

**Accuracy assessment of depth estimates from variation in pre- and post-  
processing of multi-beam SONAR surveys in a fjord environment**

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**ABSTRACT:**

The demand for accurate, high resolution bathymetric maps has risen with increases in utilization of offshore resources. This demand has been met with advances in technology. However, surveyors must trade-off between high data quality and minimizing survey costs. Outer beams of modern multi-beam SONAR systems, particularly when wide-beam swaths are used, return the most errors, as opposed to the nadir of a survey track-line. This is due, in part, to the inherently wider beams and the greater amount of time required for the outer angled pings to reach their destination and return. This study closely examined the accuracy of the Kongsberg EM302 outer beams during a survey in a fjord environment aboard the R/V Thomas G. Thompson. An area within Nootka Sound, British Columbia, Canada was surveyed first with a control and then the outer beams of both wide-beam and narrow-beam swaths were aligned with the center line (nadir) of the control survey. Beam spacing was also adjusted between equidistant and equal angle modes during narrow swaths, to determine if a difference between the two were significant. The processed surveys were examined for significant differences in depth. The results of this investigation illustrate that the outer beams of a wide-beam survey produce a significant number of errors compared to the nadir beams and that sound velocity is a contributing factor to post-processing error.

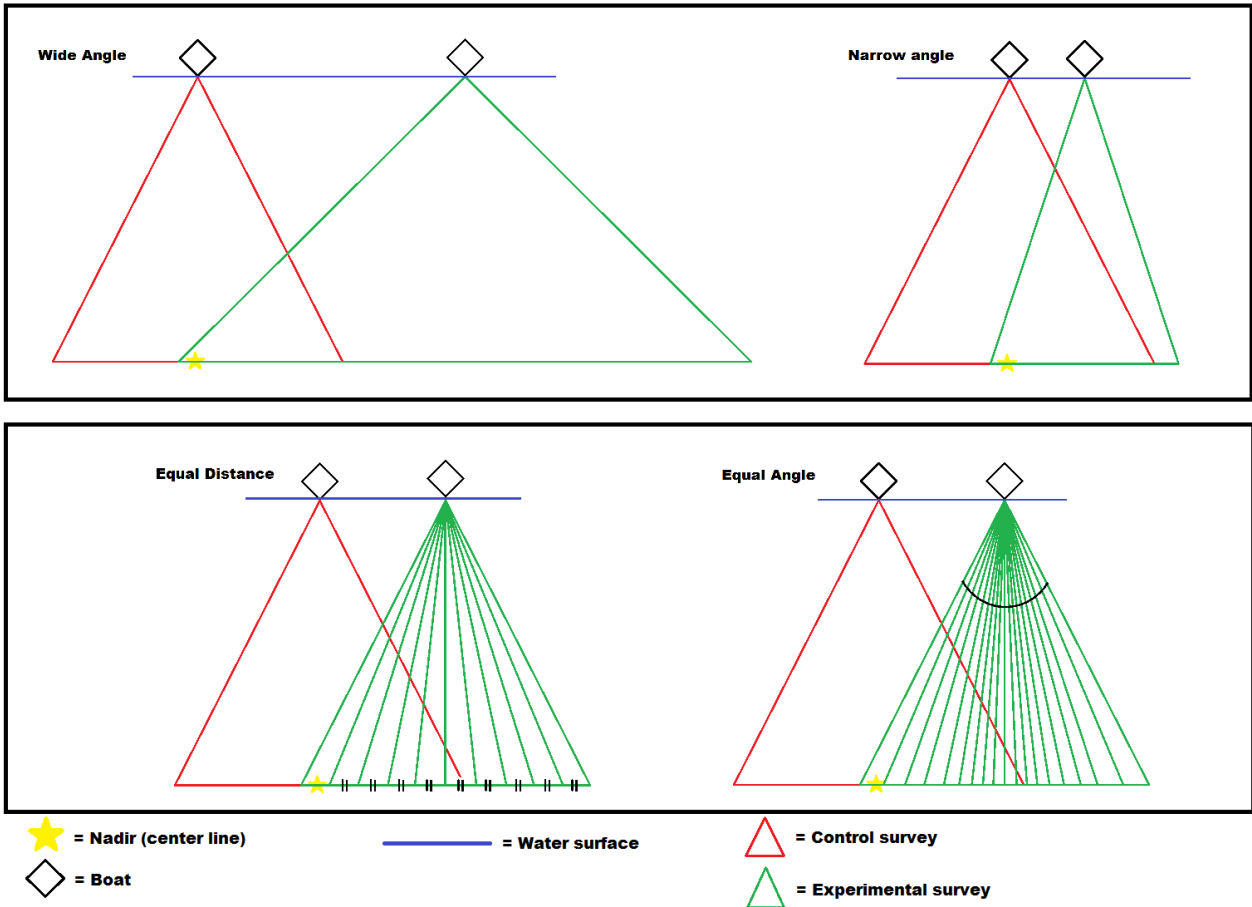
## INTRODUCTION:

As international trade, deep sea research, oil exploitation and national defense has increased traffic on navigable waters, so has the need for reliable maps of the seafloor. Recent advances in science and technology have met this demand with constant improvements of both hardware and software used in multi-beam SONARs for hydrographic surveying. However, these technologies have performance limitations requiring hydrographic surveyors to make cost-effective decisions in the design of acquisition surveys that can reduce the accuracy of the resulting bathymetric map. Decisions in beam spacing and width, acquisition of sound velocity profiles (SVPs) and collection strategies for tide height can affect the accuracy of the finished product; as well as unforeseen decisions during the survey that could alter the original survey design.

Prior to the actual acquisition of sonar data, hydrographic surveyors establish design parameters for the survey, which include beam swath width and beam spacing; typically, the widest swath width will be used in order to cover the most area in the least amount of time. Unfortunately, the outer beams of multi-beam SONAR systems, particularly when wide-beam swaths are used, return more errors than the nadir (centerline) of a survey track-line. This is due to the greater amount of time required for the outer angled pings to reach their destination and return. Beam spacing determines how many beams aim for a particular area of the swath and can be set to either equal angle (EA) or equidistant (ED) configuration. Depending on the beam spacing and swath width chosen and the depth of the survey area, depth measurements can be less accurate due to gaps from fewer pings measuring larger areas. During surveys, Sound Velocity Profiles (SVPs) are used to account for variation in the travel time of the sound source due to stratification of the density profile. This profile is made from measurements of salinity,

temperature and depth by either a Conductivity, Temperature and Density (CTD) on-station profile or an Expendable Bathymetric Thermograph (XBT) taken while the ship is underway. In coastal waters and estuaries, SVPs quickly become inaccurate due to the changing input of fresh water (Dinn et al, 1995). Should SVP data be incorrect or left out, the measurements acquired for the outer beams can be grossly skewed (Schnare, 2014). During post-processing, the tidal data is applied to establish a final depth relative to a user-defined vertical column. The quality and accuracy of these tide height measurements are dependent upon where the information is gathered and the precision of the measuring tools, as well as how regularly measurements are taken. Because all of these potential sources of inaccuracy in the final depth estimate are related to the “travel time” between the transmission of the sound source and the reception of the reflected acoustic return, the outer-beams of multi-beam SONAR – which must travel the furthest from the sound source – have potential for the largest amount of uncertainty.

**Figure 1**



**Figure 1** A representation of how the study was conducted on the R/V Thompson. A control survey (red) was made and the nadir (yellow star) was identified; then surveys were conducted with the chosen variable combinations (green), making sure that the outer beams overlapped the nadir.

This study investigates the uncertainty and potential use of outer-beam SONAR data in hydrographic surveys of fjord environments. The study was conducted on the R/V Thompson in Nootka Sound, British Columbia, Canada and examined the accuracy of the outer beams of the Kongsberg EM302, which is a multi-beam system. Uncertainty in depth was determined using the coefficient variance (CV) at chosen points within a swath from predetermined survey lines designed to exhibit differing degrees of overlap and different uses of beam angle during data acquisition. This study compares the CVs of wide swath- equidistant (W/ED), narrow swath- equidistant (N/ED) and narrow swath- equal angle (N/EA). Figure 1 illustrates the differences in

these variable combinations. Additionally, variation in resulting depth estimates from these acquisition methods are compared in four post-processing conditions: A) survey lines with only outlier correction, B) survey lines with outlier correction and tide correction, C) survey lines with outlier correction and SVP correction, and D) survey lines with outlier, tidal and SVP corrections. In this way, the study examines the four “conditions” in which survey lines are corrected for potential errors during data processing and three “variable combinations” that can be configured during data acquisition (W/ED, N/ED and N/EA). I predict that W/ED will produce the most error and SVPs will contribute the least amount of error.

