The Influence of Water Column Variability and Seafloor Topography on Multibeam Bathymetric Mapping

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Abstract

In shallow water surveying there are multiple challenges for the accurate mapping of submarine features. Surveying over multiple stages of a tidal cycle and acquiring data from multiple orientations of the submarine feature are two survey strategies that bathymetric surveys can utilize to ensure more confidence in their data. During post processing bathymetric surveyors must often manually analyze the accuracy and confidence of the location of depth estimates before moving on to create base surfaces. Errors can be hard to identify due to the vast amount of individual points that comprise these estimates. The purpose of this study is to identify influences of seafloor topography and variability of sound velocity properties of the water column on the accuracy of multibeam depth estimates. This study examines the multibeam sonar data from a survey of repeated observations of the underwater feature of Williamson Sill in Nootka Sound, B.C. Canada on the 17 of December 2015. The observations grouped by their position on the sill feature the tide height at the time of acquisition create the research design for evaluating variation in depth estimates. The data were post processed using CARIS HIPs where base surfaces and range in depth estimates were derived. When these groups were compared, the variation between groups suggests that relative position to an underwater feature exerts a large amount of influence on survey accuracy, while tidal height appears to exert little influence on accuracy.

Introduction

The physical structure of the seafloor plays an important role in many ocean sciences studies. In current ocean science research detailed characteristics of the seafloor are obtained from multibeam sonars. The application of multibeam sonar ranges from the observation of different biota such as sea grass to tracking where the movements of past glaciers shaped the seafloor (Anderson et al. 2002; Komatsu et al. 2003). After its creation and initial use in the 1960s as a military project for the US Navy, sonar use has expanded and is now used by many different professions (Theberge Jr and Cherkis 2013). Although sonar is used in a range of varying applications, the basic factors that contribute to uncertainty and error in the interpretation of acoustic soundings have remained the same.

In near shore environments, also known as littoral environments, the tidal driven mixing of the water can result in noticeable changes in the water column(Li and O’Donnell 1997). These different characteristics such as salinity, temperature, and particulate matter all affect water density (Li and O’Donnell 1997). Bathymetric surveying using multibeam sonar systems (MBS) relies on precise measurements of water density over depth to accurately represent the speed of sound (sound velocity profile or SVP). Once an SVP has been measured it can be applied to a “distance for time” calculation and an estimate of the seafloor’s depth can be made.

In an estuary environment, sills which are remnants of glacier moraines, exert an enormous amount of influence on the oceanographic processes of mixing the water column. This influence can play an important role in the temporal variability in the speed of sound through that water column. Additionally the sill’s size and shape can have direct influence on currents flowing over it, water masses moving into the estuary, and biological life in the estuary (Xing and Davies 2007). The influence from the sill can result in different water column properties for a distance of a few hundred meters (Rüggeberg et al. 2011). Water column mixing in an estuary is not driven solely by the ebb or flood of the tide, but also upon the magnitude of the tide. A weaker tide can be assumed to have less of an effect on mixing, thus leaving a more stratified water column. In this way the changes in the characteristics of tides over sills play an important role in the properties of the water column and therefore an important role in the speed of sound through the water column. These changes in water column characteristics make sills an ideal location to study the effects of how changes in the water column properties effect the interpretation of sonar returns.

This study is focused in Nootka Sound of Vancouver Island, B.C. Canada, a series of fjords and fjards carved during the retreat of the Cordilleran Ice Sheet (Ryder et al. 1991) (Figure 1). A glacial moraine, a large mound of deposited glacial debris, forms a sill at the mouth of the sound. Additionally there are other sills located throughout the various fjords and fjards that are evidence of various glacier retreats and advances. The Williamson Sill, selected for this study, is located on the north side of Gore Island in the Williamson Passage of Muchalat Inlet (Figure 1 and Figure 2). The location of the Gold River as well as several smaller creeks feeding into Muchalat Inlet up channel from Williamson Sill provides a continuous input of freshwater into the Inlet (Figure 1). During tidal ebbs and floods the fresher water in Muchalat Inlet and more saline waters in Nootka Sound are exchanged.

This interaction creates a gradient of changing properties of sound velocity over short spatial and temporal scales. A study in the coastal waters of the Caspian Sea found a change in sound velocity over a halocline of 28 m sec-1 (Jamshidi and Abu Bakar 2010). This inaccurate sound velocity results in errors of depth estimates due to uncertainty in the time for distance calculation use of the acoustic backscatter signal generated by the multibeam sonar.

The orientation of the face of a submarine feature relative to the source of the acoustic signal also affects the timing and intensity of acoustic returns. Every sill is unique as a feature, but there are some similarities shared across all sills. Their sloped sides and crest faces create differences in the orientation of the acoustic signal relative to the survey vessel. Due to these unique angles of reflection (aspects) of the acoustic signal, inaccuracies in depth estimates can occur.

By repeatedly acquiring acoustic returns during different tide stages over the three faces of a sill feature, this study hopes to identify the effects of tides and orientation on the accuracy of sonar returns in an area of high tidal exchange.

Methods

The survey of Williamson Sill took place on the 17th of December 2014 in Muchalat Inlet onboard *R/V Thomas G. Thompson* using the Kongsberg Marine EM302 Echosounder sonar array. This multibeam sonar system (MBS) operates at a frequency of 30 kHz and has a depth survey range of 10-7000 meters (Kongsberg 2013). The survey was designed to acquire data of the Williamson Sill over a single tidal cycle. A single sound velocity profile was acquired early in the survey during low tide. Repeated survey track lines were planned over the sill in opposing directions and at different times during the tide cycle (Figure 3).

The geographic registration of the depth estimates along the swath can then be altered by changing the reception angle of the transducer and thereby increasing the ping density within a narrower band of the swath. Changing the ping density is accomplished by altering the reception angles, in either an equidistance or equiangular configuration. A swath in an equidistance configuration will have all returns spaced in an equal distance apart. A swath in an equiangular configuration will have all returns received with equal angles off of nadir. As the depth changed along the ship track while it was passing over the sill feature the equiangular pings became more closely spaced to account for the change in depth. This in turn effected the ping density along a swath resulting in some swaths with a larger amount of pings located at or near nadir than swaths that were formed using the equidistant method.

