software and the analysis are separable” as he and I discussed the intertwined nature of instruments, software, data, and scientific analyses. When research is being conducted at the extreme of what is technologically possible and at the boundaries of existing scientific knowledge the process of understanding what is being worked with is harder. This echoes the point in the scientific software development literature, discussed in Chapter Two, that knowing what to software to build or the results it should produce up front may not be entirely feasible.

The idea of a simple bug appearing in the Radio group's work is not actually so simple. It could arise as an artifact of any of hundreds of elements whether that is in the telescope itself, the telescope's data collection systems and configuration decisions, or the software they are analyzing the data with. A bug may turn out to be an unintended feature, something useful to the analysis work. This flexible and changing arrangement of scientists must collectively know how all of these elements of the science work together, they must understand the multiple infrastructures at hand. Is a bug actually a bug or is it a natural phenomenon appearing? This is the type of concern that is often an ongoing question in this high-precision work.

And so you see features, and whether or not they are bugs or – so bugs you worry about 'cause you just want 'em to go away, but a lot of them are unintended features. [Laughs] And so I, I, in that they aren't a bug, per se, and it may even be doing it exactly the way you designed it, but you realize that that's not what you needed. But to isolate that if you don't know how it works is really hard ...
(Magnus, interview)

Doing this complex high-precision work challenges an individual's ability to conceptualize the whole. It requires cooperative work to accomplish. The Radio group must form many different cooperative work arrangements in conjunction with their WRT Collaboration colleagues to work on distinct elements of the software pipelines and the telescope itself. The multiple infrastructures influencing and being shaped by the Radio group's work requires that they work on a complex array of different common fields of work. In the end no one individual can do this work alone, it must be cooperative.

– and then it gets to be, as the team gets larger, to a scale where no person quite fully conceptualizes everything, but how do you get a team that works together and has a deep conceptual understanding in a lot of areas so that you can go diagnose this, and I think that's the real challenge in my mind of precision work.
(Magnus, interview)

Layers and layers of noise, foregrounds, and systematics—those effects that corrupt the data and do not go away as larger quantities of data are integrated together, I elaborate more

below—are peeled and polished away, producing droves of new data products that encapsulate different understandings of the science and analysis over time. Simultaneously different assumptions and pieces of knowledge accumulate in the software and data products. The different decisions made for the analysis at a particular point in time shape these products. The software is fundamentally representing and recreating the operational state of the telescope yet it is continually mutable as these researchers better understand their science and change how different functions work or execute it using different settings or data. The software is in this sense a novel telescope or instrument since it is transforming data.

In practice the US EoR pipeline is an enacted infrastructure coming out of the Radio group’s work, bound and tangled up with the WRT while intentionally being flexible and extensible enough to work with other telescopes. Their design and operation are shaped by the WRT instrument since they were conceptualized with this device in mind yet they are able to transcend this one project alone through the efforts of the Radio group as they begin work on new telescopes. To delve further into how the US EoR pipeline expresses the Radio group’s scientific method I am now going to examine a few different aspects. These aspects demonstrate various ways this software is entangled with the WRT infrastructure, how it is used by the Radio group to address different scientific goals, and what the work of playing whack-a-mole with systematics does for this arrangement of scientists.

Entangling the software with an underlying research infrastructure

In Chapters Four and Five I examined the Widefield Radio Telescope project and how the EoR Science Collaboration creates resources for scientific inquiries. These resources are primarily data products created by using the telescope through its monitor and control software. The data products are entangled with the observation process since a Science Collaboration configures the

instrument to meet its needs and because of the actual operational characteristics during each observing period (i.e., how warm or cold the observatory site was, was an antenna tile broken, etc.). Much of this entanglement is sustained because the WRT project designed its instrument and data products to be self-documenting with all of this metadata about actual operating behavior captured and stored with the observation data.

This entanglement is sustained on in to the Radio group's software. The US EoR pipeline layers on further information about the operation of this software, both into databases on the RadioCluster and into data products. I see many ways that the Radio group's expression of their scientific method in software are entangled with the underlying WRT infrastructure. I'll examine two here. First, Abner's Munchy software running the pipeline on the RadioCluster. Second, by delving into the telescope beam model encapsulated in CalibratorImager.

Ensuring reproducible and replicable analyses in part with Munchy

Munchy is actually the first piece of the US EoR pipeline when I list the pipeline's primary components. This component was created by Abner as he was tasked with operating the group's pipeline on the RadioCluster with various pieces of data. Scientifically Munchy is not implementing any of the complex mathematical operations, but for actual sustainable and reproducible scientific practice it is absolutely vital to marshalling data and coordinating analyses over time. It is where data is intentionally included or excluded by one of these scientists trying to answer a particular question, all while ensuring they can keep executing CalibratorImager and ImgPower with that data and the same settings time and time again.

Munchy is Abner's construction for abstracting and codifying the different steps to these analyses so that they are reproducible and self-documenting, similar to how I described the telescope as self-documenting in Chapter Five. Munchy is the first point in the US EoR pipeline

where a researcher must select which data to work with. It helps the other components of the US EoR pipeline to become embedded, infrastructural components of the US EoR group's work by abstracting away the work to execute them. Munchy is bound up with the RadioCluster and the data of the US EoR group, the glue tying these many infrastructural components from different layers together.

Munchy is a series of scripts that manages the initial pre-processing of data stored on the RadioCluster and executes particular analyses. Munchy's scripts call upon the database that documents where raw observation files are stored on the RadioCluster, see Figure 17 above. Munchy also retrieves data from additional databases, including metadata from the ControlMonitor system along with a quality control database the US EoR group has developed (referred to here as QualityControlDB). QualityControlDB is also where Munchy will store a record of its processing of a given observation, making the operation of the US EoR pipeline self-documenting just as the WRT instrument does. Munchy is purpose-built by Abner for the Radio group's analyses and designed to function on the RadioCluster specifically. It entangles the US EoR pipeline with the WRT infrastructure by working with the particular databases and file storage configurations instantiated on this computing system, the installed base that the US EoR group created as part of the WRT project. Simultaneously within the layer of infrastructure that the Radio group is enacting Munchy does work to ensure that the various data products are addressed as resources for the particular investigations of the Radio group.

Munchy embeds a piece of software from the WRT Collaboration that I refer to as FlagAvg. FlagAvg is a piece of processing software developed to take the "raw" files from the telescope and complete a set of "pre-processing" actions before outputting either a CASA²⁹

²⁹ <http://casa.nrao.edu/>

measurement set or UVFITS files—both common and somewhat standardized data storage formats in astronomy (cf. National Radio Astronomy Observatory, 2010a; National Radio Astronomy Observatory, 2010b). Munchy is designed to have FlagAvg output UVFITS files which become the initial data product for CalibratorImager. FlagAvg uses metadata from the database of the WRT data archive to correct signals for different cable lengths, calculate initial coordinates of sources on the sky, average the data to reduce its volume, and very importantly flag bad signal channels from the observation and remove Radio Frequency Interference (RFI). All of these elements would reduce the precision of the resulting analysis.

FlagAvg's outputs are the first points where the Radio group assesses the observation data after it is collected. Munchy's employment of FlagAvg is the first step to the Radio group's data analysis, pruning away unwanted and invalid observation data. FlagAvg is the first component of the US EoR pipeline to transform and shape the raw telescope data towards a product that expresses the conventions of the Radio group's practices. Munchy as a component of the Radio group's pipeline grew out of Abner's work to computationalize the many individual tasks necessary to select a desired observation's data from the cluster and feed it to FlagAvg.

Key to the operation of the US EoR pipeline is the selection of data to be processed by a component. An individual researcher completes the data selection for an execution of the pipeline based on their particular goals at the time. To ensure replicability these choices are written into scripts that Munchy uses to execute particular analyses. FlagAvg has over twenty potential parameters to be defined for an execution, let alone the different parameters necessary for taking in the desired observation date and time and pulling the appropriate information out of the databases. Writing and re-writing scripts to do this work would present myriad opportunities for errors to slip into the analysis work.

... so I've sort of built up this script to kind of remove a lot of the things that you want to feed it, and so there is like a low level that takes a bunch of different very specific parameters and I wrapped that around other scripts, that just give it – you give it a fewer parameters and that figures out what those other ones need to be... (Abner, interview)

Abstracting away the detailed parameters to the series of Munchy scripts so that only a day or series of days has to be specified—and even this ended up being hardcoded for particular analyses of interest to ensure consistent selection of data—enables Abner to ensure that every time data is processed or re-processed through the pipeline it is completed in a replicable and reliable manner. This reduces the potential for mistakes from a mistyped command for example. Ensuring reproducibility and minimizing opportunities for mistakes is a perpetual theme in scientific software development research and editorials—see Chapter Two. In this case Abner and the Radio group are attempting to do so unlike the cases many of those papers and editorials lament. This group is exhibiting care and thought in their production and use of software and their scientific practice.

Extending the notion of self-documenting to the US EoR pipeline

Abner is also able to have his Munchy scripts engage in “bookkeeping” of the successes and failures when processing individual pieces of data, self-documenting the US EoR pipeline’s operation in the QualityControlDB. This produces more metadata about the pipeline so that the group will have a log of what data has been processed into which data products and very importantly by which versions of the CalibratorImager and ImgPower software. The different databases that Munchy interacts with to do this have been developed over time. QualityControlDB is the attempt to store this information that helps the Radio group keep the different data product resources they create addressable in their infrastructure over time.

Nima explained the use of the QualityControlDB while commenting that it is actually a “high-jacked database” on the RadioCluster since they repurposed an unused existing database table. She explained that the Radio group wanted a record of all executions of the pipeline so as to detail the settings used and the myriad intermediate data products produced. They wanted this database to be housed on the RadioCluster computing system since this is where their analyses are executed and saved. In other words, they wanted to entangle this information where the resources of their infrastructure are stored, keeping all of this embedded in the WRT infrastructure.

Nima and the Radio group ran into a problem attempting to store this self-documented metadata on the RadioCluster. Neither they or their US EoR collaborators had the necessary administrative permissions to modify the database on the RadioCluster to even add a new table for storing their data in. Nima commented that those responsible for maintaining the RadioCluster were not responsive to emails requesting this type of change (a common issue regarding maintenance or changes to this shared system, as I noted in Chapter Five). Therefore, she and Darcy “just picked one [database table] that nobody uses anymore” on this computing system and “high-jacked” it for their metadata tracking purposes as the QualityControlDB. This approach enabled them to accomplish the task they need to complete, yet it could lead to a breakdown in their infrastructure should something happen with this database that they do not entirely control or if this unused and high-jacked table does come into use for another purpose.

The QualityControlDB is a central location to capture the different decisions regarding the execution of the components of the US EoR pipeline, the bookkeeping Abner describes or what I call the self-documenting of this pipeline. QualityControlDB was created by Nima and Darcy a few years into the Radio group’s production of software as the Widefield Radio

Telescope came online as an operational instrument and the US EoR group began to engage in continuous, intensive data analysis work. Previously such information was stored scattered in different individual's Evernote³⁰ documents—typically that of Nima or Abner since they were responsible for executing jobs on the cluster for the Radio group—or in a Google Docs spreadsheet-based “grad student queue” that Abner created during my time observing the group but that fell out of use as analysis tasks became more complex.

While observing all hands meetings I would continually see Abner provided with different executions of the pipeline to run so that some facet could be tested. He would keep notes then copy them into the spreadsheet of tasks that he kept to illustrate not only just how much work he had to do but also to track nuances of each execution's testing parameters, what data was used and why, where the data products created end up being stored on the RadioCluster, and so on. The implementation and shift to automatically capturing some of this information in the QualityControlDB shifted some of the documentation of the infrastructure's use into a resource and out of the scattered notes of graduate students.

QualityControlDB and the Munchy scripts help make the US EoR pipeline self-documenting over time by capturing information about its executions and the resources it creates. This process extends the reach or scope of the data analysis decisions beyond the Radio group into the US EoR group and larger EoR Science Collaboration should an individual wish to trace out how the work was conducted. Over time these researchers can use this information to recall and query how analysis was done and what products it created.

Conceptually Munchy is quite simple yet in practice it captures and coordinates myriad technical details that are necessary to analyzing EoR data on the RadioCluster. As a component

³⁰ <https://evernote.com/>

of the pipeline it is key to this system becoming infrastructural within the US EoR group. Abstracting technical details away and documenting operations lets the details of the RadioCluster merge into the background leaving different researchers to focus on their science. Munchy helps the Radio group and their US EoR group collaborators capture much, but not all, of their analysis in a traceable and replicable manner, becoming a central component to keeping their ongoing research work functioning. It entangles the US EoR pipeline with the infrastructure of the Widefield Radio Telescope.

As the Radio and US EoR groups extend their work to use other existing or new telescopes it is reasonable to question how this entanglement will need to change or not. As a component and resource the RadioCluster is the purview of the US EoR group which was constituted under the auspices of the WRT Collaboration. A new or adapted version of Munchy could be implemented to work with a different computing system and its nuances. Or perhaps the RadioCluster will extend outside of the WRT Collaboration and become a resource for multiple different telescope projects, with the arrangement of researchers in the US EoR group maintaining this system still. I think this will be an interesting question as the Radio group positions their data analysis software to extend beyond the WRT project and this US group potentially extends beyond the WRT project. For now, what I can do is shift to examine how the model of the WRT's beam is entangled in CalibratorImager.

Accurately modeling a telescope's beam when calibrating data

Another example of the entanglement of the Radio group's US EoR pipeline with the WRT infrastructure brings me back to the telescope beam model. I noted above that one differentiating element of CalibratorImager is its use of an accurate model of the telescope's beam that is produced within the WRT Collaboration. In Chapter Four I pointed out that for every single 2-

minute observation there can be 256 beam directions and over the course of a night as the Earth rotates and the telescope is electronically pointed this changes the shape of the beam, visible in Figure 20. This changing shape is what must be accurately modeled since it encapsulates how well the telescope is capturing radio signals. Grasping how this beam model is used in CalibratorImager’s data analysis helps to explain another aspect of the US EoR pipeline’s entanglement with the WRT through data products.

I explained earlier that CalibratorImager is different from pre-existing and commonly available radio astronomy data analysis software since it accurately models the telescope beam. When first taking me through the details of his software Igor explained how standard radio astronomy software, such as the Common Astronomy Software Applications (CASA)³¹ or Miriad³² packages, use a beam that is “one just single, simple shape that’s the same for all” antennas in a telescope. Igor posits that this “works reasonably well, but when you are trying to capture effects that are rather subtle, you lose a lot of that information.” A single, simple shape is acceptable for telescopes with narrow fields of view or those that are capturing individual bright sources. This is the exact opposite type of data that is collected for EoR research with the Widefield Radio Telescope where it is precisely the subtle effects that are sought out. Using an accurate model of the actual telescope beam for every observation in CalibratorImager represents a fundamentally different approach to data analysis than generic radio astronomy software.

A beam model in an interferometer is used to grid the different visibilities to the uv plane (a commonly used mathematical frame of reference that expresses distance in wavelengths). Putting the data into the uv mathematical plane through gridding is fundamental to the Radio group’s analysis to decrease the overall computational load and reduce the mathematical

³¹ <http://casa.nrao.edu/>

³² <http://www.atnf.csiro.au/computing/software/miriad/>

complexity and the potential for unintended error. Visibilities again are the quantification of the strength of an electromagnetic signal from a source that is captured by a telescope. They are how the brightness of a particular source is determined. The members of the Radio group conveyed that in radio astronomy visibilities are considered to be pure data, the reality, whereas synthesized images are seen as contaminated with the transformations of researchers.

So there's this deep belief in old-school radio astronomy that the visibilities are pure and you can't throw them away. You have to keep them, that they're the reality and everything else is corrupted. (Brianna, interview)

This notion that visibilities are pure or real was quite fascinating to hear about since from my perspective visibilities are still a social knowledge construction, flawed like anything else but still connected to the natural phenomenon. Brianna and other members explained that in the past radio astronomy as a field felt that visibilities were information lossless, they contained everything about the signal captured with an instrument. In the past images were a lossy transformation of visibilities. Images by default lost data about the signal and this could impact results. Yet as cosmologists worked in the 1990s and on they constructed a lossless approach. Members of this field determined mathematically that as long as visibilities are transformed using an accurate beam shape the information can be preserved according to the socially constructed theory. This is known as software holography. Brianna declared that this software holography approach “is completely alien to old-style radio interferometry.”

Software holography is the technique that Igor is implementing in CalibratorImager, translating this cosmology theory into software that acts on the Radio group's data. His software is creating these synthesized images that I was seeing the Radio group work with and these images are complex constructions. Group meetings would result in conversations about very intricate details that most of the group had not really thought about. Yet to ensure their work was

high-precision they had to collectively work to understand these nuances, really getting a feeling for why some effect visible in a power spectrum plot may stem from a simple implementation detail in CalibratorImager. The details of the telescope beam model end up being quite important to the entire approach.

Describing the beam model Igor explains that “in principle” the beam model is different for each baseline pair (the signal between two antennas) and each frequency captured, see Figure 20 above for example shapes. There is always a central core of concentric circles in the telescope’s beam because the instrument captures signal most effectively in this area. To the sides of this core are differently shaped “side lobes.” Side lobes are a result of the WRT’s construction and vary in shape as the device is electronically pointed over an observing night. Delaying the signal captured to direct the instrument results in various elongations and contractions of parts of the signal collected with the antennas. Igor explained that the side lobes in the telescope’s beam are not typically well modeled by the Radio group or the WRT Collaboration. They are an ongoing research task that can be focused on by someone in the WRT Collaboration but for the moment are accepted as is in the Radio group’s day-to-day work. To avoid contamination of the signal the Radio group is looking for they try not to use data from the side lobes in their analysis.

Igor has constructed CalibratorImager to use the WRT’s beam model in the process of gridding the data. Gridding will take each individual visibility and multiply it by the appropriate telescope beam model for that visibility, that notion informing software holography as a scientific method. Igor notes that there end up being some 170 million calculations here and optimizing the computational efficiency of this has been key to getting the US EoR pipeline to operate successfully. Igor and the Radio group’s approach to gridding is “fundamental” and a

differentiator for the US EoR pipeline because of their use of beam models that are accurate for each visibility rather than applying a general beam model to all of the data uniformly as other pre-existing processing and analysis packages would do.

Gridding is this one function. “Visibility grid.” And that is just taking each visibility, multiplying the particular beam model appropriate for it by the complex visibility, and putting it down into the uv grid, and doing that for all 170 million. And so to do that efficiently, you work out a variety of ways that you can do many operations efficiently and simultaneously, but those are sort of in the details. (Igor, interview)

Gridding is the process where the visibility data that CalibratorImager works with is put into the uv mathematical space in a uniform manner. Gridded data makes the computational processing in ImgPower simpler since everything is laid out uniformly. Igor commented that data from interferometric telescopes can be processed and analyzed in an “ungridded” manner but this is not the approach he and the Radio group have followed. Igor emphasized to me that an ungridded approach would be far more computationally intensive and complex.

The telescope beam model Igor uses is a data product that is produced by a subset of the Widefield Radio Telescope Collaboration who have formed a cooperative work arrangement to create this artifact. During our discussions Igor stated that he tries to not have to be involved in the development of this model. This work requires significant mathematical modeling and empirical measurement of the beam and he already had more than enough work to tackle. Instead he is incorporating the work of researchers elsewhere in the WRT Collaboration, entangling elements of CalibratorImager’s implementation with a data product produced by the kernel of the telescope’s infrastructure. Using CalibratorImager with data from a different telescope similarly requires the beam model of that device.

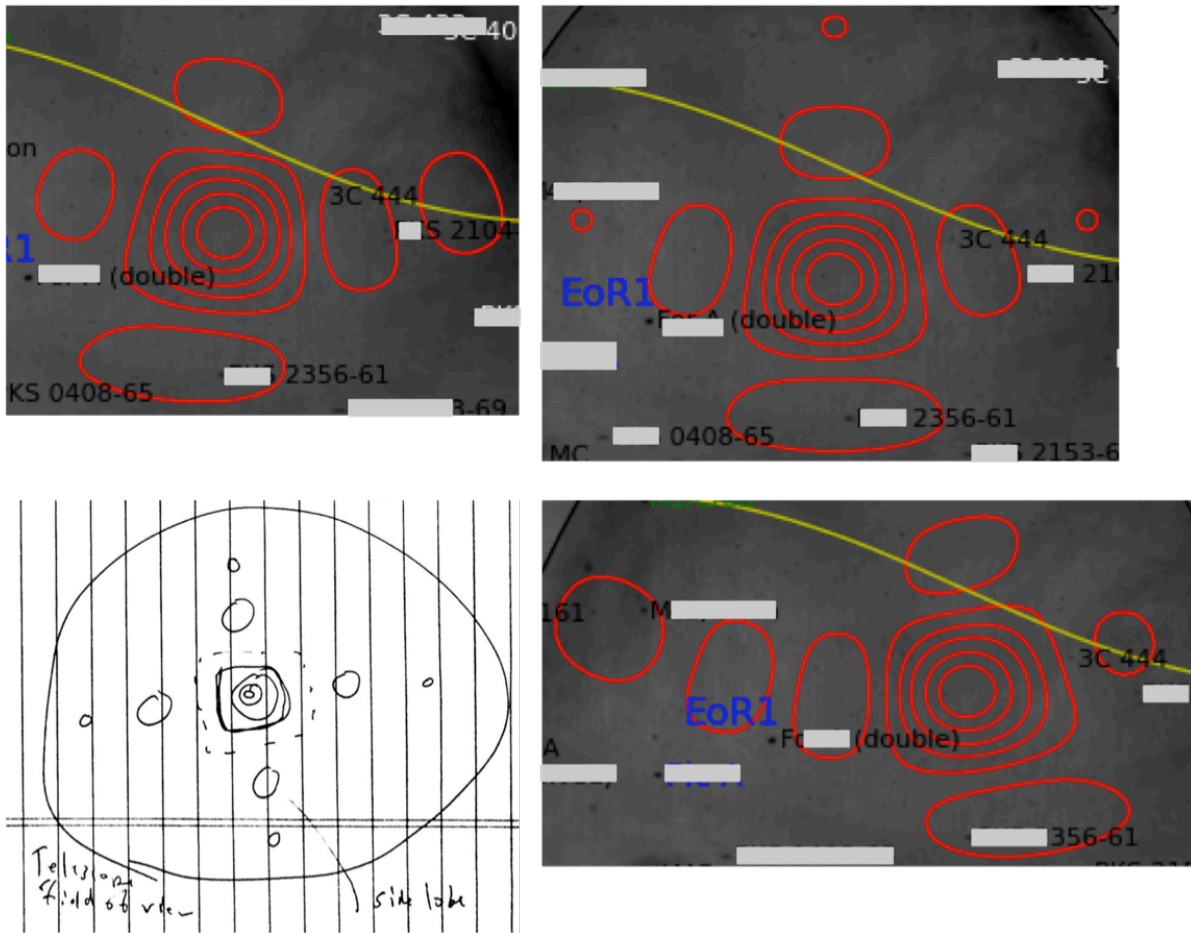


Figure 20. WRT beam shapes.

In red are beam shapes from diagnostic plots while the hand drawn example is from an interview with Brianna. The central beam is a series of concentric circles while the individual circles scattered around the outside are “side lobes” where signal response is not uniform. Identifying information censored in grey. The example on the bottom right was often referred to as a lobster beam within US EoR group conversations.

Igor adapts some implementation details of this beam model data product to work in the context of CalibratorImager but otherwise relies upon the efforts of the researchers in the WRT, who are producing this product as part of a particular common field of work in the overall WRT Collaboration. This is a situation where I see that Igor consciously restricts how much work he does to interrogate this element of the software and telescope, exploring it enough to ensure it works appropriately in the context but no more. Working to model the telescope beam himself is not of direct research interest to Igor so he relies upon collaborators, but Igor still must

understand how the beam model and of course the telescope function to be able to incorporate them in the software he is producing if it is to work as desired.

