Multibeam Surveys on the Fraser River Delta, Coping with an Extreme Refraction Environment

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Abstract

The Fraser River Delta is a salt wedge estuary on the southern coast of British Columbia that feeds a significant amount of freshwater into the Georgia Basin. Hydrographic surveying through this strongly stratified (> 20 m/s) and quickly changing water mass using multibeam echo sounding techniques presents several major challenges. Solutions, both in the data acquisition stage and the processing stage, are required to produce accurate, useful data.

During the summer of 2001, a large area in Georgia Strait on the mouth of the Fraser River was surveyed for the Geological Survey of Canada in support of their “Georgia Basin Geohazards Initiative”. The echosounder used was a Simrad single transducer EM3000. A Brooke Ocean Technology Moving Vessel Profiler 30, an underway (in stride) ocean profiling system, was installed just prior to this survey.

In data acquisition, the collection of a large number of spatially dense sound speed profiles becomes critical. The use of an underway-sound speed sensor greatly increased the speed with which we could collect these samples. The procedures for taking samples were refined to minimize sounding interruption and maintain the safety of the instrument. In order to increase the accuracy of the data, post-processing methods were investigated to attempt to correct for any changes. This includes recomputing departure angles and raytracing using spatially interpolated sound speed profiles.

The extreme refraction conditions encountered in this area were expected to make surveying with a multibeam sonar a significant challenge. Surprisingly, the special case of a strong surface sound speed anomaly (restricted to a small percentage of the water column) combined with the flat-line, electronically steered array resulted in manageable and predictable errors. This special case will help us to understand similar refraction issues in areas where their influence may be subtler.

Introduction

The use of multibeam sonars for accuracy-critical applications has now become widespread. Along with the adoption of the multibeam as the instrument of choice of most hydrographic applications, has come the challenge of minimizing any associated errors. The dominant error remaining to be satisfactorily solved is caused by the fact that we have an imperfect knowledge of the water column and the accompanying changes in sound speed with depth. This causes an unknown propagation and refraction error that adds a major source of uncertainty to depth measurements, particularly with high oblique angles.

During the summer of 2001, the Pacific Region of the Canadian Hydrographic Service (CHS) was tasked with carrying out a multibeam survey in the Strait of Georgia and specifically along the Fraser River Delta (Figure 1). This was expected to be a very challenging area due to the refraction issues caused by a major influx of fresh water from the Fraser River. The CHS had recently acquired a system for monitoring the sound speed profile in near real time and this survey would provide an excellent testing ground to determine if the refraction errors could indeed be overcome to a satisfactory level.

Fraser River Delta

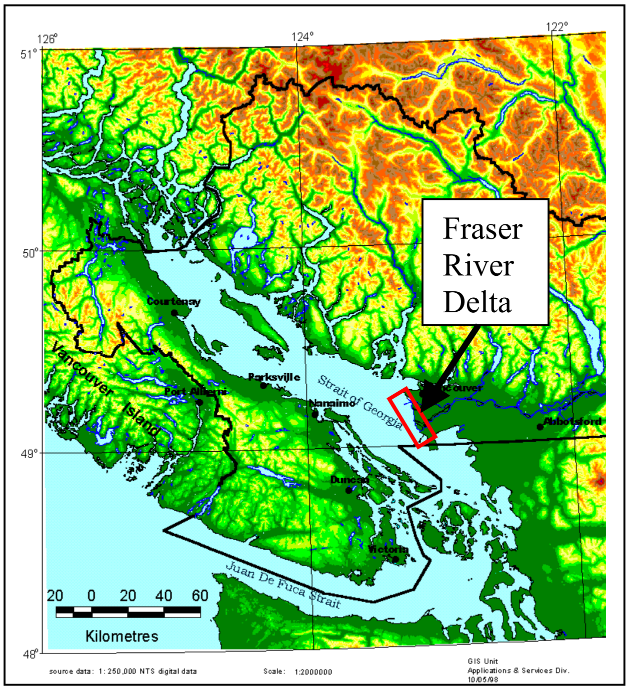


Figure 1 Location of Fraser River Delta within Southern British Columbia and Georgia Strait (source: Environment Canada, 1:250 000 NTS digital data)

The Fraser River is one of Canada's major rivers with a watershed that covers approximately one quarter of the province of British Columbia. The delta has a 37 km long front with 4 major channels (figure 5). The Fraser has an average estimated annual flow of 3000 cubic metres per second and an estimated sediment deposit of seventeen million cubic metres per year. The tides of the estuary are mixed, predominantly semidiurnal with a mean range of 3.1 metres and a spring tide range of 4.8 m. These conditions combine to form a dynamic oceanographic environment.

The River is split up into four main arms on the delta as shown on Figure 5. The South Arm is the most significant, with seventy five percent of the flow, followed by the North Arm with fifteen percent and then the Middle Arm and Canoe Pass each with five percent [Thomson 1981].

The survey off of the Fraser River was carried out in support of the "Georgia Basin Geohazards Initiative" being undertaken by the Geological Survey of Canada, Pacific-Sidney Subdivision. The primary objective of the initiative is to provide the geoscientific knowledge necessary for effective decision-making on environmental and resource management issues in the Georgia Basin. Ideally it would useful to be able to monitor small-scale seabed creep and failures as well as areas of deposition. This would require repetitive surveys at decimetre-level vertical accuracies.

Survey Platform

The survey vessel used, the Revisor, is a 40 ft Canoe Cove fibreglass survey launch that was originally designed and built for chart revisory surveys. Its primary missions for the CHS are to survey high traffic and critical areas as well as a continued revisory survey role.

Survey Instrumentation

Simrad EM3000

The EM3000 is a 300 kHz, 127-beam sonar system, with an effective 120° of swath. The transducer is a flat Mill's T cross, flush-mounted on the keel in a level configuration normally pitched bow up 3 degrees for improved water contact. The system has a beam width of 1.5 degrees at nadir (this increases in the across track dimension as the beams are steered away from nadir) and is capable of depths in excess of 100 metres, depending on the bottom backscatter strength and water column attenuation.

MVP 30

Figure 2 Moving Vessel Profiler 30 winch, overboarding sheave and freefall fish (disassembled)

The Moving Vessel Profiler is an “underway” ocean-profiling system built by Brooke Ocean Technology Limited of Dartmouth, Nova Scotia. By “underway”, it is meant that water sound speed profiles can be collected to survey depths while the vessel is still in motion.

The system is comprised of four subsystems; the winch, the overboarding sheave, the free fall fish (figure 2) and the controllers (figure 3). The sound speed measurements are taken with an Applied Microsystems Limited acoustic time of travel sensor on the towfish. The sensor has a 0.05 m/s accuracy and an update rate of 25 Hz.

