Inter-calibrating multi-source, multi-platform backscatter data sets to assist in compiling regional sediment type maps : Bay of Fundy

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Abstract

The Bay of Fundy has seen ongoing multibeam mapping since 1992 as part of a series of local projects, and in a major regional program in the last 2 years. The survey sensors include Kongsberg EM1000, EM3000, EM1002, EM3002 and EM710 with centre frequencies ranging from 70 to 300 kHz. All data is acquired through the Kongsberg standard backscatter data reduction process that is supposed to generate estimates of seabed backscatter strength, ideally an inherent property of the seafloor. To achieve this data reduction, assumptions are required about absolute source level, pulse length, absolute and time varying receiver gains, seawater attenuation coefficients and sonar transmission and reception sensitivities. Because of uncertainty in all of these, the standard output value is effectively a relative measure. As a result inter-survey consistency is poor. A method is therefore required to pick an arbitrary reference (sonar hardware and software configuration) and adjust every other survey, through overlapping coverage, to that reference. For each configuration, specific adjustments need to be made to both absolute levels, variations by angle, by pulse length settings and correcting for applied attenuation coefficients. Once all these corrections have been made, a second set of adjustments needs to account for the spatially variable shape of the inherent seabed angular response curves.

Introduction

As part of the Geoscience for Ocean Management (GOM) program within Natural Resources Canada, a regional multibeam mapping effort is underway (Fig. 1), designed to cover the majority of the seafloor of the Bay of Fundy.

The mandate of the GOM program is to: “*deliver the geoscience knowledge base for informed decision making in Canada’s offshore lands, to ensure that natural resource development does not harm the environment and that appropriate land-use decisions are made balancing social, economic and environmental considerations*”.

In the case of the Bay of Fundy, the prime land (seabed)-use issues relate to the fisheries (lobster, scallop, aquaculture), aggregate extraction and, most recently, the potential for in-stream tidal power (Hagerman et al., 2006). In all three cases, the concern is primarily with the surficial substrate which in turn controls the benthic habitat; the available grain sizes and sorting; and the erodability of the seabed. Clearly, therefore, means by which the type of surficial substrate may be identified are of paramount importance. Acoustic backscatter strength measurements have been collected as part of the multibeam surveying and are a viable means of remotely sensing that substrate. The aim of this paper is to present the results of that backscatter imaging and illustrate particularly the limitations in that measurement when being acquired from multiple platforms and sensor types.

Instrumentation and Survey Evolution

Multibeam mapping in the Bay of Fundy first started in 1992 when the CCGS Frederick G. Creed undertook experimental trails of the first EM1000 (95 kHz). Between 1992 and 1994 three projects were conducted in the Margaretsville to Minas Passage region (Fig. 1) to test sediment classification methods (Hughes Clarke, 1993) and to examine bedform dynamics (Hughes Clarke et al., 1996; Campbell et al., 1997). In 1996 and 1999 two further surveys were undertaken with the Creed EM1000 by NRCan focussing on areas of suspected seabed dynamics – the Cape Enrage area and the mussel ridges area (Wildish et al., 1998).

