Proper Environmental Reduction for Attenuation in Multi-sector Sonars

Rodrigo de Campos CARVALHO, Brazil and John E. HUGHES CLARKE, Canada

SUMMARY

Multibeam backscatter data represent a major seabed discrimination tool. For seafloor characterization, however, one of the most significant limitations is the absolute calibration. There are many components of this and environmental and frequency controls on the backscatter level are two of the most important ones. As many multibeam backscatter data are reduced imperfectly for attenuation, this paper examines how important it is and how consequential it is. It introduces a precise and explicit method to properly compensate given a CTD and full knowledge of specific sector frequencies used, as long as the absorption coefficient already applied is preserved. Example cases are given for two different frequencies for historical data that were imperfectly compensated and the method is demonstrated.

Key words: Absorption, Attenuation, Backscatter, Multibeam, Sonar

1. INTRODUCTION

If properly compensated, multibeam backscatter data can provide valuable information about the nature of the seafloor, such as bottom type or bottom micro roughness and their respective lateral and temporal homogeneity. As part of that compensation, frequency and environment-dependent attenuation must be correctly applied.

Rapidly advancing technology has put at the service of contemporary Hydrography more modern equipment, including new multi-sectors sonars. Unlike older single sector systems, those new devices are capable of operating simultaneously on different frequencies, dividing their transmit fan in multiple sectors and even in multiple swaths (Figure 1), with the purpose of allowing a sufficient and uniform sounding density alongtrack at reasonable vessel speeds. This helps to ensure IHO compliant target detection. When combined with FM pulses, which provide longer range capability, it can reduce ship surveying time.

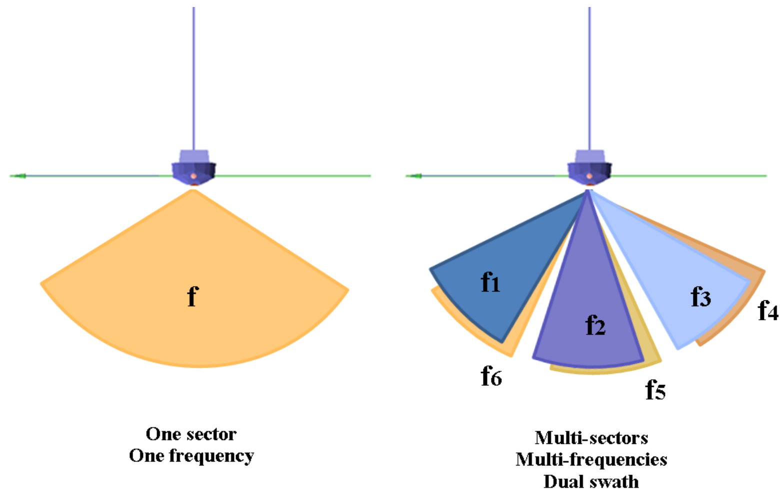

Figure 1 Old version of multibeam echo sounder (MBES) with only one sector one frequency (left) and new version of MBES with multi-sectors multi-frequencies dual swath (right).

Figure 2 (left) shows an example of EM302 operating in a Dual Swath, Medium Mode. As we can notice, operating at that mode, the system generates 8 different sectors, each one with a different centre frequency, divided in two swaths.

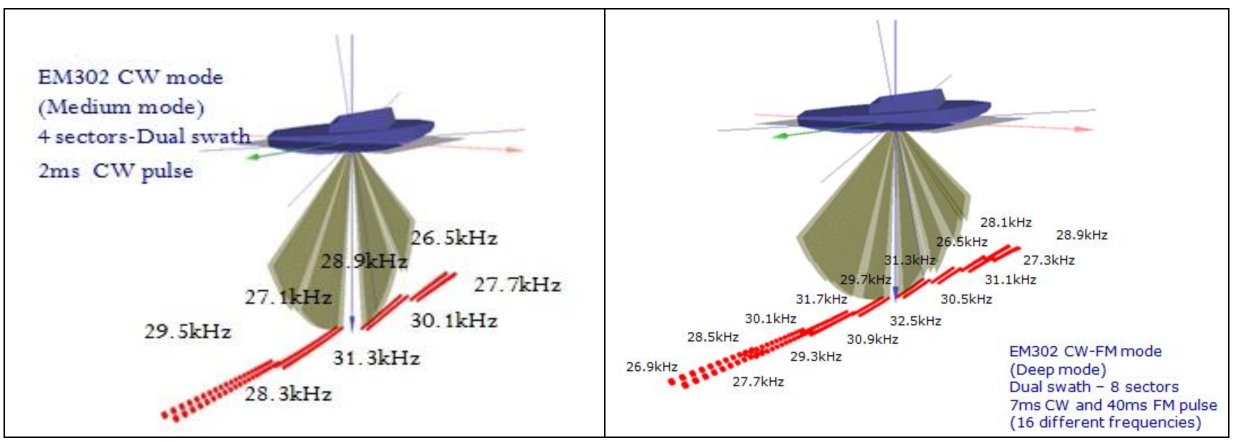

Figure 2 Multi-sector sonar (EM302) operating in a Dual Swath Medium Mode (left) and in a Dual Swath Deep Mode (right) (Hughes Clarke, 2011).

However, as attenuation is frequency dependent (also depends on temperature, salinity, pH and pressure, as we are going to discuss in detail later), each sector suffers with different wave absorption, with an impact on the backscattered signals and their products. Attenuation issues can become worse in cases like the one presented in Figure 2 (right hand): it is also an EM302, but operating in a Dual Swath, Deep Mode, with 16 different sectors and 16 different frequencies; thus 16 different attenuation values.