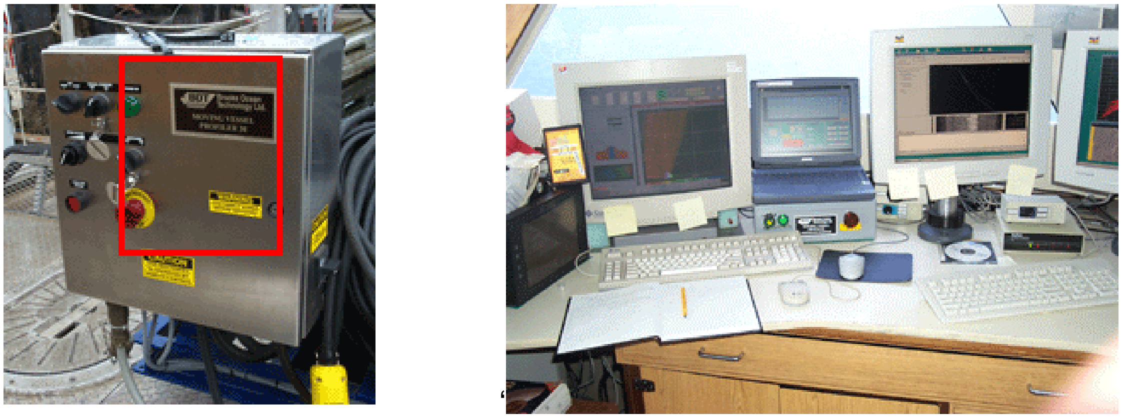
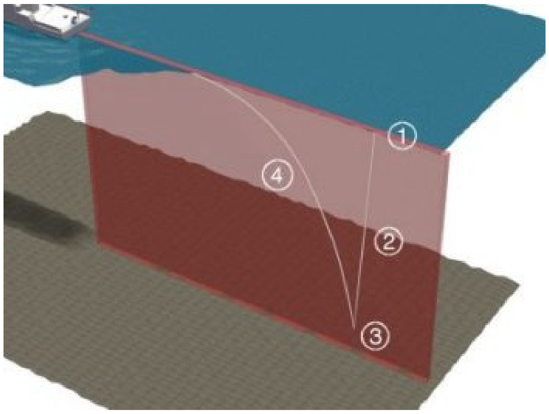


Figure 3 MVP 30 deck and remote controllers

The basic principle of this system is to enable underway profiling by quickly releasing a fish off the stern of the vessel fast enough that the fish essentially free falls to a desired depth and then retrieves the fish for the next cast. A major advantage of this technique is that when the fish is released, it falls essentially vertically over a known depth, after which it is very rapidly pulled away from proximity to the seabed. As there is minimal forward motion close to the seabed, even in the case of a rising seabed, the risk of grounding the sensor is minimized.



Sound Speed Profiling Sequence of Events

1. Fish Release
2. Fish freefall
3. Maximum depth
4. Retrieval

(source: http://www.brooke-ocean.com/)

Figure 4 MVP profiling cycle

Survey Methodology

Multibeam

The multibeam survey was carried out using standard Canadian Hydrographic Service practice. This practice requires that lines be run in order to obtain 200% coverage at maximum speeds of 12 knots. Lines are run freehand in order to “paint” the area by following the previous line’s outer beams. This results in an effective line spacing of 1.7 times the water depth.

MVP30

This was the first official survey with the MVP 30 for the Pacific Region of the CHS and so procedures were developed and improved throughout the survey. For this survey the frequency of casts was set at every two thousand meters along-track (approximately every 10 minutes) or when the observed surface sound velocity changed by greater than 3 metres per second. The actual cast methodology consisted of two separate procedures depending on the desired depth of the cast.

For casts shoaler than 30 m, the tow fish was released and allowed to stream out the stern of the vessel with no reduction in speed. The system is capable of reaching this depth while cruising at 12 knots, which is a maximum for this vessel. As soon as the sensor reached the target depth, the profile is automatically sent, via serial line, to the Simrad multibeam controller software. At this point, it is then checked and edited if necessary. It was then necessary to stop logging in order to introduce a new profile.

For depths of over thirty metres it was decided to give the coxswain a “slow down” fix just prior to starting the cast, enabling the fish to descend farther, owing to the fact of not using line for forward movement. With the vessel in minimum forward motion (1-2 knots) this typically enabled depths of 90m to be reached. As soon as the profile had been loaded the vessel resumed full speed and the survey continued.

The fact that the vessel was still in motion while data logging was stopped and the sound speed profile was entered meant that there were small sounding gaps in the coverage. For a typical sound speed profile cycle, this would result in a maximum of 20 metres along track of missed soundings. This was seen as a compromise between survey efficiency and data quality. Due to the methodology of 100 percent overlap, it was rare that an area was completely missed by the system, however redundancy was obviously lost.

The system is fully capable of cycling through casts non stop, with the primary limiting factor being the time required to retrieve the fish. In order to most effectively utilize this system it would be ideal to cycle the MVP at its maximum rate and obtain higher resolution coverage of water layer structure in an area. However, as noted, there were two reasons this was not feasible. The first is that it is presently necessary to stop logging in order to input a new profile and the second is that it is sometimes desirable to sample deeper profiles. Sonar system software updates can presumably easily solve the former problem while the second problem is just a factor of this particular system and its capabilities. For surveys that routinely survey deeper waters, a larger vessel with an appropriately larger MVP would, ideally, be used.

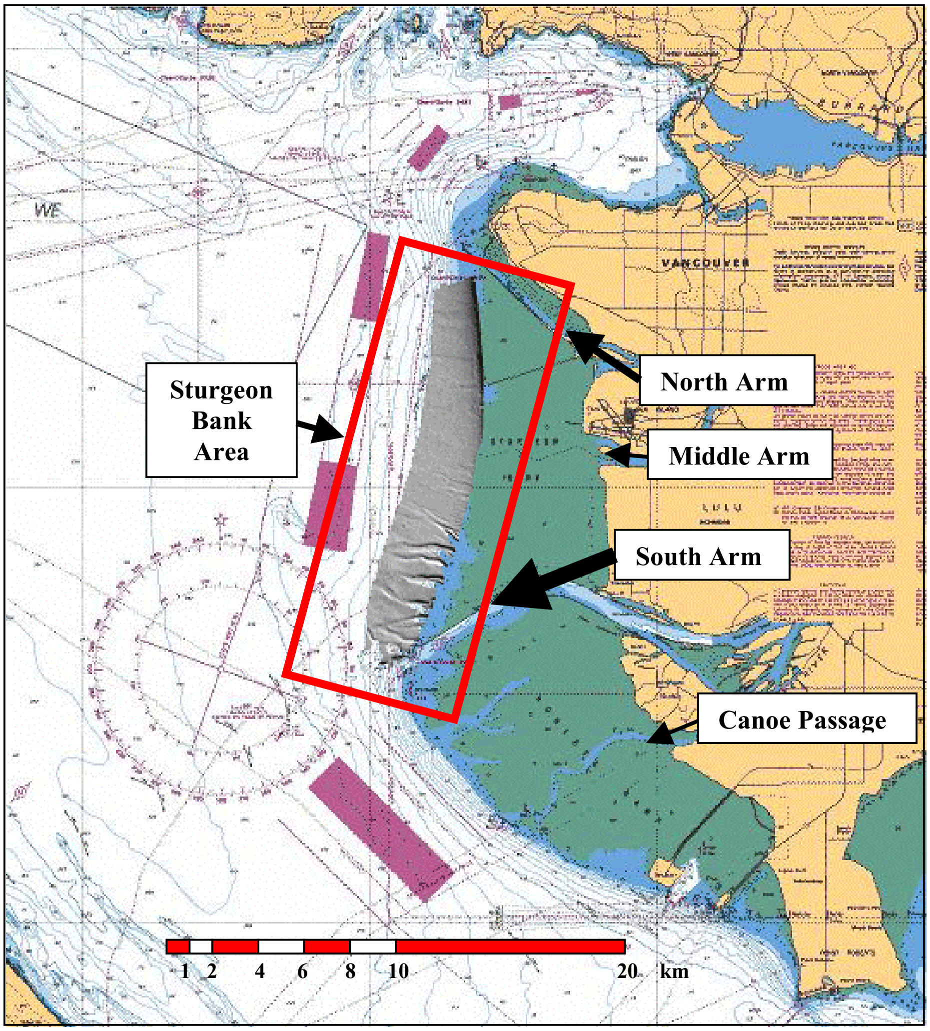


Figure 5 Fraser River Delta survey area showing sun-illuminated EM3000 survey coverage (background is extract of CHS chart # 3463)

Test Area

An area was selected in order to empirically determine how well the use of the MVP solved the problem of refraction errors. The portion of the survey selected was the Sturgeon Bank area, which is bound on the north and south by the two major arms of the Fraser River as shown in Figure 5. The area is approximately 15 square kilometres with depths ranging from 2 to 140 metres. The survey consists of 15 sub-parallel lines broken down into 66 separate segments to enable the updating of sound speed profiles. A total of 60 separate casts were used for the entire area over a period of three days.