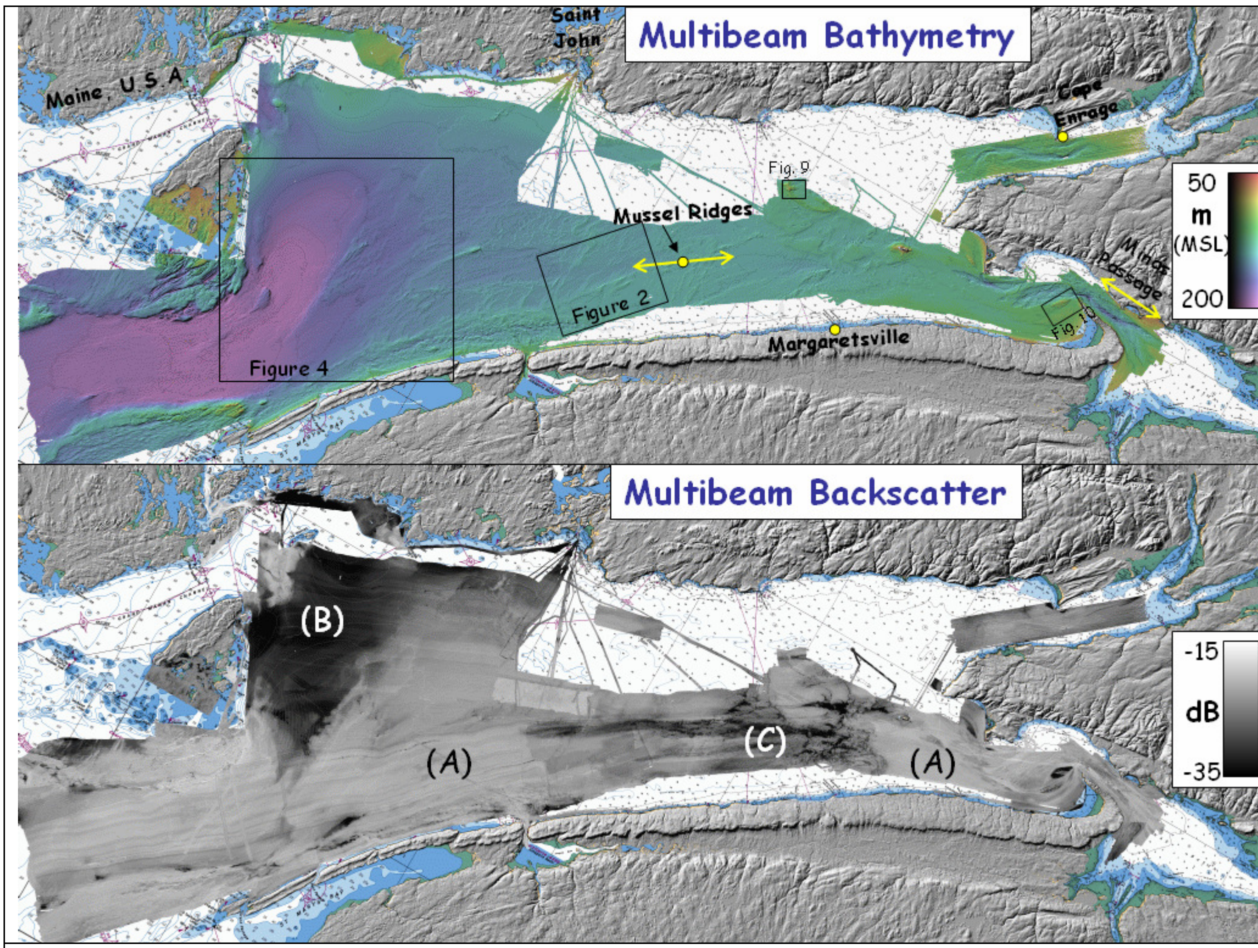


Figure 1: Multibeam compilation from 1992 to end of 2007

From 2000-2005, coastal surveys were undertaken using EM3000 (300 kHz) equipped launches (Plover and Heron) along the New Brunswick shore extending from the border with the United States to Saint John. These operations were in very shallow water, addressing coastal issues such as disposal site dynamics (Parrott et al., 2002), Marine Protected Areas (Byrne et al., 2002), aquaculture sites (Hughes Clarke et al., 2002, Wildish et al., 2004) and benthic habitat as well as providing training for students (at UNB).

In 2006 and 2007 a much larger scale program was initiated as part of the Geoscience for Ocean Management (GOM) and Ocean Action Plan (OAP) programs. These surveys have involved 5 multibeam-equipped platforms:

1.	CCGS Frederick G. Creed	EM1002	(98 & 93 kHz)	2006	2007
2.	CSL Heron	EM3002	(300 kHz)	2006	2007
3.	CCGS Matthew	EM710	(71, 74, 77, 83 & 97 kHz)		2007
4.	CSL Plover	EM3002	(300 kHz)		2007
5.	CSL Pippit	EM3002	(300 kHz)		2007

This most recent phase of these surveys has provided by far the greatest coverage. Almost all the areas surveyed in 1992/3/4 have been resurveyed, in part due to data quality issues, but also in order to directly monitor the > 13 years of change (Hughes Clarke, 2008). The 1996 and 1999 areas, however, have not been resurveyed.