#### METHODS:

During the pre-planning stage for the hydrographic survey of Nootka Sound, British Columbia, Canada, which took place in December 2014 onboard the R/V Thomas G. Thompson, survey lines were established that provided control and experimental variation in beam spacing and swath width, while ensuring that the outer-beams of the experimental survey ship tracks overlapped the nadir of the control survey ship tracks.

Figure 2

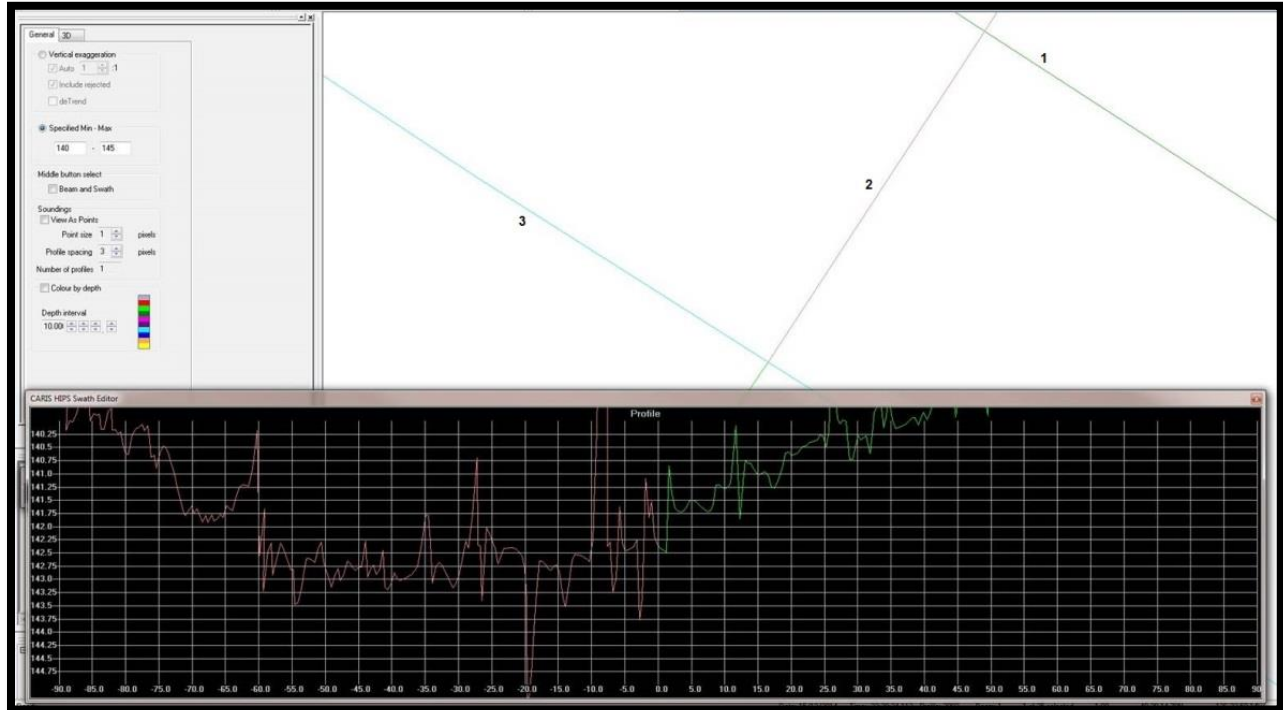


Figure 2 An example of how the depth measurement comparisons were made during Condition A. Lines 1 and 3 are the survey track lines. A point on the nadir line (1) was chosen and a singular swath line (2) on the variable survey line (3) was found which overlapped the chosen coordinate on the nadir line. The x-axis is distance from nadir (0.0) and the y-axis is depth in meters.