While an imperfect attenuation coefficient has no effect on bathymetry accuracy, it significantly reduces the utility of the backscatter strength. As we move towards more precise calibration of backscatter strength to get additional information about the nature of the seafloor, such as bottom type or bottom micro roughness and their respective lateral homogeneity, the requirement for precise attenuation coefficients becomes increasingly important.

Currently, the need for a better calibrated acoustic backscatter strength estimate is driven by operational needs in oil field development, environmental monitoring and defense applications. For an oil platform to sit on the bottom we must know the geotechnical properties of the seafloor. Another application is in environmental monitoring of fishery habitats. Nowadays, as we mandate to preserve offshore resources, we must know the bottom substrate for certain species. In some particular cases, monitoring environmental changes is also mandated. Such change is likely to be very subtle, requiring very precise calibration.

Finally, two defense applications are with submarines and seabed mines. As submarines often sit on the bottom, it is critical to know the seabed classification to guarantee they are not going to damage the hull. Besides that, seafloor characterization is important to decide the place to launch seabed mines: if the bottom has too many boulders, we might not find the mines later; if the bottom has a substrate where a seabed mine can be buried, it should be avoided also. In both applications, precise backscatter calibration is required.

2. ENVIRONMENTAL CONTROLS ON ATTENUATION

Currently, the attenuation of sound in sea water is considered to be the sum of three contributions: those from absorption in pure water and from chemical relaxation processes in magnesium sulfate ($MgSO_4$) and boric acid [$B(OH)_3$]. As contributions from other reactions are insignificant, they are not included (Francois and Garrison, 1982, a, b). Based on this, the general equation for the attenuation of sound in sea water, which applies to all oceanic conditions and frequencies from 200 Hz to 1 MHz, is written as:

Total absorption = Boric Acid Contribution + Magnesium Sulphate Contribution + Pure Water Contribution

$$\alpha = \frac{A_1 P_1 f_1 f^2}{f_1^2 + f^2} + \frac{A_2 P_2 f_2 f^2}{f_2^2 + f^2} + A_3 P_3 f^2 \quad (1)$$

where f is the frequency of the sound in kHz, f_1 and f_2 are the relaxation frequencies of boric acid and magnesium sulfate (also in kHz), and P_1, P_2 and P_3 are non-dimensional pressure correction factors.

Based on the detailed Francois-Garrison equation for sound absorption in seawater (Francois and Garrison, 1982b), the main factors that affect attenuation are:

- frequency, which depends on the echo sounder and its frequency variations by sector;
- depth, also understood as pressure;
- pH;
- temperature; and
- salinity.

Figure 3 shows the frequency, temperature and salinity dependence of attenuation from 10 to 500 kHz (current frequency range of multi-sectors multi swath sonars) at 0 m depth, according to the model developed by Francois and Garrison [1982]. We can also notice in this Figure the frequency range of new MBES: EM122 (11 to 14 kHz), EM302 (26 to 34 kHz), EM710 (70 to 100 kHz) and EM2040 (200 to 400 kHz). Inspecting these graphics, we conclude that:

- increasing frequency also increases attenuation. Thus, multi-sectors systems have to apply unique values for each sector;
- attenuation in salt water is much greater than in pure water and it is not a linear relationship;
- increasing temperature decreases attenuation at all frequencies except in the immediate vicinity of relaxation frequencies f_1 and f_2 (equation 1 above), where attenuation is increased (Aislie and McColm, 1998).

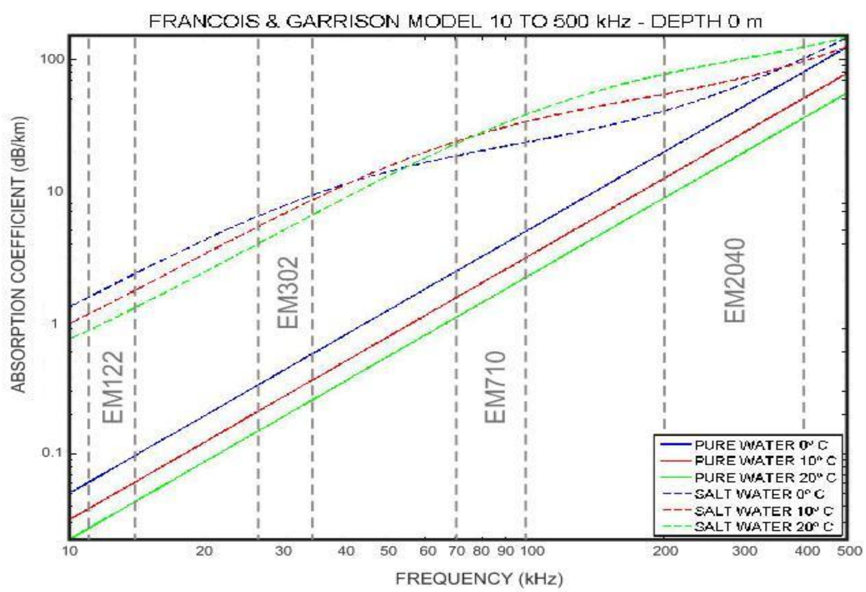

Figure 3 Pure water (S= 0‰ and pH=7) and seawater (for S= 35‰ and pH=8) absorption for three temperatures (0, 10 and 20° C) for frequencies from 10 to 500 kHz, according to Francois and Garrison model [1982]. In grey, the frequency range of the new MBES: EM122, EM302, EM710 and EM2040.