Once all the data were collected, the raw data are loaded into a bathymetric mapping program, CARIS HIPs ver. 8.1 for post processing. The post-processing phase began with an examination of the influence of tidal driven changes in the water column. Three ship track lines were selected for their location in time, allowing for the examination of sonar returns during three unique tidal stages (Figure 3). Two of the ship track lines were from East to West, and one was from West to East. This allowed for data collected from two different aspects of the sill's orientation to the survey vessel to be compared and contrasted. Each ship line was broken into spatial subsets consisting of 29 individual swaths that allow for the investigation of three unique features of the sill: the face, the top, and the back. These subsets of front, top, and back were then reduced to the inner quartile of the swath eliminating the variability found in outer beams. The subsets were then binned in 5 meter increments away from Nadir. Using the "Swath Editor" tool in CARIS, the range in vertical distance between depth estimates within these bins was recorded (Figure 5).

A sample of six swaths were randomly selected from each of the subsets. Each of these randomly selected swath was examined individually to identify and count the number of "outliers", or extreme differences of depth estimate relative to the adjacent depth estimate. If a sounding was found to be more than 0.5 meters shallower or deeper than its immediate neighbors it was tagged as an outlier. After each outlier was identified, its distance to Nadir was recorded.

Results

The characteristics examined in “Swath Editor” found no trend in the range of depth estimates when surveyed at different tidal stages. All three survey lines had subsets whose ranges in depth estimations were comparable. At low tide the range in depth estimations for the subset containing the front of the sill as approximately 5 meters (Fig. 4A). At both mid tide (maximum flood tide) and high tide the ranges of depth estimations were 5.06 meters and 5.33 meters respectively. There were similar results for subsets containing the back of the sill and subsets containing the top of the sill (Fig. 4A & 4B). Figure 1 indicates that as the tide rose from a low tide to a high tide (indicating that saltier water from Nootka Sound was flowing into Muchalat Inlet and thus over Williamson Sill) no clear trend emerged indicating a change in accuracy. When clear outliers were removed from the data the maximum range in which subsets varied from line to line was .8 meters (Fig. 4B).

A clear trend was found in the range of depth estimates for different subsets. For all three survey lines the subset containing the top of the sill was the smallest in range estimations (Fig. 1). The subsets containing the front slope of the sill had ranges of depth estimates that were larger than the top of the sill, but smaller than the back slope (Fig 4.). Additionally, in all three survey lines the subset containing the back slope the sill has the greatest difference in range between all three subsets (Fig. 4). The subset containing the back slope had a difference of over 1 meter in the range of depth estimation during the High Water Slack Tide stage when outliers were removed from the data (Fig. 4B).

There was no discernable effect on the range of depth estimates, or the number of outliers in regards to a change in survey aspect. The largest difference in range of depth estimates between the two different survey aspects was 0.8 meters for the front of the sill. The smallest difference in range of depth estimates was 0.12 meters for the top of the sill. It is worth noting that there was a difference in the range of depth estimates between Lines 03 and 17, both of the same aspect, of 0.76 meters (Fig. 4B).

Additionally, an analysis of the location of the outliers in regards to distance from Nadir revealed interesting results. Outliers were more likely to be located closer to Nadir (Fig. 8). Additionally, the survey lines where the receive angles were altered using an "equal angle" configuration had more outliers than the "equal distance" approach. Line 03 which was an "equal distance" line had on average half of the number of outliers than Line 17, which was an "equal angle" line (Table 1).

Discussion

Results from the Williamson Sill survey indicate that changes in water column properties during tidal exchange had the least affect in the estimate of depth. Inaccuracy in the calculations of sound velocity or a dynamic change in water column properties between survey intervals is required to experience a significant error in depth estimates. Using the rules of thumb from *Principles of Naval Weapons Systems*, a book on US Navy Weapons, a 1ppt increase in salinity corresponds to approximately 1.3 m/s increase in the speed of sound through water (Hall 2000). A difference in salinity of 8 ppt over a distance of 100 meters (a mean depth of the sill) would result in a difference in depth estimations of only .7 meters, less than 1% of the sill depth. Data from this investigation suggests that over the time frame of one tidal cycle there was little change in the water column that greatly affected the speed of sound and subsequent estimates of depth. The range of depth estimations remained relatively unchanged as tidal water was exchanged.

Sill physiognomy was found to be a major factor on the perceived error in sounding returns. The reason behind this effect most likely is from the unique shape of sills. Because sills were formed by the advance and retreat of glaciers their faces can vary in steepness (Anderson et al. 2002). The east side of Williamson Sill was noticeably steep than the west side. This can be expected because when the Cordilleran Ice Sheet advanced it advanced from the east moving towards the Pacific Ocean (Ryder et al. 1991). This would have resulted in a steeper east side of the sill as the ice would have been pushing up against it during its growth phase (Martini et al. 2011) (Figure 4A&B and Figure 6). The larger range in depth estimates of the back side of the sill most likely results from the steeper slope over the same horizontal distance used in the swath editor. Therefore it is critical for future surveyors to reduce the number swaths when surveying slopes. A failure to do so would create the appearance of error in larger range in depth estimations because there is a greater vertical range that the swaths cover due to the fact they are covering a slope.

The orientation of the survey relative to the face (aspect) of the sill was found to have little to no influence on the accuracy of ping location. When the sill was surveyed along an East-West direction (Line 03 and Line 17) the range in depth estimations on the different faces was not found to significantly different from when the sill was surveyed in a West-East direction. Although there were differences in range of depth estimates, there was not a clear pattern that one aspect versus the other accounted for greater variation in the range of depth estimates. Both survey orientations contained similar amounts of outliers and ranges in depth estimates.