In post-processing, the raw data were imported into CARIS version 8.1. Once the raw data were cleared of obvious outliers in Swath Editor (the lower panel in Figure 2), geographic coordinates were chosen using the upper panel in Figure 2, which correspond with a single swath to a nadir position on a control track-line and overlapping outer-beams on an experimental line. The CARIS Swath Editor mode was also used to determine the depth of the chosen coordinate. As shown in Figure 2, by locating the point of measurement on the x-axis and adjusting the Specified Min-Max for the y-axis to a five meter range, the depth measurement for the chosen point can be placed to the nearest quarter meter (0.25m). This process was performed ten times for each of the following experimental variable combinations: wide swath, equidistant; narrow swath, equidistant; and narrow swath, equal angle. The data were then modified to include tide correction with the outlier correction (Condition B). Ten depth measurements were collected

again for each of the variable combinations as close as possible to the predetermined coordinates. The third post-processing condition (Condition C) was addressed by adding sound velocity correction (SVP) to Condition B and depth estimates were again collected for each of the variable combinations. The fourth post-processing condition (Condition D) combined outlier, tide and SVP corrections. Depth estimates were collected again for each of the variable combinations as close to the predetermined coordinates as possible. During Conditions B, C and D, the chosen coordinates were matched manually and as close to the original coordinates as possible. Each “variable combination” had ten depth measurements recorded for each processing “condition”, for a total of 120 depth measurements.

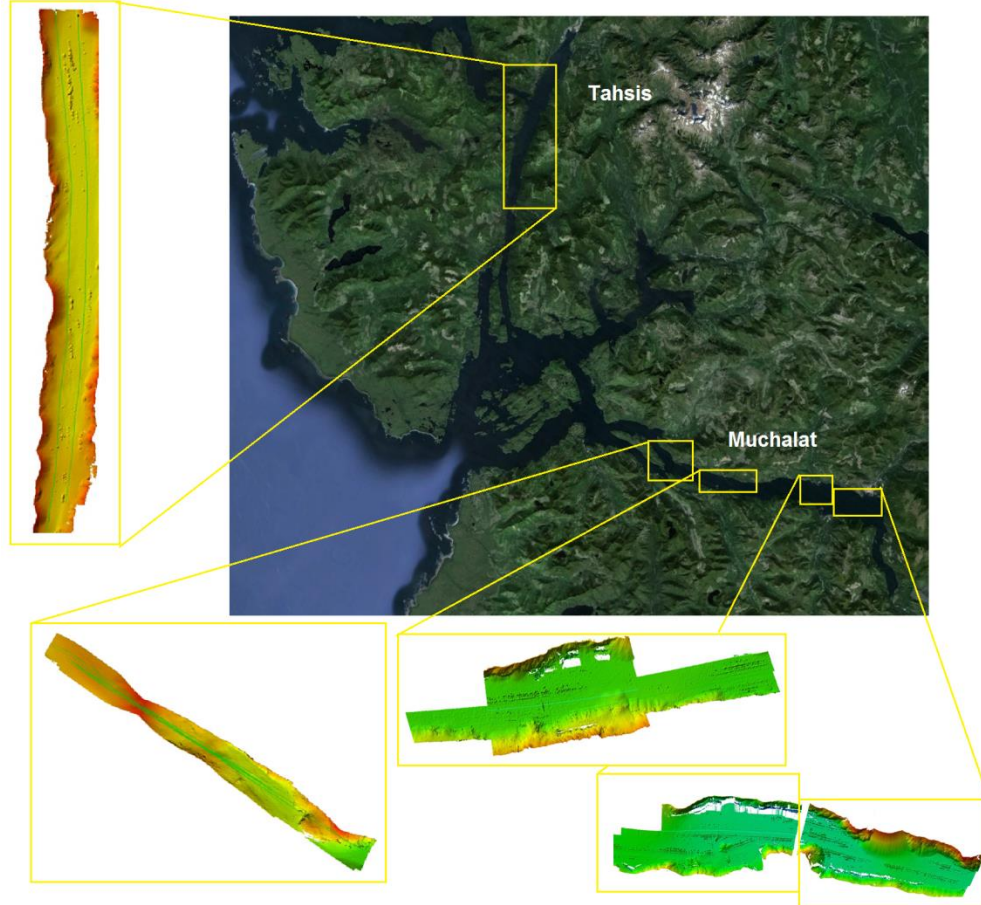
The mean and standard deviation (Equation 1) were then calculated for all collected measurements and the coefficient variance (Equation 2) for the three variable combinations.