The influx of the two major arms of the Fraser River, which together account for 90% of the fresh water flow and the estimated 17 million tons of annually deposited sediment, creates a dynamic oceanographic environment. The stratification of the water column under these conditions, which varies spatially and with tide, is particularly critical when echo sounding with an oblique incidence echo sounder due to the associated refraction errors.

Depth Measurement Fundamentals

In order to determine the position and depth of a point on the surface of the ocean floor we require some essential pieces of information. These are; the position and orientation of the transducer (at transmit and receive), the sonar-relative steering angle of the acoustic wave (whether electronically steered or physically pointed), a two way travel time and the speed of sound in the water column (including at the transducer face).

Assuming a robust bottom detection algorithm, we can use this knowledge to confidently estimate the depth and position of any point on the ocean floor within transmit/receive distance from our transducer.

Ship Orientation and position

Navigation and attitude information is provided by a POSMV GPS-aided inertial system. Horizontal positional accuracy is +/- 5 m using a wide area differential GPS link. Attitude measurement has a claimed accuracy of 0.05 degrees in roll, pitch, and heading. Heave accuracies of 5 percent of heave amplitude or 5 cm are measured within motion periods of less than 20 seconds. The calibration of the system is tested using the patch test procedures that have become standardized in the hydrographic community.

Water Column

The structure of the water column in the area of the Fraser River was a major concern, as the influx of fresh water causes a major speed of sound differential in the top layers of the water column. As was expected, the top 20 m was constantly changing, however below this depth the speed of sound remained relatively constant reflecting the more stable water mass below this depth.

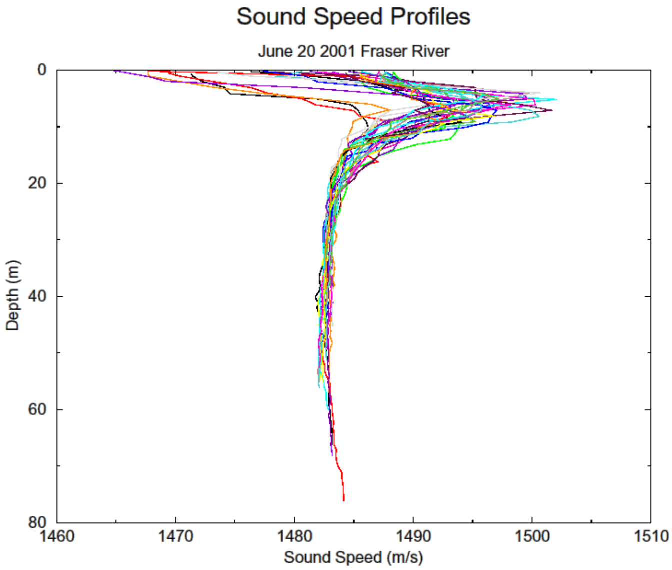


Figure 6 Example sound speed profiles

Figure 6 shows the typical range of sound speeds on a single day of the survey. The surface sound speeds varied from approximately 1460 to 1500 m/s over the duration of the survey.

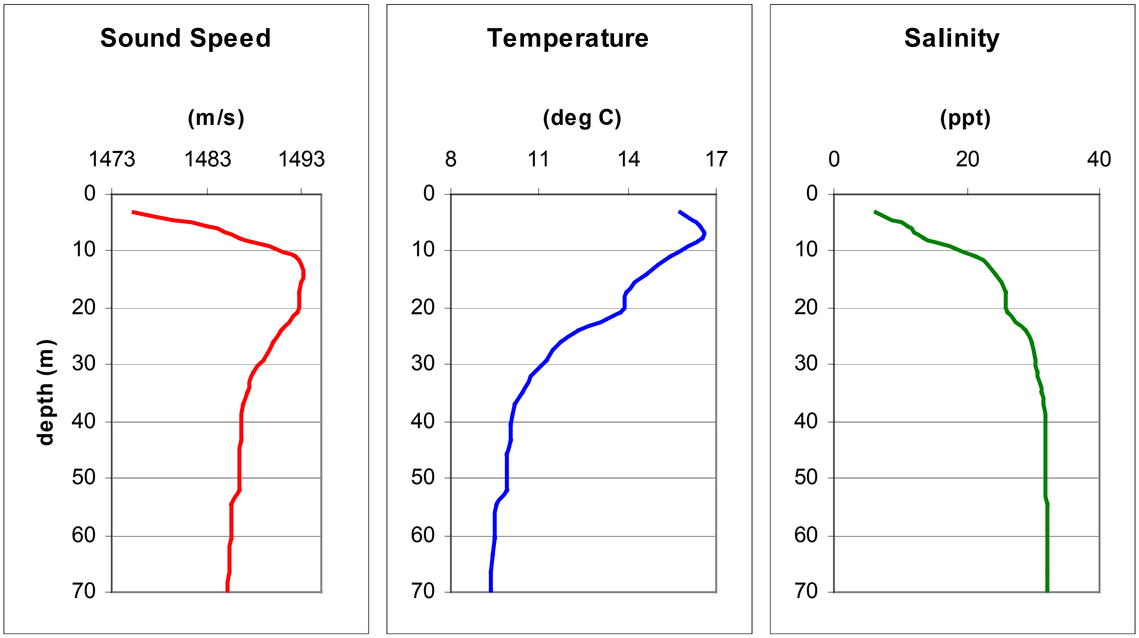
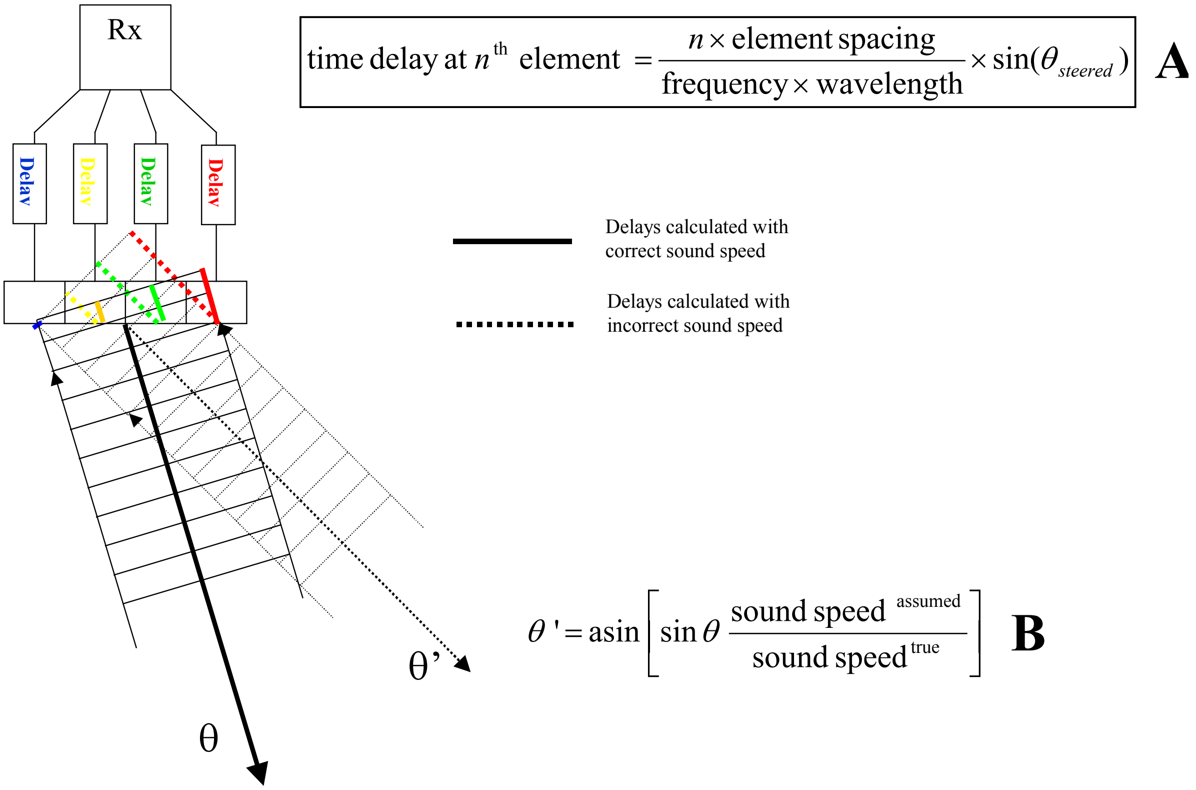