Results in the location and count of outliers relative to the center of the swath did not as expected indicate greater consistency close to Nadir. Because the signal from Nadir has the shortest distance to travel then that of the returns locate further along the swath, greater consistency in depth estimates is often expected. However, this survey has found the opposite. One possible explanation for the greater number of outliers being located near Nadir is that the EM302 is better suited for deeper waters (Kongsberg 2013). Use in shallow waters with the EM302 could result in slight errors due to the shallow depth. It is reasonable to suspect that the points under Nadir are receiving the strongest signal from the transducers. This stronger signal penetrates the sediment layer and returns from depths below the surface as troughs as seen in Figure 5. These would then appear as outliers on the swath editor. Another possible reason behind the increase of outliers could be the difference in using an “equal distance” transducer array versus an “equal angle” array. As the seafloor rises due the slope of the sill, an “equal angle” array would result in a greater concentrations of pings located closer to the Nadir (Figure 6 and Figure 7)). As the number of pings increased the likely hood of greater variation also increases. The increased number of pings closer to Nadir would then be more likely to have a greater number of outliers near Nadir as well. This appears to be the case because both Line 17 and Line 31 were set up using the “equal angle array” while Line 03, which had a lower number of outliers closer to Nadir was in the “equal distance” configuration.

Conclusion

The survey of Williamson Sill shows the importance of careful planning in respects to bathymetric surveying. The results suggest that while changes in sound velocity can influence survey results, the frequency in the application of sound velocity correction need only match that of significant exchange of water properties. Even though the tidal driven variations in the water column above this survey site lacked significant changes in the sound velocity profile, that does not mean that other sites experience similar variations in the water column. Bathymetric surveyors should ensure that they have an understanding of the tidal driven changes in the water column that effect their survey location. Additionally the results indicate that the aspect of the seafloor relative to the ships track has little effect on the accuracy of depth estimates. This suggests that surveyors could utilize a survey track containing a single aspect of the seafloor and have confidence in the resulting base surface created from the data. However it should be noted for high definition or extremely strict survey requirements, an additional aspect would give the resulting base surface a higher degree in confidence. The finding that outliers in depth estimates appeared in greater numbers near Nadir in the inner quartile of a swath poses the question: what is the cause for this? There are too many factors for this paper to surmise why there were more outliers closer to Nadir. If a causation could be found and adjusted for, it is reasonable to assume that surveyors would have less errors to search for in post processing, making this a worthy topic for future studies.