Various people are working on that. There is a graduate student at [Institution X] who is trying to empirically measure the beam and the people at [Institution Y], put together—umm did some extensive numerical simulations, modeling and software stuff that put together the beam, the model that we're currently using. ... Umm, I mean there's a lot of different elements to it and umm so I've fiddled with the implementation parts and splitting things apart, but otherwise I'm staying away from it. (Igor, interview)

As I wrapped up my data collection I inquired again about the WRT Collaboration's beam modeling efforts when talking with Igor. Igor responded that in the last year he "needed to completely tear apart the way that the beam model was internally interpreted and passed around [in CalibratorImager], in ways that was going to completely break code" so that he could incorporate the product of that arrangement of individuals elsewhere in the WRT Collaboration properly. This data product is not a static element but rather one of the myriad interconnected data products that are the focus of different cooperative work arrangements throughout the Widefield Radio Telescope project. The efforts of individuals in the WRT Collaboration creating this product shape CalibratorImager and Igor's work since he must adapt both his own software and the particulars of their data product to suit the analysis approach he and the Radio group are implementing in the US EoR pipeline. This is an example of how Igor's software is co-constructed (Fujimura, 1996) with the WRT Collaboration's data product, the Radio group's scientific method, and the guiding cosmology theory and mathematics. CalibratorImager is shaped and refined in concert with the beam model, among other elements of this work.

Igor is primarily producing CalibratorImager for use with observation data from the Widefield Radio Telescope. Over the course of my study he would reiterate how he has designed this pipeline to be generalized enough to work with data from other interferometric instruments.

Constructing this approach has been much of his scientific output in the last few years and he does not want it to be useful only with one project and its instrument. Of course each of these instruments will have a different design and as a result beam shape but Igor's novel approach can still be applied because he can change out the beam model used in CalibratorImager. Making the beam model a data product and interchangeable was built-in early on during his work. Igor explained to me that he built-in this capability because he was trying to implement support for a couple of instruments beyond the WRT. His goal was to have the data analysis approach he was implementing in CalibratorImager be applicable beyond just one instrument and he also wanted to test the approach with other data since the WRT was not yet fully constructed.

The CalibratorImager pipeline's primary use is with WRT data and in Igor's words it is "biased" towards this device. It is purposefully intimately bound up with the design of this instrument in multiple ways, the beam model being just one, and the Radio group's approach to and stance on data analysis. Igor's design decision of making the beam model interchangeable through a data product enables him to more easily make CalibratorImager generalizable as a cosmology data processing pipeline while maintaining the entanglements with the WRT project.

As a high-precision calibration and imaging pipeline CalibratorImager is useful for multiple scientific goals. In the Radio group's work this was most visible thanks to the software's two different operational modes and the corresponding scientific uses of each.

Two modes for operating CalibratorImager, two different scientific goals

Over the course of my data collection Igor, Abner, Peg, and the other members of the Radio group made it clear that CalibratorImager in fact has two main modes of operation that are interconnected yet separate. The two modes are Production and Deconvolution. Production takes raw data (or intermediate data products previously partially analyzed) and runs it through all of

CalibratorImager's functions to output calibrated and imaged data products that are necessary for further analysis in Brianna's ImgPower software. The members of the Radio group refer to this regularly as the First Pass or Production work. Deconvolution on the other hand is a particular technique for making maps of sources in an interferometric telescope's data and it is the final possible step of the CalibratorImager pipeline. It is the element that is of much interest as a scientific contribution for Igor since the particular approach to implementing this technique is a novel effort, translating a theoretical approach into functioning software.

Both modes share most functions in CalibratorImager but diverge near the end of its execution, see Figure 18 earlier where Deconvolution splits off in green. Analyzing data in the Production mode supports the Radio group's goal of measuring the EoR signal by creating power spectrum since it produces data products suitable for use in the ImgPower component of the VisPower pipeline. Deconvolution in contrast is used scientifically to produce better catalogs of different astronomical sources in the sky above the WRT. At the same time this catalog is used to improve future executions of CalibratorImager when run in the Production mode. The two modes as I explore here illustrate how the Radio group employs this data analysis software while simultaneously working to better understand its operation so it can be improved.

A Production mode to create precision imaged data products and remove foregrounds

The Production mode is the primary mode of operation where raw data is processed all the way through CalibratorImager to produce data products that can be used in ImgPower to create a power spectrum. Power spectrum are then used for the group's EoR science analyses. The scientific goal for the Production mode is to be able to remove unwanted data, including the signal from bright sources in the WRT's field of view, to create as precise of imaged products as

possible. This is the Model Subtraction step visualized in Figure 18. These sources are cataloged through the Deconvolution mode as well as Peg's work.

Model Subtraction is removing the power present from the "foregrounds" in the data. Foregrounds are the bright sources in the sky that mask the EoR signal by adding to the power captured with the WRT, an example being galaxies in the telescope's field of view. Across all of the Radio group's work trying to probe the Epoch of Reionization the precision of their analysis is fundamentally limited because of foregrounds that will be captured in the data. Abner explains in his dissertation that there is a "sea of foregrounds that cover the sky" in their data as well as thermal noise in the frequency range they are interested in. I've stated elsewhere in this dissertation that thermal noise in the sky will be reduced and go away in the Radio group's analysis as more and more data is integrated together. Foregrounds in contrast will not go away as more data is integrated and must be addressed by trying to avoid them during data collection and through the subtraction step in CalibratorImager.

Running CalibratorImager in Production mode with the goal of then running ImgPower results in five HEALPix cube data products. The HEALPix cubes store the calibrated and imaged data that is the result of all of the different operations in CalibratorImager to transform the original raw telescope visibilities. The five image cubes output by CalibratorImager include: 1) the "Dirty cube" (the raw data gridded), 2) the "Model cube" (what the data should look like based on the sky model used in the execution of the pipeline), 3) the "Residual cube" (the subtraction of the sky model from the dirty cube), 4) the "Weights cube" and 5) the "Variance cube". The organization and creation of each of these cubes enables particular operations in the ImgPower pipeline.

The Weights and Variance cubes each contain numeric information about the data and its processing necessary for Brianna’s statistical calculations in the ImgPower pipeline that I described earlier. Creating the Dirty, Model, and Residual cubes enables Brianna to develop a series of different tests in ImgPower by carving up the data in different ways. She purposefully visualizes the Dirty, Model, and Residual cubes in her 2D power spectrum plots to surface different facets of the data, see Figure 2 or Figure 23. Carving up the data in different ways is known as “jack knifing,” a concept I’ll examine in Chapter Seven.

Early in the production of the US EoR pipeline Igor was only providing one out of the three image cubes as an output of CalibratorImager. To be able to run ImgPower Brianna needed at least one of the three plus the weights and variance cubes to make power spectrum but it could be either the Dirty, Model, or Residual. The power spectrum would simply change depending on what Igor output. As Brianna and the rest of the group were trying to develop their feeling for the analysis software and the telescope they came to realize it is actually useful to have Igor provide all three image cubes to Brianna. Seeing the Dirty, Model, and Residual cubes of their data side by side in the 2D power spectrum plots allows them to qualitatively compare different transformations output by their data analysis techniques. Brianna has in fact come to exploit the different characteristics each image cube captures in the jack knifing and testing practices that I discuss in Chapter Seven.

CalibratorImager’s Production mode in the end most importantly outputs data products to enable further analysis work in Brianna’s software. Out of that software the Radio group is able to work on EoR science goals. The Production mode is also used in the group’s work to interrogate and better understand their own analysis. Igor can create different plots from the different intermediate data products that he saves in a Production run to help surface information

about the telescope’s operation, see Figure 22 in Chapter Seven for examples. These plots will visualize the antenna tiles that produced data that is being analyzed, information about the signal in the data, and images of the sky in the telescope’s field of view with different sources visible. These plots are integral in Igor and the rest of the Radio group’s efforts to assess what they are constructing. The Production mode could not fully function if it did not have a catalog of sources in the sky to subtract. To create this CalibratorImager’s Deconvolution mode must be run.

Deconvolution and the process of constructing improved catalogs of the sky

Deconvolution is the second mode of CalibratorImager and it is used for holographic mapmaking, the process of determining what foreground sources are present in the collected EoR data. Deconvolution is a series of yet more mathematical operations. Deconvolution takes the calibrated and gridded data and processes it to go from an “unknown state,” where it is not known what foreground sources are in an observation, to determine where they are located to build up a model of the sky—referred to as the Sky Catalog or Sky Model interchangeably.

Deconvolution is the analysis process of inverting the convolution process (the mathematical operations performed during calibration—the Fourier transforms) and taking the measurements captured back to the mathematical space that the instrument lives in. Brianna and Igor both describe the Widefield Radio Telescope instrument as “living” in a Fourier mathematical space, which is a transformation of the actual overhead, physically curved sky that interferometric cosmology data is constructed in. EoR data is captured along the different baselines that are formed across pairs of antennas in the WRT and this means the signal that is captured is fundamentally sampled only in particular locations and not uniformly. This introduces “hash” in the sampled signal since there are holes. Undertaking the deconvolution

process is necessary to transform the measurements that are captured in the uv plane back to the sky in as mathematically accurate of a way as possible.

So this is the way to think about it, I think. If you have – so we detect our data – our instrument actually lives in a Fourier space. So we actually detect the data in what we call the uv plane, which is the Fourier – 2D Fourier transform of the sky. And we have baselines, antenna pairs, in that space here, here, here, here, here, here. But it's not uniformly sampled. We only have samples in certain spots. If you just put that data back down and Fourier transform, you have hash because you have all these holes in your data. And deconvolution is going from this – from your measurements back to a sky the best way you can. (Brianna, interview)

Deconvolution enables the Radio group to improve their Sky Catalog data products through yet another series of mathematical operations that help them to detect sources to a fainter level. Improving this data product in turn improves future iterations of their data processing since a better constructed account of the different sources of strong signals in their data are removed and this overall improves their analyses. Deconvolution is a computationally intensive process and it would not be feasible to operate this mode of CalibratorImager on the full set of observation data gathered. Therefore, subsets of observations are run through Deconvolution to help improve the Sky Catalog data product that will be used when analyzing more data.

Peg is the PhD student in the Radio group who is working on producing and validating Sky Catalogs using the Deconvolution mode of CalibratorImager and her own software. She describes how Deconvolution in CalibratorImager uses an algorithm to search for “local maxima,” aka the brightest sources, in the data. The local maxima are then categorized as a distinct source if it is within a certain radius and above a particular signal to noise ratio threshold. Sources again might be entire galaxies in the WRT’s field of view. However, these outputs are really “source candidates” because much of what comes out is not an actual source and therefore must be validated through the different pieces of software she develops.

[Deconvolution] extracts sources. Mostly radio galaxies. And with that information such as how bright it is, the flux value, how sensitive the measurement was at that point, the signal to noise value, the beam value as to how sensitive the instrument was. Things like that. (Peg, interview)

Peg's work producing and validating existing and new Sky Catalogs is developing an important data product for the US EoR pipeline. However, throughout my study her software work was separated from the main development and debugging thrust of the US EoR pipeline. Peg relies upon the US EoR pipeline software as a resource for doing her own work. She is employing the infrastructure being enacted by the Radio group for her scientific investigations, but her software itself is not directly incorporated into the pipeline and at the time was not even available in the same GitHub repository of the code.

Peg runs CalibratorImager in the Deconvolution mode to obtain a new Sky Catalog data product. She then works with this output data product in her own set of software scripts. These scripts employ various statistical procedures and some machine learning algorithms to assess the sources that are detected and whether they actually exist in the sky or not. Peg pointed out that her work to accurately catalog sources requires precision analysis of both the data and CalibratorImager's manipulations of the data by the time it is provided in a deconvolved state. Her own work is shaped by Igor's analysis approach in CalibratorImager since any flaws imparted by this software to her data products influence her own work by potentially leading her to misunderstand or improperly analyze an output. Peg has to develop a feeling of Igor's software as well as the WRT as an operational instrument to do her science, knowing when to question her own software or the operation of CalibratorImager and its resulting data products. Over time as Peg conducts her work—producing her software—her refined Sky Catalog data product in turn feeds back into CalibratorImager's executions. She is iteratively shaping its data

products and over time the algorithms that are implemented as different bugs are found, studied, and resolved through her own work classifying sources visible in the southern sky.

Deconvolution along with calibration and gridding with the telescope beam model all demonstrate novel elements of CalibratorImager. These components all express facets to Igor and the Radio group's methods for high-precision cosmology data analysis. Producing this software in the first place is only the beginning of their work. Creating this software and data products requires they have some idea of the design and operation of the Widefield Radio Telescope. What really comes to matter is how the US EoR pipeline functions when working with data in varying quantities. The Radio group's cooperative work comes down to continually assessing the US EoR pipeline's operation. This is how they not only better understand the software they have created but also do their data analysis and figure out what scientific questions they are asking, can ask, and need to ask. The software expresses the knowledge they are producing about high-precision analysis of data from wide field of view array telescopes, the nuances of the WRT itself, and previous versions of the software. Doing this results in Brianna, Igor, Abner, and everyone else continually hunting down systematics making use of their feeling for the telescope and software.

The ongoing game of whack-a-mole with systematics

Many of the flaws inherent to the data produced by the Widefield Radio Telescope are referred to as systematics, as I briefly noted in Chapter One. Data collected with any instrument is not perfect. It will be filled with flaws and artifacts of the observation process. For a valid scientific analysis to be completed the data therefore must be calibrated and cleaned to remove known flaws. Doing this ends up in part revealing new, or different aspects to existing, systematics in the Radio group's analysis.

Calibration in CalibratorImager is a point in the US EoR pipeline software where I can easily see Magnus's notion of the software being the translator between the instrument and the theory since "essentially what your software's job [sic] is to start with a pile of numbers and ask certain questions" (Magnus, interview). In a full run of the Production mode, Calibration must solve what Igor characterizes as "millions of equations for thousands of unknowns" so that the raw data can be made to "look the most like the model that you are telling it should look like" (Igor, interview). This is part of Igor and the Radio group's work of transforming their data into the socially constructed conceptual space where they conduct analysis. Brianna elaborates that Calibration is an over-determined problem in the Radio group's work. They have N -squared visibilities captured from the WRT antennas and they're solving equations for N tiles of antennas. Out of this over-determined mathematical problem there will be residual values since calibration cannot be perfectly accomplished. Calibration will not only solve these millions of equations but also have to remove different elements that result from the flaws—intentional or unintentional—in the telescope's design, the instrument's "systematics."

Systematics are a recurring concern in the development of the US EoR pipeline, really in any data processing pipeline for the WRT or in cosmology in general. Over the course of my data collection I became accustomed to hearing about systematics. They are the ongoing flaws captured in data products that muddle the Radio group's high-precision analysis. Much of their software production is really focused on identifying and removing systematics—Chapter Seven examines how plots facilitate this work. Continually hearing the term systematics in discussions and observations led me to ask each individual to define the term for me.

These discussions clarified my understanding that systematics broadly are what an instrument does that is not "clean" and that would not be present in an "idealized" or theorized

device. This is the disconnect between the socially constructed model of the science, the built scientific instrument, and the realized version of a phenomenon captured in the data products produced through the EoR Science Collaboration’s cooperative observation work. Finding and fixing systematics is part of the basis for needing to understand the instrument in their bones. Without this collective understanding of the telescope and the US EoR pipeline software teasing apart flaws would not be easy or perhaps possible.

Nima immediately summarized systematics for me as “the instrument being a jerk” while Abner and Brianna both noted that they are “anything that is gonna corrupt your signal that is not a, like a thermal noise” (Abner, interview). Systematics may appear in data as noise, but unlike Gaussian random noise³³ present in the data they do not reduce down and go away as more data is integrated together. In fact, Brianna commented that systematics “don't integrate down. They just stay there. So as you integrate lower and lower and get rid of your noise, they [systematics] start popping out even more, and more, and more. That's our Whack-A-Mole thing.” The Radio group’s “whack-a-mole” thing is their perpetual bug hunting work rooting out these systematics and sources of noise.

There are many different systematics that pop up in the Radio group’s EoR data. A simple example of a systematic to be calibrated out of the data is that of the telescope’s bandpass shape. This is an inverted U-like shape of the captured signal across different frequencies. A bandpass restricts the range of frequencies captured and the shape in the Radio group’s data results from the built design of the Widefield Radio Telescope. Brianna sketched these multiple times during interviews while Abner showed me diagrams output from CalibratorImager that show the band pass, see Figure 21. The inverted U-like shape introduces small gaps between

³³ Gaussian random noise is expected and understood since it behaves according to expected statistical distributions and is a phenomenon that can be modeled and handled with cosmologist’s mathematical tools.

frequencies in the data. These gaps must be appropriately accounted for in the calibration steps if the data is to be accurate and usable for scientific analyses, much of the data at these edges is intentionally flagged and thrown out by CalibratorImager.

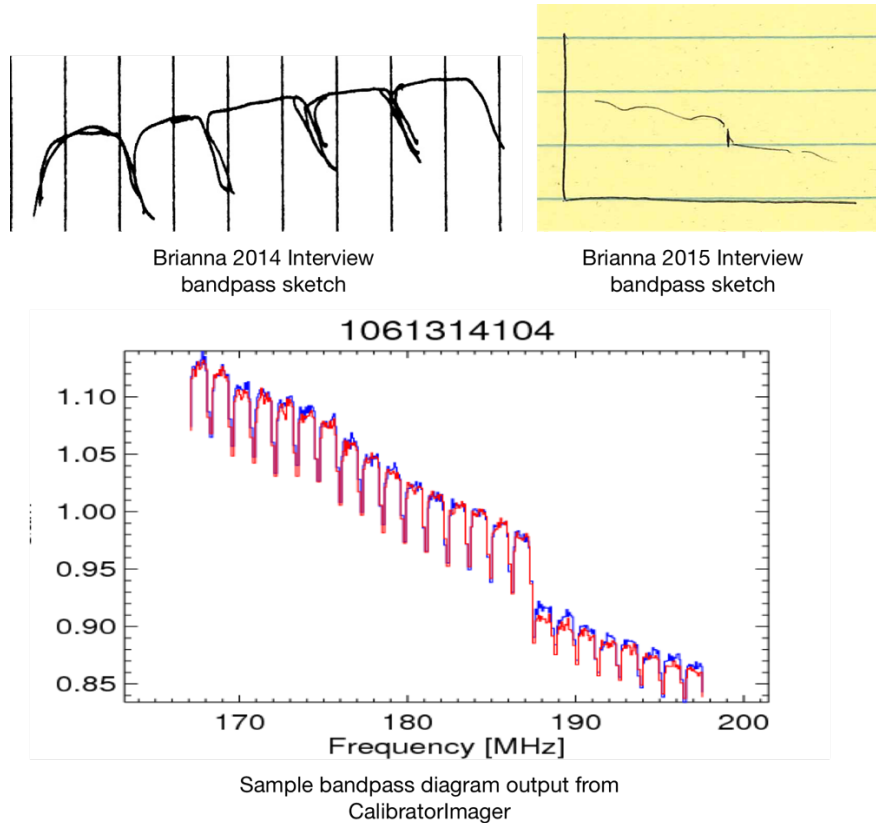


Figure 21. Sketches and a plot illustrating bandpass edges.
Gaps in the signal the telescope captures result from the instrument being most sensitive at the center of a frequency band and dropping off near the edge.

Abner explained to me that the bandpass edges result from a design constraint in the telescope when the signal is converted from analog to digital resulting in less signal sensitivity near these edges. Calibration and flagging is not perfect, so at times these errors remain as systematics leaving unwanted power in the signal being analyzed. Igor's initial approach to this systematic was to have CalibratorImager fit an average bandpass filter across all of the observation frequencies when calibrating data. As the Radio group was iterating to push their analysis to be higher-precision this decision was no longer holding up. New approaches to

calibration needed to be designed and implemented. Nima was tasked with beginning to determine new approaches to this crucial step of the US EoR pipeline for future data analysis.

There is one thing that's just part of the design of the instrument. We, in order to save on computational costs you have these kind of bandpass structures, which is that you are more sensitive to frequencies in the center of the band, then it kind of falls off and you're not really sensitive to these edges. (Abner, interview)

One other important example of a systematic is that of the “fourth line bug.” In Chapter Four I pointed out that each of the Antenna Tiles are connected to the Analog Beamformers with one of six types of cable. Through their data analysis the Radio group learned that signals travel through each somewhat differently, a not entirely unexpected issue since physical components vary somewhat in their characteristics. Because of the differences there was reflection of the signal appearing in their data. Through their cooperative analysis Igor came to address this systematic by adjusting the calibration equations to account for the six particular cables in the WRT instrument. This only came about as Brianna discovered the reflection in some of her 2D power spectrum plots. I'll examine how all of this unfolded in Chapter Seven.

Uncovering systematics and addressing them in their software, as these calibration examples illustrate, is how the Radio group grows to better understand the instrument that is producing their data and their own analysis software and practices. There is a constant back and forth with how the software expresses their understanding of the science, data, and instrument and elements that are not yet understood or even known.

Summary

This chapter illustrated how the Radio group's scientific work producing software crafts this perpetually adjustable material to express their unique approach to doing a high-precision scientific data analysis. Munchy, CalibratorImager, and ImgPower all result from this one

group's constructed scientific method and the different infrastructural commitments they are working with (e.g., the policies of the WRT Collaboration, the goals of the EoR Science Collaboration, etc.). These different pieces of software express how Abner, Igor, Brianna, Nima, Peg, and Magnus approach studying the Epoch of Reionization as part of an international telescope project and its infrastructural work.

The US EoR pipeline is created in the context of multiple different infrastructures and cooperative work arrangements—the WRT project and instrument, the EoR Science Collaboration, the US EoR group, and so on. In practice this software has become the research infrastructure for advancing the Radio group's scientific goals as well as those of their collaborators in the US EoR group and the larger EoR Science Collaboration. Many elements are the focus of ongoing scientific work for Igor and Brianna (among others) while simultaneously being products that different individuals rely on functioning stably day-to-day in their own work. To successfully build this pipeline the Radio group must be able to open up and examine their software as different systematics or other bugs arise as well as invert the infrastructure of the WRT to assess when some phenomena is the result of the telescope's design, its operation one night, or maybe something in the sky.

The work I see Magnus, Brianna, Igor, and the rest of the Radio group doing with and through software is redolent of Fujimura's (1996) description of cancer researchers crafting their science by "shaping and adjusting materials, instruments, problems, theories and other representations, and social worlds as well as themselves and their laboratories" (p.207) in a co-constructive process, as I introduced in Chapter Two. I am not examining how this group's work translates among different social worlds in cosmology but I am seeing how doing their local work in Seattle is in dialogue with work in the rest of the EoR Science Collaboration. They are

creating doable problems in cooperation with their collaborators (Chapters Four and Five illustrate many facets of this) by building and sustaining the Widefield Radio Telescope. But their work is only really beginning once EoR observation data is collected.

As part of the EoR Science Collaboration this software is one of two official mechanisms for doing data EoR analysis. By designing and exchanging data products both of these pipelines result in scientific methods for creating knowledge. The software and its outputs are traceable and able to be interrogated over time and among different research contexts because of the self-documented metadata stored in QualityControlDB and every data product. The Radio group's software and its data products are perpetually entangled with the WRT's infrastructure, being constructed and shaped by the larger decisions of the EoR Science Collaboration and the WRT's built instrument. The US EoR pipeline has grown beyond just the Radio group's work, subject to use by collaborators elsewhere in the United States. How this expanding cooperative use shapes the US EoR pipeline software as more individuals come to use either the full pipeline, individual pieces of its software, or just its data products is a question that remains to be seen in future work.