The majority of the area surveyed in 2006 and 2007 was by the Creed EM1002 and Matthew EM710 systems. The launches, equipped with EM3002 systems, focussed primarily on the near coastal (<30m) regions, in which many of the land-use issues lie.

Backscatter Data Manipulation

The backscattering coefficient for a particular sediment at a given frequency is an inherent property of that material and varies only with grazing angle. The backscattering coefficient is calculated as a dimensionless ratio of the power backscattered by unit sold angle with respect to the product of the incident intensity per unit area and the area instantaneously ensonified (Mitchell and Somers, 1989). The backscatter strength (herein referred to as the BS) is most often quoted and is just $10\log_{10}$ of this ratio. While the definition is straight forward, arriving at that dimensionless ratio is fraught with system calibration and normalization issues.

Most modern multibeam sonar systems provide a measure of the peak or average backscattered intensity (measured as a voltage on the receiver array). This value is not an estimate of the backscatter strength since it is a function of the system and geometric parameters. To reduce this value to a measure of the bottom backscatter strength, the system must account for:

1. Sonar source levels, pulse lengths and receiver sensitivity.
2. The 3D beam patterns of the transmit and receive arrays.
3. Spherical spreading and particularly ocean attenuation coefficients at that frequency.
4. Applied real-time time-varying gains (TVG's).
5. Local seabed slopes

All Kongsberg EM multibeam systems use a data reduction scheme (Hammerstad, 2000) designed to reduce the received intensity values to a first-order measure of the bottom backscatter strength by including corrections for all of the steps listed above. Such a data reduction provides a stable relative value for a sonar system with a given set of hardware (transducers and electronics). The validity of this data reduction, however, is limited by two aspects (Hughes Clarke, 1993):

- there are usually discrepancies between the actual hardware performance and the design (1,2,4)
- there are environmental assumptions in the calculation including (3,5)

Since these surveys have taken place using 5 different Kongsberg EM multibeam sonar types, from 5 different survey platforms with over 15 years of software and hardware upgrades, imperfections in each of these models and assumptions provide uncertainty in the absolute estimate of bottom backscatter strength (see Fig. 2a). Even with this uncertainty the separation of materials with strongly contrasting BS such as boulders and clay (> 30 dB contrast) is not an issue, but the delineation of the variations between muddy sands and sandy muds and coarse and fine gravels (< 5dB contrast) becomes a challenge.