Besides that, after the thermocline (which has a great impact in attenuation due to the temperature gradient), when temperature values get more stable, attenuation decreases while pressure (depth) increases. Finally, increasing pH slightly increases attenuation, but as the typical pH variation in the oceans is small: “The surface waters of the oceans are slightly alkaline, with an average pH of about 8.2, although this varies across the oceans by ± 0.3 units because of local, regional and seasonal variations” (Raven et al., 2005). Consequentially, its impact on overall attenuation is also small.

Thus, as environmental controls affect attenuation and that, in turn, affects backscatter strength, we have to measure them. The previous standard hydrographic method was to measure sound speed only; so many surveys do not have the environmental information. Earlier versions of SIS (Seafloor Information System) required manual input of a single value. That was empirically altered to account for sector frequency differences. Currently, SIS (Kongsberg Maritime, 2009 and 2010) approaches are either based on providing an approximate salinity and a sound speed profile to approximate the environment or an option to provide a CTD input. Any one of these options is dependent on real time availability and correct extrapolation. What is being proposed herein is an automatic method that can get the environmental information that we believe better represents the survey area, from a World Ocean Atlas (WOA) or World Ocean Database (WOD), for example, and reapply it to the collected data, compensating for the attenuation difference.

3. PROPOSED METHODOLOGY TO REAPPLY ATTENUATION

This proposed methodology represents an alternative to the method currently used to calculate the mean absorption coefficient within the several sectors of new MBES. As currently implemented in SIS, it is calculated for an average depth for each sector centre frequency, which is reasonable most of time due to the fact that the cumulative absorption curve does not vary much. On the other hand, under special geometries such as that shown in Figure 4, where some sectors are going down hill and others are going up hill, that assumption is not quite right. In that situation, strictly each beam needs its own cumulative attenuation, as it differs with depth. Notice in Figure 4 that inside the same sector (same centre frequency) the cumulative absorption varies with depth, as represented by red circles in the plot in the right side. Therefore, in some circumstances, if not properly compensated, that cumulative absorption difference can generate backscatter strength fluctuations that may affect backscatter mosaics used for seabed characterization.

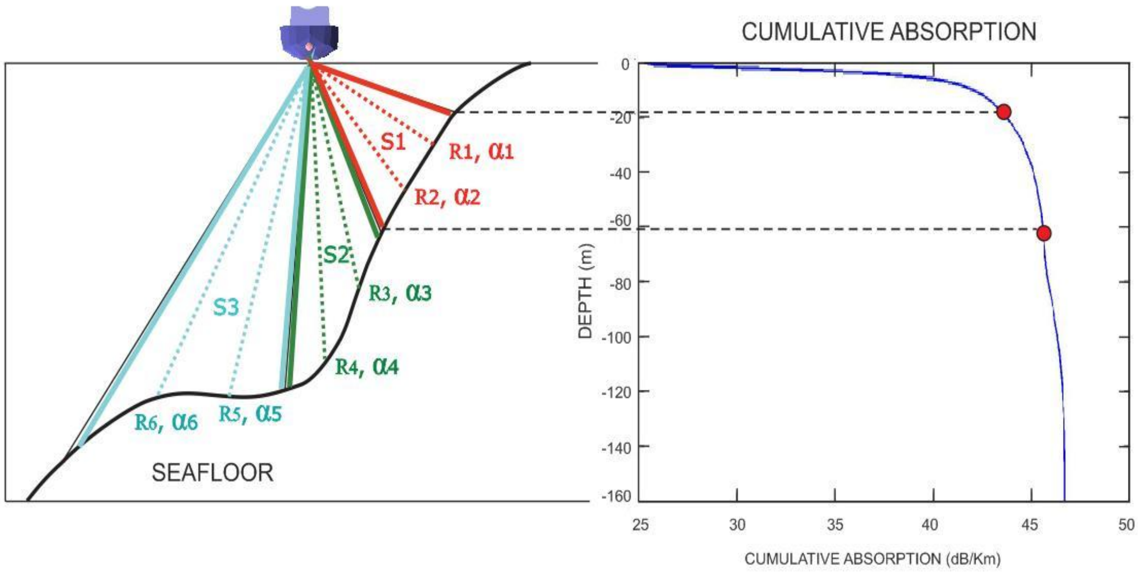

Figure 4 Multi-sector MBES operating in special seafloor geometry. Notice that inside the same sector (same centre frequency) the cumulative absorption varies with depth, as represented by red circles in the plot in the right side.

Based on that limitation and on the several attenuation controls discussed earlier, the proposed methodology comprises the following steps:

1. Ray trace each beam individually inside each different sector (different centre frequency) throughout the several layers of the water column, resulting in one different range for each beam: R_1, R_2 … R_6, as shown in Figure 4.
2. Apply Francois and Garrison Equation [1982] to calculate the absorption coefficient *in situ* for each layer of water column.
3. Calculate the cumulative absorption coefficient (α) for each beam, resulting in an individual α for each one (not just by sector as it is currently done): α1, α2 … α6, also shown in Figure 4.
4. If the cumulative absorption coefficient for each beam is different from the mean absorption coefficient provided by SIS (Kongsberg Maritime, 2009 and 2010) for each sector, the difference is used to calculate the gain correction in dB (based on the range), which should be applied to the original backscatter image (created based on mean absorption coefficient provided by SIS), to generate the corrected backscatter image.