To develop an understanding of the Widefield Radio Telescope infrastructure in their bones requires doing all of this work producing software. Recursively the group ends up needing to develop a deep feeling for and understanding of their own software as well. Producing this software is creating many different expressions of knowledge, from the software itself to the data products as instantiations of analyzed data at particular points in time. To produce and use their software the Radio group must engage in an iterative, ongoing process of better understanding the Widefield Radio Telescope as a device, flaws and all. Software as a sociotechnical construct and human endeavor in this group encapsulates many of the myriad facets to the science. It is

truly a mutable, multifaceted set of complex relations among many constructed artifacts and practices. Software is one of the primary materials involved in the group's production of knowledge and working on the US EoR pipeline is how the Radio group does their science.

I have explained how the group is engaged in an ongoing game of whack-a-mole with systematics in their data. Really grasping how this unfolds requires understanding how they test their software. This requires discussing how the Radio group tests and debugs this software using plots, a language of this group. This is the focus of the next chapter.

VII. Plots as A Language to Interrogate Infrastructures

The beauty of images is situated in front of things, that of ideas behind them. So that the first sort of beauty ceases to astonish us as soon as we have reached the things themselves, but the second is something that we understand only when we have passed beyond them. — Time Regained, Marcel Proust

Introduction

Explaining the US EoR pipeline and the Radio group's work producing it I have so far not really delved into one major facet to this cooperative work, their use of plots. Plots, recall from Chapter One, are visualizations that capture scientific knowledge, the natural phenomena being sought (e.g., the EoR signal), effects from the design and use of the Widefield Radio Telescope, and effects from the design and use of the different software analyses (either the US EoR pipeline or the LivePipeline here). I began my study without giving much thought to visualizations of data as being important to scientist's software. Yet from my earliest observations and interviews the importance of these artifacts in the Radio group's work emerged, especially the ideas behind them. Plots are a language of the group in Magnus's terms. They are central to the Radio group's work enacting infrastructure as they produce software and their scientific analysis.

Key to producing software is testing and evaluating its operation. The argument of this chapter is that the Radio group's software testing or debugging work and scientific data analysis are intertwined and conducted using the many different plots they produce as they attempt to develop an understanding or feeling of these multiple layers of infrastructures in their bones. Plots are the inscriptions and traces of the different states of data analyses in software over time. These artifacts visualize and concretize facets of the Radio group and their collaborator's many different data products, becoming the physical artifact that the members of the group coordinate around during their meetings and conversations. Plots in the Radio group are used to interrogate

the multiple layers of infrastructures that they work in. Effects from systematics—such as the bandpass shape or the 4th line bug—that emerge visually must be traced out and understood. Plots are part of the story explaining how the US EoR pipeline software emerges into and does work in the physical world.

Scientific software development (SSD) literature—discussed in Chapter Two—expends significant effort discussing software testing practices. The Radio group’s work testing their software deviates from the software engineering methods examined in scientific software development studies, yet at the same time is akin to many of the aims and goals of such practices. They have created a rigorous, methodical practice for testing the operation of the entire pipeline but this is not automated as testing practices in software engineering aim to be. Science and technology studies scholarship on the other hand examines how scientists create and use visualizations to draw a natural object as an analytical object that can be probed (Vertesi, 2015). Rather than focusing on how the Radio group designs these scientific objects I shift perspective to focus on the use of visualizations to interrogate infrastructure in the course of analyzing data. These interrogations cross the three layers I have visualized at different points in this dissertation, but always result in changes to the top layer in the US EoR pipeline software since it is the element of the Radio group’s work that is mutable and able to be refined over time. They are integral to the Radio group’s ongoing interrogations of infrastructures.

I show how analyzing data and testing software (a simultaneous activity) in the Radio group is conducted using plots and contrast this with SSD and software engineering testing ideas. The ways that the Radio group employs plots illustrates the care and thought that go into their software production, and the testing that is inherent in that work. In this work it is hard, if not impossible, to really separate the science from the production and refinement of software as this

work is how the scientific method is enacted, but as a result of the timeframe of my data collection I can explicitly state that the work I studied was not offering new findings about the Epoch of Reionization. The Radio group's scientific outputs were about the method and instruments being created.

To begin I will discuss my typical experience attending one of the Radio group's weekly all-hands meetings. Weekly meetings are the activity that really foregrounds the group's plot-driven work in my data.

Cooperatively analyzing plots in a Radio group weekly meeting

My first interactions with the Radio group as a whole took place in the May of 2012 during my exploratory data collection. The first regular group meeting that I attended was a harbinger of every future meeting I would attend, even though I had no clue that it would be at that stage. This meeting was one of the Radio group's regularly scheduled all hands meetings that take place weekly. During these meetings every member in attendance will offer an update on the work they are engaged in and discuss problems that have come up in the course of their work. Some meetings will have a discussion of a journal article that was selected prior to the meeting for everyone to read, although throughout my attendance the discussion of the work to build their software would more than consume the allotted time for the meeting. Plots were quickly visible to me as a primary component of the group's work thanks to this type of meeting.

The May 2012 meeting began with roundtable updates about each individual's work. Igor and Brianna first offer short updates on their progress developing CalibratorImager and ImgPower. Their work on this software was still in its early stages I now realize. The telescope itself was more than a year away from being completed but Igor was deep into building CalibratorImager and trying to get it to work with some pre-operations telescope data. Brianna

was in the midst of designing early versions of her plots while also working on software for the telescope.

Magnus cheerily next asks me what I have going on this week. I noted I was engaged in lots and lots of paperwork since I was consenting multiple research groups for the *Interacting with CI* study while working on a conference paper. Following my update Peg, Abner, and some undergraduate students offer their updates. The roundtable update would be repeated across all of the Radio group's all hands meetings that I attended. Magnus's inclusion of asking me for an update on my own work during every meeting always made me feel welcome.

Following the updates, the group shifted to analyzing some data that Igor and Magnus were discussing that morning prior to the group meeting. I noted in my field notes that this shift in the meeting took place as Igor spread out plots across the table, twenty-six four by four diagrams of similar data along with five to six other printouts (Figure 26 and Figure 25 below convey this approach scaled up during another meeting). All of these printouts were plots of data produced by CalibratorImager as it functioned at that time (see Figure 22 for representative examples). As Igor spread these plots across the table I noted how everyone at the meeting stood up and migrated to huddle over the printouts along one side of the table. As everyone huddled they started to interpret the plots as Igor explained what they were showing. My field notes made a point of stating that in this meeting he described particular filtering and analysis processes that he was working on in CalibratorImager. The plots that Igor spread on the table were the representation of the phenomena he was trying to understand in the group's early test data and his software. These artifacts made the digital software code into something tangible for the group to cooperatively assess in an analog environment. These individuals could cooperatively discuss different facets thanks to the common, accessible representation immediately in front of them.

Igor and Magnus proceeded to explain the data presented in the plots. Brianna, Abner, Peg, and a couple of undergraduate students all begin to examine the various plots in detail. Various individuals speak up about different errors that they notice as they try to understand Igor's software analysis. This turns into a discussion about both the data and the software that is producing these plots. Concerns were being raised about the coordinate systems used for working with the data and how this aspect of the software is implemented. Igor describes using code from someone outside of the group without changing much of it. Magnus raises a potential issue with the construction of this code as the definition of a key variable for the telescope's pointing on the sky is apparently different throughout the code. This elicits a groan from everyone present but led me to wonder how much software from outside the group was being enrolled in the pieces Igor and Brianna were building. Igor comments that this coordinate systems issue could be artificially "boosting" their results in the plots. This dialogue between the individuals huddled over a set of plots helps Igor and the group as a whole to work towards a shared understanding of their analysis (i.e., the software being produced) and to debug the aspect of CalibratorImager that Igor was working on at the time.

Igor says that the code he is currently working with he copied from Mitch someone (not group member). He states that he hasn't really changed much. Magnus says he wouldn't be able to guarantee that the zenith is defined the same way throughout all of that code, indicating he is familiar with the code in question. Magnus states that this could be introducing error into the data. The group as a whole groans at the thought. Igor thinks that this may be giving them an artificial boost in their results then. (Fieldnotes, 2012-05-23)

Throughout the group's conversation my field notes capture how Magnus uses this analysis process as a teaching opportunity. He explains limitations in their analysis approach versus one from their collaborators elsewhere in the WRT Collaboration while also explaining how the telescope as an instrument is designed to function. I noted that Magnus's explanations

were especially directed towards Abner and Peg as graduate students beginning to work on the software analysis. Throughout this discussion Magnus repeatedly uses his body to illustrate the field of view of the telescope on the sky. He physically moves and holds his hands up to demonstrate how it would look if a person were standing out in the desert at the telescope site and looking up at the night sky. Explanations like these take place multiple times, especially when there is a disconnect between his understanding of some element of the data being captured and visualized in Igor's plots versus the understanding that Igor or Brianna are expressing in the conversation.

Throughout the remainder of this meeting the members of the Radio group continue to discuss different elements of the data and software processing that are visible in the plots Igor has shared. Magnus encourages the members present to discuss any patterns they are seeing in the data. He expresses a belief in this type of "qualitative" analysis where plots of the data are laid out and examined by multiple members of the group. In essence to let their eyes help them see features and details. He would end up repeating this notion to me and others in the group many times over the course of my data collection.

While I did not know it at this formative stage of my engagement with the Radio group this practice of qualitative plot analysis to assess data and software was the activity I would observe regularly in the Radio group's meetings. The importance of plots to the group's practices was only reinforced when Brianna and other members noted during interviews that plots are Magnus's "favorite thing" to work with. Over time I would learn that the individual who brings the most plots for discussion to the meeting is deemed by Magnus to be the person who "wins the meeting." This brief example of conversations oriented around plots begins to illustrate a software production and research practice rooted in the creation and interrogation of these

artifacts. The graduate students and post-doctoral researchers in particular become engaged in analysis work around plots since they are directly responsible for producing the software and artifacts being examined. In time I would come to learn that there are a wide variety of plots being created and used in the Radio group's cooperative work.

Plots as a language in the group's cooperative work

The brief example of my first Radio group meeting only begins to capture the role of plots in their work. This early experience of examining plots to understand the data being captured with the Widefield Radio Telescope and the functionality of the software being produced captures the broad importance of plots to their research work. Plots are a "language" in the Radio group's cooperative software production and data analysis because they are a representation of the many layers of infrastructure enabling them to ask and examine different scientific questions.

Plots continually emerged in my data as one of the most prominent elements of the Radio group's cooperative work. I rapidly became accustomed to huddling over tables filled with plots during meetings or having extended discussions about different versions in interviews. While talking with Magnus I directly asked him to discuss the role of plots in the group's work. This elicited the response, after a long pause for thought, that "plots really are our language. They're our words" before reflecting that:

they're [plots] interesting 'cause they're about how we present the data via the software to ourselves, but there's also a very strong science theory side to them in that by choosing a plot you said this is what I think is important. ... Uh, because, uh, or another way of doing, you know, what is our task? Our task in the end is to take two petabytes of data and reduce it to five numbers. [Laughter] Maybe three.
(Magnus, interview)

Plots are central to the Radio group's overarching research task, that goal of producing the five or three numbers as Magnus good-naturedly reflected. Plots are also the mechanism that

translates the data and software analysis into a form that the group can use to teach themselves and produce new knowledge. In my analysis I have come to see that plots are the visualization of data products. Plots are a key facet to data products being coordinative artifacts since they are made tangible and able to be cooperatively discussed in a visual form.

Magnus's caveat that there is a strong "science theory side" to plots is important to foreground here as well. While the US EoR pipeline as a set of software and data products is key to producing and enacting this group's overall research infrastructure, the selection of plots and the underlying data is just as important of a component of the Radio group's scientific research work since this is how they end up expressing the scientific knowledge that they are contributing to cosmology as a field. Even the choice of which type of plot to create, discuss in a meeting, or include in a publication changes the conversation since many of these are novel products of the Radio group and their collaborator's practices. The development of these plots is how the Radio group figures out what questions it is asking of its data and analysis that are all rooted in statistics. Plots help the group understand the questions they are asking and can ask.

And so I think the, the development of the plot is interrelated to the analysis because you're on the fly trying to figure out really what the questions are. ... A-, a-, and one of the things I love about statistics is that math is really easy. Statistics are hard, but all the hard is what was the question you were really asking, and almost all statistics errors are because you set a sentence with a question and then you math – translated it to a mathematical quest—equation, and that mathematical equation was asking a different question than you thought it was. [Laughs] (Magnus, interview)

I would extend Magnus's point to say that as a language in their work plots are how different components of the work are interrogated. Their software as a scientific product is not just a translation of scientific theory into digital code and the use of that code to shape data before producing these visualizations. Their software is a set of relations that include the digital code, the data products, and the visualizations of the data products as a material representation of

the digital, mutable elements. Plots become the tangible aspect of the data product threads among their software, telescope, different arrangements of researchers, and so on.

The medley of plots created in the Radio group's cooperative work

Brianna, Igor, and the rest of the group end up creating a diverse medley of plots in their work. I delved into Igor and Brianna's CalibratorImager and ImgPower pipelines in Chapter Six. Both of these components once again create the many different plots of the data products being processed and produced. Before I examine more about how these plots are used I want to briefly discuss some of the varieties the group creates, see Figure 22 and Figure 23 below for examples.

CalibratorImager produces a large assortment of plots. Many of these plots are useful for diagnostics of the data and telescope. Figure 22-A is an example of the shape of the bandpass filtering across frequencies that I discussed in Chapter Six. This systematic is accounted for in Igor's calibration step of CalibratorImager and visualizing the shape across frequencies illustrates for the group where they can expect signal to be strongest. Figure 22-B displays the calibration phase calculations CalibratorImager completed for all 128 tiles of the telescope in this observation. This enables Igor or another group member to assess how well this calculation was completed. This type of plot also foregrounds when a tile of antennas in the telescope was not functioning appropriately, as is the case in tile 105 that is greyed out in this example. The data from tile 105 was flagged as bad by either FlagAvg or CalibratorImager and removed from further analysis. Figure 22-C is an example of the telescope's central beam while Figure 22-D is an image with the sources detected in the beam's field of view circled. These sources will become part of the Sky Catalog data product that Igor and Peg work on.

All four of these plots are a visualization of not only the captured observation data but also the state of the telescope at the moment of data collection and importantly the state of

CalibratorImager’s implementation as data analysis software when the data was analyzed. They are the representation of these many entangled elements of the Radio group’s work, surfacing different aspects to the observation and software as well as decisions made by individuals over time in the course of analysis. CalibratorImager’s different plots are used in the Radio group’s process of determining what questions they can ask and should ask in their scientific work.

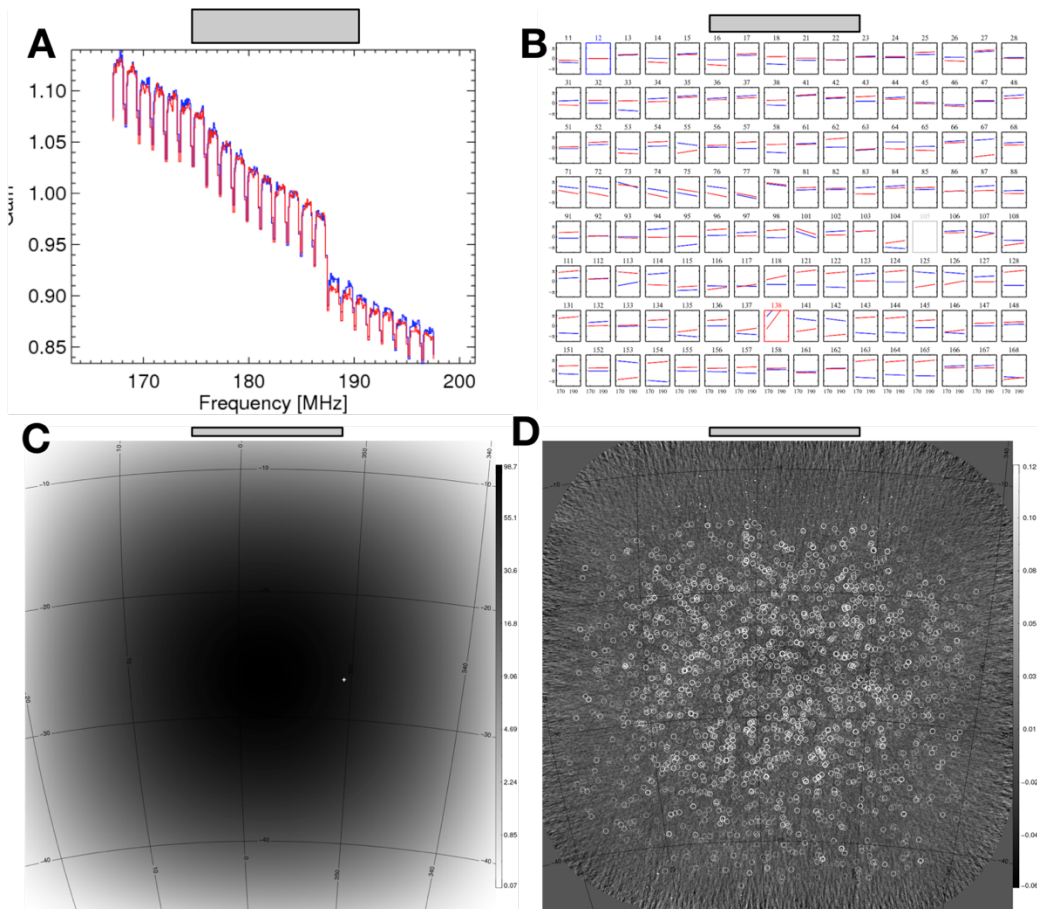


Figure 22. Example plots output by CalibratorImager. These include: A) a bandpass diagram, B) a calibration phase diagram, C) a beam image, and D) an image of sources in the data with rings to highlight each. Each of these plots is used by Igor and the Radio group to evaluate the data captured and the instrument’s performance.

After CalibratorImager there is of course the ImgPower pipeline produced by Brianna. The final outputs of the US EoR pipeline will be power spectrum plots from Brianna’s ImgPower software. Power spectrum traditionally were one dimensional (1D) graphs, Figure 23-

A. This is how the intensity of the 21-cm signal of the Epoch of Reionization is presented in theoretical work and through some other analysis techniques. Novel to the Radio group and WRT Collaboration’s work are two dimensional (2D) power spectrum plots, Figure 23-B, in the wavenumber \mathbf{k} space. This \mathbf{k} -space is a specific constructed mathematical frame of reference that the interferometric data from the WRT is placed in through the analysis approach implemented in CalibratorImager and ImgPower. This 2D power spectrum is a novel representation of an interferometric telescope’s data in the instrument’s mathematical space such that there is an “EoR Window” above and to the left of the two diagonal lines. The solid line is where the Radio group expects power from foregrounds to be bleeding into the plots from the horizon. The dashed line is where they expect power to be coming in from the edge of the telescope’s overall field of view. Brianna’s plots include these solid and dashed lines as guidelines for an individual assessing the information conveyed in this visualization.

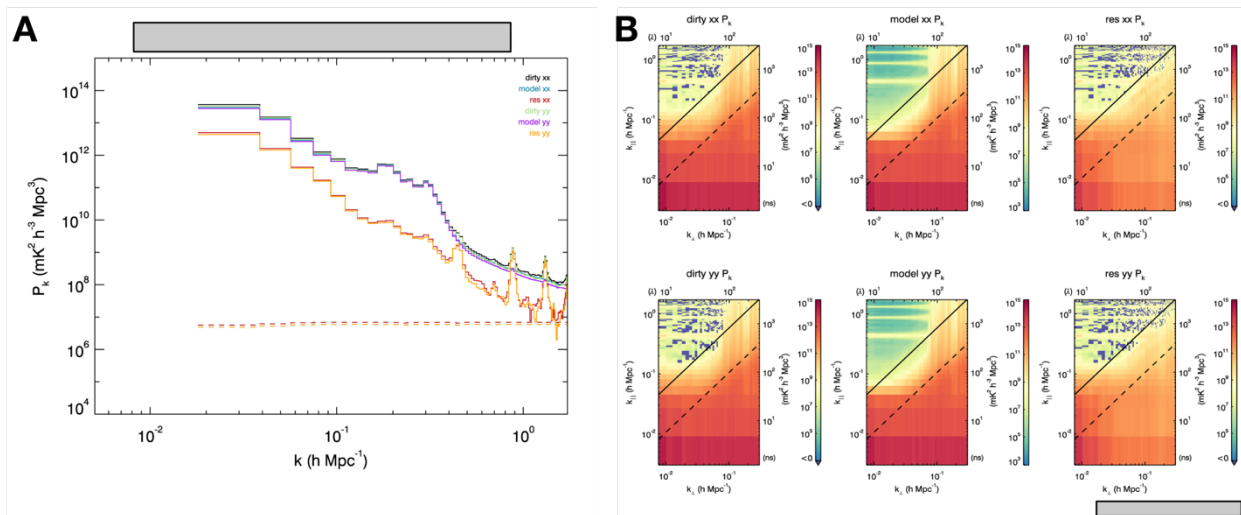


Figure 23. Example plots produced by ImgPower. These power spectrum plots are used for pipeline debugging and scientific analyses including: A) a 1D power spectrum, and B) a 2D \mathbf{k} power spectrum.

The EoR Window is where the Radio group and their collaborators will be able to assess the 21-cm signal’s intensity in a 2D power spectrum plot. The Radio group as well as others in

the EoR Science Collaboration and the larger community of EoR scholars have worked to theoretically describe the EoR Window as well as the effects of foregrounds (that I discussed in Chapter Six) on this window. The mathematics and cosmology driving this two-dimensional representation are complex and far outside of the scope of this dissertation. What matters to me is that this novel plot concretizes the data, the telescope's operation, and the Radio group's software analysis.

The 2D power spectrum ended up being the most commonly discussed plot in my data collection because it is the mechanism in which the effects of the telescope, its operation, and the software are continually visible. Even more so than CalibratorImager's plots, these complex plots visualize the Radio group's data analysis approach that is implemented in software, as well as design elements of the WRT instrument itself. Looking at Figure 23-B in the "model xx" or "model yy" panels (the two in the middle) segments of blue-green with horizontal lines in yellow are visible. These three horizontal lines are expected because of the WRT's design with course band filtering and illustrate that one expected bandpass systematic I examined in Chapter Six. I noted in Chapter One and Chapter Six how the emergence of a fourth horizontal line (the 4th line bug) revealed an unexpected bug that required cooperative testing and analysis to figure out how in the end CalibratorImager needed to be modified. I'll explain this work later in this chapter.

As the Radio group's software production progressed Brianna designed additional ImgPower plots. Part of the design of the HEALPix cube data products created by Brianna's software is to provide what she calls a "difference" cube where part of the data is subtracted from the other. One part of the data has noise and the desired signal while another is just the noise. Subtracting them in the appropriate way based on the mathematics Brianna and other members of the group worked out will leave just the desired signal. Drawing upon these

difference cubes Brianna created what she calls 2D power spectrum ratio plots (Figure 24-A) and 2D power spectrum ratio difference plots (Figure 24-B), among others. Each of these types of plots help Brianna and the Radio group during their data analysis work to surface different systematics in the data and elements of their software by revealing different expected and unexpected structures. Each of Brianna’s plots is based in complex mathematics that Brianna and others in the group worked out, but as visualizations enable easy assessment (to the trained interpreter) of the state of the US EoR pipeline, the Widefield Radio Telescope during observations, and of course the data itself.