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Figures

Figure 1

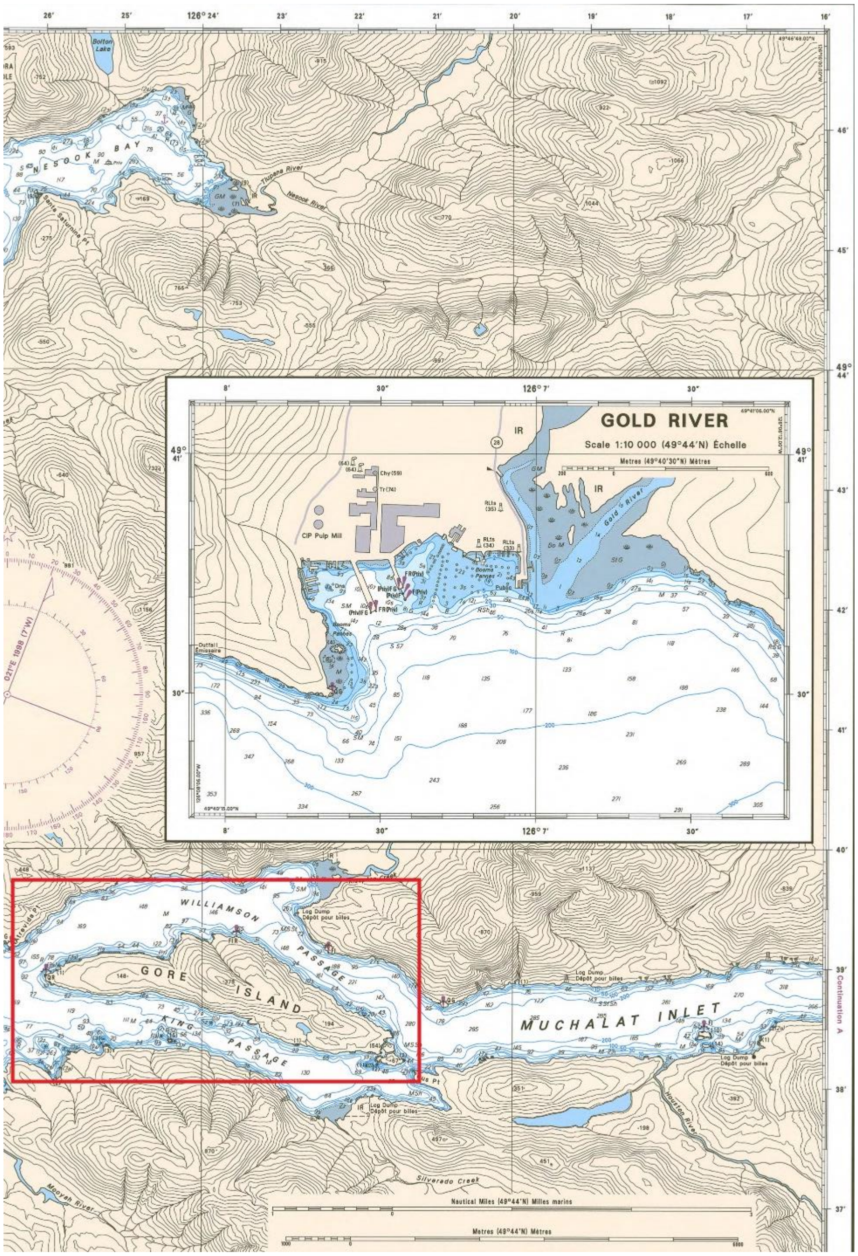


Figure 2

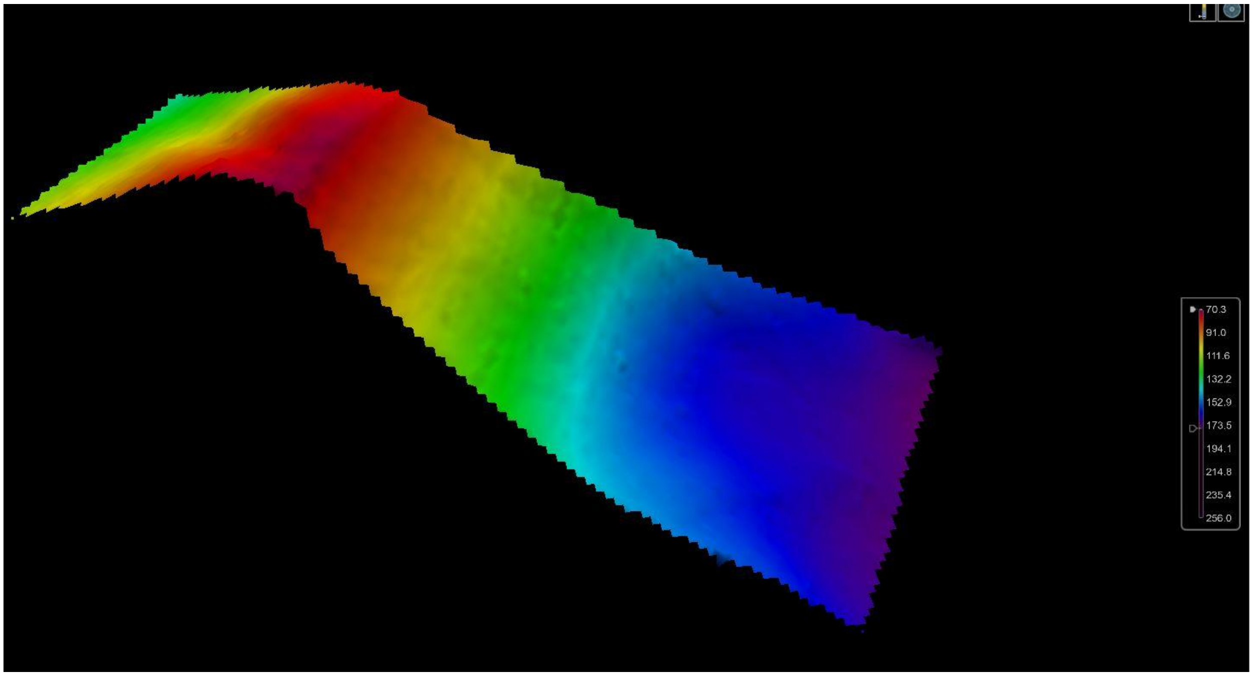


Figure 3

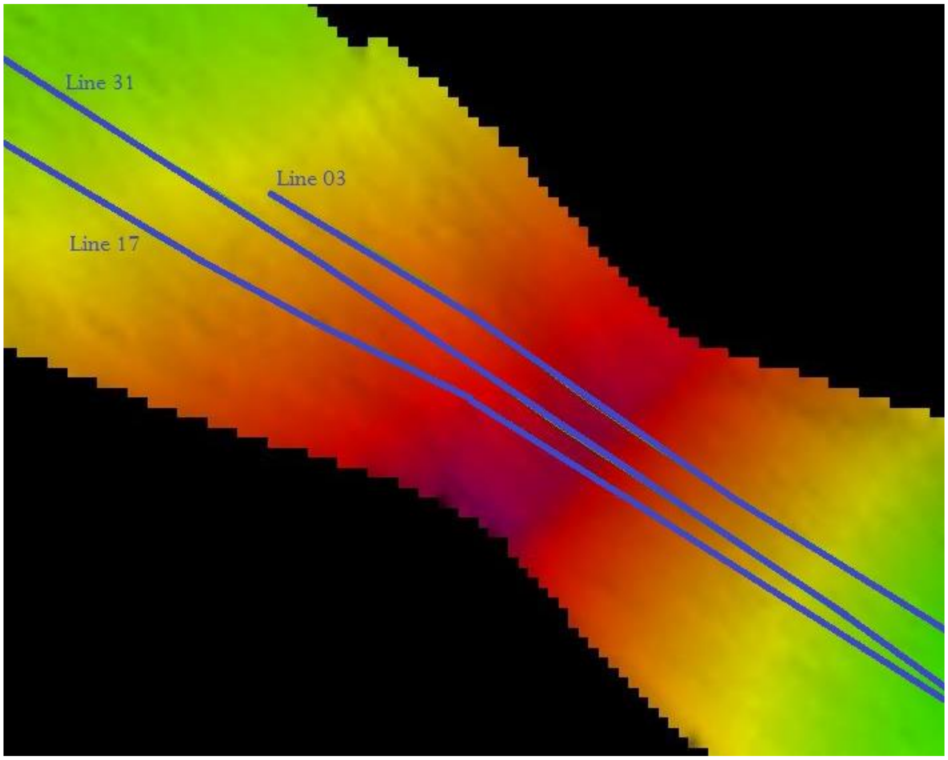
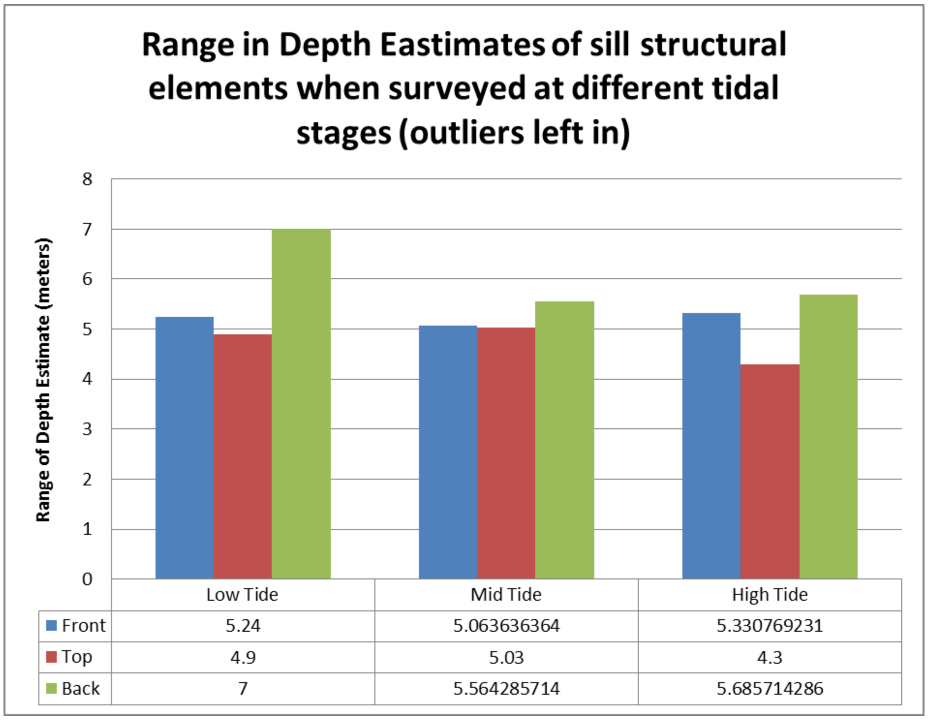
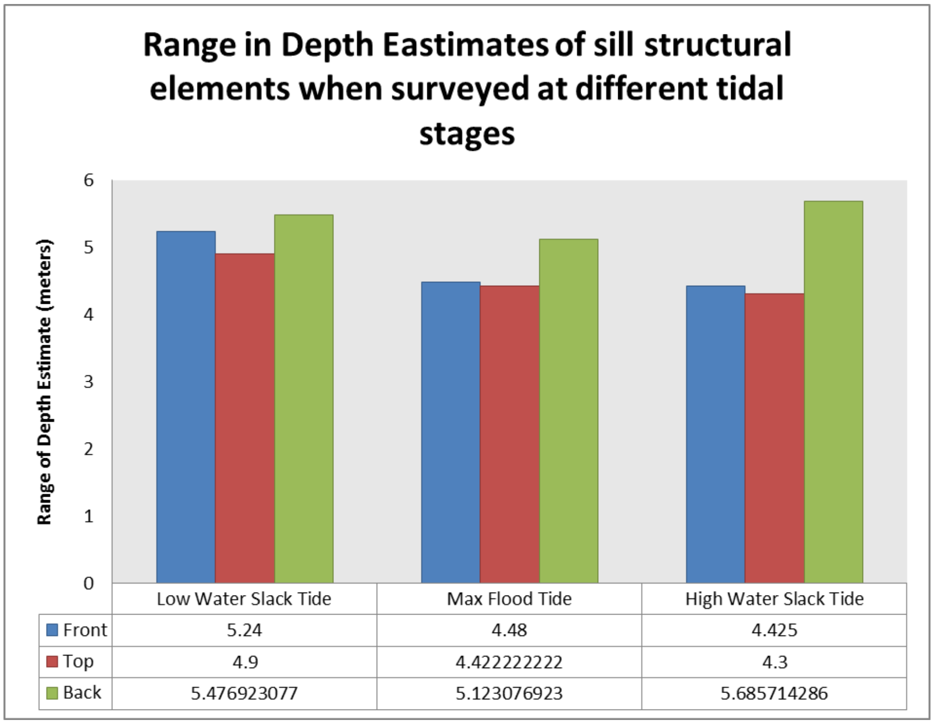