4. EXAMPLE CASES

Two historical surveys done in Upper Howe Sound (British Columbia), that had inappropriate attenuation compensation are used to demonstrate the proposed methodology. The first one was collected during the spring 2006 by an EM3002 on CCGS Otter Bay and the other was collected during the winter 2011 by an EM710 (1° x 2°), mounted on a 10 meter launch (CSL Heron). Both surveys used incorrect attenuation values: the EM3002 data were collected using the Kongsberg default value, which seems not to be the most appropriate for Upper Howe Sound; and the EM710 data used attenuation coefficients calculated based on an incorrectly entered average salinity value of 35 ppt, quite different to the right one for the same period, that is usually lower than 32 ppt in that area.

4.1 EM3002

As that 300 kHz system has just one sector, it is simpler. No CTD was acquired at the time of survey, only sound speed; and SIS version at time only allowed input of a single value. On the other hand, if we are going back to correct all data, we have to be very careful when selecting the new profile to apply. Figure 5 shows an EM3002 original backscatter data (left hand), collected from 8 to 140 m, and corrected by two quite different profiles (Figure 6) selected for the same period and location from different data sources: WOA and WOD, centre and left hand images, respectively. Notice that in both these gain correction images we can visualize the depth and incidence angle dependence, as the gain is slant range dependent.

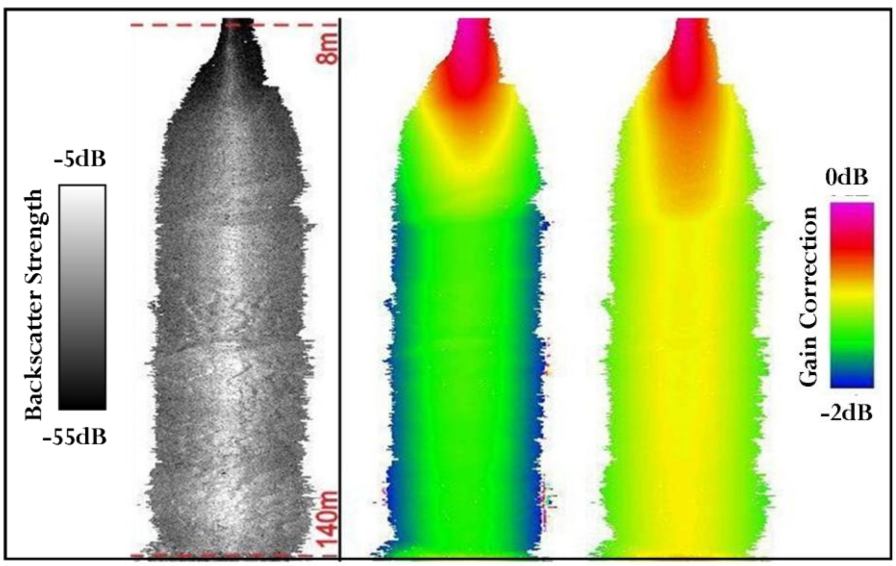

Figure 5 EM3002 original backscatter data (left) and the gain correction in dB to be applied to the original image based on WOA (centre) and WOD (right) oceanographic data selected for the same period and location.

Figure 6 shows *in situ* and cumulative absorption plots for 4 oceanographic profiles: one from WOA (in black) and the other three from WOD (in blue, green and magenta). The solid lines represent *in situ* absorption coefficients and dashed lines represent the cumulative absorptions. Notice that the three WOD profiles, actually collected in Upper Howe Sound

(Conkright et al., 2002), are very close to each other, while the WOA profile, generated by interpolations by distance and time (Stephens et al., 2002), has quite different values, generating quite different gain corrections (Figure 5, centre) when compared to the image represented in the right on Figure 5, which was calculated based on WOD profile number 0959 (Figure 6, in blue). This clearly illustrates the danger of using interpolated oceanographic climatologies in coastal waters where distinct water masses exist and can change dramatically between discrete coastal embayments.

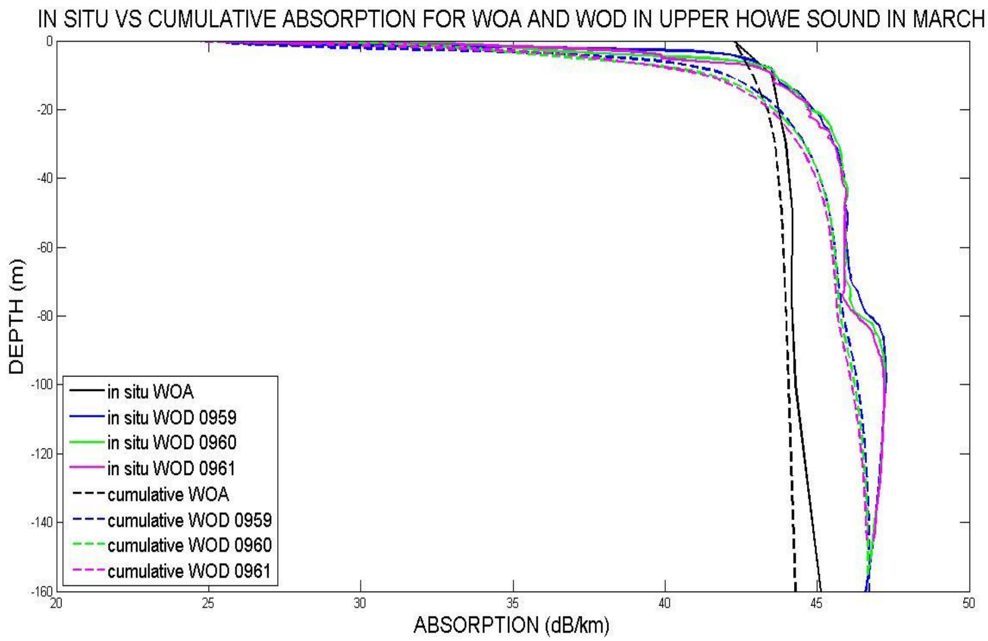

Figure 6 In situ and cumulative absorption plots for 4 oceanographic profiles: one from WOA (in black) and the other three from WOD (in blue, green and magenta). The solid lines represent in situ absorption coefficients and dashed lines represent the cumulative absorptions.

