The Ambient Soundscape of Inland Waters in Seattle, Washington: Bridge Traffic as a Source of Urban Underwater Noise Pollution?

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Abstract

Increasing human population is adding anthropogenic sources of noise to natural ambient sound levels and threatening marine ecosystem function and viability. Overwater bridges, features of the Seattle urban environment, are a potential conductor of traffic noise to the underwater environment potentially complicating the underwater soundscape. This study utilized both custom and commercially built piezo-element hydrophones to sample sound underwater. The accuracy of hydrophones was analyzed comparatively in a test pool, finding that each hydrophone responded within 10 decibels of one another. The hydrophones were also used to sample ten stations along a transect of the urban waterfront between the University of Washington and Shilshole Marina, including a station directly beneath the Interstate-5 (I-5) Bridge. All stations showed uniform idealized sound signatures regardless of their distance from the I-5 Bridge, suggesting that bridge noise is not a unique signature in the Seattle urban waterfront.

Introduction

The urban underwater ambient soundscape is composed of natural and anthropogenic-sourced sounds. Natural sources of sound include processes such as wind and wave action, bubble formation, rainfall, and tectonic motion, while anthropogenic sources include but are not limited to recreational and commercial boating and nearshore development of roads and bridges. In the past decade the global commercial shipping fleet has expanded and is believed to have increased the level of underwater ambient sound by as much as 12 decibels alone (Hildebrand 2009; McDonald et al. 2006). Seattle is currently experiencing a population boom and downtown has grown approximately 17.2%, compared to a national population growth of 9.7% between 2000 and 2010 (Levy & Gilchrist 2013). Fast-growing population in Seattle likely leads to an increased use of interstate highways for recreational travel and commuting. Since overwater bridges are often footed through water, vibrations could be adding another layer of sound to the urban underwater soundscape, further adding to the level of underwater ambient sound.

Sound is a form of energy that travels as a pressure wave with an intensity parameter measured in decibels (dB) and a frequency parameter measured in hertz (Hz). Decibels are measured on a logarithmic scale, so an increase of one decibel is equivalent to a tenfold intensity increase. Lower frequencies retain intensity over longer distances while higher frequencies attenuate much more quickly. In other words, sound waves have inherent propagation and attenuation properties depending on their frequency, which allows for the comparison of spectral levels at different locations. The I-5 Bridge footings pass through the water column and then are secured into the seabed and it is likely that energy from traffic noise is being transferred into the water in the form of low frequency sound. Sound from traffic is also transmitted through the air

but most sound moving from air to water is reflected due to a high impedance contrast between air and water.

According to Hildebrand (2009), sound wave frequencies can be divided in to three categories: low (10-500 Hz), medium (500-25,000Hz), and high (>25,000 Hz). For reference, fish hear sound frequencies between 500 to 1000 Hertz (Hz), some species up to 5000 Hz, a range within the low and medium frequency band (Wahlberg & Westerberg 2005). Low frequency sounds, such as noise from cargo ships and/or seismic exploration propagate long distances and experience low levels of attenuation, while high frequency sounds such as breaking waves or rainfall propagate short distances and experience high levels of attenuation. Therefore, low frequency sounds affect greater areas of the ocean over longer periods of time relative to high frequency sounds that affect smaller, localized areas for shorter periods of time.

Previous studies have utilized hydrophones in passive acoustic monitoring. Hydrophones have been used to study marine fish and mammal behavior (Madsen et al. 2002; Wahlberg & Westerberg 2005; Sousa-Lima et al. 2013), underwater human communication (Stojanovic 2009), and ambient underwater noise (McDonald et al. 2006; Hildebrand 2009; Haxel et al. 2013). Among these studies, hydrophones utilizing a piezo-element are commonly employed for data collection. Piezo-elements convert a pressure wave in to an electrical signal which is then amplified and recorded through external recording devices for later analysis.