Figure 4A



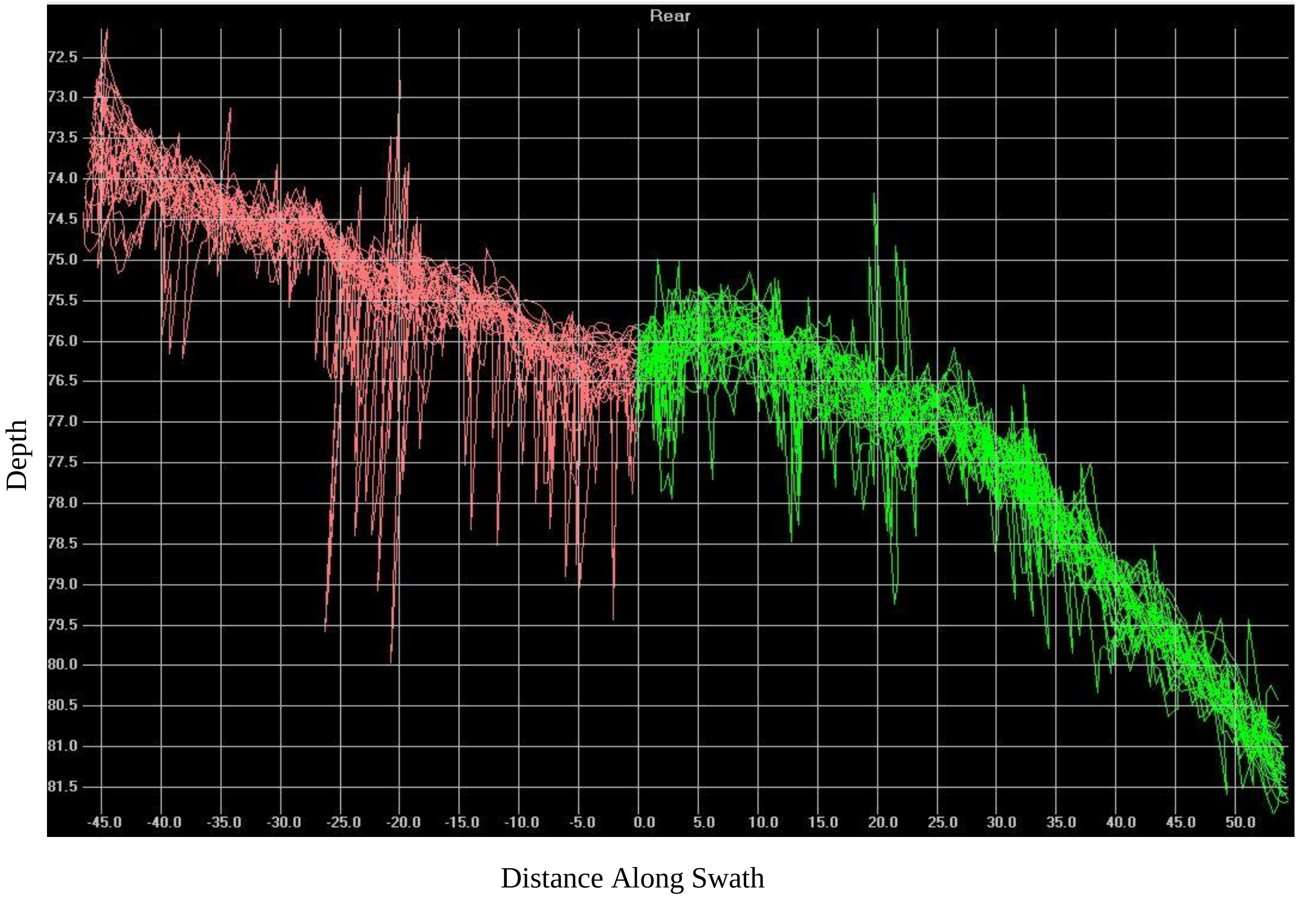
	Low Tide	Mid Tide	High Tide
🟦 Front	5.24	5.063636364	5.330769231
🟥 Top	4.9	5.03	4.3
🟩 Back	7	5.564285714	5.685714286