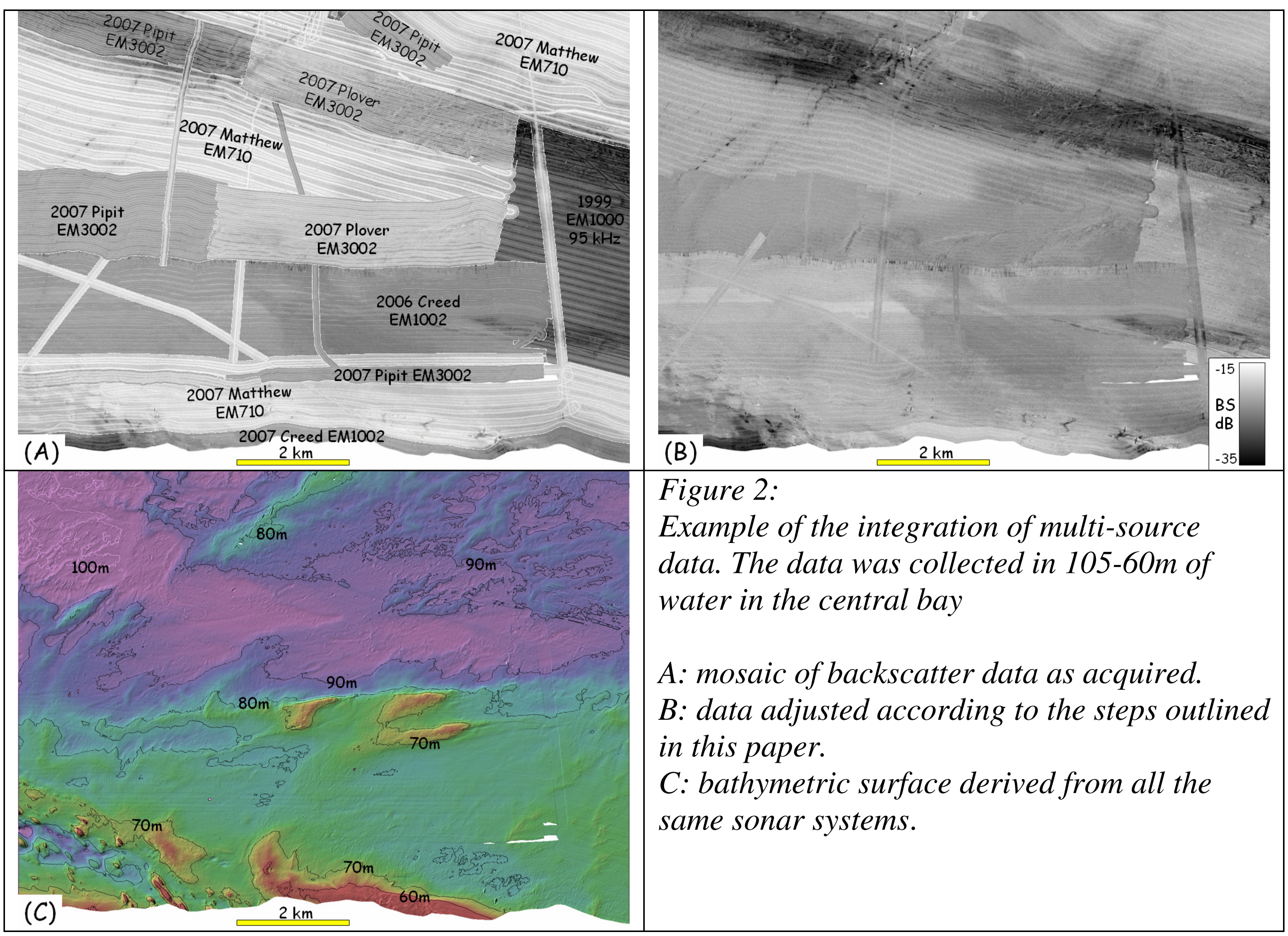


Figure 2:
Example of the integration of multi-source data. The data was collected in 105-60m of water in the central bay

A: mosaic of backscatter data as acquired.
B: data adjusted according to the steps outlined in this paper.
C: bathymetric surface derived from all the same sonar systems.

In the absence of a robust absolute calibration method, empirical approaches through inter-sonar comparisons have to be used as a proxy (Fig. 2b). This paper presents the main problems and steps taken to resolve that. Each issue is presented in turn, with examples.

Coping with Source Level Uncertainty

From the data shown in Figure 2A it is clear that the absolute level of backscatter strength for a given sediment type varies from sonar to sonar and model to model. In the absence of an absolute calibration, we can only turn to the expected BS levels for the known sediments present in the region as a proxy (table 1). Based on a compilation of calibrated BS observations, the Applied Physics Laboratory at the University of Washington has developed a backscattering model (APL, 1994). Using the output of this model typical sediment types have BS (at 80 and 100 kHz) in the following ranges at a grazing angle of 40° (50° off vertical):

Sediment type	**BS (40° grazing) 80 kHz**	**BS (40° grazing) 100 kHz**
Rough rock	-4.4	-4.2
Rock	-8.6	-8.2
Cobble	-13.0	-12.6
Sandy Gravel	-17.1	-16.8
Coarse Sand	-19.6	-19.2
Medium Sand	-22.0	-21.7
Very Fine Sand	-24.9	-24.8
Silt (high volume)	-28.7	-28.7
Silt (low volume)	-33.9	-33.9

Table 1: modelled backscatter strength levels (dB) derived from the Applied Physics Laboratory (UW, 1994) report.

40° was chosen as a representative grazing angle as this is the dominant angle of data visible in the BS mosaics. All data were normalized for beam pattern and angular response (see later discussion for methods) to a reference grazing angle in this range. From the APL (1994) report (which relies on the Jackson et al. (1986) model), it is clear that around this grazing angle the angular response (AR) curves are flattest.