Figure 7 Example relationship of salinity, temperature and sound speed

As the MVP 30 tow fish directly measures sound speed with an acoustic time of flight sensor, the actual source of the changes in the speed of sound are not known. However, using casts from a separate sound-speed and temperature sensor in the area, the salinity was calculated. Figure 7 illustrates the relationship between temperature and depth with the sound speed. This cast was taken south of survey area, but can still be considered representative of the overall water column structure in the area. It is clear that the primary control on the surface layers is the salinity whereas the primary control on the subsurface layers is temperature. The salinity and temperature will change throughout the tidal cycle, while the temperature will also have the added daily factor of solar heating.

Departure angle

With the EM3000 transducer being a flat Mills T-cross configuration, it is necessary to electronically steer to receive oblique angle beams. In order to steer a beam electronically, it is necessary to know the transducer element spacing and the acoustic wavelength of the sound wave. The manufacturer determines the transducer element spacing and frequency, while the wavelength is a function of the speed of sound at the transducer. During beamform, it is necessary to assume a speed of sound, and so this value must be fixed at some arbitrary value. This value is derived from the transducer depth sound speed value from the most recent cast or updated from a hull mounted sensor sound speed sensor. For time delay beam forms, it is this absolute value that is used to calculate initial time delays. Therefore, during survey operations it is necessary to correct for the divergence from this absolute value. Any errors in the value used to correct for the assumed sound speed at the transducer will introduce an angular error independent of any subsequent ray tracing error.



$$\boxed{\text{time delay at } n^{\text{th}} \text{ element } = \frac{n \times \text{element spacing}}{\text{frequency} \times \text{wavelength}} \times \sin(\theta_{steered})}\quad \mathbf{A}$$

$$\theta' = \operatorname{asin}\left[\sin\theta \, \frac{\text{sound speed}^{\text{assumed}}}{\text{sound speed}^{\text{true}}}\right]\quad \mathbf{B}$$

Figure 8 Simplified 4 element transducer time delay beam forming.

In Figure 8, we can see how a simplified four-element transducer can add time delays to steer to an oblique angle. However if the speed of sound used to calculate the wavelength is incorrect, the time delays will steer the beam to an incorrect angle (Fig. 8 equation B).

In practice, the EM3000 actually uses a Fast Fourier Transform method to deconvolve an instantaneous set of voltages from across the array into their component spatial wavelengths and amplitudes to determine angle of reception. However, as with the time delay method, the relationship between spatial wavelength and speed of sound remains the same, requiring the same knowledge of the speed of sound at the transducer.

In the case of a barrel type transducer array, such as an EM1002, the physical shape of the array determines the departure angle. Because there is no electronic steering required, changes in sound speed at the transducer have no effect on the departure angle. As will be seen, this is not always an advantageous characteristic.

Two way Travel Time

The EM3000 multibeam uses a combination of amplitude and phase bottom detection to determine the point at which the sound wave impinges on the seafloor. Bottom detection will introduce a set of errors, however, unlike the biases introduced by beam steering and ray tracing errors, these will tend to be of a pseudo random nature.

Post Processing and Evaluation

Data Cleaning

In order to be certain of using the identical data set for comparisons, the data was not manually cleaned by the hydrographer. In order to rid the data of the “ridiculous” values, an automated sounding rejection program was run on all the data sets using identical rejection criteria. The program used inter-ping distance, along and across track slope values to remove the spurious data points.

Development of a “Pseudo” Reference Surface

In order to have a method of evaluating the accuracies of the depth data, a “pseudo” reference surface was calculated [Hughes Clarke & Godin 1993]. This was done by taking advantage of the large amount of overlap and resulting redundancy that is enabled by CHS survey methods. All of the sounding lines were run through “weigh_grid”, a weighted gridding program that gave a higher weight to the beams at nadir and less weight to the beams as they are steered out. The result is a surface computed that is dominated by the effect of the nadir beams where the effect of refraction, although not necessarily propagation, was least.

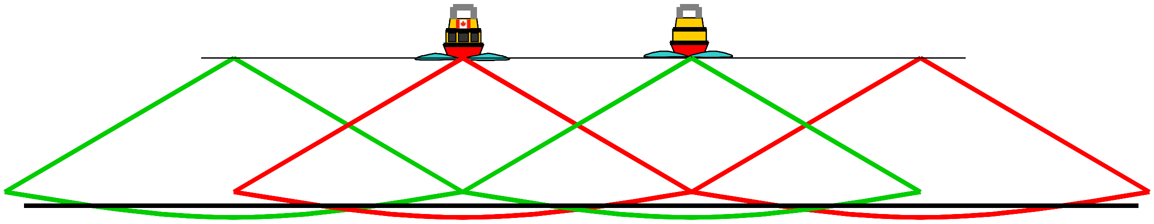


Figure 9 Representation of Survey lines with refraction errors over a true surface

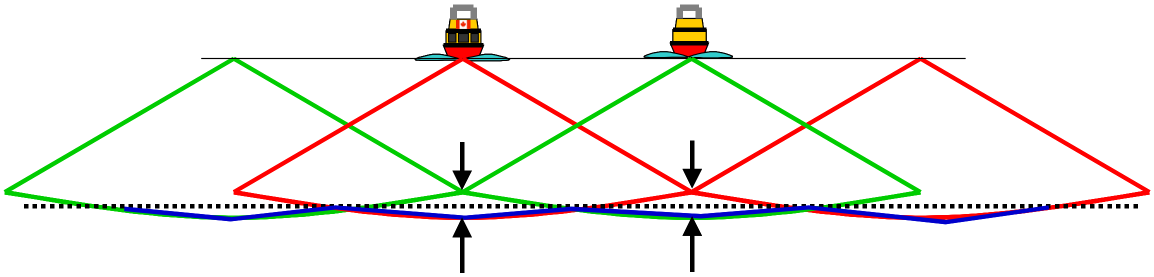
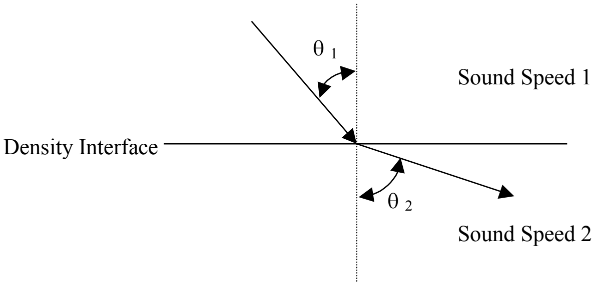


Figure 10 Representation of “pseudo” reference surface (indicated by blue line) fitted to profiles with weighted central beams

The second step was to compare individual lines with the pseudo reference surface in order to approximate the effect of refraction errors. As can be seen from Figure 10, the method results in the outer beams of the lines being compared to the reference surface, which is weighted towards the nadir beam values. The effect is that we are comparing the most refracted outer beams in each one of the selected survey lines with the least refracted nadir beams.