Figure 4B



	Low Water Slack Tide	Max Flood Tide	High Water Slack Tide
🟦 Front	5.24	4.48	4.425
🟥 Top	4.9	4.422222222	4.3
🟩 Back	5.476923077	5.123076923	5.685714286

Figure 5


Rear
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73.0
73.5
74.0
74.5
75.0
75.5
76.0
76.5
77.0
77.5
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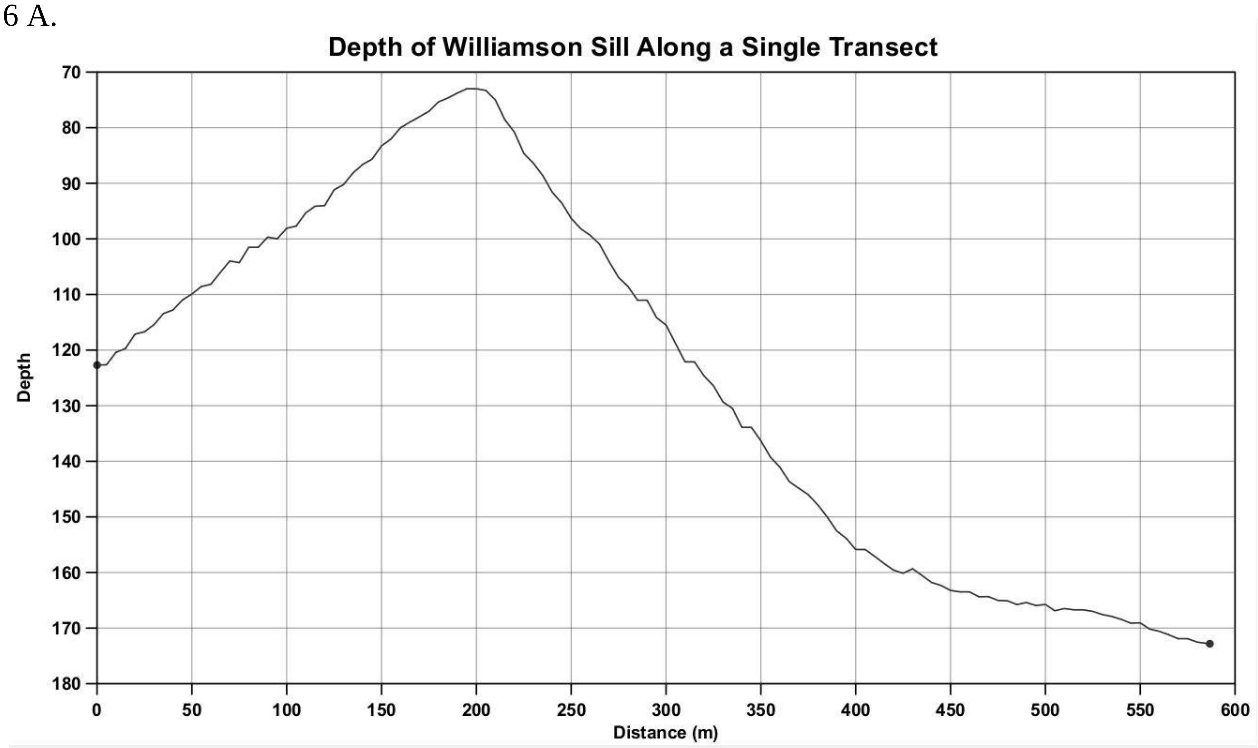
78.5
79.0
79.5
80.0
80.5
81.0
81.5
Depth
-45.0
-40.0
-35.0
-30.0
-25.0
-20.0
-15.0
-10.0
-5.0
0.0
5.0
10.0
15.0
20.0
25.0
30.0
35.0
40.0
45.0
50.0
Distance Along Swath