The dominant sedimentary facies on the floor of the Bay of Fundy are "deflated tills" (Swift et al., 1969, Fader et al. 1976) which represent seabed surface sediment in the range from coarse sand and gravels to cobbles. This is represented by areas indicated by (A) in Fig. 1. Only in the western region between Grand Manan and the New Brunswick shore do we find significant accumulations of mud (the La Have Clay indicated by (B) in Fig. 1). Well sorted, mobile medium to fine sand sheets are concentrated on the flanks of depressions along the central bay (indicated by (C) in Fig. 1 and represented by the dark regions in Fig. 2 (top-right) and in the lee of headlands.

From Figure 1 we note that the main range of BS levels seen in the Bay extend from -15 to -35 dB. This reasonably matches the APL (1994) predictions for Cobble/Sandy Gravel through to Silt. We have decided to use the BS levels output by the 1992-1994 EM1000 surveys as our reference levels for two reasons. Firstly they reasonably approximate the APL results without apparent bias and secondly, they were the first data acquired and subsequent processing had used them as a reference. These data (after empirical beam pattern corrections, which do not alter the mean BS level) are taken as the nominal “truth”. All other surveys are adjusted by overlap to best correspond to that truth. Particular complications with this method include calculating this source level adjustment accounting for changing pulse lengths, changing attenuation coefficients (see later discussion) and the fact that overlap is not always achieved.

The following table shows the currently-used dB shifts applied to each survey.

Platform	Sonar	Freq.	year	dB offset
Creed	EM1000	95 kHz	1992-1994	reference
Creed	EM1000	95 kHz	1996	0 (no overlap to check)
Creed	EM1000	95 kHz	1999	-2 dB
Plover	EM3000	300 kHz	2000/1/2	0 dB
Heron	EM3000	300 kHz	2002/3/4/5	-3dB
H. Queen	EM3002	300 kHz	2005/6	-3 dB
Heron	EM3002	300 kHz	2006/7	-3 dB
Creed	EM1002	93/98 kHz	2006/7	-5 dB
Matthew	EM710	71-97 kHz	2007	-11.5 dB
Plover	EM3002	300 kHz	2007	-9 dB
Pipit	EM3002	300 kHz	2007	-7 dB
Hawk	EM3002	300 kHz	2007	-3 dB

Table 2: dB offsets for each sensor, platform and survey.

Note that EM3000/3002 results used to vary by only 3dB, until the most recent field season. Note also that the EM710 results are the most significantly different. A noted tendency is for the more recent Kongsberg systems to generate significantly higher BS levels (5-12dB stronger). The newer sonar systems routinely report positive mean BS levels suggesting a false bias.

Note also that for sonar systems that show a systematic BS offset with changing pulse length (see discussion below), table 2 represents the offset applied to the shorter pulse length data (0.2ms in the case of the EM1002).

Once applied, these bulk offsets usually suffice for a specific sonar and platform during a survey season. One notable exception to this was the EM1002 on the Creed. Figure 3 illustrates that, from day to day, as the sonar system was turned off and on (the vessel operates only as a day boat) the absolute BS values appear to shift within typically +/- 0.5 dB. To date this has not been noted with the other sonar systems and is thus assumed to be a hardware malfunction problem. The EM3000/3002 systems are routinely restarted on a daily basis whereas the EM710 system, once turned on, tends to remain on for several days at a time.

In summary, empirically-derived BS offsets are necessary to be able to follow subtle geologically-driven geographic variations in bottom backscatter strength across survey boundaries. Even with an arbitrary reference however, BS levels with respect to that level should not be relied upon to better than about +/-2dB. This has implications for robust seafloor characterization.