This method of using a pseudo reference surface is however, an approximation. As noted by Capell [1999], for a horizontally oriented, electronically steered line array, the refraction errors actually cross over zero at approximately 45 degrees port and starboard. This effect was clearly seen with this data. However it is considered that the large number of sound profile casts results in a reference surface that closely approximates the true surface, and provides a useful check, especially when considering alternate methods of sound speed applications.

Ray Tracing



$$\frac{\sin\theta_1}{\text{Sound Speed 1}} = \frac{\sin\theta_2}{\text{Sound Speed 2}} = \text{constant} \qquad \textbf{(A)}$$

Figure 11 Application of Snell's Law

For comparison purposes the ray tracing for all the lines was recomputed with three different methods. The first was to ray trace using the updated profile logged with the survey line and applied by the manufacturer during the survey. This step was completed simply to confirm the ray tracing method and to insure results similar to the manufacturer's values. The second method was to interpolate the sound speed values between profiles. This was done using the two profiles from before and after each line. For each individual ping a new profile was calculated by weighting the two profiles depending on relative time. The third was to ray trace with an archived profile in order to determine the effect of not updating the profiles as often as was enabled by the MVP. Ray tracing was calculated using layers with constant sound speed gradient for maximum accuracy.

In order to provide an overview of errors from archived profiles three archived profiles were selected in order to obtain maximum change from the original updated profile. Figure 12 shows the three sound speed profiles selected for comparison. After completing the ray trace calculations with each profile, it was determined that the largest errors occurred using the profile taken at 12:48:17. In order to look at the worst-case scenario, this profile was used in all further calculations when using an archived profile for comparison.

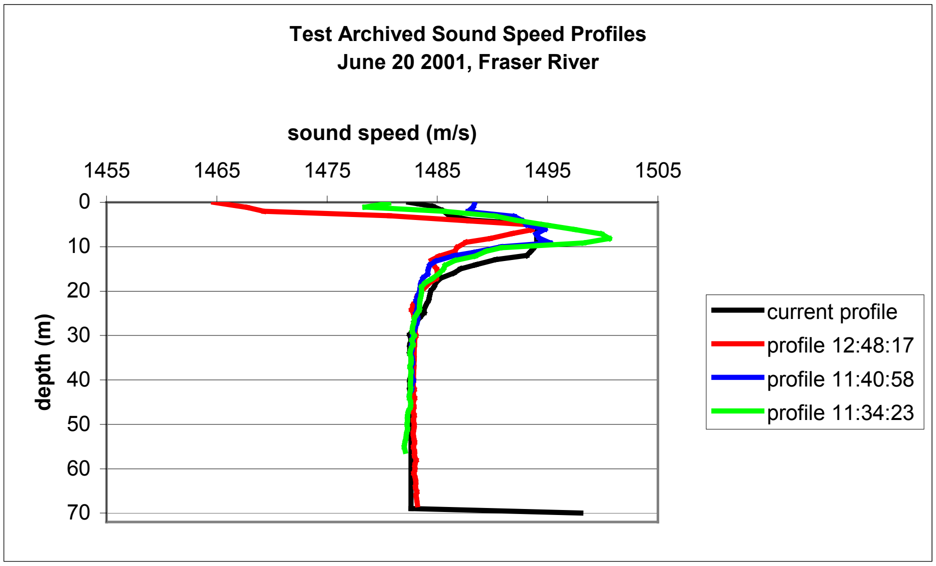


Figure 12 Sound speed profiles used for testing ray tracing methods

When ray tracing with the archived profiles, three methods where used to examine the effects of applying speed of sound at the transducer. In the first case, the effect of the speed of sound at the transducer was removed by recomputing the departure angle. This would be equivalent to using an archived profile and continuing to survey with no knowledge of the changing water column, including the surface sound speed. In the second case, the departure angle was corrected for the surface sound speed and the archived profile was used even though a mismatch existed between the surface sound speed and the archived profile. In the third method, the departure angle was corrected for the surface sound speed and a small "snapback" layer at the start of the water column was changed to the same value as the sound speed at the transducer face while using the archived profile for the remainder of the water column.

Ray tracing using the updated profile resulted in depths that where +/- 1 cm of the values obtained by the manufacturer. These differences can be attributed to round off errors as the digital logging resolution of the system is 1 cm. This step provided a confirmation of the validity of the ray tracing program and algorithm.

Ray tracing using the archived profile and a corrected sound speed at the surface resulted in profiles that were grossly incorrect at the outer beams. This illustrates that using the sound speed at the transducer in isolation will introduce errors if not used in conjunction with either a complete new profile or a "snapback" surface layer. Although this is not a realistic scenario with an electronically beam steered transducer, it is illustrative of the effect that would be encountered by a physically pointed array transducer such as a barrel array. As will be discussed later, the addition of a small surface "snapback" layer will greatly reduce errors in the case of a flat steered array.

Ray tracing using the archived profile and ignoring any changes in the water column (including sound speed at the transducer) resulted in profiles that were well within IHO accuracy values, even in the outer beams. Intuitively this would appear to be incorrect. However, for the special case of a flat transducer, the combination of the error at the transducer face and a focusing effect of the erroneous sound speed surface layer have the effect of partially cancelling each other out [Dinn 1997]. In this case of a flat transducer, the result is that both ray traces will tend to converge to a parallel path once the ray paths reach a depth where the water column is the same. These offset parallel paths will still result in a depth and across track error, however beyond the point where the two watercolumns have converged, these errors will be constant. As the depth increases beyond this point, as the absolute value of the error is constant, it will become a much smaller percentage of the entire depth solution.

The first error that occurs is at the transducer face. Due to the use of the speed of sound from the archived profile rather than the true value at the transducer face, the assumed wavelength will be incorrect. As a result of using the incorrect wavelength, the calculated departure angle will be also be incorrect. The second error is in the ray tracing path while it transits the mismatched water mass. However, the errors, in the absence of roll, will tend to cancel each other out for a flat line array. This is because the surface angle error (Fig. 8, equation B) will be equal but opposite to the resultant angular error encountered in the first step of the ray bending calculation. An equivalent explanation is to say that the Snell's constant is preserved (Fig. 11, equation A).

Following the cancellation of errors within the surface layer, the calculated ray paths will tend to converge to parallel as the sound speed values converge. The paths of these calculated and true ray trace are graphically illustrated in Figure 13, cases A and D. This situation will hold true for an electronically steered array that is level, however, as soon as roll is introduced, the cancelling effect of errors is reduced (Fig. 15, A_5 & A_{10}). As well, If an electronically steered transducer is mounted on an angle, such as with an EM3000D (Fig. 15, A_{45}), then the effect is also reduced up to the point where when a wave is broadside to the transducer the errors will be equivalent to a non steered array.

Ray tracing using the archived profile, an updated sound speed at the transducer and a small surface layer with same value as the sound speed at the transducer (fig. 13, C) also resulted in values that were within IHO specifications. This can be attributed to the "snapback" layer at the top of the water column, which has the effect of bringing the ray tracing angles back to the values used in the archived profile. This "snapback" layer consists of a fictitious small surface layer with the same value as the surface sound speed. The use of such a layer becomes important for systems that use physically pointed arrays. This is because there is no departure angle error associated with an incorrect sound speed at the transducer, the error cancelling effect seen with electronically steered system is lost (Fig. 13 B). Another advantage of applying this surface layer correction is that the error cancellation will be independent of roll. This would affect barrel array systems such as the Simrad EM1002.