Commercial grade hydrophones cost up to thousands of dollars which presents the research opportunity to prototype two hydrophone designs to maximize affordability. With the long-term goal of making acoustic monitoring more affordable and practical, two hydrophones were built and compared against commercial grade hydrophones in this study to test functionality and ensure quality data collection. The first hydrophone prototype employed a

design by the Center for Ocean Science Education Excellence Technology and Engineering for Knowledge (COSSEE-TEK) and the second prototype was a variation on that design (Joy et al. 2014).

Anthropogenic sources of underwater sound add to the ambient noise in the underwater soundscape enhancing research interests in the potential implications human sounds may have on marine organisms and ecosystems. Recent studies have shown that various anthropogenic activities make up a significant portion of the underwater soundscape and may be a source of concern for marine ecology, though automobile traffic noise has not traditionally been included (Dahl et al. 2007; Hildebrand 2009; Haxel et al. 2012; Lillis et al 2014). This study focuses on the traffic noise from the Interstate-5 (I-5) Bridge as a baseline over a canal near the University of Washington midday in February of 2016. It is possible that migratory and resident fish in this region when exposed to excessive sound could alter their behavior and migratory paths ultimately affecting ecosystem function.

Methods

Hydrophone Prototypes

Two hydrophones were built as prototypes to test functionality of a simple piezo-element design and determine if the sensitivity was comparable with that of commercially built hydrophones. The first prototype, a build of the COSSEE-TEK Simple

Figure 1. Custom designed and built three-Piezo hydrophone (Left) and one-Piezo hydrophone housed in PVC, potted in epoxy.

Hydrophone Design by Joy et al. (2014) was made with a single 20mm piezo-element potted in a PVC head and wired to an audio cord. The audio cord fed through a RadioShack miniature amplifier on the maximum amplification setting and then to an Olympus Voice Recorder.

The second hydrophone prototype was a variation on the COSEE-TEK Simple Hydrophone Design and consisted of three 20mm piezo-elements wired in parallel (Figure 1). Piezo-elements bend when exposed to a pressure wave so an increase in surface area of piezo-elements was predicted to yield a more sensitive hydrophone overall. The three piezo-elements were placed in a larger PVC head and connected to an Olympus Voice Recorder similar to the single piezo-element hydrophone. A complete materials list for the single piezo hydrophone can be found in Joy et al. (2014).

Commercially Built Hydrophones

Two commercially built hydrophones were utilized for comparison of data - a Dolphin Ear (DE200) and a Transducer TR225/WQM. The Dolphin Ear has a bandwidth of 7Hz – 22,000 Hz, contains a 40mm disk-shaped piezo-element, and an internal amplifier. The Dolphin Ear was connected to the same Olympus recorders the custom built hydrophones used to log data. The TR-225/WQM utilizes a cylindrical piezo-electric transducer, with a linear frequency response between 1,000-30,000Hz. TR225 was wired through the RadioShack mini-amp and Olympus recorder, similar to the custom built hydrophones.

Data was also collected using a Cetacean Research Hydrophone, though is not used in this study. It was unique in that it had its own internal recording device. The one-piezo, three-piezo, DE200, and TR225 had an external recording apparatus, located above water. This allowed for the ability to start and stop sound recordings while the hydrophone heads were deployed underwater. The Cetacean Hydrophone, having the internal recording device, had to be turned on at the beginning of data collection and record the entire time the hydrophone was in

the water. Because of this uncertainty in isolating data collection times, data from this

hydrophone is not included in this study. The design and build component of this experiment

allowed for individual recordings at each station owing to the ability to start and stop recordings

when needed, critical to the success of data collection.