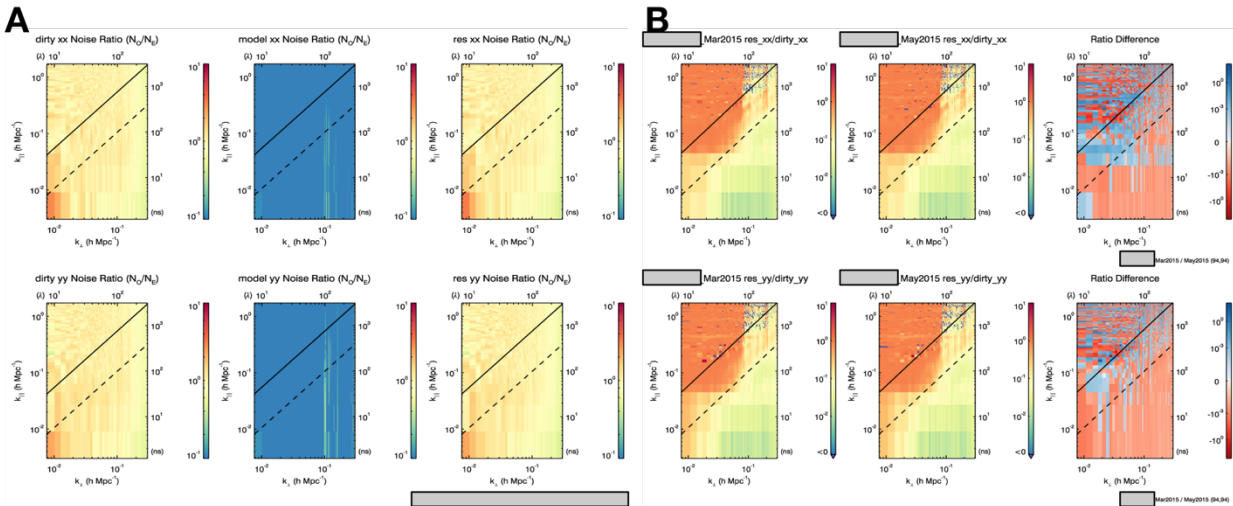


Figure 24. 2D Ratio and 2D Ratio Differencing plots produced by ImgPower. Examples include: A) a ratio 2D power spectrum, and B) a ratio difference 2D power spectrum. The construction of these plots by Brianna enables her and the rest of the group to assess whether part of their analysis performed in CalibratorImager and ImgPower is helping or hindering the overall analysis.

The medley of plots produced by ImgPower and CalibratorImager all help the Radio group with the “qualitative” analysis that Magnus emphasizes. Designing and producing these artifacts enacts a language through which these individuals can cooperatively do scientific work. As happened during the first all hands meeting I attended, multiple plots are spread across the tables in the Physics department conference room (see Figure 5 in Chapter Three) during the

Radio group's regular all-hands meetings. During US EoR group teleconferences plots will be shared digitally through the WebEx videoconferencing tool for discussion.

Plots cannot exist without data to process through the US EoR pipeline³⁴. Brianna stressed the importance of the group finally having data from the completed telescope to their software production since "you just can't find stuff until you have data." When she told me this in early 2014 the Widefield Radio Telescope had only entered an operational state in July 2013. Data was only starting to be captured and reliably transferred to the RadioCluster for the US EoR group's analysis. Prior to this the EoR Science Collaboration did not have much in the way of data to work with while building their data processing software. There was an initial test dataset produced by a 32 antenna tile fledgling version of the telescope (compared to the final device's 128 antenna tiles) but this data was not going to be representative of the final device.

Without data plots cannot be produced and as a result really digging into the software and understanding its operation and bugs is not possible. The group could not interrogate the infrastructures they were working among without plots. The plots enable the Radio group to see into their software and telescope's operation. Key to creating plots is analyzing data with the Radio group's software and as I've mentioned before doing this requires that a human select the data to be analyzed.

Cooperatively shaping analyses by making cuts to the data using plots

Over the course of their cooperative data production work that I described in Chapter Five the Radio group and the EoR Science Collaboration are producing petabytes of data. To analyze all of this data these researchers must select subsets, a type of data processing work that I describe

³⁴ Throughout my data collection the US EoR pipeline relied upon actual observation data for testing and analysis. As I ended my time with the Radio group for this dissertation they were in the midst of implementing a simulation framework within the pipeline that could produce plots without actual observation data. This simulation work is a point for future research.

in (Paine et al., 2015). In the context of this dissertation I consider this to be an analysis activity since it is a point where an individual such as Abner consciously chooses what to include or exclude. I noted in Chapter Six that between Munchy and CalibratorImager as well as between CalibratorImager and ImgPower an individual must select which data should be analyzed with the pipeline. The Radio group refers to this as making cuts on the data. Cutting data is a point in the analysis designed to intentionally involve a human in the pipeline's operation. Plots as well as self-documented metadata from the telescope and US EoR pipeline facilitate these cuts.

Analyzing different quantities of data is central to the work of testing, debugging, and revising the US EoR pipeline's components. Plots in the Radio group's work can be produced on as little as a single observation's data—a 2-minute chunk as I noted in Chapter Four—up to as many hours as have been captured and the group desires to integrate and pass through the US EoR pipeline. I described above how Igor in that meeting I attended spread dozens of plots out on the conference table. Here in Figure 25 and Figure 26 is an example of this practice scaled up during one of the Radio group's "busy days" where everyone came together to analyze dozens of plots cooperatively. The group was at a point where they were doing a larger integration of data than previous tests (more than 40 hours versus the typical maximum of around 3 hours before) in support of Abner's dissertation work. Printing out 2D power spectrum plots, on in this case 30 minute chunks of observations, and laying them out across the table helps the group qualitatively spot oddities in their analysis.



Figure 25. A Radio group "busy day" analysis using 2D power spectrum plots.
Image courtesy Magnus. The 2D power spectrum plots are arranged around a conference table and marked up by the members of the Radio group to highlight effects that raise questions about the analysis.



Figure 26. A Radio group "busy day" analysis using plots.
Image courtesy Magnus.

My initial understanding of the Radio group's work did not foreground the importance of this human selection of data, what they call making "cuts." As I worked through my diagram of their software in my last round of interviews multiple members stressed the importance of a researcher being involved in the integration of data, especially between CalibratorImager and ImgPower. The necessity of a researcher's explicit analysis and selection of data between each pipeline component became prominent and through my own data analysis I came to realize that this is one of the points where the cooperative decisions of this arrangement of researchers is shaping the resulting scientific analysis and in the end the knowledge created.

I knew at this point in my study that Abner's Munchy component is designed to automatically take data that is transferred from the Widefield Radio Telescope to the RadioCluster and process it through FlagAvg, but the inflection point between CalibratorImager and ImgPowr was less clear to me. Munchy automatically runs all data transferred to the RadioCluster through FlagAvg for a couple of reasons. First Abner wants to immediately reduce the amount of storage space that observations take up on the RadioCluster since this resource has a finite amount of space for storing data. Second, whenever an individual goes to work with a particular observation it will be available in a data product that is ready for processing with CalibratorImager. Third, the statistics and other metadata produced when running FlavAvg will be available to use in the data selection process since the Radio group intentionally keeps a "human in the loop" when selecting or integrating data. Making cuts of the data shapes what the product of all of this data analysis will be since a decision is made regarding the quality of the observations. Since this software is a piece of active, ongoing research the Radio group wants to assess the data they are using to test and refine their software, rather than just blindly working with all of the observations that they have collected.

This is not automated at this point. We have scripts that do many runs of [CalibratorImager] and that's automated, but at this point going from here to here there's kind of a human in the loop. You wanna choose data that you're interested in, because we're making UVFITS for all the data. ... But because you know this is an active topic of research, we want to know what that selection should be, and so you need a human in the loop at this point to take the output of the power spectrum and all of the other quality statistic stuff that we have and to process that and figure out what the cut should be. And then once you have that cut that you want, the rest is automated. (Abner, interview)

The metadata created through the on-duty astronomer practice during the EoR data collection process (discussed in Chapter Five), the metadata output by FlagAvg, and the additional metadata produced by CalibratorImager all result in information that the Radio group can use to select data during analyses. This guides them as they make their cuts after running CalibratorImager and before integrating data to run through ImgPower. Over time as their software production has unfolded the Radio group has progressively worked with larger integrated quantities of data in their testing. Initially working with just two minutes of data would reveal many bugs in their software. As issues were fixed the group over time shifted to working with 30 minutes of data, then 90 minutes, three hours, and so on.

Creating plots of different quantities of data being analyzed reveals different features to the observations since more data captures more signal, and of course noise. As more and more data is integrated together there will be more information for the different aspects of the software to work with resulting in a fuller picture of the sky. At the same time the residual signal being sought out begins to be drowned out by greater amounts of noise coming from systematics. The varying features that appear—such as the fourth line bug discussed below—in the EoR window need to be understood and removed, or at least reduced, through improvements to the software for the Radio group to be able to offer useful scientific findings.

Producing the US EoR pipeline and testing it with different quantities of data is not a task the Radio group undertook alone. The LivePipeline elsewhere in the EoR Science Collaboration was also being built and tested at the same time. In Chapter Four I described how the EoR Science Collaboration elected to have both of these software pipelines be able to exchange data products so that results could be compared as each approach to analysis was built. In addition to this design choice the EoR Science Collaboration also chose to define a specific subset of EoR data for each pipeline to test with. This is known within the EoR Science Collaboration as the “golden dataset.”

Defining the golden dataset to analyze while testing software

Working with all of the thousands of hours of data the EoR Science Collaboration is collecting at once using the US EoR pipeline and the LivePipeline is not feasible for many reasons, chief among them being the amount of computational time this would require. Each pipeline is also the active site of much of the various group’s research work and thus filled with endless expected and unexpected bugs that have to be cooperatively found and assessed. To facilitate each group’s pipeline testing and analysis the EoR Science Collaboration chose to define a common reference dataset for this work. This dataset is known across the collaboration as the “golden dataset.”

The golden dataset is defined by this arrangement of researchers as a single day’s worth of observations from early in the operational phase of the Widefield Radio Telescope. Igor noted that the golden dataset is 94 observations—each observation is again two minutes—from one day in August of 2013. Brianna reflected that the golden dataset was chosen when the EoR Science Collaboration was trying to “start ramping up” on the testing and use of the two pipelines. Collectively they wanted to select some data that everyone across the collaboration could begin to look at and compare results with. Brianna and Abner both noted that the members

of the collaboration selected this particular day of data because it was one of the earliest operational days where the telescope appeared to be functioning without issue based on all of the self-documented metadata they had to examine. Abner noted that before this day there was a lot of bad data while Brianna commented that some images from this day's data had been produced and "didn't look crazy."

So we kinda had some light touches on data and we had a feeling that the 23rd was maybe a good day because the instruments seemed to be behaving properly, a few people had looked at some images and they didn't look crazy. That was kind of the extent. (Brianna, interview)

The EoR Science Collaboration began working with the golden dataset by selecting what is known as a zenith pointing because the shape of the telescope beam is simplest in this case with most of the signal captured in that central core. As I described in Chapter Four a pointing in the WRT directs the telescope to capture a particular swath of the sky that is of interest while reducing the field of view. For the Widefield Radio Telescope a pointing corresponds to the set of delays that are specified for an observation in the Analog Beamformers. The zenith pointing is when the observation is directly above the telescope on the sky, see Figure 27. There are five evenly spaced pointings in each direction from the zenith. The pointings shift over the course of a night of observing and are re-oriented depending on how a Science Collaboration is operating the telescope when collecting data.

For any given night the space in the observation where EoR signal is sought will shift across several pointings. Working with data from a zenith pointing is in some ways simpler than data from other pointings because the shape of the telescope's beam and the resulting signal captured is more uniform and without as much signal in the side lobes. I noted in Chapter Six that the side lobes are not well modeled while discussing the telescope's beam model that Igor incorporates in CalibratorImager. If the Radio group were testing with pointings where there was

significant signal captured in these side lobes then they would face a different set of possible bugs arising in their software. To help abstract away this possible complication in their testing, data from pointings farther from zenith were generally less used, (e.g., data from pointings -5, -4, 4, and 5). Pragmatically foregrounds such as the galaxy also tend to appear prominently in the pointings farther from zenith as the sky above the telescope has shifted orientation.

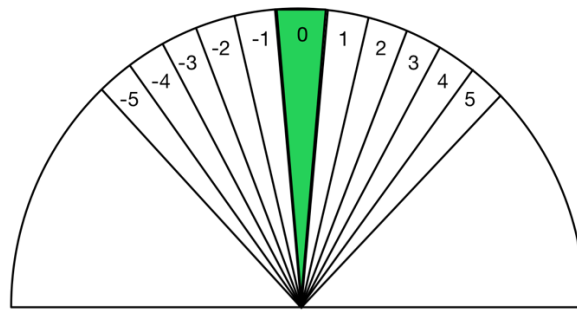


Figure 27. Widefield Radio Telescope pointings.
The diagram illustrates the WRT's pointings with the zenith or overhead pointing highlighted in green.

Defining the golden dataset and working with varying but increasing quantities of observation time from this dataset helps the Radio group coordinate data analysis and pipeline testing work with their collaborators across both the US EoR group and the EoR Science Collaboration. This is possible again because by design the two pipelines can exchange various different data products. As each group's analysis software is written, and using this one night's worth of data, data products output can be discussed and approaches evaluated. The two groups and their different cooperative work arrangements overlap by all using the golden dataset observations as a common field of work so that different analyses can be compared and contrasted as each arrangement learns more about its software analysis. When publications about these scientific methods are produced, or findings about the Epoch of Reionization are offered, data is analyzed using both pipelines with products exchanged and compared to demonstrate the variations in each set of software while also arguing for the validity of each approach.

Using a zenith pointing from the golden dataset was the first step in testing both of the EoR pipelines and demonstrates a tension in this work between finding new problems and working with quantities of data that are computationally analyzable in tractable amounts of time. As bugs were fixed the quantity of data from the golden dataset being used expanded to 30 minutes, 90 minutes, and up to 3 hours in their iterative process of analyzing increasing quantities of data. Brianna describes this as a series of tradeoffs between amounts of data that will reveal new bugs or effects and that can be rapidly processed with the computing systems available to these groups.

Brianna: So first of all, we picked the zenith snapshot, so a single obsID [observation], and we went and worked on it and compared notes. And then we started wanting to do longer and longer things, and so we went up to this three-hour set. It turns out that three hours is long enough to see a lot of stuff.

Drew: Right. I recall that.

Brianna: Yeah. So it turns out to have been a use and it doesn't take forever to run. So it's a tradeoff between can we see subtle effects and is it processable – the shortest amount of processing time to shorten the loop on development, and three hours has been working well for us for a while. We saw new things in three hours that we hadn't seen before, so the fourth line first made its appearance in three hours of data, and we can see a lot of subtle effects of [CalibratorImager] gridding and stuff in three hours and you can process it in a couple of hours, maybe a night. (Brianna, interview)

In the end the Radio group consciously selects the data they are analyzing and testing their software with manually rather than automatically computationally working with everything they collect. Increasing from single 2-minute observations upward through hours of integrations helps them surface new systematics and bugs in the analysis while balancing the computational resources they have available and to reflect on the scientific questions they are trying to ask. Key to the US EoR pipeline's operation is the use of varying quantities of data to surface these different phenomena.

The selection of different pieces and quantities of data all feeds into the Radio group's testing practices. This is a concept known as jack knifing. Before I discuss jack knifing I want to discuss the fourth line bug since it illustrates the connection among the multiple layers of the Radio group's infrastructures and demonstrates how plots are used in testing.

The Radio group's 'fourth' line bug and the role of plots in testing and analysis

The 2D power spectrum plots visualize characteristics of the Radio group's data, the Widefield Radio Telescope, and their software analysis. The fourth line bug is a simple example that I'm discussing here because it illustrates the intertwined nature of the Radio group's data, software, the Widefield Radio Telescope, and their entire approach to high-precision analyses. This bug arose during my second episode of data collection and was a significant bug to be fixed during this time period that in time faded to become a known element to account for in this data analysis. The fourth line bug is an example of how the cooperative software production is part of the Radio group enacting a research infrastructure even as a component of that infrastructure is breaking down and misbehaving.

Earlier in the chapter I described how three harmonically spaced horizontal bands are expected in the EoR Window of the 2D power spectrum plots, see Figure 23-B. These horizontal bands are a known systematic—again those flaws captured in the data that do not integrate down as more data accumulates—from the design of the WRT instrument. In January 2014 one systematic arose in the 2D power spectrum plots that was not expected. A fourth horizontal line appeared, faint but present when Brianna was analyzing three hours of data integrated together (see Figure 28 below). This became the “fourth line bug” to be analyzed and fixed.

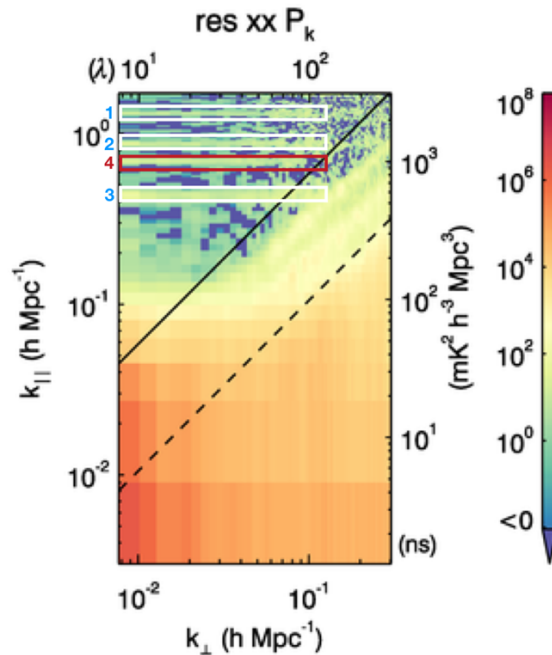


Figure 28. The 4th line bug in a 2D power spectrum plot.
The fourth line is highlighted in red while the three expected horizontal harmonic bands are in white.

By January 2014 the Radio group had progressed from testing on 2-minute observations to 30 minutes of data, then 90 minutes, and ultimately during this period 3 hours of integrated data. As Igor and Brianna fixed different bugs in CalibratorImager and ImgPower the group was to a point where new things were not being seen in plots created with CalibratorImager. They needed to look at 2D power spectrum plots from ImgPower. I arrived one day in Brianna's office for a discussion to find her and Magnus huddling over a few of her latest 2D power spectrum plots from an integration of 3 hours of data. This fourth line had appeared in her plots and she was discussing it with him after having spent time puzzling over it with Abner.

Over the course of our conversation Brianna began to explain this new bug to me. Walking me through plots she explained how the group expected three harmonically spaced bands in the EoR Window, lines 1-3 in Figure 28. Igor had just recently implemented a new calibration approach in CalibratorImager and these plots were from one of her latest runs of the

pipeline using this update to his software. An embedded aspect of the group's infrastructure had been modified. Brianna explained to me that she noticed that this fourth line appeared in between two other expected bands but was not harmonically spaced. This was immediately suspect because of the mathematics underlying the construction of these plots and the design of the telescope itself with the bandpass filter resulting in harmonically spaced bands. Brianna continued on telling me that she and Abner would have to figure out some tests to try and isolate the source of the fourth line in these new power spectrum. Having talked with Magnus they had generated some ideas to go and run on the RadioCluster to produce new plots for further analysis.

Over the next few weeks the Radio group cooperatively developed some ideas of what may be causing the fourth line bug. By the time I attended an all hands meeting during the last week of February 2014 Brianna had Abner running some tests of the pipeline using the RadioCluster. When offering her status update during an all-hands meeting she explained to those in attendance that the fourth line could be coming from reflection in one of the six cables connecting Antenna Tiles to the Analog Beamformers. The working hypothesis at this point was that perhaps one of the cables is bad and introducing noisy signal that is only now coming out in the calibration, imaging, and power spectrum creation.

Given the complexity of this data analysis software, the number of different sources of noise in the data, and the intricacies of the telescope, bugs are expected to arise at any point. Magnus commented to me that in high-precision analyses if there are not bugs then someone is not looking hard enough. During this all-hands meeting as everyone finishes updates Brianna spreads an array of plots out along one side of the conference table, just as someone does during every meeting I attend. Abner also has a new plot that he created pulled up on his laptop to share

with everyone to try and help explain the issue. This plot arranges data from each antenna tile for the specific observation as a way of binning related data together.

As the group walks through multiple of Abner's plots they end up looking at different times of the night in the data. Each plot is all receivers from a specific 2 minute window. At some point Jonah suggests a way to bin the different receivers data. Magnus suggests that this binning would be useful but that they also should fold in metadata, such as the cable length. As usual during the meetings the group works through a problem and develops potential solutions to attempt. I'm finding this to be an interesting but perhaps not unsurprising part of their research and "design" process. With regards to the plots Abner has produced Magnus notes that you can examine a specific row or column to look at tiles connected to the same receiver. This should be possible on many of the plots they often make where they display the data from all 128 tiles. (Fieldnotes, 2014-02-26)

During this all hands meeting Brianna and Abner share their efforts to understand the root cause of the fourth line in these 2D power spectrum plots. Using Brianna's printed plots and those on Abner's laptop the group as a whole break down these different pieces of data and their relation to the physical layout of the telescope. Different individuals suggest ways to bin or organize the data to try and isolate particular antenna tiles and other components. Igor ends up offering an idea of something to change in his calibration implementation during this discussion.

In the end many different possible causes are discussed and Abner writes down many things to try and test. The following day they are going to have a US EoR group teleconference and Magnus wants the group to bring this issue up for discussion with the rest of the folks around the US. When this teleconference takes place the next day Brianna suggests that the issue could be arising from early design decisions made when implementing some piece of this software. Similar to the Radio group's all hands meeting plots are shared and ideas discussed among those in attendance. The fourth line bug is present and needs to be addressed, just as many others have been and will continue to be in this high-precision analysis work.

Over time Abner and Brianna completed tests and the Radio group determined that the fourth line is coming from reflection of the signal in the 150 meter cables of the Widefield Radio Telescope. I explained in Chapter Four that there are six lengths of cables connecting Antenna Tiles to Analog Beamformers and it turns out that the 150 meter cables are reflecting the electromagnetic signal they are carrying (all of the others probably do as well). Abner is tasked by the group with modeling this cable's signal reflection and devising a calibration solution to incorporate into CalibratorImager. This calibration solution is integrated into CalibratorImager by Igor and the fourth line disappears to the point that it is not visible in 3 hour integrations of data. For the Radio group the fourth line bug is now a known systematic in their ongoing cooperative analysis. The problem is not going away, it is a permanent feature and entanglement of the telescope in the observation data, but they are able to address it in their software through changes to their calibration approach. The analysis simply incorporates the flaw and navigates around the issue to the extent possible.

A year later in January and February 2015 during my third episode of data collection I was again discussing the fourth line bug with individuals in the group. I wanted to hear about this issue after time had passed, other issues arose, and analyses had continued on. When Brianna first explained the fourth line bug to me in early 2014 it was with great urgency. It was not expected and it was a hindrance to their analysis. I described this briefly in one of my publications in the following months (Paine & Lee, 2014). By the time a year had passed the fourth line bug was just part of the work, a known issue but not one that was a major concern. It was an embedded facet of the data products produced with the Widefield Radio Telescope and something the Radio group's data analysis practice simply needed to account for in their software. Abner described that in the end they determined the problem was the cable reflections

and commented that “for a while we were doing a good job of removing it” with their calibration solution. But as Abner integrated 40 hours of data for his own dissertation work the fourth line bug was appearing again, as in fact was a fifth line bug. Improvements can always be made to the analysis but for the time being the bug was no longer an unexpected, unexplained issue.

So we put in a bit or you can optionally say calibrate the 150-meter cable length, and it includes that in the solution. We have noticed though as you go longer, integrate it longer, it creeps back in, and that’s why you can see it. It’s very plain when you integrate up to like 40 hours, so we need to do some more work to get better solutions for it to remove it again, but yeah. So it has worked as an intermediate solution, but we need to do a better job of determining the true reflection, like the reflection co-efficient so we can get it out. (Abner, interview)

The fourth line bug as one fairly simple example illustrates a few interesting aspects of the Radio group’s cooperative production of software. This example concretely shows how plots surface different phenomena embedded in data products in this group’s high-precision scientific analysis. How plots are constructed—both as a designed object and in particular instantiations based upon the amount of data included and the version of the software used—changes their visualization of this scientific analysis. Following the emergence of an unknown systematic in a 2D power spectrum plot enables me to follow moments in the Radio group’s cooperative analysis and testing work. I can begin following a few individuals and see how this expands to include a larger cooperative work arrangement composed of members from the overall project.