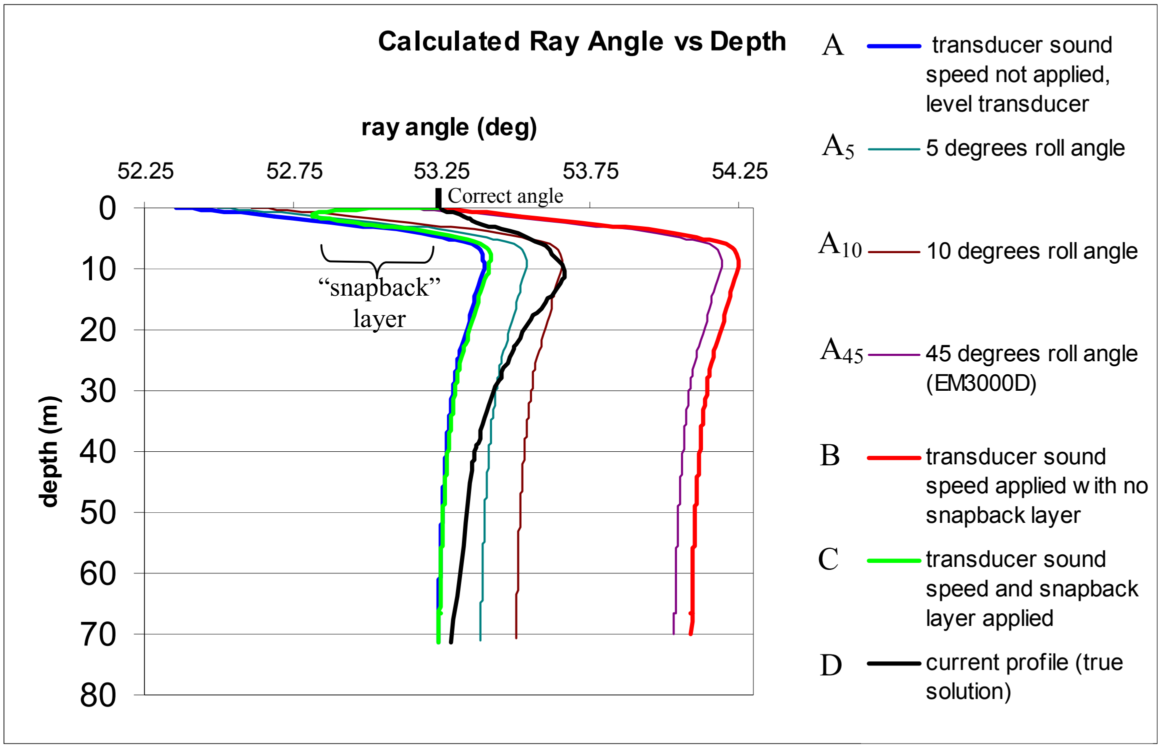


Figure 13 Calculated ray angles with varying applications of surface sound speed. For the special case of the transducer sound speed not being applied, the associated errors due to roll (or mount) angles are also shown for 5, 10 and 45 degrees.

Figure 13 graphically illustrates the various ray tracing calculations compared to the true ray trace using the current, updated profile. In this ray tracing example, the only ray tracing solution that was significantly in error from the true depth was the solution using the archived profile and the sound speed applied at the transducer (Fig. 13, B). This particular situation would also arise in the case of a barrel type array with an incorrect sound speed profile as the departure angle is fixed.

Summary of Results of Ray tracing

In order to graphically represent the overall errors obtained from the various raytracing methods used, each survey line was compared to the reference surface. The method used was to take the last 100 pings from each file and, using Ocean Mapping Group software, to calculate an average percentage depth difference from the pseudo reference surface, binned by beam angle. The end of the file was used in order to look at soundings that were furthest in time from the last sound speed profile update. This was done at every beam angle from –60 to +60 degrees. The use of 100 pings helps to eliminate individual noisy soundings, while retaining the overall trend of depth errors.

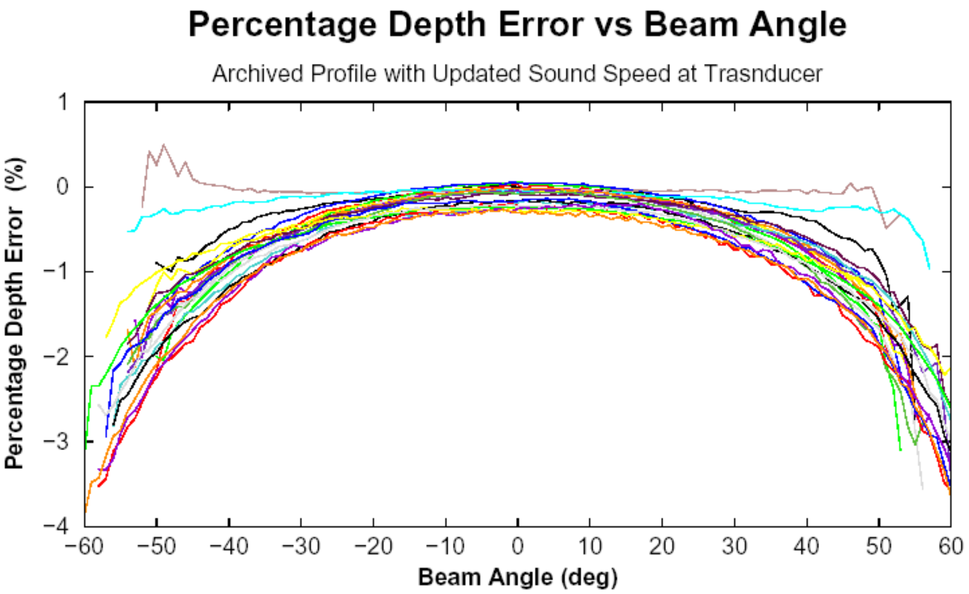


Figure 14 Percentage depth error using archived profile and updated sound speed at transducer with no snapback layer

Figure 14 depicts the errors resulting from using an archived profile and adjusting the speed of sound at the transducer even though a mismatch is seen between the surface sound speed and the sound speed profile. This is the raytrace method that is illustrated in Figure 13, case B It is clear that the change in the water column after the archived cast was taken, very quickly diverged to the point of making any soundings obtained in this way beyond accuracy limitations.

This would indicate that using a correct departure angle with an incorrect sound speed profile would result in major angular errors. This could be the situation in the case of a barrel array transducer that does not have a current sound speed at the transducer value. This type of transducer always has the “correct” departure angle as it is physically pointed and does not require beam steering. When used in conjunction with an improper sound speed profile these errors will result. As the departure angle is fixed, in the absence of a complete new profile, the solution is to use a small “snapback” layer at the surface with an associated sound speed identical to the sound speed at the transducer face. This method is graphically illustrated in figure 13, case C.

The next figure illustrates the percentage depth errors from ray tracing methods that result in acceptable error values. Case A is the method of using an archived profile without updating the sound speed at the transducer. Case B is the method of applying each cast to the sounding data in real time as the casts are received. Case C is the post processing method of interpolating between sound speed profiles so that each ping uses a profile that is a weighted combination of the profile at the start and end of each line.