**Equation 1:** 
$$s = \sqrt{\frac{\sum(x - \bar{x})^2}{n - 1}}$$

**Equation 2:** 
$$cv = \frac{s}{\bar{x}} \cdot 100\%$$

$\bar{x}$  is the mean of the differences between the control and experimental depth estimates of one variable combination.  $s$  is the standard deviation of one variable combination with  $x$  representing the differences of the control and experimental depth measurements and  $n$  equaling ten: the number of measurements taken per variable combination. For this study, coefficient of variance as a percent indicates that error increases as percentage increases.

## RESULTS:

**Figure 3**

**Figure 3** Base surfaces of the general locations of the bathymetric surveys using only the lines chosen for post-processing. Four sections were taken from Muchalat Inlet and one longer section was taken from Tahsis Inlet.

During data acquisition of the entire survey, approximately 200 survey lines were acquired. After careful examination of which lines met the necessary parameters for this study, 21 were chosen for post-processing. Figure 3 illustrates the finished product of the chosen lines. Lines were excluded for use that did not have complete documentation in the data log book, documentation of SVP application or did not meet the condition where outer-beams overlapped the nadir of a control survey line. These experimental restrictions for complete documentation and confidence in acquisition settings resulted in the exclusion of any wide swath equal angle data. During post-processing, coordinates were manually determined for each predetermined

point of measurement. This became the step in the experimental method with the most potential for human error, as matching the exact coordinates every time was difficult using the CARIS Swath Editor mode for a single swath.

**Table 1**

<b>Condition A) Outlier correction</b>			
<b>Variable combination</b>	<b>W/ED</b>	<b>N/ED</b>	<b>N/EA</b>
<b>CV (%)</b>	81.20191	69.84907	64.82604
<b>Condition B) Outlier and tide corrections</b>			
<b>Variable combination</b>	<b>W/ED</b>	<b>N/ED</b>	<b>N/EA</b>
<b>CV (%)</b>	79.06768	57.03962	90.03886
<b>Condition C) Outlier and SVP corrections</b>			
<b>Variable combination</b>	<b>W/ED</b>	<b>N/ED</b>	<b>N/EA</b>
<b>CV (%)</b>	76.58936	69.94697	89.02767
<b>Condition D) Outlier, tide and SVP corrections</b>			
<b>Variable combination</b>	<b>W/ED</b>	<b>N/ED</b>	<b>N/EA</b>
<b>CV (%)</b>	81.2292	61.57303	67.40131
W/ED= Wide swath, Equal Distant beam angle. N/ED= Narrow swath, Equal Distant beam angle. N/EA= Narrow swath, Equal Angle beam angle.			

**Table 1** The coefficient variance of the three variable combinations (wide swath equal distant, narrow swath equal distant and narrow swath equal angle) for each of the four conditions implemented during processing (A- only manual outlier correction, B- outlier and tide correction, C- outlier and SVP correction and D- outlier, tide and SVP correction ).

When comparing beam width in Condition A, the coefficient of variance for N/ED produced a lower value than W/ED. The CV for N/ED also produced a lower value than the CV for W/ED for Condition B. For Condition C, the N/ED CV was still lower than the W/ED CV;

however, the W/ED CV decreased and the N/ED CV increased relative to Condition B. And when proper processing conditions were met (Condition D), the CV for N/ED was again lower than the CV for W/ED.

When comparing beam spacing, the CV for N/ED produced a higher value than the N/EA CV for Condition A. When conditions included outlier correction and tide correction, the CV for N/EA produced a higher value than the CV for N/ED. The N/EA CV was higher than the N/ED CV for Condition C. When proper processing conditions were met (Condition D), the N/EA CV was still a higher value than the N/ED CV, but was closer to the CV for the N/ED value than the previous condition.