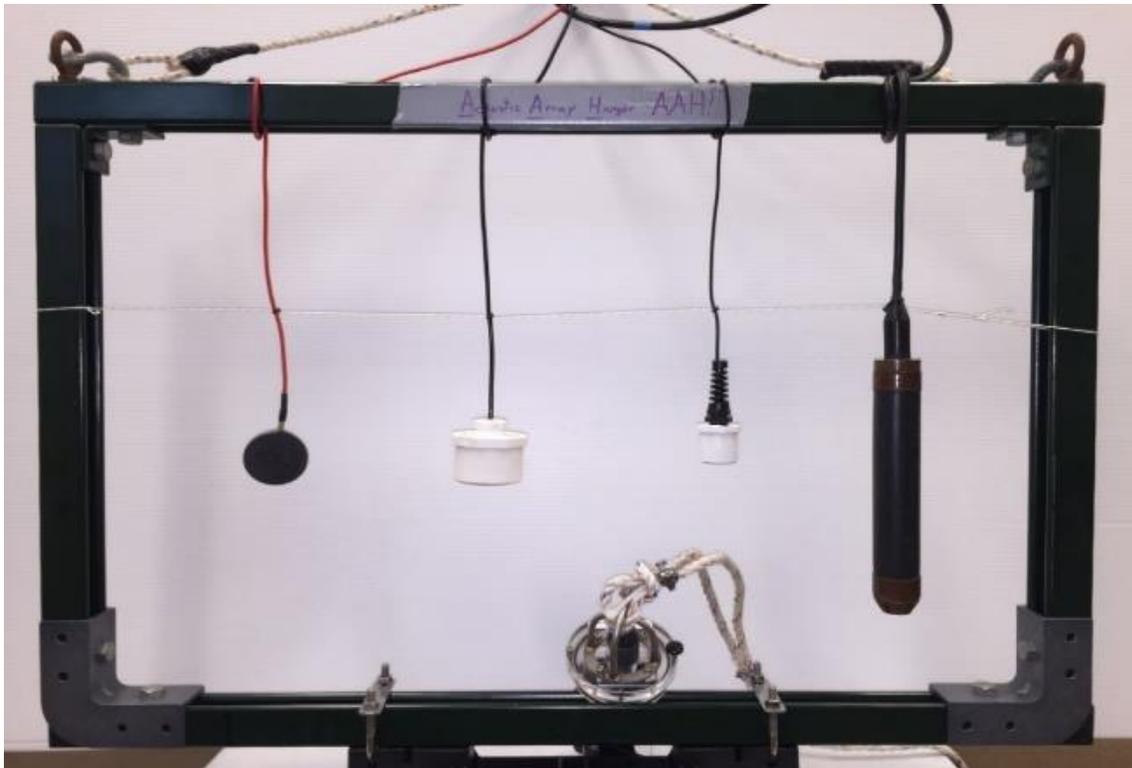**Inter-Calibration between Hydrophones**

Figure 2. AAH (Acoustic Array Hanger). Hydrophones are mounted, left to right, DE200, three-piezo, one-piezo, TR225, and bottom Cetacean Research Hydrophone.

The one-piezo, three-piezo, DE200, and TR225 were then mounted on a square frame

made of metal struts, called the Acoustic Array Hanger (AAH). This allowed for concurrent

deployment of hydrophones and capability of simultaneous recordings (Figure 2). An inter-

calibration experiment was conducted in a 7 x 3 x 4 meter concrete and air insulated pool located

at the University of Washington. The AAH was deployed with all four hydrophones on a line to

one meter depth in the pool to test the response of each hydrophone to a known sound source. A

5,000 Hz sound was emitted using an acoustic transmitter deployed at a one meter depth 3 and 5

meters from the AAH. A 10,000 Hz sound was also emitted at 3 and 7 meters away from the

AAH. Sound was dispersed between each trial so there was no lingering reflections from one

trial to the next.