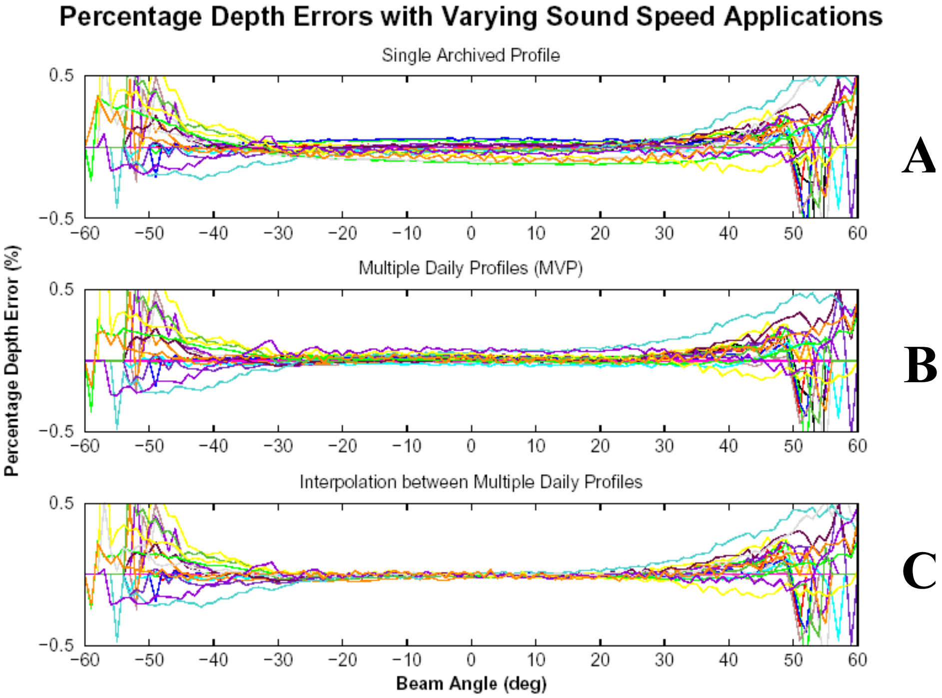


Figure 15 Percentage depth errors comparison using archived and updated profiles. A represents pings obtained when using a single archived sound speed profile, B represents using the updated profiles provided by the MVP and C represents using the MVP profiles with weighted interpolation.

As can be seen from Figure 15A, the overall errors, especially in the outer beams, are not significantly higher when using an archived profile with uncorrected sound speed at the transducer over multiple updated casts. However one can see that at nadir the data does have increased errors. This is due to the fact that the calculations were done with an archived profile with grossly incorrect sound speeds near the surface. The incorrect sound speed values partially cancels out the refraction errors, however the harmonic sound speed (which controls propagation) will be incorrect. This would be the equivalent effect that would be observed when using a single beam echosounder with incorrect sound speeds. Although this error is much smaller in magnitude than the refraction errors, it still needs to be seriously considered in the overall error budget.

The second conclusion that can be gained from Figure 15B and C is that the difference between using all the daily profiles and the interpolated values between each profile provides only a small improvement in accuracy. This would indicate that the method of using the MVP (at approximately 10 minute intervals) took a reasonable complete picture of the water column structure in the area. This conclusion is in agreement with the findings of Hughes Clarke et al [2000] for Georges Bank survey operations. However, by interpolating between profiles it would eliminate the “step” effect that occurs due to the sudden switch from one profile to the next. In the case of this survey, there was a pause between start and end of line and so this effect was not evident. However, it is assumed that logging software will be modified to accept profiles in real time. This small increase in accuracy would be useful in monitoring large-scale changes as well as compensating for instances where there is a lower frequency of sound speed profile casts.

This would indicate that when using an electronically steered transducer such as the EM3000 it is possible to not correct for the surface sound speed and allow the errors to partially cancel each other out. It is important to realize that this assumption would only be valid when the changes occur in the top surface layers with a corresponding stable water mass that is the large percentage of the entire water column.

In order to clarify these effects further, the 100 final pings that were ray traced using archived and multiple profiles were directly compared to lines that were ray traced using interpolated sound speed profiles. This has the effect of displaying only errors related to ray tracing while eliminating other errors seen previously that could be due to positional, tide, or long term heave errors. From Figure 16 it is clear that the refraction errors are within reasonable error expectations, and again the effect of the incorrect harmonic sound speed can be seen, especially at nadir. The point at which the errors cross zero corresponds to approximately 45 degrees as predicted by Capell, [1999]. In the majority of survey projects, the harmonic sound speed is an insignificant error. However in the case of conditions like that on the Fraser River delta, where there is a large sound speed anomaly at the surface, this becomes the dominant error and actually offsets and partially cancels the refraction error in the outer beams.

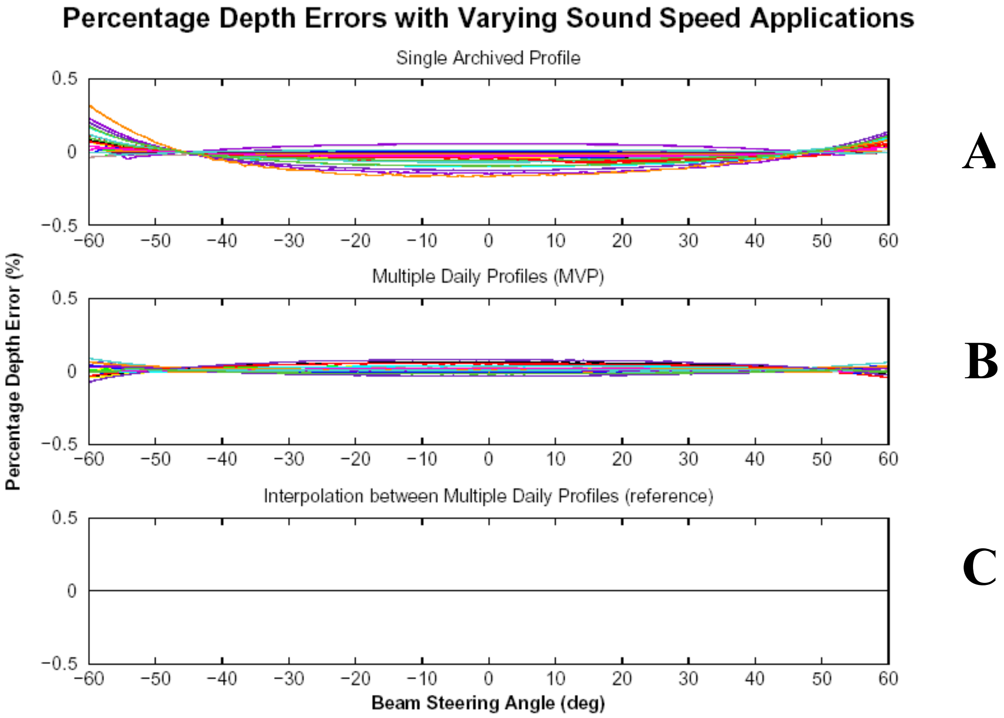


Figure 16 Idealized percentage depth errors comparison using archived and updated profiles. These errors are calculated for refraction and sound speed errors only. A represents pings obtained when using a single archived sound speed profile, B represents using the updated profiles provided by the MVP and C represents using the reference lines with weighted interpolation between MVP profiles (therefore will have null value when compared to itself).

What is also clear from the combination of Figures 15 and 16 is that there remain some significant errors that are clearly not directly related to refraction. The specific source of these errors is uncertain, however they appear to be similar throughout differing raytracing approaches. These errors can be attributed to a combination of long period heave, roll biases and the position uncertainty on steep slopes of the bank and its channels. Although the errors appear to grow as one moves to the outer beams, much as would be expected with refraction errors, this is due to the weighting applied in the pseudo reference surface, which is systematically less as one moves away from nadir.

The depths of these soundings are in the 70-metre range. As these depth errors do not increase once the ray paths are parallel, they will become a small percentage of the total depth. Therefore, in order to determine resultant errors at all depths, the same ray trace was used to calculate the errors that would present if the archived profile had been used in depths between 1 and 70 metres.