Figures 7 and 8 show us the cumulative absorption difference between the original value manually input into SIS and the value calculated using the proposed methodology, based on WOD profile 0959, for the nadir beams and outer beams at 45° launch angle, respectively. Notice that in both Figures the variations in cumulative absorptions are greater in the first layers (represented in green), where most oceanographic variation occurs, getting more stable with depth due to both more stable water mass and the integration approach used to calculate the "cumulative" value. Gain corrections that should be applied to the original backscatter image are represented in cyan and we can clearly notice that gain increases with range, represented in magenta, highlighting its range dependence relationship.

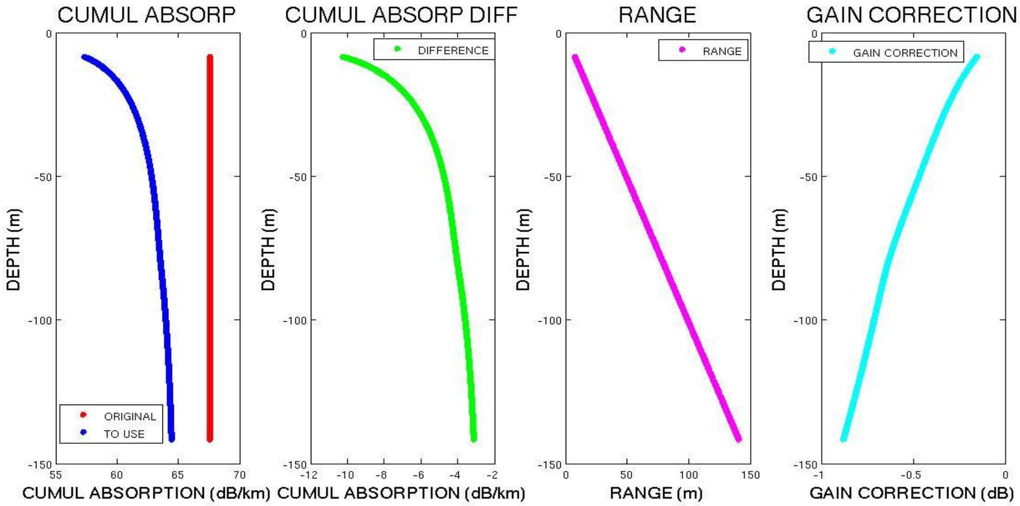

Figure 7 EM3002 corrections for nadir beams considering the WOD CTD profile number 0959. Red represents the mean absorption coefficient calculated by SIS and applied to the original backscatter image shown in Figure 5 (left); blue represents the cumulative absorption calculated by new methodology and green represents the difference between them. Magenta represents the nadir beam range and cyan shows the gain correction that should be applied to those beams.

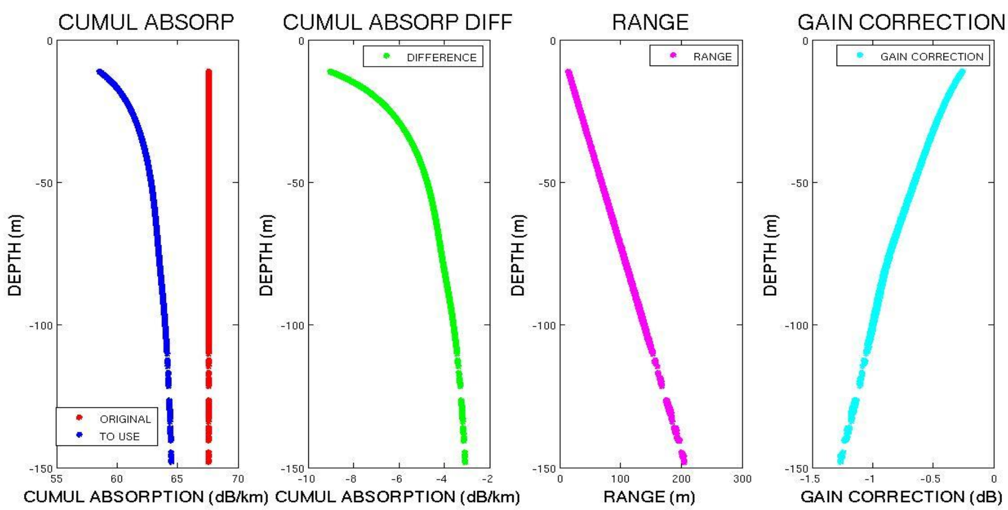

Figure 8 EM3002 corrections for outer beams at 45° launch angle considering the WOD CTD profile number 0959. Red represents the mean absorption coefficient calculated by SIS and applied to the original backscatter image shown in Figure 5 (left); blue represents the cumulative absorption calculated by new methodology and green represents the difference between them. Magenta represents the outer beam range and cyan shows the gain correction that should be applied to those beams.

4.2 EM710

Unlike EM3002, EM710 system is more complex. Instead of one single sector we have several sectors that switch through several centre frequencies depending on the operating mode.