The results of the test-tank deployment showed that each hydrophone responded to 5,000

and 10,000 Hz sounds at both 3 and 7 meters away (Figure 3). All four hydrophones behaved

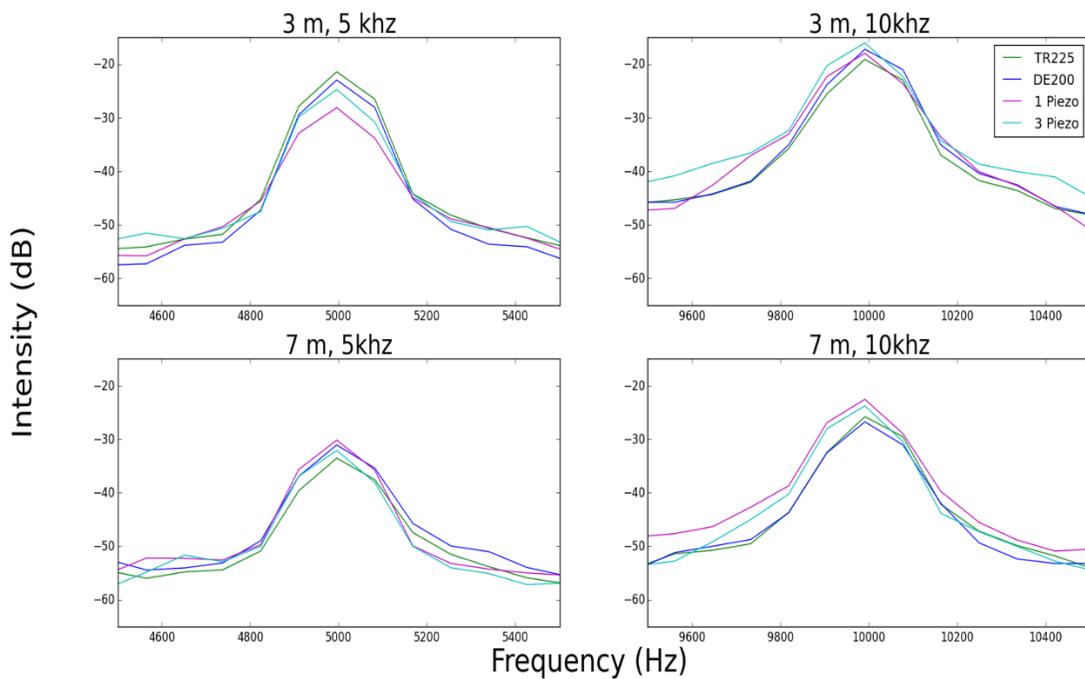within approximately 10 decibels of one another in each trial.

Figure 3. Relative behavior of hydrophones in test tank with known sound source. The response of each hydrophone to the 5,000 and 10,000 Hz sounds sourced from transducer, located 3 and 7 meters from the AAH. Less negative values of intensity are considered "louder".

Field Deployment

Field data was collected on February 12th, 2016. The AAH was deployed from R/V

Clifford Barnes at 10 stations between the University Of Washington School Of Oceanography

Dock in Portage Bay and Shilshole Marina (Figure 4). At each station, R/V Barnes engines and

generators were turned off for approximately thirty seconds to eliminate boat noise

contamination in samples. The AAH was deployed and 30 second clips were recorded with all hydrophones at each station. Other transiting boats were not in sight during recording periods at each station, so no localized boat traffic is expected to have been detected by the hydrophones. However, lower frequency sounds from unknown sources may have been detected from great distances away.