The fourth line bug surfaces the deep interconnection of the Radio group’s complex software analysis with the other infrastructures they work to enact. Data products created and used in the US EoR pipeline when visualized through plots create a tangible thread that brings to the forefront the intertwined relations among their infrastructures and practices. In use these data products and the plots of them are coordinative artifacts, providing a tangible artifact of this work to discuss. The discussions between individuals and during meetings produced tests to run

and hypotheses about the source of a systematic. A simple unexpected horizontal line necessitates a deep interrogation of myriad interconnected facets of the data analysis software and the telescope's physical construction, inverting pieces that had become embedded in the background of this group's emergent and in-flux infrastructure for high-precision cosmology data analysis.

The fourth line bug arose right around the time when the Radio group's software was near the point of being ready for the group to implement their primary formalized testing practices. These are what they call "jack knife" tests. The group's testing and analysis up until this point was extensive but the shift to being able to conduct jack knife tests brought new structure and rigor to the process.

Jack knifing as a concept for teasing apart data and software

Testing the US EoR pipeline's components requires continual iteration between writing the software, executing it using data, and analyzing the different plots output. Testing is at heart a process of analyzing this emergent infrastructure, probing and shifting its components to better meet the group's scientific goals. The recurring testing practices that I observed in the Radio group's work are described by these researchers as jack knife testing. Jack knife testing is conceptually simple but enables rigorous comparison of outputs from the US EoR pipeline.

Jack knife testing consists of carving up data (or in this group's extension of the notion the software's operations) and comparing different outputs. Brianna introduced the concept of jack knife testing to me, commenting that in physics it is typically the process of breaking up data in different ways to engage in comparisons so that different phenomena can hopefully be seen that would not otherwise be noticed. A variable from the observation data is chosen and isolated so that the group can examine the effect it has on their analysis approach. When I asked

Brianna what this term meant she explained that jack knifing is “carving up your data in different ways and seeing if you see different things in the different pieces.” She offered an example of a radio signal bouncing off of the moon and appearing in the data very faintly when multiple observations are integrated together.

In Brianna’s moon example signals in the FM radio band broadcast on Earth travel into space and end up bouncing off of the surface of the Moon back to Earth. The Widefield Radio Telescope is not intentionally observing at these frequencies, but some radio frequency interference (RFI) from these broadcasts can end up in the collected observation data. This RFI is such a faint signal that it is not visible in images produced from an individual two-minute observation. When many observations are integrated together and a power spectrum plot produced the signal can become visible. One possible jack knife test would then be to “carve up your data into moon and not moon. ... And you make power spectra of each of them, and you see if there's any difference. And if there is, you exclude the moon from the data you integrate on” (Brianna, interview).

This simple idea of carving up data to isolate some phenomenon is a convention of practice in Brianna and the rest of the Radio group’s ongoing analysis work that is being constructed and in time embedded such that it must be learned by new members joining the group. During my second episode of data collection Brianna was just getting to the point of having `ImgPower` implemented in the manner that she wanted to support jack knife testing. Brianna, Igor, Abner, and the rest of the group had of course been testing their software analysis approach for multiple years up until this point, finding and squashing endless different bugs and restricting and refining their scientific method in this co-constructed process (Fujimura, 1996).

But this was not enough for the Radio group. They wanted to be able to conduct more rigorous tests and Brianna was enabling this by crafting ImgPower to produce differencing plots.

Producing differencing plots for use in jack knife testing

Jack knife testing in the Radio group is accomplished through the analysis of power spectrum plots. Brianna designed her ImgPower software to output not only 1D and 2D power spectrum plots but also the “ratio” and “ratio difference” versions of the 2D plots in Figure 24 above and “differencing” plots below in Figure 29. Brianna creates differencing plots by taking two 3D HEALPix cubes and subtracting them, then binning (organizing like data together, i.e. data from the same pointing on the sky) and plotting the result to produce this visualization of how well the US EoR pipeline is or is not subtracting unwanted power out in their analysis.

The differencing and ratio differencing plots are intentionally designed to be used in the process of jack knife testing by harnessing key details of the design of the data products that she and Igor exchange. Brianna’s differencing plots produced by ImgPower enable the comparison of either: 1) different days of data collected with the Widefield Radio Telescope, 2) or different analyses of the same data, i.e. the difference in implementation of some aspect of the US EoR pipeline software. Producing differencing plots on a selected observation for every change in the CalibratorImager software emerged as a testing practice characterized by Igor as “power spectrum as version control” for example.

Differencing plots were specifically created for jack knife testing because from the perspective of the Radio group their analysis is improved if a power spectrum output by ImgPower is better. What counts as better depends on the group’s cooperative qualitative analysis assessing whether effects from the signal in foregrounds or systematics are reduced and

falling out of the EoR Window in the power spectrum plots. Removing this signal decreases the amount of contaminating noise in that window. That noise masks the sought after EoR signal.

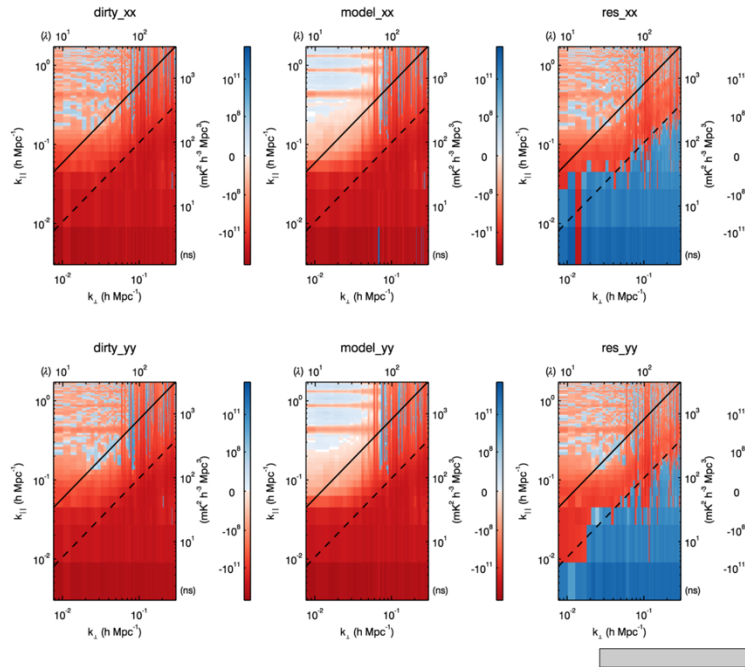


Figure 29. A 2D power spectrum differencing plot.

ImgPower's differencing plots result from subtracting one HEALPix cube from another. Brianna explained that blue and red can be either good or bad depending on the plot and the conventions constructed by the group for that instantiated output.

The difficulty with using plots as a language and mechanism for testing and analysis is that changes in a power spectrum plot are not necessarily easy to see if a change in the US EoR pipeline software results in a subtle effect. In addition, Brianna's regular 2D power spectrum plots cover many orders of magnitude of the signal captured which also makes it difficult to see changes. Brianna designed differencing plots explicitly to help highlight subtle changes in the analysis by foregrounding changes in contrasting blue and red.

And so we have really realized that the measure of whether something makes things better is whether it makes these plots better. And often these plots, the ones that aren't differenced, cover ten orders of magnitude, so it can be hard to see subtle changes because it's just a subtle change in a color bar that covers seven, or eight, or ten orders of magnitude. So by differencing them, we can see highlights of what those things are. (Brianna, interview)

Abner explained differencing plots to me by describing a test with one day's data. He explains in this vignette how all of the data for a particular pointing would be used to form a power spectrum by binning the data together. The data for the same pointing from another day is then used to produce a second power spectrum. Typically, this second day would be that of the golden dataset that the EoR Science Collaboration cooperatively defined for comparing analyses among pipelines. One power spectrum would be subtracted from the other leaving the difference in power. This is then plotted by `ImgPower`. In Abner's example here the particular pointing of the telescope on the sky is chosen to be constant between the two different day's data. This is the variable that is not changing and is being jack knifed in this test.

Abner: Yeah. So these difference plots are differencing the power spectrum that we create using two different sets of data. So here we're testing the day, so we choose all of the data from a given pointing. This time it was minus two pointing—so two pointings before zenith.

Drew: Okay.

Abner: And then we compare it on the August 23rd day, and it's written in Julian dates, and I now know the Julian date of August 23rd, 2013.

Drew: I was going to say I do not. [Laughs]

Abner: As well as the following Tuesday. [Laughs]

Drew: And why the following Tuesday?

Abner: So we've done it with all the different dates, but that just happens to be the one that's on top [of a pile of printed plots he's showing me]. And so you form the power spectrum from both of them. They visually look the same, so what you can do is subtract the two and compare to see if there are any obvious things that are sticking out. This is an example of actually a pretty good one where it's all hashy. It's red and blue; it's everywhere. There's no clear pattern there. There's maybe a little bit of a smudge of blue there, maybe a little bit there. Well –

Drew: And so you do not want a pattern here?

Abner: We don't want a pattern, but I can show you examples where there are clear patterns. This one from that same, I think it's a Tuesday. But the pointing two. So this is two pointings after zenith.

Drew: After, okay.

Abner: And there's a huge difference in the power spectra.

Drew: Which is resulting in the huge amount of blue?

Abner: Yeah, all the blue, so that means that the August 23rd was higher for some reason and we need to sit down and think about that –

Drew: And so to you that's a jack knife test where you can start to then have to inquire –

Abner: Yeah, yeah.

Drew: as to the source of this error I guess?

Abner: Right. And it really helps us find systematics by you know figuring out what was going on this day that made it so bad. If we can figure out what that was, we can go back and look at does this occur in other days where we didn't see it but it's there. (Abner, interview)

In this instance of a jack knife test that Abner walked me through the Radio group will difference data from two days, resulting in differencing 2D power spectrum plots. They will visually examine the resulting plots and look for patterns across multiple days. The goal is for the differencing plot to be “hashy” where there is no discernable pattern. Should an unexpected pattern be visible then this prompts a discussion and reflection among these researchers about what might be the underlying cause. In Abner's example one day's power spectra was significantly different from the other resulting in more blue, which in this plot is not what they would wish to have since more power is being subtracted thanks to a change in the software.

Using differencing plots (among others) the Radio group is constructing a shared understanding of their data, software, and the telescope through this process of jack knife testing. In conjunction with all of their work writing the software this testing work rounds out the Radio group's ongoing scientific analysis. Working with the software, data products, and plots they

evaluate these intertwined infrastructural components to better understand the Widefield Radio Telescope, their software, and eventually the intensity of the EoR signal they are capturing.

Brianna explained the concept of jack knifing as common in physics with regards to data. Different in the Radio group's work is the extension of the idea to use it to test different versions of their various pieces of software. The testing Abner was tasked with during the fourth line bug episode required modifications to CalibratorImager's operations. The ongoing work that the group undertakes, and had been undertaking over years prior, really comes down to assessing whether changing X or Y element in the software improves or worsens a power spectrum. Jack knifing formalized these practices. In particular, Igor crafted the "power spectrum as version control" practice as a way to reliably jack knife CalibratorImager as he makes significant changes.

Jack knifing CalibratorImager, the "power spectrum as version control" practice

Beginning in 2014 the Radio group really began to intensively test the components of the US EoR pipeline with collected EoR data. Igor conveyed to me that over the course of six months of 2014 CalibratorImager's 30,000 lines of code had some 70,000 changes logged in the GitHub repository. This massive re-write changed many details of his software as the group collectively constructed new approaches to components of his calibration and imaging. As a result of the rapid pace of Igor's changes to CalibratorImager Igor found the need to develop a methodical jack knife practice for this software because power spectrum plots were being rendered incomparable. Igor determined that he and the Radio group needed a way to test CalibratorImager that brings together software, plots, and the common reference golden dataset. Igor did this with the practice known as "power spectrum as version control" (PSVC). The PSVC

practice became integral to enabling the Radio group to have traceable scientific analyses over time as the implementation of this key piece of software changes.

Igor constructed the power spectrum as version control practice to be a semi-automated process that becomes a convention of practice in his day-to-day work refining CalibratorImager. The PSVC practice integrates the Radio group’s use of GitHub for storing the versions of their software, a shared Dropbox³⁵ folder for storing and sharing power spectrum plots, and a subset of the golden dataset to enable traceability and reproducibility in their group’s ongoing data analysis and software development. Igor created PSVC so that for every GitHub repository check-in of a change to CalibratorImager he will take the resulting version of the software and use one specific observation from the golden dataset, pushing it “all the way” to a power spectrum plot. It is semi-automated since he manually starts the execution of this on his desktop computer in his office rather than having some automated process do this for every GitHub check-in of his code. PSVC is however designed to be repeatable, using a single 2-minute observation and a stable version of Brianna’s ImgPower software in its operation.

The check-in of a version of CalibratorImager to the Github repository will produce what is known as a “git-hash.” The git-hash is a unique identifier for this version of the software in the repository. It is traceable over time through a search function provided by GitHub and other commonly available git version control tools. Igor’s purpose-built PSVC analysis script will then create a new directory in the Radio group’s shared power spectrum Dropbox folder, naming the folder with that git-hash so that it is easy to know which version of the code itself produced the plots that will be stored inside. Igor’s script then processes the one particular observation from the golden dataset—out of the 94 total observations from that date—through the versions of

³⁵ <https://www.dropbox.com/>

CalibratorImager and ImgPower being tested on his local desktop computer. Out of this a “reference power spectrum” is created and saved to the shared Dropbox folder with the git-hash as part of the filename and embedded as text in the plot. Doing this produces an artifact of the state of the data analysis software that Igor or others in the Radio group can compare future iterations with as they refine and improve their software.

at every git-hash we [the Radio group] have a reference power spectrum of what that looked like at that point and, or with various features turned on and turned off so that you can do a comparison of all right, there is some change. Having just done this one change out of all of the other ones, what change does it have on the power spectrum? Does that make sense? (Igor, interview)

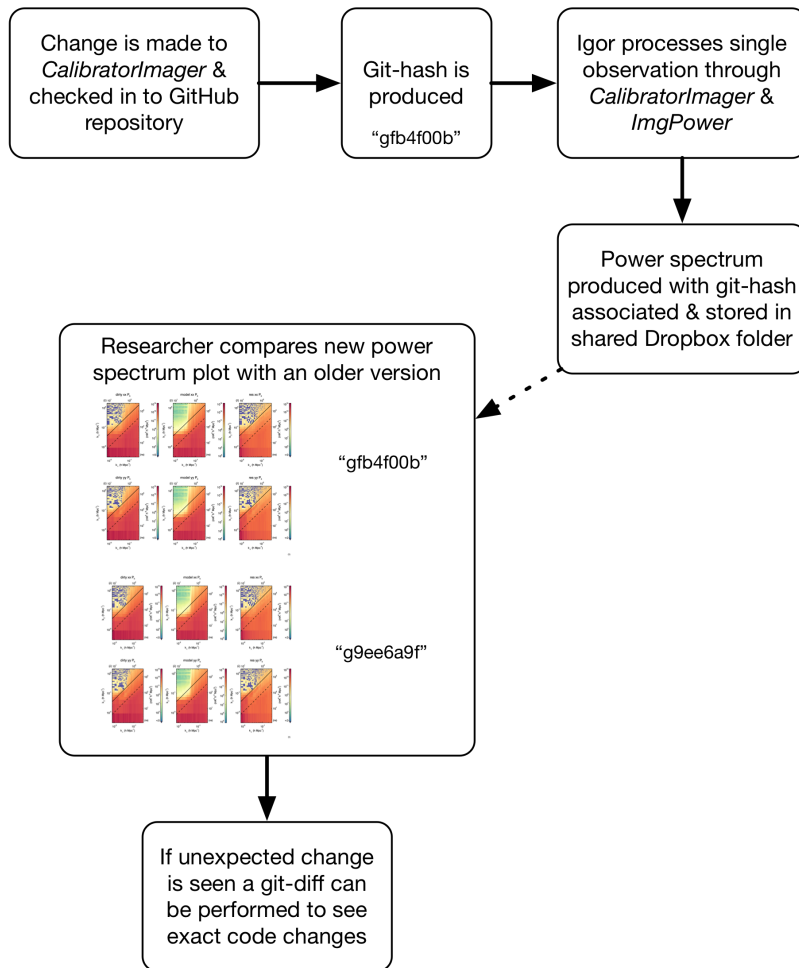


Figure 30. The Power Spectrum Version Control (PSVC) practice. The steps outlined by Igor enable him to create a 2D power spectrum plot that corresponds to a version of the software so that changes are traceable over time.

Through the PSVC process Igor produces a series of reference power spectrum plots. The different changes to and features of CalibratorImager are now comparable over time. Igor can also use the reference power spectrum plots created to jack knife a particular version of his software by turning different features on or off then comparing the output to that reference version. He noted that he runs this process three to four times per day (it takes around four hours for each run on his computer) and as a result is running nearly continuously on his local machine. The process is semi-automated since Igor executes it through a script manually for every check-in of a change to CalibratorImager on his local machine.

Once the power spectrum plots are produced Igor or another researcher in the group can analyze these plots to assess how the changes to the software are changing the resulting power spectrum. This practice relies upon the Radio group's continual qualitative analysis of plots to help enable any individual to follow the impact of changes to the data analysis approach as it is expressed in the software. The tangibility of these plots, visualizing the intertwined data analysis software and telescope infrastructures, provides a mechanism for any individual to invert these layered infrastructures and at least notice when something unexpected arises. They may not immediately know how some effect came about but having the sets of reference power spectrum plots is a prompt for them to begin interrogating their analysis.

When examining one of the reference power spectrum Igor or another member of the Radio group can perform a "git-diff" if a change is noticeable in the plot. Git-diff is a tool that is part of git as a version control system. It differences two versions of code, displaying the lines of code in each piece of software that have changed between two versions. Using the git-diff tool and the power spectrum plots a researcher can examine the changes between two versions of the software. This enables Igor, Abner, Brianna, or anyone else in the Radio group (or even US EoR

group) to analyze how the new implemented approach is impacting the data analysis. Doing this they are jack knifing two versions of CalibratorImager. For example, as Igor or Nima work on changing the different calibration operations in CalibratorImager they can use the PSVC practice to jack knife the original set of operations with a new version. Any changes in the power spectrum can then be analyzed by this person or the group and assessed before development continues.

Igor found that being able to easily trace changes among the different versions of his software was increasingly important as new and very different operations were implemented and tested. Through this practice the Radio group is able to maintain better insight into the implementation of CalibratorImager and the resulting power spectrum pipeline as part of their data analysis work. The PSVC is one easily accessible mechanism for opening up parts of the black box that CalibratorImager can often be for members of the Radio group who are not directly working on its myriad elements (i.e., members other than Igor or Nima recently).

The PSVC as a process is one way that the Radio group extends the concept of jack knife testing from being primarily a way to probe their data to also being a probe of changes in their software. But the PSVC practice is only useful so long as Igor sustains the practice, continuing to do the work to run his software for every change checked into his GitHub repository. Creating and sustaining this practice does help Igor balance one tension he was facing in his work, that of providing a stable infrastructural component for other researchers in the US EoR group and maintaining his active research through this software.

Balancing active research work with the need for a stable production infrastructure

PSVC is a simple, semi-automated practice that was created and put into use by Igor. This practice is a result of the intersection of his need to maintain and sustain some version of

CalibratorImager as a stable, infrastructural piece of the Radio group and their collaborator's high-precision scientific analyses while also continuing to develop this software as the focus of his active research.

The tension between building and sustaining an infrastructural component and doing novel research is raised in multiple CSCW studies of scientific infrastructures (Lawrence, 2006; Ribes & Finholt, 2009). Igor's case is actually a bit different since he is a stakeholder on both sides of the tension rather than one or the other. Part of his work is to sustain the US EoR pipeline as an operational and scientifically useful data analysis infrastructure for collaborators throughout the EoR Science Collaboration. At the same time, he needs to continue advancing his own research goals that are being expressed through his work on CalibratorImager. Igor's continual, iterative work on CalibratorImager impacts the work of everyone in the Radio and US EoR groups as well as the EoR Science Collaboration to a lesser extent. Being able to trace how it changes is therefore necessary to being able to continue to do scientifically rigorous analyses.

Working through many tests and implementing changes inevitably results in changes in the power spectrum plots being produced. Tracing the cause of these changes is not easy if many changes have been made to Igor's code since a power spectrum plot was last produced because these revisions can have compounded effects on the resulting power spectrum. Igor conveyed this when describing the necessity of his new PSVC practice by spelling out in detail that making "a lot of different changes" simultaneously results in difficulty attempting to trace the effect of a single change in a power spectrum plot. The complexity of the processing and analysis decisions encapsulated in CalibratorImager creates a situation where it is not necessarily "intuitive" to the researcher how one change affected the end product many steps later. This turned out to be a major problem for the Radio group in the latter half of 2014.

Using CalibratorImager to achieve a scientific data reduction—taking hundreds or thousands of observations and removing spurious data—means the ideal scenario would be to know “precisely” what takes place as a result of each operation. During the first half of 2014 Igor undertook a flurry of debugging and re-writing of CalibratorImager’s code. Igor’s comment that some 70,000 changes to CalibratorImager’s code illustrates the significant development work that this software underwent. The ability to readily understand how a change impacted the power spectrum was greatly hindered since it might be many iterations between a change being implemented and saved in the software’s GitHub repository and a test being executed by Abner, Nima, or another researcher in the US EoR group.

The thing is, you make changes along the way and the power spectrum changes quite significantly or, and in ways that are not always easy to understand, especially when during development you’re making a lot of different changes and it’s difficult to, when you see a large change in the power spectrum there, it’s rare that there is an intuitive understanding of “oh that is obviously caused by this.” And by large, I mean it’s significant and measurable. ... and when you’re trying to have a scientific data reduction in which ideally you know precisely what is going on and you’re analyzing everything optimally and ideally, a significant change like those things of a appearance or disappearance of a feature is, is worrisome. (Igor, interview)

Brianna described how this feedback loop within the group between Igor developing CalibratorImager and others testing it with different pieces of observation data was large and slow. Between Igor’s implementation of a change to the software and an effect being noticed in the power spectrum could be multiple members of the group and varying lengths of time. There was a real need within the group for Igor to make his revisions traceable all the way through to a power spectrum plot. In essence what Igor needed to be able to do is a combination of software engineering’s notions of integration and regression testing, as I’ll elaborate in the next subsection. A change in one part of CalibratorImager needed to be evaluated for its impact to the

entire system (in this case the analysis's output power spectrum plot) to ensure that it is not negatively changing the overall outcome.

So we've been using these differencing plots for a long time and somewhat more recently we've actually [Igor] has gotten this piece running on his machine and he's started doing umm sort of acceptance testing on every change he makes. So when he makes a small change, he has a standard set of data, one obsID that he runs through the whole thing and makes a difference with the standard – the last good thing, and he can see immediately what that change did in the power spectrum. ... And that has been revolutionary because there's not this big huge loop to go through three people to tell him, "No, you screwed something up," or "Yeah, that was great." (Brianna, interview)

CalibratorImager as a pipeline in and of itself and as a piece of the US EoR pipeline is simultaneously an “active site of research” and an integral infrastructural component. Making his significant changes Igor did take advantage of one feature of GitHub, that of making branches to his code. Branches in version control systems are a mechanism for saving and eventually merging different changes to the software. A developer can work in branch A without affecting branch B. Igor maintains a master branch of CalibratorImager's code that ideally remains stable and is able to be used in a production setting by other individuals in the Radio group or the larger EoR Science Collaboration to do different data analyses. Igor then created a fork of the master branch (a common software engineering technique) to continue his ongoing development work. The need to create something like the power spectrum as version control practice arose when Igor went to merge his fork back into the master branch. The volume and scope of changes he had made to the software was so extensive that too many elements of the power spectrum plots changed. It was not possible to compare previously created plots with new ones, making it difficult for Igor, Nima, Abner, or the rest of the group to understand whether some new aspect of CalibratorImager was indeed desirable or not.