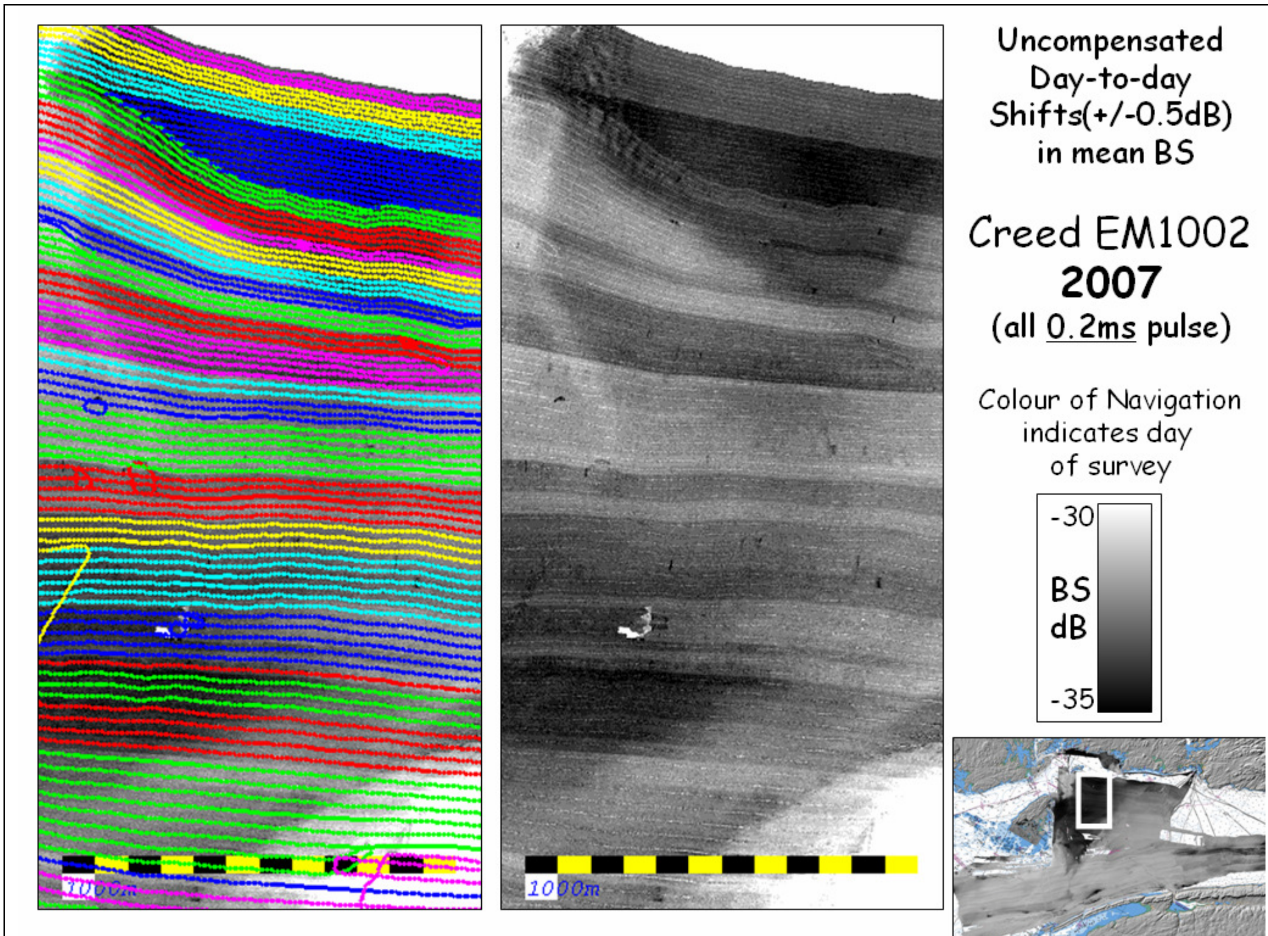


Figure 3: Illustrating, uncompensated day-to-day +/-0.5 dB shifts in apparent EM1002 source level. This was present for both 2006 and 2007 data and occurred superimposed on top of the 0.2-0.7ms pulse length shifts. Note that the greyscale represents only 5 dB range.