Figure 6

6 A.



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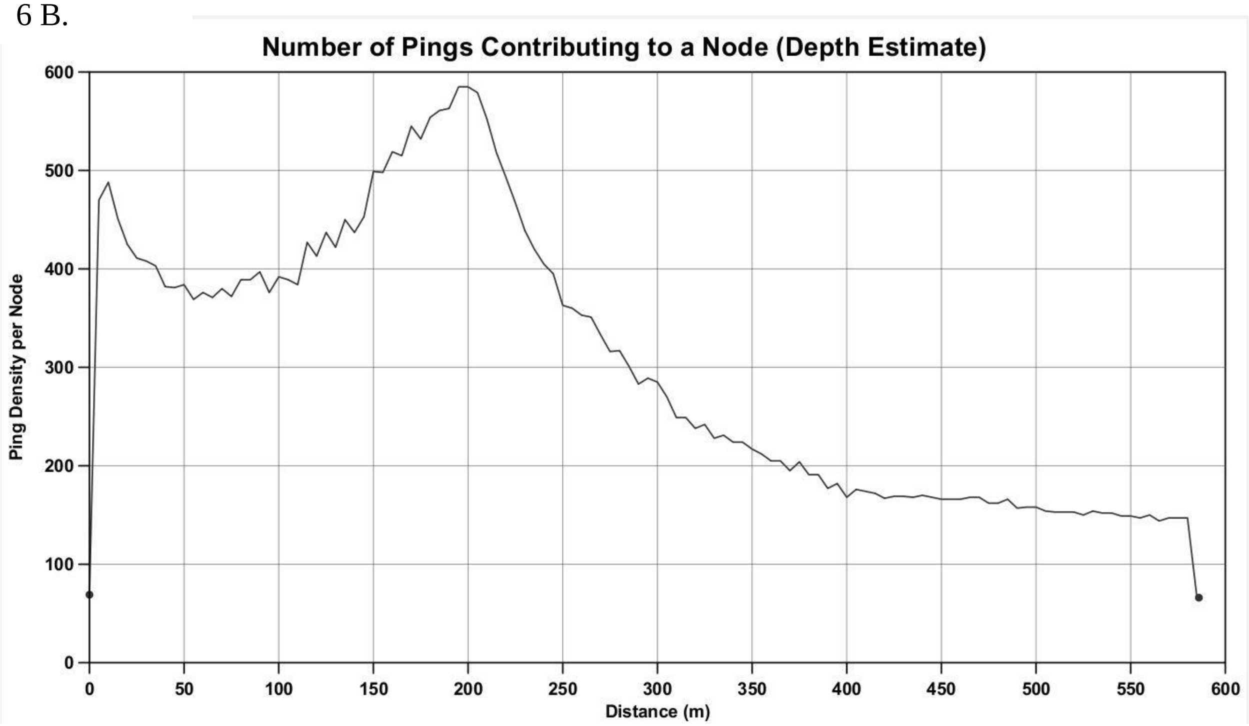
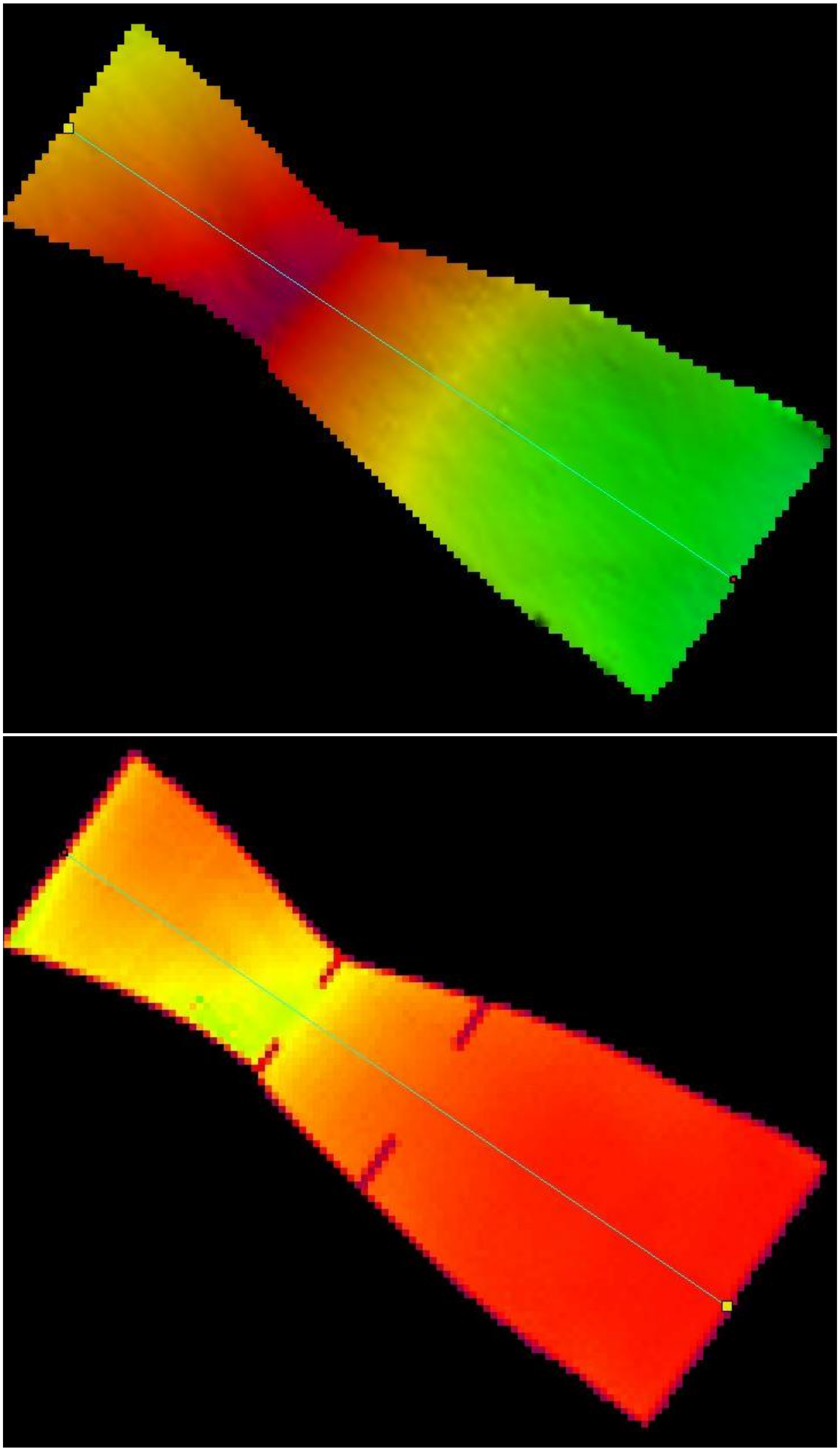