While a CTD was used for 0-30m, no extrapolation was available. The sound speed was extrapolated (erroneously using default Northeast Atlantic values) and the attenuation coefficient calculated by inversion, erroneously assuming 35 ppt.

Figure 9 shows an EM710 original backscatter data (left), collected from 36 to 280 m, and corrected by a WOD CTD profile that we believe represents the Upper Howe Sound surveyed area at that time (January 2011) better. Notice the gain correction image in the centre and the zoom in (at right) in that same image in the boundary where the EM710 switches from shallow mode (100 to 200 m) to medium mode (200 to 300 m). Now, besides the depth and grazing angle dependence, we can even notice the distinct gain corrections applied to the inner and outer sectors, and to the first and second swaths of the dual ping system (horizontal light and dark stripes along the image at right, consecutively).

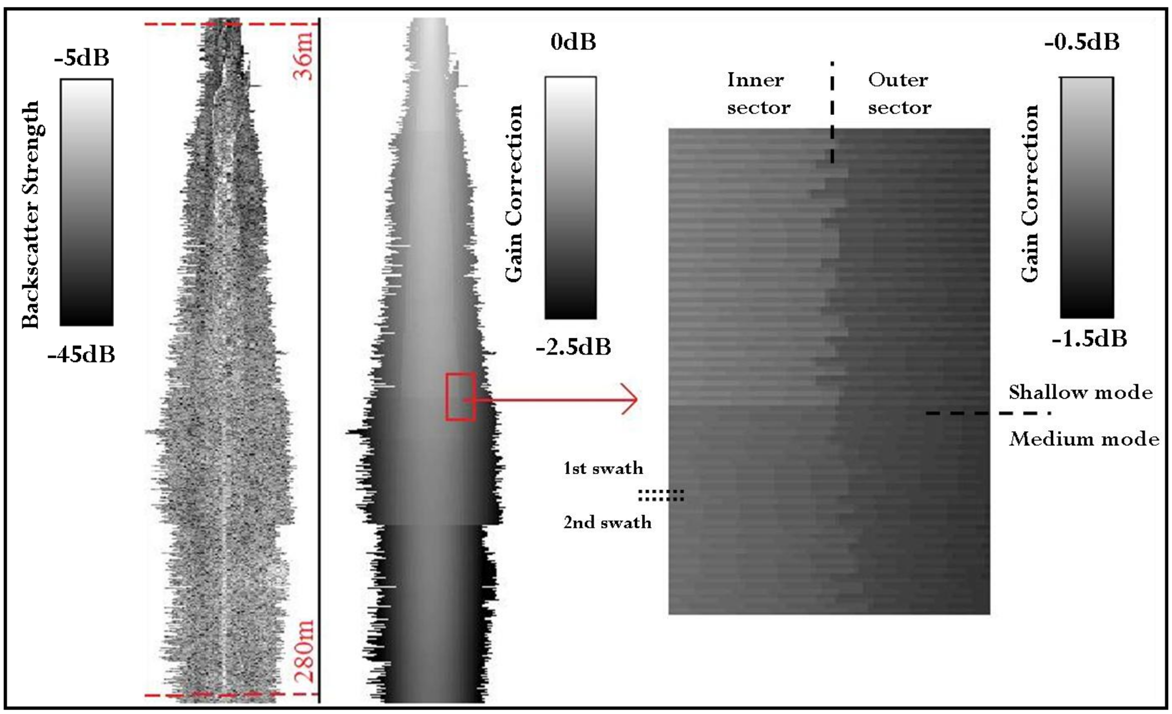

Figure 9 EM710 original backscatter data image (left), the gain correction image in dB (centre) and the zoom in of the boundary where EM710 switches from shallow to medium mode (right).

Figures 10 and 12 show us the cumulative absorption differences between the original values calculated by SIS and the values calculated using the proposed methodology for each different centre sector frequency detected, for the nadir beams (Figure 10) and for the outer beams at 60° launch angle (Figure 12). Notice that the cumulative absorptions applied by SIS for all centre frequencies are more than 2 dB/km greater than the cumulative values calculated using the new CTD profile. It means that the original backscatter image was over compensated by Time Varying Gain (TVG). In addition, observe that, as the sector centre frequency switches according to the operating mode, which also depends on the depth, each plot only contains information for specific depth ranges.

Figures 11 and 13 represent the nadir beams at 77, 81 and 89 kHz sector centre frequencies and outer beams (60° launch angle) at 73 kHz sector centre frequency, respectively, the cumulative absorption difference (in green) between the values calculated by SIS (in red) and the values calculated using the proposed methodology (in blue), the range (in magenta) and the gain correction (in cyan) that should be applied to the original backscatter image. Analyzing these plots, once again, we visualize the range dependency.