Igor explained that during 2014 in the development branch he had changed how the telescope beam model data product was used to the point that code broke. As a result of this and other changes the power spectrum became “very noticeably different” which is definitely not a desirable outcome. Throughout this work he had not yet started producing power spectrum for every change so the group had to spend a significant amount of time trying to reconcile his changes with their impact on the power spectrum plots.

Umm, so, uhh that was partially behind back in June when I needed to really create a new development branch was that I needed to completely tear apart the way that the beam model was internally interpreted and passed around, in ways that was going to completely break code, and especially since it was going to be a major rewrite, it was going to be broken for some time so it was off in this other development branch, and with things where – and this then caused the conflict, which took a long time to resolve, that there were a lot of changes that should not have changed the power spectrum, but the power spectrum was very noticeably different. And so this is, so we spent around a month in the fall really trying to figure out what was it that made the power spectrum different and trying to reconcile those changes so that we could merge the code. (Igor, interview)

Out of this breakdown in the group’s practice to help stave off such issues in the future Igor devised the power spectrum as version control practice. This helps to close that “huge” feedback loop Brianna describes and supports the group’s effort to jack knife changes to their software. The PSVC is just one example of the Radio group’s testing of their software but it highlights the inseparability of plots from their testing and analysis work yet again. This group has constructed their scientific practice around plots as a language, whether for figuring out what scientific questions to ask or to tease apart their entangled data, software, and telescope.

I noted above that Igor effectively needed to create a cross of two software engineering testing approaches. I came to this realization when revisiting scientific software development literature and the focus on software testing practices within it.

Jack knifing contrasted with software engineering testing approaches

The Radio group's jack knife approach to testing their data and software are a methodical use of plots in their cooperative work. A jack knife test controls at least one variable so that comparisons between pieces of data or versions of software are able to be completed. These practices help the Radio group better understand their data and software while trying to improve their high-precision analysis. Chapter Two discusses scientific software development (SSD) research, in particular how software testing practices are a particular realm of concern to these computer science researchers. Software engineering as a field advocates a variety of methods for testing software and Nanthaamornphong and Carver's (2015) recent systematic literature review posits scientists typically use variations of unit testing, integration testing, and regression testing if they test the software they are developing. I as a result am interested in how the Radio group's jack knife testing compares to these software engineering practices. I see their jack knifing as helping to ensure reliable, verifiable software given how their work questions all of the intertwined facets of their infrastructures, but perhaps this is not immediately visible in a software engineering frame of mind.

To begin recall from Chapter Two that unit testing is the process of taking one operation or algorithm in a piece of software and writing a test to verify it produces an expected output (Agile Alliance, 2013). Unit tests are meant to be automated and run whenever any segment of code is changed to ensure that the operation the test is concerned with still functions properly. The Radio group's testing did not include explicit unit tests during my data collection. I did not explicitly ask why there was no unit testing being done since I was more interested in learning about the practices they developed as a group rather than trying to have them compare their work with ideas from software engineering. I wanted to set aside my earlier training and learn about

the approaches they created. How unit testing could or could not be accomplished is a worthwhile question for future studies of their work since successfully implementing and writing Unit tests would increase their ability to trace changes in their software. I imagine unit testing ought to be feasible to implement for at least pieces of the Radio group's software. This would first off require that there be a unit testing framework available for doing so in the IDL programming language that CalibratorImager and ImgPower are written in (or if there is not then someone in the Radio group or EoR Science Collaboration taking the time to implement one). The probable biggest hindrance would be an issue frequently raised in SSD discussions of scientists testing their software, the inability to know what a result should be before the software is run (Kanewala & Bieman, 2014). Many of the operations CalibratorImager and ImgPower complete do not have a simple, distillable answer that could be written into a unit test. Instead it is the emergent effect of many operations being completed that produces a result that Igor, Brianna, or the rest of the Radio group can evaluate for its scientific efficacy. As a result, I find that it is more worthwhile to compare jack knifing to the concepts of integration and regression testing.

Turning to think about integration and regression testing I see work taking place with jack knife tests that is similar to these software engineering practices. Integration testing as I explained in Chapter Two is the testing of the integrated elements of a piece of software to see how they function as a whole. Regression testing evaluates how a change to a piece of software compares with a previous version, immediately surfacing an issue if something that was functioning breaks down. Reflecting on the explanations of jack knife testing I just described, they are practices that enable a form of integration and regression testing. Changing some part of CalibratorImager requires that data be analyzed with both it and ImgPower to produce a power

spectrum plot. To me this is integration testing of the US EoR pipeline since the whole of the software pipeline is being evaluated. At the same time the Radio group often ends up comparing the new power spectrum plot with an earlier one that was produced with a different version of the software. The power spectrum as version control practice especially illustrates this. This is regression testing of their software. This is similar to Easterbrook and John's (2009) characterization of climate modeler's testing with visualizations as a form of continuous integration testing, even though these scientists just saw this activity as part of conducting their experiments (p.70).

I see the Radio group's ongoing analysis and testing of their software, in particular through jack knife testing, as serving the same goal as software engineering integration and regression testing. The major difference is one of automation. In these software engineering practices, different frameworks and tools are available (depending on the particular programming language and setup a developer is using) to perform integration and regression tests through the automatic execution of a variety of unit tests. The closest the Radio group's testing gets to being automated is when they create scripts to execute a desired analysis repeatedly on the RadioCluster using the same observation data every time. Igor's PSVC practice also enables the Radio group to regression test changes to CalibratorImager so long as someone manually goes in to do a visual comparison. In contrast to idealized software engineering practices the Radio group's testing is not fully automated yet it does achieve the same end goal, just in a perhaps more limited way.

It is reasonable for a scientific software development scholar to question why the Radio group does not implement automated testing frameworks and practices. But to immediately think this might be a silver bullet supporting their cooperative work would be to ignore the importance

of their plots in data analysis and software testing. Plots are their language and how they understand the operation of their complex software and the telescope. Particular functions in the software could potentially be unit tested automatically for correctness, but defining what ‘correct’ means would not always be easy, and integration and regression tests would be much more difficult to automate because the exact output may not be knowable in advance. Automation would also essentially miss the point of the Radio group’s testing with plots. That they are a visual representation that fosters conversation and reflection about not only how the software works but what the data is and what questions they are even asking.

Testing in the Radio group’s work requires the visual analysis of plots to interpret how these multiple, complex infrastructures are functioning and most importantly whether they as researchers are asking the correct question or producing results for the question they think they are asking. Testing is not a simple churn and repeat process, it is a continual reflective scientific analysis task. A researcher studying this high-precision scientific work should not be shocked that these scientists are not adopting explicit software engineering testing tools and methods. Even though they are enacting an infrastructure that many different researchers are relying upon the software, data, and practices that are this infrastructure’s components are continually being refined. Major revisions may change the substrate underlying an individual’s scientific analysis but on the whole the software development work of the Radio group is working to sustain a rigorous scientific method. I believe that the conversation ought to be reframed to continue to try and understand how this group of scientists is rigorously and repeatedly doing scientific analysis through and with software and plots as their materials. I have not delved into the actual design of these plots as a scientific process and I imagine doing so would flesh out this story and help to continue to characterize how the Radio group does their science.

Summary

My examination of the Radio group's plots, serving as a language in their cooperative work, has looked at how these artifacts visualize the coordinative artifacts (data products) that connect their multiple layers of infrastructure. I did not begin my dissertation work expecting to need to understand scientific visualizations as a tool for interrogating multiple infrastructures, yet from seeing how the Radio group uses plots I have gained a new perspective on the production and testing of software in a highly specialized domain. In Chapters Four and Five I investigated the Widefield Radio Telescope as a multinational project that is building a telescope and infrastructure for cosmology research. In Chapter Six I explained the Radio group's software itself as the expression of their scientific method enacting an infrastructure for probing the Epoch of Reionization (on top of the WRT infrastructure). In this chapter my exploration of plots demonstrates another side of the threads that connect all of this interwoven cooperative infrastructuring work. Plots illustrate how different details come to the foreground and move to the background as different bugs and research concerns change within the Radio group, and the group's knowledge about all of these components increases.

Plots are visualizations of the inscriptions captured in data products that can be scattered around conference tables and huddled over or digitally pointed to during teleconferences. From one of the first meetings I attended to the multiple conversations I witnessed about the fourth line bug, plots were the material with which Magnus, Brianna, Igor, Abner, Nima, and Peg conveyed their science to themselves. They enable these individuals who all contribute to the group's research infrastructure to discuss particular elements and address breakdowns, all while resulting in new and changing conventions of practice. When the fourth line bug emerged Brianna was creating a plot that she was intimately familiar with yet because of the data analysis expressed in

that version of the software with a particular data product that day a new systematic popped out resulting in multiple rounds of assessment and testing by the Radio group.

The notion that plots are a language for the Radio group is simple but vital, and should not be downplayed. The group's scientific method expressed in software is only part of their work analyzing data. These individuals use plots in part to figure out what data to include or exclude in analyses. The inclusion or exclusion of data shapes the analysis, restricting and redefining the realm of possibilities for what systematics or other bugs may be found and what knowledge will result about the Epoch of Reionization. Testing and analyzing data and software by examining plots is part of the Radio group's work of sustaining doable problems as Fujimura (1996) might say. This is how they articulate different alignments among resources across infrastructures in their work. Defining and working with the golden dataset as part of the EoR Science Collaboration is one example of this arrangement of scientists cooperatively creating a mechanism for exchanging knowledge and assessing each other's different approaches to knowledge production.

The Radio group constructs a large variety of plots as they do their work and I only examined a few of the most common here. Looking at the Radio group's medley of plots I have seen how their high-precision analysis producing software as part of the Widefield Radio Telescope project comes together. Plots provide me with a tangible artifact to trace out connections among the multiple intertwined infrastructures of this group's cosmology research—from the different seemingly insignificant elements of a novel telescope (simple but purposefully chosen cables) to implementations of different pieces of software. How plots are designed and produced is a product of this group's cooperative work. Plots become the language through which they coordinate testing and analysis, figuring out how to ask scientific questions of their

various data products. New versions and variations of plots are often created in the group's work as they try and answer new questions that arise. Brianna's creation of differencing plots helps the group continue to be able to see into their software, the telescope, and their data. This is how they see their physics as Lynch and Edgerton (1988) might say.

Doing a high-precision scientific analysis in this group is partially accomplished by creating and running the US EoR pipeline. But this software, and the telescope infrastructure underneath it, would not matter if it were not for the different practices the Radio group enacts. Analyzing data and testing software by creating and working through different jack knives is how this group methodically works to better understand the method they are creating, the data they have collected, and the science that drives them. Jack knife testing and qualitatively analyzing plots are not automated tasks, they require the care and knowledge of the humans in this pipeline in the moment, yet as I discussed the effect of this work is similar to practices espoused in software engineering. The Radio group can only fully test their software through the many of the different plots that they create. The exact output for an algorithm often cannot be pre-determined since the input data will surely have flaws in it. Testing the US EoR pipeline software must be treated as part of the Radio group's cooperative construction of knowledge.

I have now examined many components of the Radio group's emergent research infrastructure and the conditions that is results from. I can now step back to reflect on how all of these components and my different themes come together in this dissertation's final chapter.

VIII. Conclusion, Producing and Working Among Multiple Infrastructures

The impression is for the writer what experiment is for the scientist, with the difference that in the scientist the work of the intelligence precedes the experiment and in the writer it comes after the impression. What we have not had to decipher, to elucidate by our own efforts, what was clear before we look at it, is not ours. From ourselves comes only that which we drag forth from the obscurity which lies within us, that which to others is unknown. — Time Regained, Marcel Proust

Summarizing this software and cosmology practice

Software and twenty-first century scientific research go hand in hand as I have illustrated throughout this dissertation using the case of the Radio group's cosmology research. I have described how this one group in Seattle, WA engages with colleagues across the globe to contribute to and work among the multiple infrastructures necessary for them to be able to probe the Universe's past. Through this cooperative work they theorize, design, build, test, and reflect on a wide variety of knowledge products—from the hardware components of a telescope, and its software control systems, to the complex and novel data analysis software that is central to the Radio group's expression of their scientific method. These highly skilled cosmologists cooperatively develop a deep understanding of their science, software, and the telescope they rely upon for data through their cooperative work. The narrative presented in this dissertation communicates how software matters as a central part of scientific practice in the Radio group's work.

My dissertation addresses gaps in CSCW research by illustrating how the Radio group's work contributes to multiple layers of infrastructure as they simultaneously work among these layers. I show how their practices enable them to work among the embedded relations of multiple layers of infrastructure. Taking software as my object of inquiry and conveying how it is their material for communicating their scientific method demonstrates the depth of knowledge

necessary to do high-precision scientific analysis work. How cooperatively producing software puts into practice this particular cosmology science. I asked how this group of cosmologists is enacting infrastructure through their production of data analysis software. This question results from my recognition that the layers of accumulating elements making up this cosmology group's cooperative scientific practice result in materials and moments spread across time and space, enabling the construction of knowledge about the Universe by more than just these individuals in Seattle. They rely upon resources being created and made available from the Widefield Radio Telescope project—whether these resources are data and an instrument to produce it, or policies for publications to ensure scientific credit and the ability to foster individual's careers—so as to be able to produce software and enact a research infrastructure.

My earliest data collection probed this group's work contributing to the Widefield Radio Telescope while building the earliest versions of their data analysis software. My subsequent data collection examined how they iterated this software to enact scientific method, and work to stabilize this pipeline as a scientific instrument. My final episode of data collection triangulated my understanding of their work, and asked these researchers to reflect on what they had accomplished. At the same time, I was beginning to see their data analysis software become infrastructural, supporting particular scientific inquiries of the EoR in a shift from extensive work building and stabilizing their scientific method.

Enacting a research infrastructure through a group's cooperative work

Star and Ruhleder (1996) emphasize that infrastructure emerges in practice for people. The infrastructure I see emerging from the Radio group's work is oriented around the US EoR pipeline. This pipeline is a collection of different pieces of software (mostly produced by this one group although one key piece, FlagAvg, is built by an outside collaborator). It is also in part this

group's different data products (and plots of them), and importantly their different practices involving these artifacts. Producing the Munchy, CalibratorImager, and ImgPower software, along with the endless different data products, enables Abner, Igor, Brianna, and the rest of the Radio group to enact a research infrastructure for analyzing interferometric data because these resources are the materials around and through which their cooperative work unfolds. These pieces of software began as efforts for primarily the group's use, but over time were positioned as official outputs of the WRT Collaboration, as I explained in Chapter Four, and in practice are relied upon by many members of the US EoR group to do their scientific work.

For any member of the US EoR group or WRT Collaboration using the US EoR pipeline requires learning its conventions of practice; from how CalibratorImager configures its representation of the Widefield Radio Telescope, and the sky it is inscribing, to the design and construction of HEALPix cube data products that are produced for power spectrum creation. At the same time producing this software requires learning the conventions of practice the EoR Science Collaboration creates to produce data. Using data products created by some version of the US EoR pipeline requires understanding the operations and assumptions that transformed the initial data into the output form. Becoming a member of the Radio group (or of the collaboration's they work with) requires learning how to interpret their variety of plots and being able to use them as a language to convey the scientific questions being studied, as well as the operation of the telescope and software. Plots enable these researchers to open up and examine the enacted effects of their data analysis decisions. Different elements of this software merge into the background of their work, only to surge to the foreground when breakdown occurs—the example of the fourth line bug emphasizing the six cables connecting Antenna Tiles to Analog Beamformers being one case.

Perhaps the biggest challenge the Radio group faces over time is sustaining and maintaining this software so that it is stable and usable for scientific inquiries while continuing to re-construct different facets as their research approach is adjusted and adapted to new research questions—the quintessential task of science in action. Changes in this local group’s membership, let alone that of their collaborators, results in a need to be able to teach newcomers how to use this data analysis software. New members must begin to learn the group’s conventions of practice, how CalibratorImager and ImgPower are designed, and so on. For Brianna, Igor, and other individuals who have been doing this work for years this upends their embedded assumptions, requiring they re-examine and explain them to new group members.

Changes in the infrastructures underneath this data analysis software layer (since the WRT is being expanded and other entirely new telescopes designed and built) contribute to this challenge as well. New or changed instruments produce data products with different characteristics and this will force at the very least CalibratorImager to be adapted and re-shaped in part. Practices will have to be re-examined and potentially modified to be able to embed different underlying infrastructures into the US EoR pipeline, and the Radio group’s work.

I discussed in Chapter Six how Igor wants CalibratorImager to be a general-purpose data calibration and imaging pipeline. In practice he has developed his software to work with different telescopes. I see Igor managing this challenge in his own aspect of the Radio group’s work, from early testing work with data from pre-existing telescopes to adapting CalibratorImager to work with a revised WRT beam model. Seeing how Igor, and collaborators, continues this work as an extension to the Widefield Radio Telescope is built (work was beginning at the end of my study) and entirely new interferometric telescopes are built (the Radio group was collaborating on at least one new instrument as well) should offer a fruitful

avenue of inquiry for continued study of CalibratorImager's flexibility in this cooperative scientific work. Their software will have to change and mutate to work with different underlying instruments, even as it already changes as systematics or other bugs are found and resolved.

The confluence of software, data, hardware, and practices in the Radio group's work is always slightly shifting, but as they co-construct some of these elements they maintain coherence so that doable problems can be studied (Fujimura, 1996). Breakdowns in the software and WRT instrument are regular but the work of fixing and re-shaping these resources as new information is produced is the work of science in action. Doing this science and sustaining this emergent infrastructure will require that the Radio group begin to function as a kernel, engaging in addressing work to maintain the resources they are producing (Ribes, 2014). To some extent the Radio group's addressing work is visible already as Igor and Brianna ensure their software functions for other scholars while they iterate on its design and use. This all takes place in light of their continued efforts to better understand the instrument and software using plots.

A language of plots and a scientific method expressed in data analysis software

The Radio group's software is their unique stance for achieving a high-precision data analysis. The US EoR pipeline software creates and depends upon many different data products to do this scientific work. With this pipeline the group produces a medley of plots that visualize these data products. These plots furthermore create a visual language for cooperatively understanding the mutable set of relations that is this data analysis software. As artifacts the group's plots capture and visualize entanglements of the Widefield Radio Telescope's operation, as well as that of the data analysis software. All of the different infrastructural components I have examined in the Radio group imbue data products with different effects of their work. Creating plots of data products results in a tangible material that a researcher can use to think through these effects, and

the connections among the different layers of infrastructures they are producing and working among.

The fourth line bug illustrates this in the Radio group's data analysis because it is a systematic resulting from the construction of the physical Widefield Radio Telescope and its necessarily imperfect materials. In the course of working with power spectrum plots of observations (such as Figure 28) in the golden dataset, Brianna was able to find a systematic that traces back through the software past the operation of the instrument into its physical design and construction. Since the software as the material for analysis is mutable it is adapted to account for this artifact of the instrument after many rounds of cooperative debugging, using plots as a language for discussing and questioning issues. Beginning with Brianna and Abner, before spiraling outward to include the rest of the Radio group, and eventually the US EoR group, plots enable these researchers to understand what the instrument did, how their software is working, and the questions they are trying to ask. Brianna did not complete this alone, she needed the understanding of the instrument and this software that the collective of the group has produced.

Producing a solution to the fourth line bug by modifying the calibration approach in their data analysis software fixes the flaw for the moment, making it a known systematic that is accepted and dealt with in the ongoing analysis. As more and more data is integrated the precision of the analysis will need to be adjusted to continue to address this systematic successfully. For the immediate moment it was ameliorated to an acceptable degree, but when this software is the expression of their scientific method it must continue to be adapted in light of improved knowledge about any of the many elements in this work.

Bowker's (1994) idea of an infrastructural inversion is that an analyst flips assumptions and re-evaluates the relationships among infrastructural components and practices. Using plots in

debugging work is such a process of inverting the different components of these two infrastructures, questioning design choices and their effects. Plots concretize what the Radio group is trying to communicate through their software, and in discussions become an artifact each individual can grasp and draw upon to convey their understanding of this scientific work. As an outsider I came to see how plots facilitate rigorous testing that is comparable with practices in software engineering—akin to Easterbrook and John’s (2009) brief note about climate scientists use of visualizations when testing software, but examined in this dissertation in much greater detail. In work where the answer cannot be predicted in advance, jack knifing data and plotting it is a way to test the operational US EoR pipeline with actual telescope data. Testing *is* data analysis for the Radio group, that iterative work of polishing and shaping WRT observation data into knowledge claims about the Epoch of Reionization, eventually. All of this is accomplished by a group of individuals who are experts in different pieces of the work—Brianna in power spectrum construction, Igor in calibrating and imaging interferometric data, and so on.

Implications of having to understand multiple infrastructures to do scientific work

I cannot emphasize enough that it is only by working cooperatively to produce this software, and develop an understanding of the different infrastructures involved in the work, that this high-precision, data-intensive cosmology research is able to be accomplished. The multiple infrastructures and their many components create embedded relations that no one individual can entirely understand or keep track of. These relations existed in one manner when I began my data collection, were different by the time I ended my data collection, and will shift again in the future as the work changes. Doing this cosmology research requires a group of experts who can investigate the different relations they have embedded across their many practices and artifacts

across time and space. The different components and practices the individuals in the Radio group, and their collaborators, create can be combined and interwoven in a large number of forms. Enacting infrastructures with the varied and multiple combinations of these resources becomes necessary to do quality scientific work. Infrastructures here are not machines that can be left unattended, they truly are instantiations of methods that need to be cared for, and sustained through continued efforts to probe the relations they are composed of so that they can be improved. This dissertation examined the Radio group's varied relations at three points in time. Future work will unearth differences, and how (and in what form) their method holds up over time remains to be seen.

I stated in Chapter One that I had not heard Magnus use the phrase “understand the instrument in your bones” prior to asking him to reflect on the relationship between the telescope, data, and software in the group's work. This simple, evocative phrase really does characterize his, and the rest of the group's, ongoing work crafting and producing data analysis software to work with their petabytes of EoR data. The work within the group, and with their collaborators, is a continual process of teaching different individuals about the detailed decisions underlying different parts of this work, and trying to develop a better shared comprehension of these materials and practices for producing knowledge. This is how they interrogate what Magnus calls the “bloody subtle” effects in their power spectrum plots. Feeling infrastructures in their bones underlies the importance of producing software to articulate their scientific method. The examples I have presented underscore the necessity of this work being cooperative, and illustrate how they tease apart the embedded relations they have created through their work.

Whether it is the construction of coordinate systems in CalibratorImager, or something as simple as how to find some piece of data on the shared RadioCluster system, there is an ongoing

effort to be able to open the black boxed facets of this work. These researchers need to be able to question assumptions and choices imparted to these resources as different individuals engage with the installed base of the group's infrastructures. In an individual's day-to-day work so much of this detail can merge into the background as conventions of practice coalesce around resources that are embedded and transparent, but maintaining scientific rigor requires that upon breakdown, collectively the details can be probed and explained. Understanding the instrument in their bones is an inescapable aspect for this group working among and producing multiple infrastructures. Developing this understanding is accomplished as part of the Radio group's work expressing a scientific method in software, using plots as a language to disentangle and open up the layers of infrastructural components they create, use, and share as a collaboration.

I see the need to develop a deep grasp of the instrument and infrastructural components in this work. It truly is not just the telescope that needs to be understood in their bones, partially as a result of how large an effect seemingly miniscule design decisions can have when seeking out a signal that is heavily masked with noise. The phenomena being sought by Magnus and his group is only just becoming feasible to probe empirically, and even then in a limited way. The Radio group's work as part of the WRT project is unique in part because of how closely they work to their instruments and the large volumes of data they produce. Even if they wanted to they could not abstract away the telescope from their day-to-day work. They cannot just use "magic math" to solve oddities in their analysis because they would not be able to obtain high enough precision results to offer a valid knowledge claim about the Epoch of Reionization.