As shown in Table 1, the coefficient of variance for wide swath equal distant, narrow swath equal distant and narrow swath equal angle in the four processing conditions involving corrections for outliers, tide and SVP are high percentages. When only the manual outlier correction has been made (Condition A), all three variables are above 60% with the W/ED CV exceeding 80%. When outlier correction and tide correction are applied (Condition B), the coefficient variance for W/ED reduces to slightly below 80%, the N/ED CV drops below 60% and the N/EA CV increases to 90%. When outlier correction and SVPs are applied (Condition C), the CV of all three variable combinations are at or above 70% with the CV for N/EA at nearly 90%. When outliers, tide and SVP have been corrected for (Condition D), the CV of the equal distant variables rise above 60% – with the CV for W/ED returning to 81% – and the equal angle CV decreasing to 67%.

#### DISCUSSION:

By separating the variable combinations by conditions, the results can be more easily evaluated. For the purpose of this study, coefficient of variance as a percent infers that error

increases as the percentage increases. Comparisons of CVs indicate that the outer beams of wide angle swaths have the highest amount of error during survey. Upon review of the results shown in Table 1, CV shows a ~9% difference between wide- and narrow-beam swaths when the beam spacing is set to equidistant. This supports my hypothesis that the outer beams of wide swaths produce more error than narrow swaths. There was a ~6% difference between equidistant and equal angle beam spacing in narrow-beam swaths. When beam spacing is set to equal angle, fewer pings cover the outer-edges of the swath and produce fewer data points. This is confirmed by the increased CV of the N/EA as opposed to the N/ED.

When raw survey data is not corrected for tide or sound velocity (SVP), the numerical difference between the narrow beam variable combinations is minimal, yet is still a high percentage, and the wide variable combination is a markedly higher percentage (Table 1A). This is because the surveys are only corrected for the time between the individual tracks, which was usually less than six hours. The combined influence of tide and beam angle is illustrated in the wide range of the CV when depth estimates are not corrected for sound velocity (Table 1B). When sound velocity profiles are added to outlier corrected lines (Table 1C), the results vary for each variable combination. In comparison with Condition A, the CV of W/ED decreases, the CV of N/ED remains the same and the CV of N/EA increases. This pattern could be due to the selection of SVPs or the quality of SVPs. The decrease of the W/ED CV demonstrates the expected result which emphasizes the importance of SVP input. However, the extreme increase of the N/EA CV (relative to Condition A) for both Conditions B and C is unexpected and may be due to the fewer pings at the outer edges of the swaths in an Equal Angle setting. The variability of Condition C could also be due to the fact that SVPs measure the properties directly at the ship and not at the distant location where the outer beams reach. The lack of consistency in Condition C's coefficient of variance is a subject for further study. When raw data are corrected for

outliers, tide and sound velocity (Table 1D), the CV is still high for all three variable combinations, yet the differences between equidistant and equal angle beam angles lessen. This indicates that proper corrections during processing can reduce the concern for error during narrow swath surveys. However, the relatively high CV for the wide swath demonstrates the need to reconsider using wide-beam surveys in fjord environments.

In conclusion, when data processing is complete (Condition D), a wide beam survey has the highest percentage of error as determined by the higher coefficient of variance. Except for the unexpectedly high CV of the N/EA variable combination in Conditions B and C, the narrow swath CV percentages remained lower than the wide swath CV. This supports the hypothesis that the outer beams of wide beam surveys are the least reliable.

Assessments of each condition verify that sound velocity profiles are extremely important in post-processing. Schnare (2014) highlights that accurate SVPs are the most important data needed for reliable hydrographic maps. Dinn et al (1995) states that too few SVPs will result in poor quality data. My data concurs with Schnare and Dinn et al on the importance of SVPs, by exploring their importance in Condition C, which demonstrates a wide range in variability and thus a need for more SVPs in fjord environments.

Due to the restrictions of this study, future studies could be designed to include the investigation the Wide Equal Angle variable combination. This experimental design would be strengthened by eliminating the opportunity for user error in the recording of depth estimates at fixed geographic coordinates in the raw data and by increasing the number of sound velocity profiles acquired during survey.

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