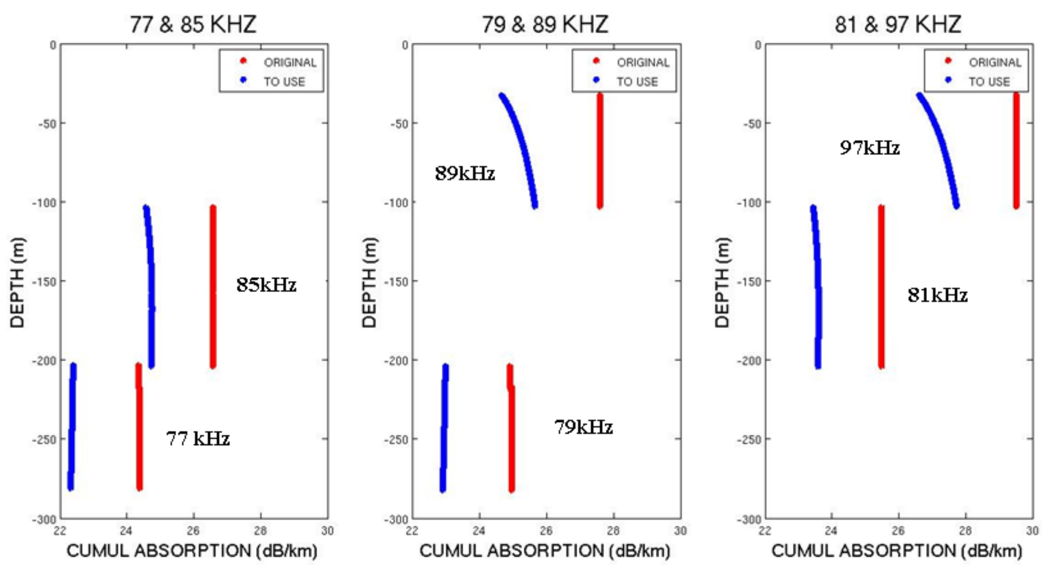

Figure 10 Cumulative absorption calculated by SIS (in red) and the one calculated using the proposed methodology (in blue) for detected centre frequencies: 77 and 85kHz (left); 79 and 89kHz (centre); 81 and 97kHz (right), considering only nadir beams.

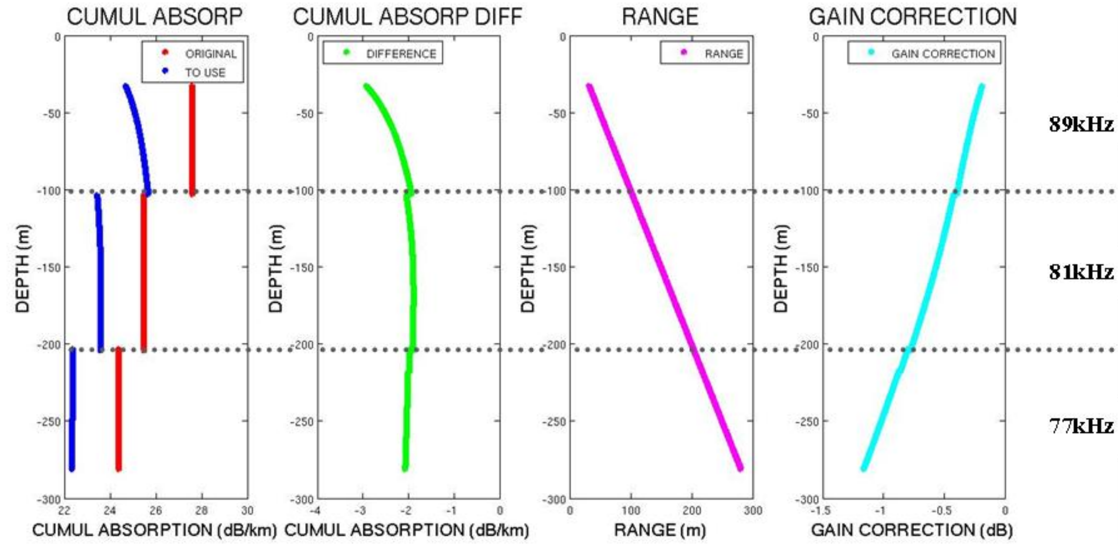

Figure 11 EM710 corrections for nadir beams for detected centre frequencies 77, 81 and 89 kHz. Red represents the original mean absorption coefficient calculated by SIS and applied to the original backscatter image shown in Figure 9 (left); blue represents the cumulative absorption calculated by new methodology and green represents the difference between them. Magenta represents the nadir beams range and cyan shows the gain correction that should be applied to them, also representing its range dependence.

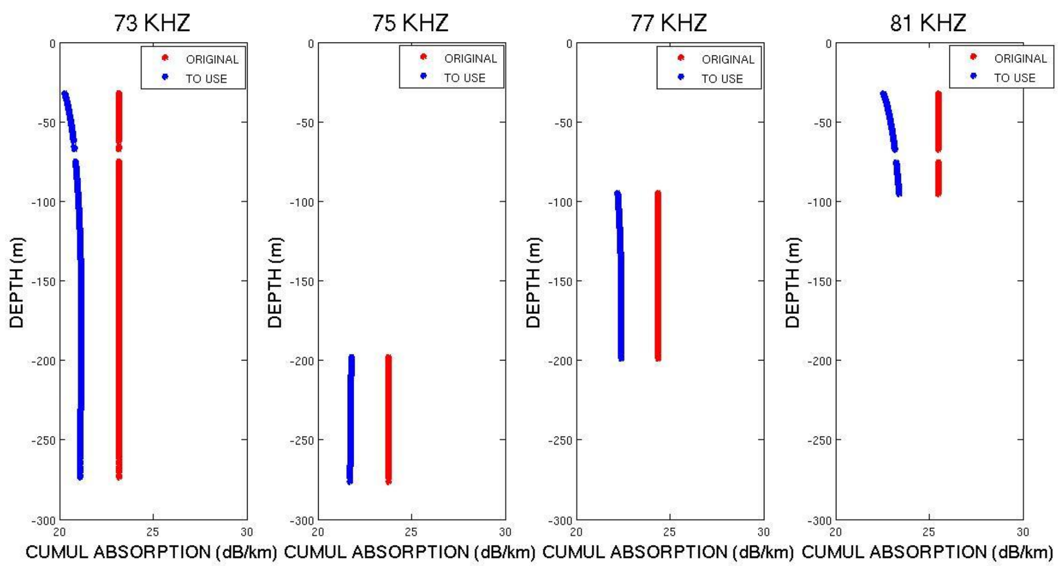

Figure 12 Cumulative absorption calculated by SIS (in red) and the one calculated using the proposed methodology (in blue) for detected outer beam frequencies: 73, 75 and 77 and 81 kHz considering only outer beams at 60° launch angle.