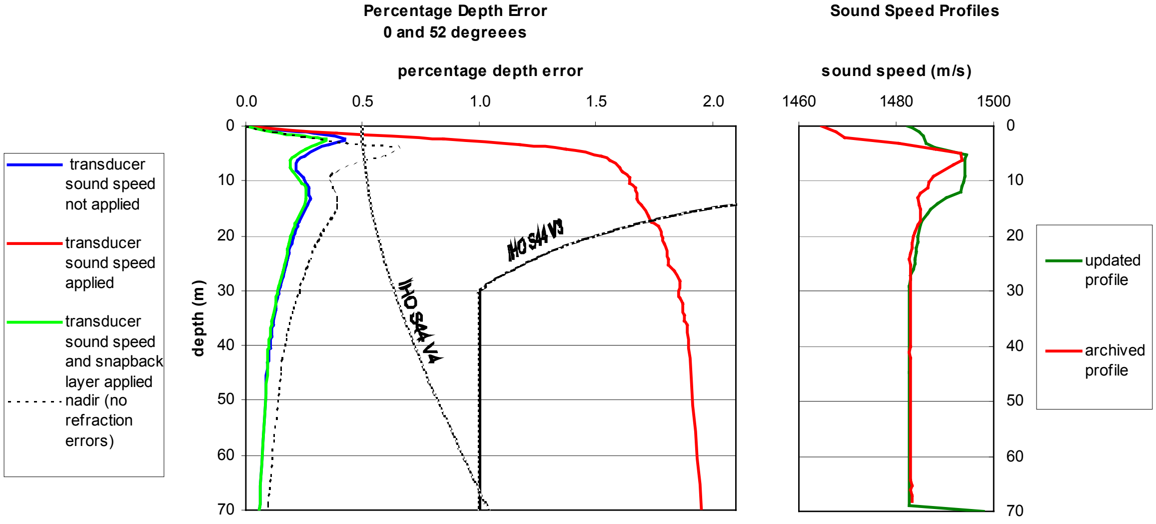


Figure 17. Example percentage depth errors due to using archived sound speed profile. The effect of different methods of applying the sound speed at the transducer is shown for a ray angle of 52 degrees. The percentage depth errors are also shown for the beam at nadir, which will not have an angular error component. The total maximum Order 1 depth accuracies dictated by the International Hydrographic Organization's Special Publication 44, versions 3 and 4, are shown for reference. The updated and archived profiles used in example are shown to illustrate the relationship with percentage depth errors.

Figure 17 illustrates once more the large error that is introduced when the sound speed at the transducer is changed in isolation. When the surface sound speed is applied in this manner, the percentage depth error increases rapidly with depth, as would be consistent with a gross angular error. However, ignoring the surface sound speed changes, or applying the surface change along with an added "snapback" layer mitigates the problem to a large extent. While this "ignorance is bliss" method does a reasonable job of harmonizing the refraction error, there is still a harmonic sound speed error due to the grossly incorrect sound speed near the surface.

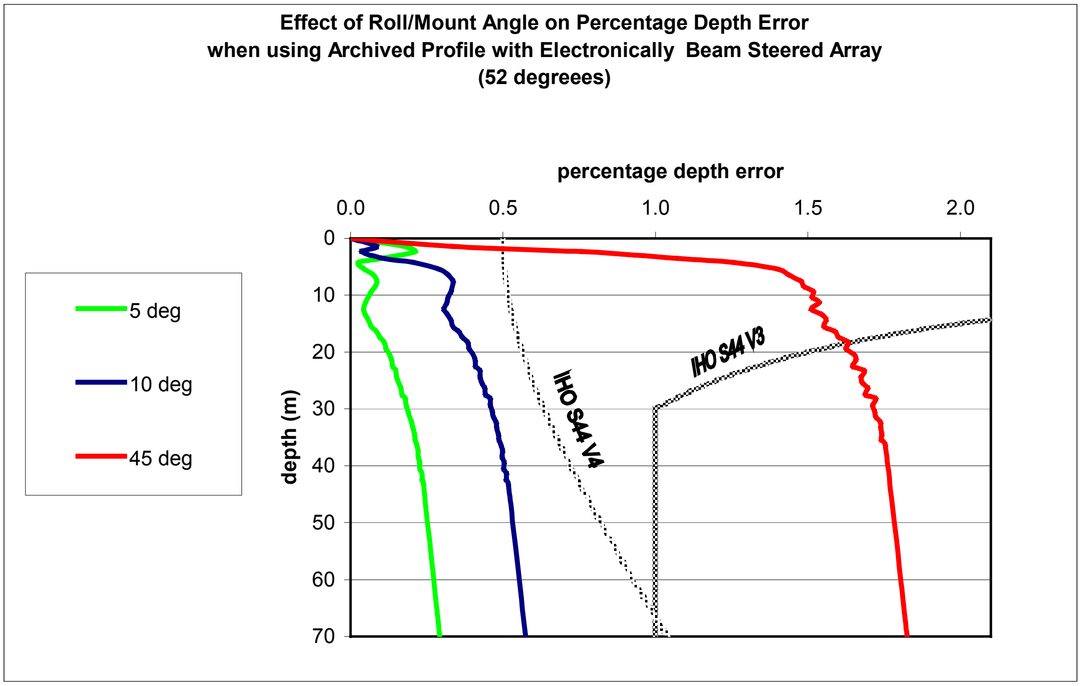


Figure 18 Example percentage depth errors due to using archived sound speed profile. The effect of applying an archived sound speed profile (with no update to the surface sound speed) is shown for a ray angle of 52 degrees with roll angles of 5, 10 and 45 degrees.

While a level electronically beam steered array has the advantage of partially harmonizing errors resulting from using an archived sound speed profile, this error reduction is lessened proportionally with the amount of roll. This effect is illustrated in Figure 18. In the case of an angle of 45 degrees, which is a typical mount angle of a dual head EM3000, the errors are very similar to those in a physically pointed array (at the angle of 52 degrees). For roll angles of 5 and 10 degrees, which are consistent with normal expected roll angles, the error is still with I.H.O. specs. However it should be noted that these errors due to roll will be of a periodic nature producing a “wobble” on the seafloor which might be confused with a motion sensor problem. Even though this “wobble” would be within IHO specifications, its presence will degrade the topographic image for the purpose of geoscientific interpretation by hiding features such as ripples and indications of slope failure.

The errors at the surface are actually reduced by small roll angles, however this is a coincidental situation caused by the calculated ray tracing solution being in fact closer to the true ray trace (see Figure 13). The percentage depth error continues to grow with depth, however, as the ray paths do not converge. This again illustrates the advantage of using a real time surface sound speed in combination with a snapback layer, as this method is independent of these roll errors.

For reference, the IHO, Order 1 specifications are shown in Figures 17 and 18. Although it should be noted that this is the total allowed error and refraction and sound speed errors can only represent a portion of this total.

Conclusions

From the data collected on this survey we can confidently come to three conclusions:

- The first conclusion is that the Moving Vessel Profiler, when used at a minimum of 2000 m intervals, was effective in capturing the spatial structure of the water column in a shallow water survey environment.
- The second conclusion is that using a near real time sound speed profiler, and the survey methodology practised by the CHS, the system is capable of obtaining decimetre level accuracy that will enable the detection of fine-scale features.
- The third conclusion is that the special conditions present in the Fraser River area surprisingly enable the hydrographer to collect data using an archived profile and no updates to the sound speed at the transducer (but only in the case of a flat, beam steered array) while still maintaining IHO specifications, at all but the shallowest depths.

It is therefore critical to predetermine the intended use of survey data and to consider survey logistics. In the case of the Pacific Coast Region of the CHS, only a single MVP is available, while two multibeam platforms are currently active with one having a flat line array and the other a barrel array. Decisions on where to deploy the system would revolve around the intended use of the data, the system configuration (flat or barrel array) and the oceanography of the area.

While it had been expected that the conditions on the Fraser River delta would represent the ultimate challenge in terms of dealing with an “extreme” refraction environment, it became clear that surveying in this kind of environment would be much more predictable than originally anticipated. This was due to the fact that, while the sound speed anomaly is extreme, it is restricted to a surface layer that represents a small percentage of the total water column. For once, two wrongs can make a right!

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