The R/V Barnes was directly beneath the I-5 Bridge at Station 2 so the most concentrated sound sourced from the I-5 Bridge was likely recorded. All other stations are a distance away from the I-5 Bridge within a time period of three hours, purely a result of ship transit time. Data was collected between 12pm-3pm Pacific Time, under the
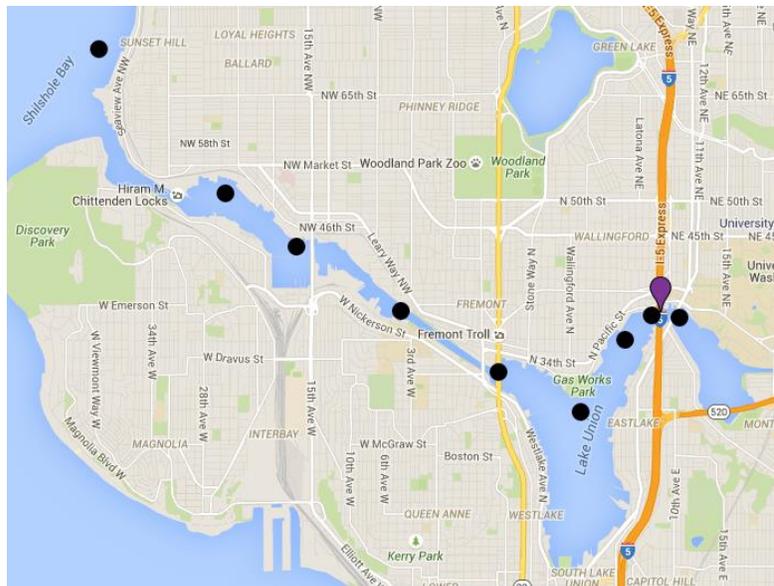

Figure 4. Locations of each data collection station are pictured here. Stations are numbered from right to left, 1-10, Station 1 being nearest UW and Station 10 being nearest Shilshole Marina. The purple marker indicates the I-5 Bridge Station, the baseline of noise for this study. For reference, the distance from the I-5 Bridge to Station 5 just south of Gas Works Park is approximately 1500 meters.

assumption that traffic in this time range would be relatively constant.

Data Transformation

Test tank data and field data were collected and recorded using Olympus voice recorders that logged data in the Windows Media Audio (WMA) file format. WMA recorders seemed to be considerably more affordable than WAV recorders, important to consider in maintaining the low-cost nature of this study. A free software was downloaded to convert the WMA files to WAV files, necessary to load the files into Audacity, a sound analyzing software also available for free download. There are many programs available, but Audacity was the most user friendly

and free. Audacity was used to perform a Fast Fourier Transform on 20 second clips of data from each station to produce spectrograms of decibel versus intensity for each data file. Spectrograms were then used to visualize both test-tank data and field data.