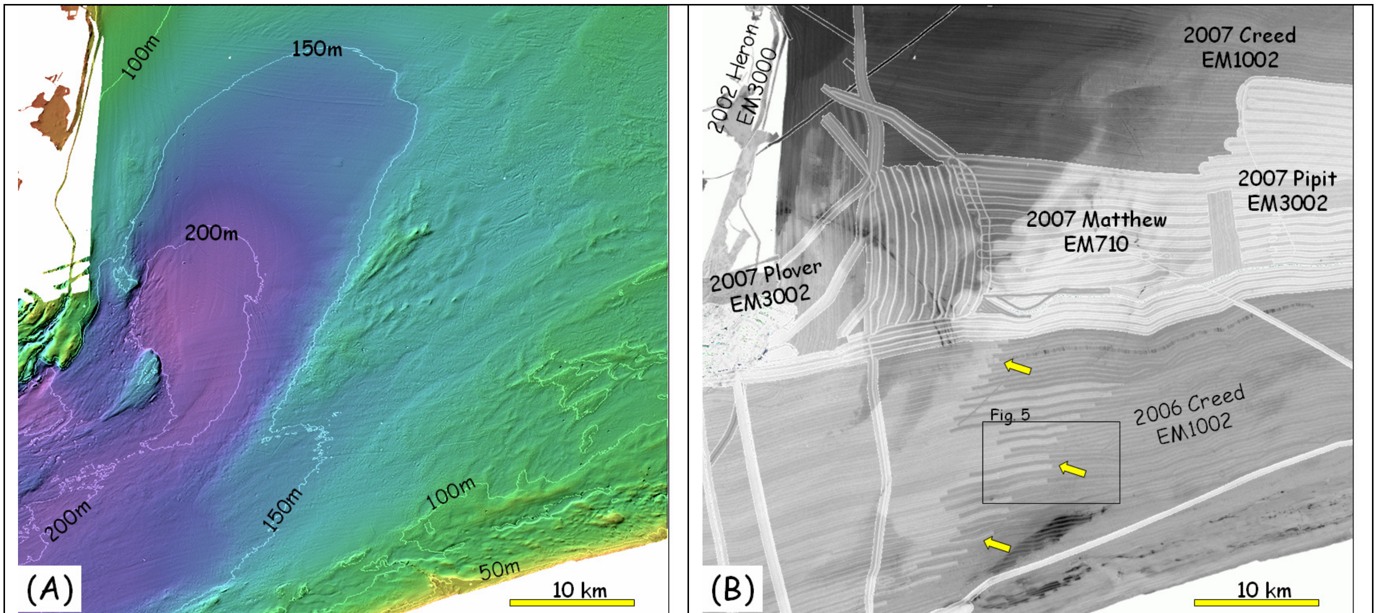
Coping with imperfectly Reduced Pulse Length effects.

To a first order, the Kongsberg data reduction routine (Hammerstad, 2000) is supposed to correct automatically for the instantaneously ensonified area resulting from a change in pulse length. The EM1000 and EM1002 sonars shift from a 0.2 to 0.7 ms pulse at depths ranging from 100 to 150m (the exact depth depends on the signal to noise ratio which depends on environmental conditions, primarily controlled in low seastates by seabed BS). Depending of the specific system however, this sometimes results in an apparent shift in the BS level.

For the case of 2006 and 2007 Creed EM1002 data, it is clear that the longer pulse length is favoured in water depths greater that 150m (Fig. 4a and arrows on b). When the pulse length shifts, there is an abrupt increase in apparent BS (Fig 5a). When comparing the BS level immediately before and after the shifts (Fig. 5c) a 5dB apparent offset is seen. Interestingly the

~3.5x factor increase in ensonified area is nearly equivalent to the 5dB step which might suggest there is no correction applied. However, equivalent work by the first author with other EM1002 systems indicates that the magnitude of this offset varies from installation to installation.

As the pulse length is recorded in every ping, a systematic offset can be applied which, together with the source level offsets, result in a much improved regional image (Fig 4C and compare Fig. 5a and b). As the pulse length change is automatically done when a signal to noise threshold is passed, one can note that the change tends to occur at a deeper depth when going down hill than when steaming uphill.