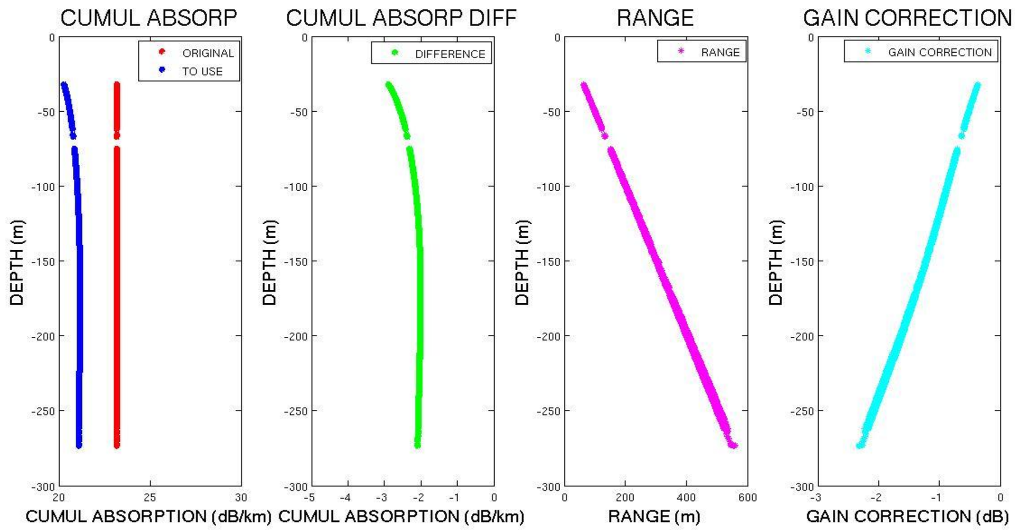

Figure 13 EM710 corrections for outer beams (launch angle 60°) and detected centre frequency 73 kHz. Red represents the mean absorption coefficient calculated by SIS and applied to the original backscatter image shown in Figure 9 (left); blue represents the cumulative absorption calculated by new methodology and green represents the difference between them. Magenta represents the outer beams range and cyan shows the gain correction that should be applied to them, also representing its range dependence.

5. CONCLUSIONS

The proposed model represents a post processing tool that allows the operator to utilize an attenuation coefficient from a more appropriate CTD, which is believed to be a better representation of the surveyed water mass in the area. The algorithm developed, automatically recognizes the frequency, the sector, the swath, the mode, the range and the ray path, calculating the gain correction and applying it to each beam of the original backscatter data, minimizing the fluctuations caused by environmental controls on it, supporting the seafloor characterization process.

Distinguishing mud from rock is easy due to its huge backscatter strength difference. However, the more typical challenge of distinguishing muddy sand from sandy mud is challenging as the backscatter strength difference between them is subtle. Similarly, distinguishing changes in surface sediments from winter to summer is usually difficult, because they may be masked by greater environmental variability. Thus, as we are particularly interested in monitoring seasonal changes in backscatter strength on the seafloor of a fjord (Upper Howe Sound) with active turbidity currents, subtle variations on it are very important and must be taken into account.

This research is one contribution toward better calibrated backscatter measurements. There are, however, many other issues to fix, which we believe have a greater impact on backscatter strength images, such as the absolute sonar source level and problems in sectors related to transmitter and receiver beam pattern variations (Teng, 2012).

6. ACKNOWLEDGMENTS

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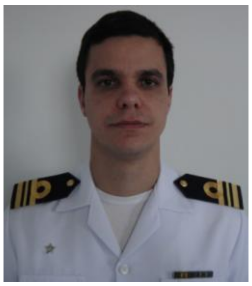
BIOGRAPHICAL NOTES



Rodrigo de Campos Carvalho is a Brazilian Navy Officer, B.Sc.E.Electronics in Naval Academy in 1999. Graduated in Extension Hydrography Course – Cat. A (IHO) in 2003 at Directorate of Hydrography and Navigation, in Brazil. Currently, he is a student of M.Sc.E. Geodesy and Geomatics Engineering at University of New Brunswick, supervised by Dr. John E. Hughes Clarke.

John E. Hughes Clarke is the Chair in Ocean Mapping and a Professor in the Dept. Geodesy and Geomatic Engineering at UNB. His prime interest lies in submarine sediment transport processes. As part of this, maximizing the information content available from integrated swath sonar systems is a major component of his research.

CONTACTS

Rodrigo de Campos Carvalho
Dept. Geodesy and Geomatics Engineering
University of New Brunswick
15 Dineen Drive, E3B 5A3, P.O. Box. 4400
Fredericton, NB
CANADA
Tel. - 506 - 470 - 2541
Fax - 506 - 454 - 8860
Email: hnrodrigocarvalho@yahoo.com.br

John E. Hughes Clarke
Dept. Geodesy and Geomatics Engineering
University of New Brunswick
15 Dineen Drive, E3B 5A3, P.O. Box. 4400
Fredericton, NB
CANADA
Tel. - 506 - 453 - 4568
Fax - 506 - 453 - 4943
Email: jhc@omg.unb.ca