The two custom built hydrophones had similar spectral responses and the two commercially built hydrophone had similar spectral responses at each station. To simplify data analysis the one-piezo and three-piezo hydrophone data were averaged and the DE200 and TR225 data were averaged at each station. The two averaged spectrograms were then combined to form an Idealized Acoustic Signature at each station (Figure 5). The commercially built hydrophones were used up until 10,000 Hz while the piezo hydrophones were used at frequencies greater than 10,000 Hz, where the piezo hydrophones were more sensitive. At approximately 16,000 Hz the hydrophones appear to enter chaos. Data is likely artificial beyond this threshold and hydrophones likely met their sensitivity threshold. Sensitivity was determined by decibel levels: higher decibel levels indicated higher hydrophone sensitivity. An error of approximately +/-5 decibels was applied to the Idealized Acoustic Signature to account for averaging of the hydrophones as well as other potential sources of error during data collection in the field.
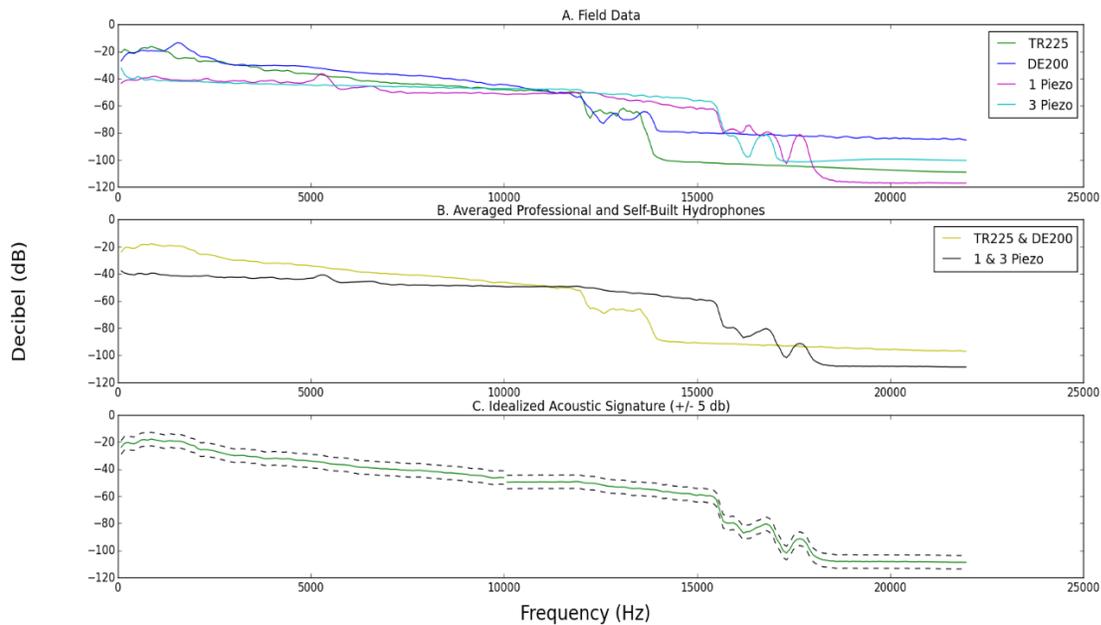
Figure 5. The process of deriving the idealized acoustic signature from the initial spectrograms of each hydrophone at Station 2, the I-5 Bridge is shown here. A - Spectrograms of each hydrophone by color. B - Average spectrograms of the Dolphin Ear and Tube Hydrophones and the one- and three piezo-element custom built hydrophones. C - Idealized sound signature including commercially built hydrophones up until 10,000 Hz, then custom built hydrophones from 10,000 Hz on. The disjunction in the data at 10,000 Hz indicates the transition between the two averaged spectrograms.

Results

Hydrophone Prototype Response to Environmental Conditions

The DE200 and TR225 hydrophones behaved similarly while the one-piezo and three-piezo built hydrophones behaved similarly. The DE200 utilized a 40mm disk shaped piezo-element while the TR225 utilized a cylindrical piezo-element, and had approximately the same decibel response. At every station, the DE200 and TR225 began with approximately -20 dB near 0 Hz and decreased with increasing frequency. The DE200 and TR225 were more sensitive (returned higher decibel readings) than the custom built hydrophones at frequencies less than approximately 10,000 Hz in the field. The one-piezo and three-piezo hydrophones were more sensitive to sound frequencies greater than 10,000Hz, up to ~15,000Hz. The three-piezo

hydrophone was not any more sensitive than the one-piezo hydrophone. Wiring the piezo-elements in parallel to increase surface area did not increase the decibel response of the three-piezo hydrophone.

Data was collected at 10 stations between the University of Washington and Shilshole Marina, Station 2 located directly beneath the I-5 Bridge. Each station illustrates a similar idealized acoustic signature: lower frequencies returning the highest decibel levels, each station beginning with a -20 dB response at 0 Hz. Each station has a sound signature that becomes irregular at frequencies at or above 15,000 Hz. At Station 2, decibel levels range from approximately -20 dB to -60 dB, indicating that low frequencies contain 30 times more power than higher frequencies, considering decibels are measured on a logarithmic scale.

Hydrophones utilized in this study were capable of recording low (10-500 Hz) and medium (500-25,000 Hz) frequency sounds in the waters between the University of Washington and Shilshole Marina (Hildebrand 2009). For the purposes of this study, we focused on the medium frequencies between 500-15,000 Hz, due to the frequency limitation of hydrophones used. Each station showed low frequency sounds registering between -20 to -25 dB, while medium frequency sounds ranged from -20 to a minimum of -60 decibels.