For these scientists (and others like them) outsiders might ask why don't they just hire professional software developers to build systems for them—this is a common tension in CSCW and scientific software development literature (cf. Lawrence, 2006; Ribes & Finholt, 2009;

Segal, 2009). The necessity of deeply understanding so many different elements, not the least of which is the scientific theory driving all of this work, illustrates why this is not possible. Professional software developers will not have the expertise in the complex science, or the instruments, to be able to build much of this data analysis software. In the future it is likely that the Radio group, or scientists similar to them, would be able to carve out elements of this pipeline that software engineers could help optimize and scale up to work on different computing platforms. But how this could be accomplished is a point for future work. The opportunity such questions offers scientists, like those in the Radio group, is to explain how they express their scientific method. They can compare and contrast their approaches to producing software with those software engineers discuss. From this type of conversation it is possible to figure out how software engineering practices might be adapted to cutting edge science contexts—adaptation of software engineering methods to scientific contexts being a point raised by Carver and colleagues (cf. Heaton & Carver, 2015; Nanthaamornphong & Carver, 2015).

The fourth line bug that results from the physical characteristics of simple cables in the telescope adds noise and detracts from the precision achievable in their results, at least until it is unearthed and worked around in the software. Having a conceptualization that Antenna Tiles are connected to Analog Beamformers through one of six cables, and being able to connect this relationship to methods of calibrating data in `CalibratorImager`, is part of understanding how data is produced and analyzed in this project. A similar need is part of the work of the post-docs in Rolland and Lee's (2013) study who had to open the black box of different variables in their work to trace the entanglements of different dataset's production. But the researchers Rolland and Lee studied did not have the deep understanding of an infrastructure available from collaborators. There was not an infrastructure in place to begin with. Instead these post-docs had

to develop this on their own and with a fair bit of effort. Scientists engaged in complex work that takes place within and among multiple infrastructures benefit from sharing this work.

Being able to unpack the details in the history of the work producing some set of data is a necessity in knowledge production—see Chapter Two. The Radio group and their collaborators have multiple research infrastructures. They create and sustain the information necessary for tracing out different entanglements over time by making resources self-documenting. Data products are a thread that aligns facets of the different infrastructures in the Radio group’s work, connecting them over time and spaces, so that altogether cosmological knowledge can be produced successfully. Designing the Widefield Radio Telescope and the US EoR pipeline as self-documenting instruments ensures that they store and make available the information central to doing high-precision data analyses. Metadata from the WRT’s operation, and the operation of data analysis software, is incorporated in data products, imbuing details such as versions of software used and elements of the telescope that were or were not functioning.

This self-documented metadata captures much about the iterative data analysis work, but it is not a catch-all for the entirety of the analysis. The intentional, human-driven cuts on data would not end up being captured in this self-documentation, but the information that cuts are based on is. It is impossible to fully capture everything about a data analysis, but working to document decisions and operations as much as possible contributes to the reproducibility of this work. This is vital as different individuals come and go from the groups involved, and helps colleagues working with different scientific aims attempt to use data products created by the Radio group’s analysis method in a scientifically valid manner. Working to document more of the information informing these cuts would surely help the Radio group (and any scientists like them) improve their research practice over time since their decisions would be more replicable

and traceable. This is to a great extent what I see as the motivation underlying advocates of open data and software in science (e.g., Goble, 2014; Ince et al., 2012; Stodden, 2012). These advocates want the necessary conditions for interrogation of research findings to be created, the type of conditions I see the Radio group working to create (even if they could do more).

For Magnus, Brianna, Igor, and the rest of the Radio group (and their EoR Science Collaboration peers) the Widefield Radio Telescope is simply one device on the pathway to bigger and more powerful instruments for peering back into time. The work the group is doing throughout my study is entirely necessary for pushing at the frontier of observational cosmology. Developing the WRT and the method encapsulated in the US EoR pipeline is how these cosmologists are able to better comprehend how to do this type of high-precision science, working through breakdowns and other difficulties so as to be able to better design future experiments (and the resources necessary to do them). Nima commented that she “feel[s] like the software should drive what the instrument looks like” but in the end “you develop the software based on what the instrument looks like.” Software should be considered when designing these complex physical instruments, yet often ends up having to be developed based on what was physically built regardless due to funding considerations or the dynamics of a multinational collaboration building these large-scale experiments. Software exists as relations between the many elements of the science in the Radio group’s work, but it is only one of many considerations in the creation of experiments and the resources to do them. The members of the Radio group are highly attuned to the production and use of software, and I believe it is important that scientists in other disciplines be deeply thoughtful about their creation and use of software for data analyses as well.

It is all too tempting to present a narrative of technological progress being a necessity to do this work. Saying that the Radio group's work is possible because of some piece of technology is far too reductionist, the context in which this work came about is shaped by endless factors. I think the case here is really that the work now producing software is part of how this group works to express and shape their future possibilities for research. At a high level all of the work I have examined in this dissertation is something of what Steinhardt and Jackson (2015) call anticipation work, the "realized, pragmatic and attainable ways actors move toward some imagined future" (p.443). The Radio group designs and builds their data analysis software, and pieces of the WRT, to enact materials that help them move towards a future goal. By developing this deep feeling and understanding of what they are producing to do work in the present they are helping to construct the possibilities for the future. All of this work now, and perhaps into the future, requires that Magnus and his group work as part of multiple infrastructures, navigating through their different entanglements day-to-day.

Implications of software as the expression of scientific method

My examination of the Radio group's software as the expression of their scientific method is a change in the perception of software in scientific work. Software is not something produced in scientific research with the exact desired operation foretold and designed from the beginning, like most commercial software that is the source of software engineering approaches. An implication from this is that scientists and outside observers cannot treat software as a neutral resource in their work. It is an artifact that is entirely bound up with the practices and assumptions of the individuals creating it, just as any scientific knowledge is, but as a knowledge product it is transferable to different contexts so long as the appropriate interrogations are conducted. I believe CSCW scholars, as well as computer scientists concerned with scientific

software development, would be wise to give this idea consideration. The extensive work on data sharing I discussed in Chapter Two illustrates this point with regards to data. Software should be investigated and conceptualized similarly. Context of production matters greatly for data and perhaps even more so for software.

The US EoR pipeline software in this high-precision cosmology research expresses the analysis, just as hand written calculations would have in the past. The analysis should be attempting to capture reality to the greatest extent possible. No scientific analysis is completed without making assumptions somewhere along the way. But what assumptions or approximations are made does deeply matter. The US EoR pipeline as a series of software components encapsulates all of this. This last bit of conversation with Brianna captures the importance of this implication when she states that they do not want to “lie” to their analysis through incorrect or simplistic approximations. They craft their software carefully to account for the reality they perceive as much as possible.

Brianna: We fundamentally believe in our group that you want your software analysis to – you don't want to lie to your analysis. You want to have in your analysis as close a representation of reality, physical reality as possible. So you want a real beam. You want baselines in the—you want to be as accurate and as realistic as you can about your physical situation.

Drew: Such as the reflections in the cables, for example?

Brianna: Exactly, all of these things, and there's subtle things in terms of the math, approximations and assumptions, and we tend to favor the ones that are not fundamentally lying to our analysis.

Drew: Versus the old-school stuff of a Gaussian beam instead of?

Brianna: Right, but we do make assump—approximations with gridding and stuff that do things and then you have to go test those just to see if, how bad they are. So we, and this is also why we tend to think very strongly in the uv plane 'cause it's how the instrument thinks. We try to be close as we can to the instrument, in terms of modeling it in a physical way, and then we try to make computational assumptions that would allow us to do our work, and then we test them to try to

see if they are good assumptions or if they are okay or not. But, so we work, we both try to do that, we try to be very realistic about our physical situation, and then we also work from very careful math that we've worked through, and then you're trying to figure out how to make it computationally feasible. (Brianna, interview)

Software is a material for capturing its creator's view of the world, and I have taken an expansive view of software in this dissertation. Mackenzie (2006) posits that counter to the direction of definitions of software narrowing and becoming more precise, being defined as code alone, his definition broadens and grows in scope. His study of software in the world becomes more about the individuals creating this artifact and their biographies. This is a lesson I believe I have echoed here in this dissertation. The US EoR pipeline reflects the stories of Brianna, Igor, Abner, and so on.

Furthermore, when the Radio group creates novel software they are doing so because pre-existing tools and methods do not work. The Radio group's research requires petabytes of data, and high-precision analysis, to be able to construct new knowledge about the Epoch of Reionization. I explained how Igor's creation of CalibratorImager sets it apart from past approaches to radio astronomy data analysis. The implication of much of this story is that for at least some scientific research previously produced software will not be sufficient. New methods must be expressed and implemented from scratch because the history or heritage of available software is not directly applicable to this new set of problems. Working to develop a software heritage for this type of cosmology research is in many ways what Magnus and his group are doing. Their work is creating an installed base of artifacts and practices for doing high-precision analyses of wide field of view telescope data where very faint phenomena are captured. By designing components, such as CalibratorImager, to work with different telescopes (i.e., by generalizing the software) this group is helping the cosmology community develop resources for

doing this type of analysis in different experimental contexts. Framing this infrastructuring work as developing heritage in this scientific community might be a way to better capture the history and culture being created by these scientists.

CSCW scholars already examine cultural heritage in the context of museums (Ciolfi et al., 2015; Maye et al., 2014). Perhaps it is time for CSCW scholars to investigate and conceptualize what the heritage of scientific software is as well. To ask how different scientific research communities come to rely upon particular pieces of software, and the scientific method(s) these pieces of software convey, across experiments and contexts. In a sense infrastructure studies examining installed bases of artifacts are doing this. But just as Knorr-Cetina (1999) posits her notion of culture adds something to the idea of practice (see Chapter Two), I wonder if conceptualizing scientific software heritage might add something important to the idea of the installed base in scientific infrastructures.

Enacting an infrastructure by producing software the Radio group is of course drawing upon some pre-existing software. They are not creating programming languages, they incorporate the FlagAvg software from collaborators, they did not design HEALPix cubes as a way to represent data, nor did they craft the file formats used in their data products de novo. What is unique is how they organized existing components while writing new scientific methods. They created practices oriented around plots to drive their software testing. All of this cooperative work expressing a scientific method through software is representing the Radio group's ontology, their view of the world and science. It is fundamentally biased towards the concerns and beliefs they collectively share. The US EoR pipeline, its data products, and their plots capture and represent only so many things and only in certain ways, as any piece of software or instantiation of a scientific method does. Taking seriously the idea that software for

data analysis is the expression of a scientific method implies that scientists must work to understand the biases inherent in that articulation, as any research really must do.

Implications for CSCW scholars investigating scientific infrastructure work

This dissertation has presented a different approach to understanding how infrastructures are created and employed in scientific research. Instead of studying a collaboration among scientists and software developers, I examined research that is so intricately connected to an instrument only the scientists themselves could do the work. This shift in focus, in essence something of a return to science & technology studies examinations of laboratories, enabled me to draw out multiple layers of infrastructure in the Radio group's work. Doing this enabled me to illustrate how the Radio group does work as part of multiple infrastructures simultaneously and continuously over time, rather than scoping all of this as one infrastructure. Out of this I believe it is beneficial for further studies to work to elicit how groups of scientists work among multiple infrastructures, looking at how practices are shaped and constructed.

Scholars studying scientific infrastructures in CSCW and related fields need to give more thought to the way they scope the infrastructures being studied, as well as the objects focused on in their inquiries. Many studies subsume what are surely multiple infrastructures as one in their inquiry. Different embedded facets are noted in these efforts, yet the details about the embeddedness itself become hard to disentangle and pull out of a black box. Caring about the ways relations are embedded in different contexts is what qualitative studies of infrastructure creation can surface, but if the object of inquiry is perceived as one large, amorphous infrastructure it can be difficult to tease apart these details. Vertesi's (2014) articulation of seamful spaces in fleeting moments was a start. I have added to this conversation, and there is more to be done.

Had I not characterized the WRT project as a research infrastructure, and the US EoR pipeline as another above it, I do not think I could have explained the co-construction (Fujimura, 1996) of the endless facets of each that I see in the Radio group's work. The work the Radio group does entangling these infrastructural components, then eventually disentangling them in the course of their work, is dependent on that collective understanding of these infrastructures in their bones, and the particular instantiations they have created. As the outside observer, if I were portraying all of this work as one infrastructuring endeavor I would be leaving out a great deal of the complexity the Radio group manages. Knowing that data products move among the different infrastructures in the Radio group's work (from the telescope up into the US EoR pipeline or LivePipeline and in turn between these pipelines) helps me understand how different scientific decisions and practices shape the materials and products of this work over time. Various accretions take shape and become bound up across these infrastructures, in this case through data products, providing an interesting opportunity for interrogating multiple infrastructures and analysis decisions over time.

Describing multiple layers of infrastructure in their work forced me to reflect on the back and forth these scientists go through between their data analysis and operation of the telescope. I think that CSCW scholars investigating infrastructure should give thought to re-thinking how they scope their objects of inquiry. Doing this they can better disentangle conventions of practice that form as part of one infrastructuring undertaking to see how they migrate to and change as part of another. Understanding how practices migrate, especially when they are associated with such an easily transferable and mutable material as software, should offer fruitful areas of inquiry for better understanding how scientists create and change their methods as problems faced shift, and new opportunities arise.

CSCW also significantly focuses on collaborations between domain scientists and software developers trying to build infrastructures (e.g., Bietz & Lee, 2009; Darch et al., 2015; Steinhardt, 2016; Young, 2015). Lost here is the opportunity to study scientists who are trying to do science and enact infrastructures precisely because their work is so deeply tied to the instrumentation they design and work with. Scientific research that is intimately connected to the development of instruments and analysis methods surfaces endless breakdowns and moments where researchers are forced to re-evaluate their work. These scholars have to learn how to deeply question their infrastructures, as I have shown, and this surfaces moments for investigation of cooperative tasks that enroll stakeholders with different areas of expertise.

Implications for science policy

Finally, the case I have presented throughout this dissertation emphasizes the importance of understanding the specifics of the production of software and data products. A common goal of twenty-first century science is the sharing and reuse of data (and increasingly software). Ideally sharing these products would be a simple task of publicly archiving and making available digital files. CSCW scholarship extensively illustrates the difficult reality of sharing data and software for reuse in different contexts (Faniel & Jacobsen, 2010; Howison & Herbsleb, 2011; Rolland & Lee, 2013; Zimmerman, 2008). This difficulty is visible in my findings here as well. To recall a quote from Magnus in Chapter Four it is to some extent pointless to share the data because of the complexity of the instrument and the necessity of deeply understanding this complexity when producing the data analysis software. Working at the precision limit of the Widefield Radio Telescope and the US EoR pipeline is contingent upon being able to deeply interrogate the inscriptions captured in data products.

An implication that I see from my study of the Radio group is that funding agencies or publication venues can continue to mandate data and software be shared. This will remain difficult and problematic, however, unless these entities mandate that (and very importantly figure out how to support) researchers share not only their products but also teach the individuals receiving and using them something of their practices. The ability to develop a deep feeling for these scientific products has to be transferred to new contexts. Supporting researcher's efforts to teach others about their software, and how to produce similar software, ought to be an endeavor supported by funding agencies. Sharing has benefits to the individuals creating the products, such as serving as currency within scientific communities that supports careers (Birnholtz & Bietz, 2003; Howison & Herbsleb, 2011), but when the expression of a group's scientific method is accomplished by producing software their local research practices cannot be disentangled from the product's use. They must figure out how to share their day-to-day practices creating and using these products for them to maintain any validity in other research contexts.

The Radio group and WRT Collaboration can and do relatively easily share different data products and the software produced in all of their work. Within the collaboration they do so to facilitate rigorous comparisons of different scientific analysis methods. Sharing software and data products publicly in contrast is part of being a good citizen in a scientific community, and meets demands from at least different agencies providing funding for the various pieces of the project. The WRT Collaboration has policies in place for requesting data products; including suggestions for whom to talk with about how to analyze it and pointers to relevant publications. This is part of the project's contribution to cosmology. The Radio group makes their software publicly available through their GitHub repositories, and communicates to their scientific communities this methodological approach through various publications. They do want their

approach to high-precision data analysis to be shared, and hopefully adopted by other scientists, and they are trying to explain how they do their work. That is a fundamental tenet of science. But how useful this software or data products are to other researchers is a valid question. As I noted above, there are many advocates of openly sharing software used to produce scientific findings so that the work is sustainable. The problem I see is that these advocates are focusing on particular instantiations of a product in the moment. But when software is the method the static forms of the product become less important in time. It is really the practices of the work that need to be shared and understood if the findings are to be understandable, and able to be recreated, over time. The Radio group making their method openly available to other researchers is integral to supporting proper assessment of their scientific findings, and tracing versions of the software is necessary, but this needs to be accomplished in conjunction with evaluating how the method has changed as the work improves.

Even as the components of the US EoR pipeline have become infrastructural within the US EoR group there has been friction in their use. Other members of this arrangement of individuals had to be taught at least some elements of the Radio group's practices. Sharing some partially analyzed data product (i.e., HEALPix cubes from CalibratorImager) is entirely feasible since it is already part of the Radio group's practice, but doing so is to share a product that has even more layers of prior research decisions associated with it than raw telescope data would. Making these products self-documenting by encapsulating metadata is one step to ensuring they can be used properly in new research settings. If the Radio group is able to engage with researchers trying to adopt these products, to help these outsiders with their work, then success would seem to be more likely.

Limitations of my study and some thoughts for future work

All research projects have limitations. This dissertation only followed the work of a single group of researchers while slightly touching upon their collaborations with colleagues around the world. I cannot offer comparisons with the practices of the other members of the US EoR group or larger EoR Science Collaboration since I did not directly interact with these groups (aside from attending a few US EoR group teleconferences). I can only speak to the ways I saw the Radio group interact with the larger WRT project. This prevents me from offering a truly ecological perspective on the design and construction of the Widefield Radio Telescope, or the construction of the LivePipeline. I cannot attest to the decision making process that led to the writing of the WRT's various policies that I discussed in Chapter Four, I can only discuss how they shape the Radio group's ensuing work. I have attempted to triangulate what I directly learned about the WRT project from the Radio group by collecting archival materials for my analysis. Archival materials have their own limitations as they are the after the fact, closed up representation of a negotiated process, but they are a mechanism for comparing and contrasting what I learned about first hand. My study would be bolstered with additional data collection covering other elements of the WRT Collaboration. As a single site study I also cannot draw comparisons to other groups of cosmologists studying the Epoch of Reionization (whether in the WRT Collaboration or not) and the practices they have.

Another researcher studying the Radio group may not have had my interest and understanding of software which is part of why this is my unique narrative. Training as a software engineer taught me to approach software with particular development methodologies and perspectives. I worked to avoid imposing these perspectives on the work I was studying. I attempted not to introduce software engineering language or concepts, and if they came up in

conversations I tried to specifically ask what the individual discussing it meant, rather than just assuming this person and I were thinking of the same thing. This way I learned what the many terms and practices in the Radio group's work mean in these individual's own terms. My data collection furthermore never focused on studying the Radio group's particular coding practices. This is a much more micro-level task than I wished to engage in, but studying this group's coding practices would surely unearth further details about their scientific method.

Future research to address these limitations can immediately address gaps in my findings by studying other groups within the WRT Collaboration. Qualitatively studying how the individuals responsible for the LivePipeline alone would begin to enable comparisons with the work I presented here, and would begin to help in characterizing how apt and transferrable my portrayal of software production as the expression of scientific method is. I know that the Radio group's work is predicated on a deep belief that this type of work requires being intimately connected to the instrument. Studying other fields where this is also the case could lead to interesting comparisons. Giving some thought to what software production as the expression of scientific method might mean in cases of work that is not so deeply bound up with the instrument would help to develop the language I believe still needs to be worked out to better explain this phenomenon. In qualitative research it is common to use different pieces of software to organize and code data. I used atlas.TI for this task in part. Asking how this, or similar, piece of software shapes my own research method would be a worthwhile exercise for examining the validity of this construct. At what point can a piece of software be treated as just a tool for work, and not interrogated deeply by its user?

Shifting orientations to software away from it being just a tool for scientific research to my characterization of it as an integral material is only a beginning. Thinking about the field of

software studies as an influence I think that my study expands upon these scholar's examinations of code and expression to focus more on the emergent effects of software by looking at this material in an infrastructural sense. A facet that I left out of the scope of this dissertation's narrative is the choice of programming languages for producing software. Programming languages are important forms of knowledge since they are how subsequent individuals express their ideas, they are a powerful ontology. Asking how the language choice of a group of scientists constrains and shapes their knowledge production is an important task to be undertaken. Programming languages, like infrastructures, embed and abstract certain decisions while enabling approaches in certain ways. Probing the ontological role and influence of programming languages in scientific software production should help to better describe the co-construction of high-precision scientific analyses like the Radio group's.

Throughout this narrative unpacking cosmology research, I have endeavored to treat software as anything but a boring, immaterial facet to this twenty-first century scientific work. To me software remains an intriguing product of cooperative scientific work. Seeing how the Radio group truly thinks through and with this discursive and mutable set of relations as they enact infrastructures only begins to unpack this material. Continuing to probe and portray the work software does across different social worlds in scientific research is entirely necessary to understand what it means to cooperatively do scientific work today and into the future, across different geographical settings. Grasping and appreciating software in science matters.

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Appendix A: A Brief Overview of Cosmology and the Epoch of Reionization

Observational cosmology, such as the work of the Radio group, applies empirical techniques to gathering and analyzing data about the Universe's history³⁶. The Radio group's scientific work is empirically expanding knowledge of early stages of the Universe using a new interferometric telescope—see Chapter Four or Appendix B for details. The group's science is predicated upon The Big Bang theory. Elements of this physics theory are what their US EoR pipeline data analysis software end up expressing. Loeb (2006) lays out the history of the Universe's development and notes that starting with the Big Bang the Universe is believed to be expanding over billions of years with elements forming, changing, and developing into stars and galaxies.

One key milestone in this development is that of the Cosmic Microwave Background (CMB) radiation. A NASA team describes how Big Bang theory predicts cooling of the gas in the Universe as it expands and thus there should be radiation “that is literally the remnant heat left over from the Big Bang”, this is the Cosmic Microwave Background (NASA/WMAP Science Team, 2014). The CMB emerges approximately 400,000 years (exact ranges vary somewhat as new knowledge is produced) after the Big Bang and marks the beginning of the cosmic “Dark Ages,” which last until approximately one billion years later. During the few hundred thousand years prior to the CMB the Universe was dense, hot, and extremely ionized. This earlier period of history is impenetrable to our instruments that rely upon electromagnetic waves to peer back in time because of this ionization. In fact it was only in early 2016 that earlier periods of cosmic time opened to humanity's examination through the findings of the Laser

³⁶ I am grateful to Magnus for providing me with feedback on the science of this section and correcting multiple misunderstandings on my part.

Interferometer Gravitational-Wave Observatory (LIGO) collaboration (Ligo Scientific Collaboration et al., 2016; Overbye, 2016; Plait, 2016).

The CMB very suddenly takes this opaque state of the Universe (when gas is ionized) and turns it clear (where the gas is neutral). Following the CMB are the cosmic “Dark Ages” where there are not yet galaxies or stars in this neutral, clear space. As a result, scientists cannot see anything in the Universe during this time period. Beginning around one billion years after the Big Bang the first galaxies and stars are lighting up and producing the light that scientists can begin to probe with telescopes. Cosmologists flesh out their understanding of this time period by relying upon the radio light emitted from the neutral (e.g. not ionized) hydrogen atoms that made up the early Universe. The emission of this light is known as the Epoch of Reionization (EoR) and this is what the Radio group is specifically studying.