Figure 7

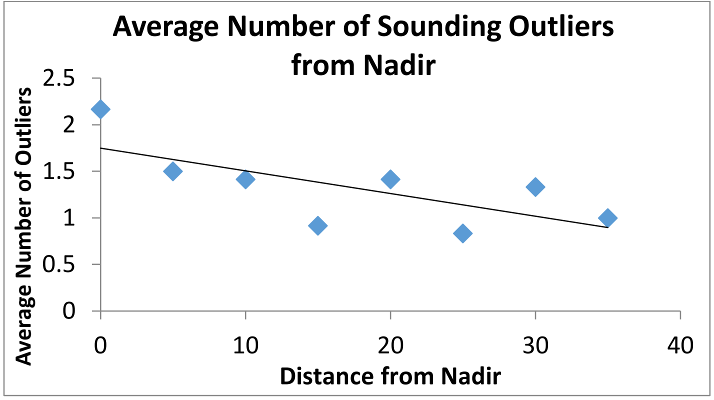


7.A

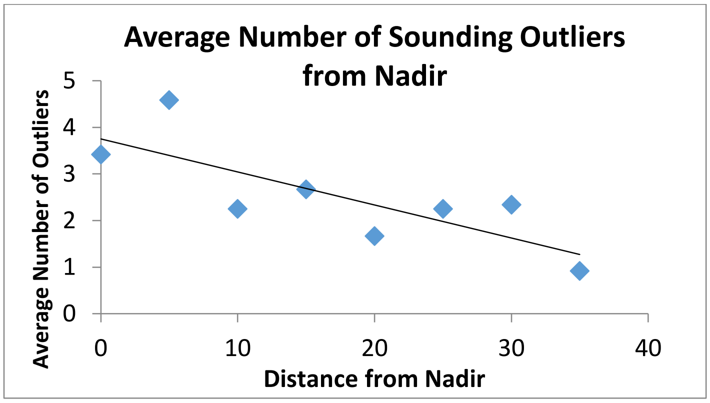
7.B

Figure 8

Line 03 (Equal Distance)



Line 17 (Equal Angle)



Line 31 (Equal Angle)

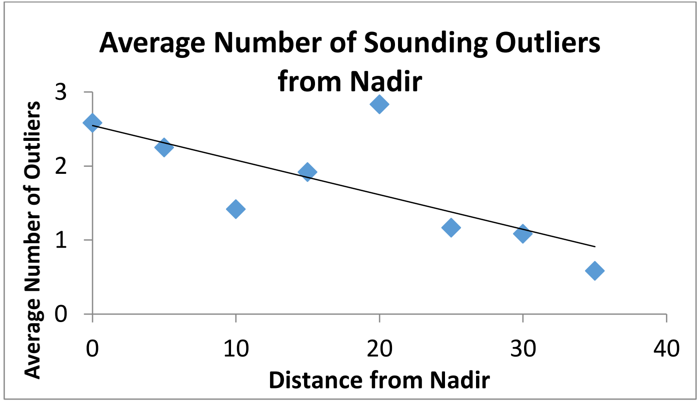


Table 1

The Average Number of Outliers in a Swath per Survey Line		
Line 03 (Equal Distance)	Line 17 (Equal Angle)	Line 31 (Equal Angle)
10.5	20	13.8

Figure Captions

Figure 1. A chart of the location of Williamson Passage, the survey location, in Nootka Sound, B.C. Canada. The survey was located on the North Side of Gore Island. Muchalat Inlet and many of the streams that feed into it can be seem. Gold River is located in the chart insert and is at the far east end of Muchalat Inlet.

Figure 2. A three dimensional view of Williamson Sill in CARIS 3D Viewer. The steeper East side of the sill can be seen in the forefront while the shallower slope side is in the back ground. The vertical distance is exaggerated with a 2:1 scale for better visualization.

Figure 3. The location of the three survey lines over the sill. Lines 03 and 17 were surveyed in the East to West direction while Line 31 was surveyed in the West-East direction. Additionally, Line 03 was set up in an “Equal Distance” array while Line 17 and 31 were set up in an “Equal Angle” array.

Figure 4. *Figure 4A* represents the range in depth estimations of during different tidal stages. Outliers are left in and the graphs represent raw data. The different subsets of the sill: front, top, and back are shown with the different ranges of depth estimation. The table below provides exact values for each subset of the sill for each tide. *Figure 4B* represents the same three tidal stages with the same three subsets: front, top, and back after the obvious outliers (points more than .5 meters higher than their immediate neighbors) removed. The table below provides exact values for each subset of the sill for each tide.

Figure 5. This is a view of swath editor in CARIS HIPS. The pink lines represent the Starboard depth estimates while the green represents Port. Outliers can be seen as the large spikes that

extend well beyond the grouping of the majority of the points. The distance along swath is broken into 5 meter bins. Depth can be seen on the Y axis.

Figure 6. Figure 6A represents a signal transect of depth estimation of Williamson Sill. The transect distance starts at the West of the sill of the sill at the location 49° 39’ 21.68” and 126° 23’ 11.52” and ended 587 meters later at the East side of the sill at the location 49° 39’ 10.47” and 126° 22’ 47.92”. Figure 6B represents a transect of the density individual Depth Estimates which then contribute to a Node which is a depth estimate of a location which then is input into the base surface in CARIS HIPS.

Figure 7. Figure 7A shows the depth base surface of the sill with the transect from Figure 6 shown in blue. Figure 7B shows the density of depth estimations contributing to a Node, which is a depth estimate of a location which is then input into the base surface in CARIS HIPS. The dark color represents a smaller density of depth estimations that are impacting a single node while the light color represents a higher number of depth estimations that are impacting a single node.

Figure 8. Figure 8 shows the average number of individual depth estimates that are considered outliers per 5 meters from Nadir. There is a decreasing trend of outliers as distance grows from Nadir. Line 03 was in the equal distance configuration while Lines 17 and 31 were in the equal angle configuration.

Table 1. Table 1 indicates the average number of outliers in the inner quartile of a six individual randomly selected swaths per survey line.