The stations all behaved similarly to Station 2, directly beneath the I-5 Bridge (Figure 6). Considering the 10 decibel error of hydrophone response comparatively, the deviation from station to station below ten decibels is not significant. The low frequency band had a maximum decibel difference from the I-5 Station with 7 decibels, and the medium frequency band had a maximum decibel difference from the I-5 Station with -4 decibels (Table 1).
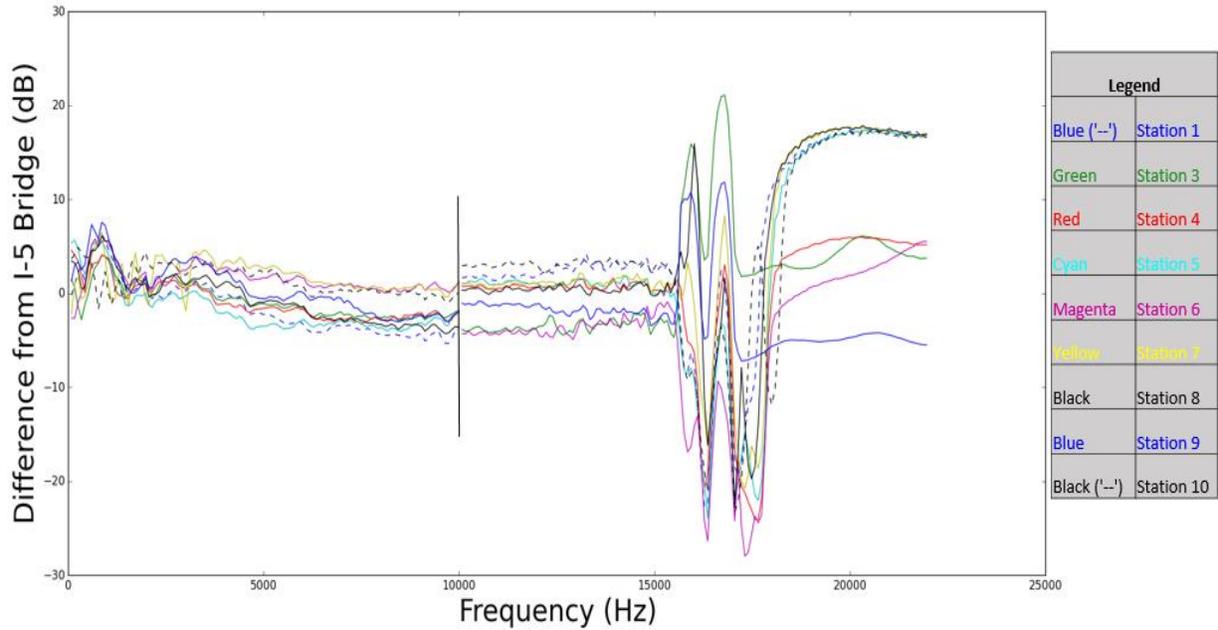
Figure 6. Decibel difference of each station from the I-5 Bridge (I-5 Bridge - Station #). Positive differences indicate I-5 had a greater decibel response, while negative differences indicate I-5 had a lower decibel response. The vertical black line marks the shift in idealized sound signature from the commercially built hydrophones to piezo hydrophones, maximizing sensitivity of reported measurements. Beyond approximately 15,000 Hz, hydrophones appear to reach their sensitivity threshold, returning an artificial response.

Table 1. Maximum decibel differences in low and medium frequency bands.