The Radio group is probing the Epoch of Reionization using 21-centimeter tomography. This technique takes advantage of changes in the Hydrogen gas present at this point in the Universe’s development. Photons are emitted from Hydrogen when its electrons flip magnetic orientation. Cosmologists use these 21-centimeter photons to probe the overall structure of this early, dark period of cosmic history since the photons are light that is visible to scientific instruments. This is 21-centimeter tomography and as a result, “by studying the detailed physical properties of the radiation, we can learn about conditions in the universe on very large scales at very early times, since the radiation we see today has traveled over such a large distance” (NASA/WMAP Science Team, 2014).

Exploring the Dark Ages using the 21-centimeter sky requires factoring in one other major cosmic factor—namely that cosmic expansion has stretched the photons to longer wavelengths. As scientists today peer back in time they are seeing electromagnetic radiation with

extended wavelengths because the present is quite distant in time from when the radiation was produced. A 21-centimeter photon emitted at the beginning of the Dark Ages appears today to scientific instruments with a wavelength of 210 meters while a photon emitted toward the end of the Dark Ages is shifted to between one to two meters (Loeb, 2006, pp. 50-51). This phenomenon is known as a redshift and is discussed in standardized units such as a redshift of 6, 7, 8, 100, or 1,100 as time progresses further and further back towards the Big Bang. The Radio group's measurement of the Epoch of Reionization is always dependent on the particular redshift of the signal in an observation. The measurement will be different for different frequencies since they correspond to different redshifts.

Today the redshifted wavelengths of the 21-centimeter line fall into the low frequency radio segment of the electromagnetic spectrum. These are studied by cosmologists using radio telescopes built out of low-frequency antennas. Scanning the range of wavelengths that correspond to different time periods within the Dark Ages cosmologists can build up a three dimensional map of the distribution of the neutral hydrogen versus the ionized hydrogen, which theory predicts will be present in bubble like shapes as galaxies form. Loeb describes how tracing the "sharpness" of the bubble's boundaries will enable cosmologists to answer questions as to whether reionization of the gas is caused by massive stars or black holes. The patterns imprinted on this early light capture the state of the Universe shortly after the Big Bang, and tell scientists about the seeds of the galaxies that are visible now billions of years later.

The work of the Radio group and their collaborators is opening up a new era of cosmic history to humanity's investigation. It is investigating how galaxies and stars first formed. The 21-centimeter signal I just discussed is especially faint at this point in cosmic history and obscured by many different sources of noise. This makes 21-centimeter tomography a difficult

task. To gather enough signal with a telescope it must first be designed appropriately to not only capture the signal at the red-shifted frequencies but also capable of capturing and reducing enough data to drive down the noise in this very low signal-to-noise situation. To actually engage in 21-centimeter tomography novel interferometric radio telescopes must be built by taking advantage of recent advances in inexpensive, commodity computing hardware.

The process of working with interferometric data requires significant processing of the raw collected data using many complicated techniques that are an advancement from past radio astronomy techniques. Sufficiently probing the Epoch of Reionization requires high-precision analyses using petabytes of data as I showed through this dissertation. The Radio group's cosmological research opens up new periods of cosmic history, letting humanity today peer back in time. Work on human temporal and geographical scales is peering back into cosmic temporal and geographical scales that are not readily fathomable in anyone's day-to-day life, but this work does contribute to some of the most basic human knowledge.

Appendix B: Correlation and Interferometric Telescope Design

Introduction

This appendix examines two key elements of the Radio group's work. First I discuss the concept of correlation. This is the scientific concept driving interferometric telescopes. Second I examine in more detail the components of the Widefield Radio Telescope that were introduced in Chapter Four.

Correlation, the soul of interferometry

Interferometric telescopes capture electromagnetic signals (radio waves) and combine them to extract information about the Universe. Interferometry is a technique for taking electromagnetic signals and superimposing them to extract information. This technique is employed in a variety of devices, from fiber optic telecommunications systems and medical imaging systems to optical and radio telescopes. Interferometry is not something that I ever expected to need to learn anything about yet it is at the core of the scientific techniques of the cooperative work I studied.

Interferometric telescopes can be built out of an array of dishes that physically move to point at a location on the sky or an array of antennas that are steered on the sky by electronically delaying the signals. The Widefield Radio Telescope is not a dish telescope. It is a device built out of arrays of low-frequency antennas that are able to capture the very diffuse Epoch of Reionization signal. The Widefield Radio Telescope is an array of 2,048 dual-polarization dipole antennas that are organized into 128 tiles—dipoles are a pair of antennas with equal and oppositely charged magnetic poles separated physically by some set distance. The WRT captures signals using the 128 tiles of dual-polarization dipole antennas. The captured signals are then

mathematically superpositioned together through a complex chain of hardware and software devices known as correlators (since they correlate signals together) to produce views of the sky.

A correlator in an interferometric radio telescope is a hardware, software, or hybrid hardware-software component designed to calculate the level of signal correlation between all antenna pairs at all of the frequencies in an instrument's observation band. Correlation is key to any data produced in the WRT Project. I naively inquired of Brianna as to what correlation allows the group, and radio astronomers in general, to accomplish. She readily responded, "correlation is the soul of interferometry" before continuing on to describe how correlation functions in a general mathematical sense and in practical terms for a radio telescope:

So what it does is it – let me see. Basically it allows us to measure what the difference between – or what the relationship between the electric field at one antenna is and the relationship with another antenna. And the purpose of it is that it's reconstructing – it allows us to reconstruct the spatial electric field pattern on the ground. And from there, we can reconstruct sort of the electric field that's coming from the sky. So the electric field that comes from the sky and hits the ground, actually it turns out it's a little bit magical. [Laughter] But mathematically, that propagation from the sky to the ground is a Fourier transform. So if you take – if you can perfectly measure the electric field on the ground and you take a Fourier transform of it, you get the sky. (Brianna, interview)

Igor describes correlation to me by offering a comparison with optical telescopes or the digital cameras that are everywhere today. Igor explains "with a normal telescope you are actually capturing the light, the intensity" through a gridded array of pixels. A modern digital camera that uses a CCD (charge-coupled device) sensor captures the intensity of the light hitting each pixel. Putting together all of these intensity readings across a gridded array of these pixels produces a synthesized image since the variation in the intensity is visible. This is the fundamental design of the sensors in everything from advanced optical telescopes to widely available digital cameras in smartphones.

Unlike with optical telescopes, “with an interferometer it’s not as straight forward as” putting together gridded signals Igor forthrightly notes. He emphasizes that for most interferometric radio telescopes it is not efficient to have a regular grid of sensors (antennas here instead of the CCD pixels in a camera). Instead the array of antennas is arranged in a purposeful manner with some densely clustered and a few extended off in different directions. This is to enable the radio telescope to measure Fourier modes. Fourier modes are how the electric field on the sky above (i.e. the radio signal) is measured.

A Fourier series is a mathematical technique for representing a wave-like or periodic function by decomposing the function into a weighted sum of a series of simple Sine waves that are referred to as Fourier modes. The weights or coefficients of the Fourier modes are a one-to-one mapping function between this reduced form and the original periodic function. Brianna explained to me that a Fourier mode in an interferometer allows power to be measured across different scales to produce a response function. If an interferometer can measure a sufficient number of Fourier modes then they can be used to produce a synthesized image of the sky. This image is created by inverting this Fourier transformation. Igor first taught me this by very nicely noting that he thinks of these modes as “clues in a crossword puzzle” where:

You know that on scales of this size, say a meter across, you have this much power across the entire image. And you not only have one direction, say a meter, but it’s a meter in the northwest direction say. And then you also know how much power is on the meter scales in the southwest direction and you know how much power is on two meter scales. And so you have all of these clues. And if you actually have enough of those measurements that will uniquely define the image. (Igor, interview)

Correlation is the scientific technique that is key to the process of collecting data in the WRT project. It enables cosmologists to take the electromagnetic signal gathered from many antennas to produce an image of the sky. Designing correlators for telescopes is one area of

possible scientific contribution in a project such as the Widefield Radio Telescope. The synthesis of all of the collected signals—these different measurements of power at different scales—enables cosmologists to produce images using interferometric telescopes as long as there are enough measurements captured to densely fill an observed space. Taking the basic output of a correlator and analyzing it to produce images is what Igor’s CalibratorImager software does.

This is a highly simplified introduction to interferometry. For the purposes of understanding the WRT as an instrument the basic idea that signals from across the sky are captured then relationships between them determined is what matters. Knowing that the data is put into a uv mathematical frame of reference was important for my data collection as Igor, Brianna, and the rest of the Radio group continually reference their data in this mathematical space.

The components of the Widefield Radio Telescope

The Widefield Radio Telescope is an engineered device with many technical details that are important to the Physics and Astronomy community who build and use such devices. For the purposes of this dissertation a simple understanding of the overall composition of the device in the context of the interferometric scientific drivers just discussed is all that is necessary. The components of the WRT are laid out visually in Figure 14 in Chapter Four.

The WRT as a scientific device is temporally and spatially connecting remote desert locales with urban university campuses through software telecommunications networks. The composition of this hardware-software instrument appears in the structure of all of the Radio group’s data and over time is represented in the design and construction of their software as well—points I elaborated throughout the chapters earlier. Igor and Brianna must not only model the idealized structure of parts of the instrument in their data analysis software but iteratively

incorporate details about its flaws and unexpected behaviors. They and the rest of the Radio group (as well as their EoR Science Collaboration colleagues) in their software production end up inverting the infrastructure to untangle these hardware components.

Analog hardware elements

The Widefield Radio Telescope is an array of hardware components³⁷. The first components of the instrument are Antenna Tiles, abstractly visualized at the top of Figure 14. The WRT is composed of 128 of these Antenna Tiles. Each tile has 16 dual polarization dipole antennas arranged on a mesh grid. These antennas are how signals are collected, the first point in creating inscriptions in data products. All 16 antennas on an Antenna Tile are connected to a device known as an Analog Beamformer.

The Analog Beamformer is the hardware device which receives the signal from each antenna and adds them together before sending the signal over a wire back to a Receiver. A telescope built out of an array of antennas does not physically move to peer at different phenomena in the sky. The Analog Beamformer is the mechanism that enables the WRT to be pointed at different phenomena, for a telescope that cannot be aimed is probably not all that useful. Each Analog Beamformer is connected to a Receiver via a coaxial cable that is one of six lengths—a seemingly insignificant point that becomes important down the road during data analysis in the Radio group’s software in the example of the 4th line bug that I briefly noted in Chapter One and discussed further in Chapter Seven. The Widefield Radio Telescope has sixteen Receivers. A single Receiver is connected to eight Analog Beamformers/Antenna Tiles.

The Receiver is the point where the analog signal from each antenna is converted to a digital signal and a coarse filtering of the frequencies collected is completed. It is physically

³⁷ WRT-Pub-2013-WRTSystemOverview

placed at a distance from the Antenna Tiles and Analog Beamformers to help limit any interference and noise from seeping into the collected signal since even the slightest fluctuations in power going through the device's power supply can impact the signal. The coarse filtering of the signal frequency is necessary to constrain the signal to frequency range of interest. This coarse filtering and analog to digital conversion results in 256 individual signal channels of data.

The user of the telescope (e.g., a Science Collaboration) can then define a subset of 24 channels to be formatted and transmitted over a fiber optic connection by changing the settings of the Polyphase Filter Bank in the Online Processing element of the telescope. This filter bank is implemented in FPGAs (field programmable gate arrays), a hardware-software device for processing data. Here in the Receiver the transition of the telescope from purely hardware into a hardware-software combination takes place. The selected signal channels will pass from the filter bank to the final hardware-software component, the Correlator, for a given observation session. Correlated data will be written into the telescope's Online Archive through the Data Capture software. The choice of signal channels by the telescope user shapes the data collected since it is a mechanism for constraining and restricting the quantity captured. Every step through the instrument's chain of hardware and software is a step in this process of reducing the data on the way to making a knowledge claim, all the way through data analysis software like the US EoR pipeline or LivePipeline.

Signals converted in the Receiver are transmitted over fiber optic connections to the telescope's filter bank then Correlator. The Correlator once again is a key component of an interferometric telescope and is one of the novel components of the Widefield Radio Telescope. Designing and building this Correlator is a research contribution in and of itself for some members of the WRT Collaboration. The WRT's correlators will take the 24 coarse frequency

signals that are passed in and complete a finer transformation down to 40 kilohertz channels from the input frequencies that are slightly over 1 megahertz using FPGAs (field programmable gate arrays, a common type of programmable hardware device). The signals will then be correlated—relationships determined for every combination of signal between each antenna tile for every channel—using standard graphical processing units (GPUs) that might be found in a high-end desktop computer but are programmed for this mathematically intensive task.

It's just over a megahertz on each channel. And so the correlator gets 24 of those. It does a finer frequency channelization to get down to I think it's 40 kilohertz now, so quite fine. And then it does the correlation stage. So the frequency channelization is in FPGAs. The correlation is in GPUs. So it's a hybrid. And there's just – you're correlating every antenna with every other antenna at each frequency. And there's two polarizations that come in and you cross-correlate between them, so you have four sets of polarizations, the XX, the XY, the YX, and the YY, at every frequency for every pair of antennas. (Brianna, interview)

The WRT Correlator is a complex hardware-software system—since the FPGAs and GPUs are programmed with custom software—that shapes the digitized data from the Receiver and mathematically reduces it while placing it in a scientifically useful form. The Correlator is built from not only FPGA and GPU hardware devices but also common computing server hardware and “bespoke software” applications implemented across these different hardware platforms. This is in contrast to the option of building custom application-specific integrated circuits (ASICs) in place of FPGAs that used to be common in cutting-edge scientific applications. The data output from the Correlator becomes the “raw” or starting data that the Radio group will work with in their software production and data analysis. This data is stored in the WRT Collaboration's data archive and a clone in the United States—discussed in Chapter Five.

This short overview of the Widefield Radio Telescope's components describes the chain of hardware and software devices. Some of these devices are quite simple, the dipole antennas

for example. Others are simple yet the design decisions inherent in the device are important for high-precision data analysis. As an infrastructural endeavor the WRT Collaboration has to ensure that these components are stabilized and turned into a scientific instrument. My data collection did not extend to this work so I cannot speak to the addressing activities that the infrastructure's cache must do directly maintaining the telescope. What I can speak to is how the EoR Science Collaboration uses the instrument to produce their data, the focus of Chapter Five, and how the Radio group inverts this infrastructure in the course of their software production and data analysis, the focus of Chapters Six and Seven.

Epoch of Reionization observations are battling significant amounts of noise that is naturally occurring in the Universe (Gaussian random noise), that is produced by humans (Television signals for example), and that is inherent in the telescope's components that I just described. Any conversion of an analog signal to a digital signal is subject to noise while also fundamentally losing signal when a continuous analog signal is discretized into something that can be stored as 1s and 0s. The data that is produced with this instrument is an expression not only of the electromagnetic signal captured but also the particular configuration decisions employed by a Science Collaboration for their observations. The width of the channel frequencies changes what is captured and stored for analysis. The arrangement of the different Antenna Tiles will change the characteristics of the captured signal that is correlated. The Analog Beamformers and Receivers are also of interest to my understanding of the data produced since these devices again influence the resulting software the Radio group is cooperatively producing. The knowledge different individuals in the Radio group have about these different telescope components are employed throughout their process of producing software and analyzing data.

Appendix C: The EoRLive Website

The EoR Science Collaboration's on-duty astronomer practice was organized around the EoRLive website. This bespoke website was designed by the collaboration to offer information about the state of the Widefield Radio Telescope's EoR data collection and its transfer to the RadioCluster in the United States. The EoRLive website is hosted in the United States and overall is oriented towards the US EoR group more so than the International EoR group because of its focus on data transferred to the RadioCluster. During my data collection two versions of the EoRLive website existed and both versions were built by graduate students working in the US EoR group. The EoRLive website last consisted of three webpages during my data collection (it has subsequently broken down and was not fixed at the time I wrote this appendix).

The homepage of the EoRLive site provides a dashboard of the EoR observation status with an emphasis towards the data copied to and converted on the RadioCluster for the US EoR group. It is a central point where any member of the EoR Science Collaboration can see the status of the latest observations that may be of interest to their work. The brief display of the most recent log entries also foregrounds when the last on-duty astronomer made an entry and whether the instrument was performing as expected or not. In light of the breakdown of the on-duty astronomer practice that I witnessed, this information display also has the effect of surfacing how infrequently individuals may or may not be performing this task.

The homepage of EoRLive displays overview information about EoR observations. This includes information about the most recent observations, listing the latest five or so observations including their start/stop times, the number of files produced, the WRT project identifier, the observation number, and the programmed human-readable name for the observation set. This display will also list the count of scheduled observations including the total and the number to

take place within the next 24-hour period. Below this display is the latest observation log which displays a few of the latest entries made in the system by an on-duty astronomer. The homepage also displays a couple of visualizations. The first is a chart of the number of hours already observed and scheduled to be observed, the amount of data available on the RadioCluster, and the amount of data that has been processed from raw WRT files into UVFITS files (the first data product used by the collaboration in their pipelines). A second graph displays the data transfer rate between the WRT telescope and the RadioCluster archive. This graph foregrounds any breakdowns in the automated process of transferring observations and highlights when an individual manually triggers a transfer of data since this is visible as a spike in the transfer rate.

Finally, the last and perhaps most interesting display on this main page is a gallery of the telescope's ten or so most recent beam images, corresponding to the observations listed in the above summary information displays, see Figure 31 below for an example. The beam image visualization not only shows the current shape of the telescope's beam which changes as the instrument's pointings change, but also the area on the sky that it is observing, points of interest in the field of view, and the location of the different EoR fields where the collaboration expects to find the faint signal that they are trying to capture. The location of the EoR field is important since this is where the EoR Science Collaboration expects to find the signal they are looking for with the least interference. The beam image is placed at the end of the main page yet provides the most readily assessable snapshot of the view of the telescope for a particular observation. Scrolling through the gallery an observer can trace the progression of the data collection over the course of a night, seeing when phenomena of interest may or may not be present.

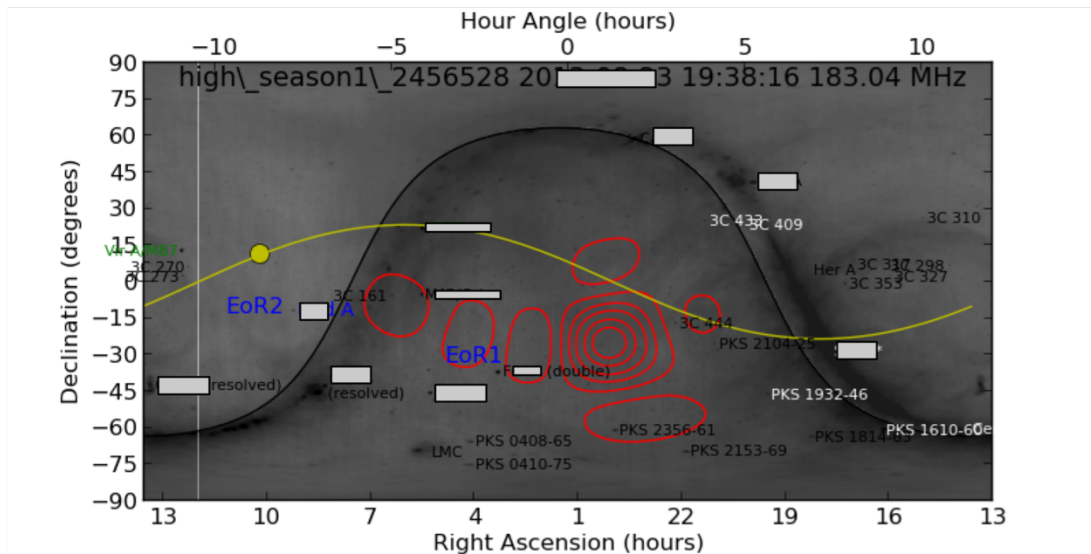


Figure 31. Beam image display on the EoR Live website.

The beam shape is shown in red, EoR fields of interest in blue, the path of the sun in yellow, and the shape of the galaxy as the black line. Grey boxes added to censor identifiable information.

The second page of the EoRLive site is dedicated entirely to displaying observation logs and providing authenticated users the ability to post new entries. In the first and second versions of the EoRLive website logs include the observation date, the observer name, and an entry about the observation in a notes field where brief information about the state of the telescope is listed. On the first version of the site there was an additional “Problems” column where a brief reason for the observation could be entered. In the second version of the site this was updated to a “Tags” column where once again the reason for the log entry can be provided (e.g., “fine”, “no data”, “hardware issue” or so on). The change from the Problems column to the Tags column however brought the ability for the page to be sorted by particular tags so that logs related to specific issues can be found easily. The second page of the site rather than providing a quick glance at the status of observations instead lets an individual look through the archive of metadata created to see whether the telescope has been functioning, whether observations were canceled or completed successfully, and so on.

Finally, the third page of version two of the EoRLive website provides a variety of links to related important webpages, categorized as “useful” and “internal” links. The “useful” links include the observers schedule that is stored in a shared Google Docs spreadsheet and many of the WRT’s ControlMonitor webpages that are maintained by the operations team. The “internal” links point to the “legacy” EoRLive website (what I refer to as version one), an archive of its data, and an administration webpage. The choice of links to include on this page reflects primarily those necessary to the successful ongoing enactment of the on-duty astronomer process since the ability to monitor the telescope depends not only upon the overview information displays on the first page of the EoRLive website but very importantly access to the internal WRT infrastructure monitoring tools. The observer’s schedule is a no-frills, publicly accessible spreadsheet in Google Docs that lists observation days and the individual who is responsible for online and offline monitoring on that day, below in Figure 32. It enables anyone within the EoR Science Collaboration to see not only their own responsibilities but also those of other members.

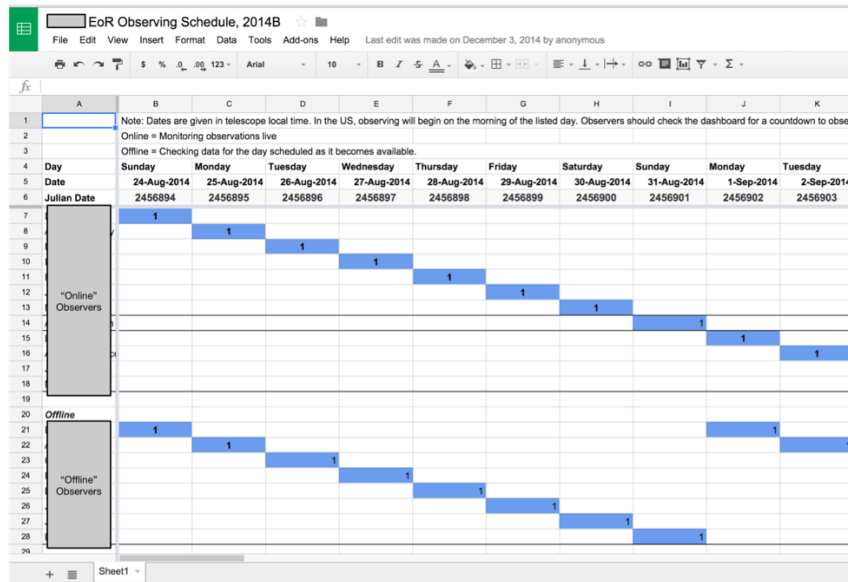


Figure 32. EoR observing schedule spreadsheet.
 This Google Spreadsheet is linked to from the EoRLive website and each day has an online and offline observer scheduled.

Together all three of these webpages provide a central location where any member of the collaboration can see the status of scheduled EoR observations. The creation of this centralized information source as a webpage rather than some other less readily accessible system enables any member of the EoR Science Collaboration to quickly assess the state of observing and share information. The various information displays reveal key elements of the WRT's operational state that pertains to EoR observations. This visualizes aspects of this particular common field of work that is part of this cooperative work arrangement. Data is the product to be collected and this practice was a part of the EoR Science Collaboration's cooperative work to create this important resource.

Curriculum Vitae

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Education

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Archival Publications

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