	Low Frequency (0-500 Hz)	Medium Frequency (500-15,000 Hz)
Max Decibel Difference	7	- 4

Discussion

This study examined the ambient underwater soundscape of Seattle's urban waterfront that includes the in-water footings of an interstate highway bridge, a heavily populated urban lake, and narrow ship canals. The results of both the test pool and field experiments indicate that the one and three piezo-element hydrophones had very similar responses at all decibel levels and the size of piezo-element utilized did not affect the sensitivity of the hydrophones (Figure 3).

This difference of 10 decibels between hydrophones for all trials in the test tank were not significant relative to the noise level experienced in the field.

All stations in the field are also within <ten decibels of the I-5 Bridge station within the low (0-500 Hz) and medium (500-15,000 Hz) frequency bands (Figure 6). The low frequency band has a maximum decibel deviation from the I-5 Bridge of 7 decibels, while the maximum deviation in the medium frequency band was -4 decibels (Table 1). Considering that the hydrophones responded within 10 decibels of each other in the test pool and at all stations in the field, suggesting that the soundscape is uniform among all stations sampled. This study may have collected conservative estimates of the intensity of the soundscape because of the timing of data collection, as major traffic times are not included.

It was hypothesized that the I-5 Bridge would emit a sound signature that would decay in decibel level with distance from the bridge according to frequency. However, when characterizing the sound signature of each station as an idealized signature from all hydrophones, the distance of those stations from the I-5 Bridge did not demonstrate a significant difference in sound intensity according to frequency so propagation and attenuation properties of sound were not studied. The uniformity of the idealized sound signatures of all stations regardless of their distance from the I-5 Bridge suggests that bridge noise is not a significant localized signature and does not uniquely identify the soundscape at that location along the sampled transect of inland waters of Seattle, Washington.

Conclusions

The soundscape was uniform at each station sampled with an error of approximately 10 decibels. Each station behaved similarly to the I-5 Bridge (Figure 5), with higher decibels

readings in low frequencies and lower decibels in high frequencies, consistent with low frequency sounds having a greater presence in time and space in the ocean. The distance between UW and Shilshole Marina has a considerable amount of boat traffic that contributes to the soundscape episodically, not recorded in this experiment. This experiment aimed to control for episodic events by making sure no other boats were transiting in site during data collection, as well as silencing the R/V Barnes during data collection.

As human population continues to grow, episodic events are likely to become more constant in time and will ultimately increase decibel levels of the ambient soundscape. It is important to consider that the data in this study were collected between the hours of 12pm and 3pm. Higher traffic times, such as rush hours, would likely result in an increased input of sound to the urban underwater environment, where very early morning hours would likely contribute less sound. Sound is an important parameter to understand because ecosystem and organismal behavior may be altered if ambient sound is too loud. Underwater organisms often rely on sound to transit, mate, and communicate, so it is important to understand and mitigate anthropogenic sound sources that may interfere with these activities.

The field experiment was conducted under the assumption that the sound signature measured directly beneath the bridge represented sound transfer from the bridge footings into the water. This is likely to describe the sound the bridge was emitting but could have been more effectively measured by fixing a hydrophone, vibration sensor, or accelerometer on the bridge footing itself to measure exactly how much sound energy was being produced by the bridge at a point where it were in contact with the water.

In future studies, it would also be beneficial to better control for time. Deploying all hydrophones at the same time, instead of within a three hour period would increase the validity

of the results. Additionally, it would be interesting to take sound samples at several times throughout the day during times of varying traffic volumes, to measure the difference in underwater sound levels according to time and traffic volume. It may also be important to increase the duration of sound samples. This study measured 20 seconds of sound at each station. Though it is not likely, episodic events could have occurred during each recording that could not be heard above water, resulting in similar sound signatures at each station.

Ultimately, sound is a difficult parameter to measure in the urban waterfront, and underwater in general because of the great distances it travels, the attenuation and propagation properties of sound and the impossibility to control for sound input in the urban environment. This experiment is one step forward to understanding the urban underwater soundscape, which should be continually studied to better understand the anthropogenic input to underwater sounds, an important aspect of life in the underwater environment.

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