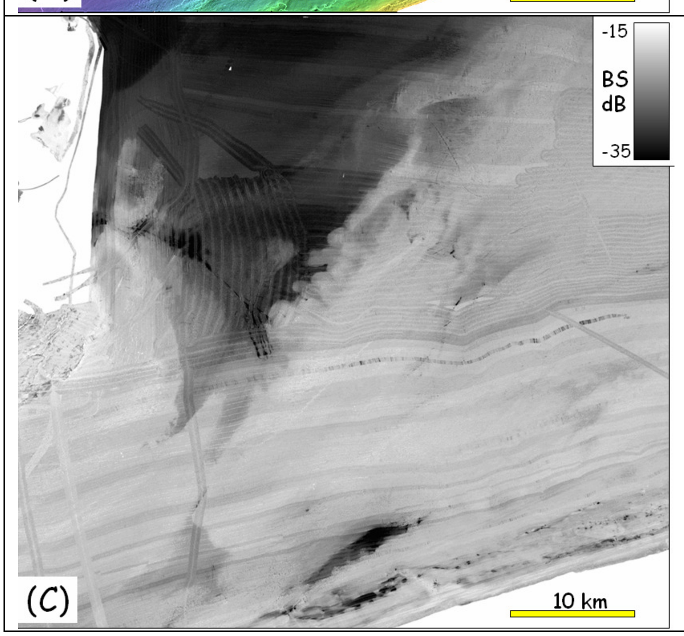
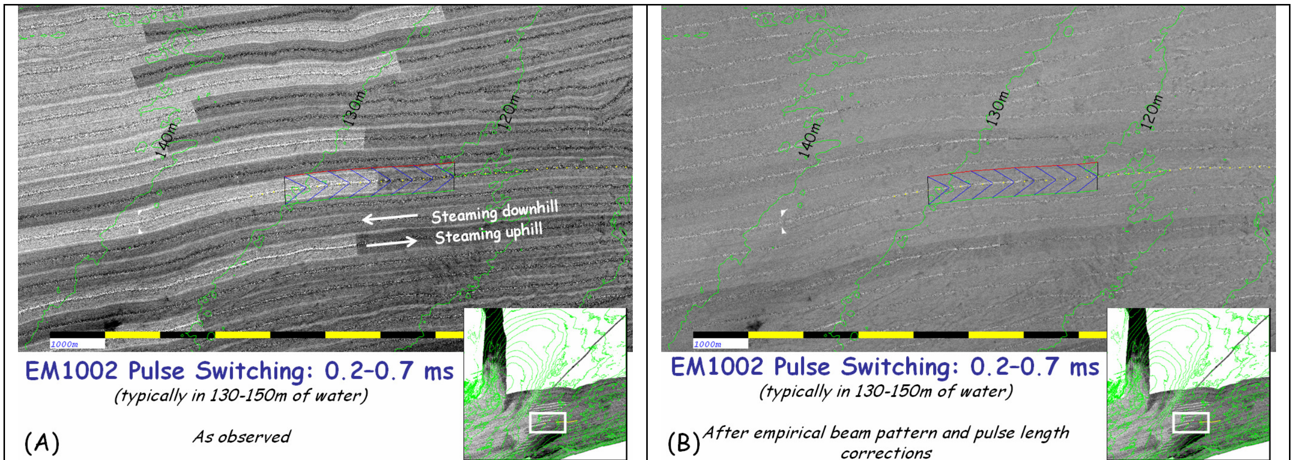


Figure 4:
A : Bathymetric surface showing changing depths that drive pulse-length changes
B : Compilation of BS measurements using as-acquired Kongsberg TVG reduced data. (sonar types indicated). Arrows indicate regions where the EM1002 pulse length is changing.
C: After reduction for relative source level, pulse lengths and sonar-specific empirical beam patterns. Note the residual +/-0.5dB changes in the EM1002 data (highlighted in Fig. 3).

There are two additional concerns with the EM1002 pulse length shifting. Firstly the change in the apparent near-specular response (Fig 5c) shows up as residual nadir stripes in the mosaic data after correction. This would lead to two different estimates of the shape of the near nadir AR which would confound classification schemes that use this information (e.g.: deMoustier and Alexandrou, 1991, Hughes Clarke, 1994).

The second concern is that, with the changing range sampling interval resulting from the change in the pulse bandwidth, the spatial texture is notably different. For those seafloor characterization methods that use texture including grey level co-occurrence matrices (Pace and Dyer, 1979; Reed and Hussong, 1989), intensity probability density functions (deMoustier, 1985) or along-trace spectra (Pace and Gao, 1988), a change in texture will result in different statistics.



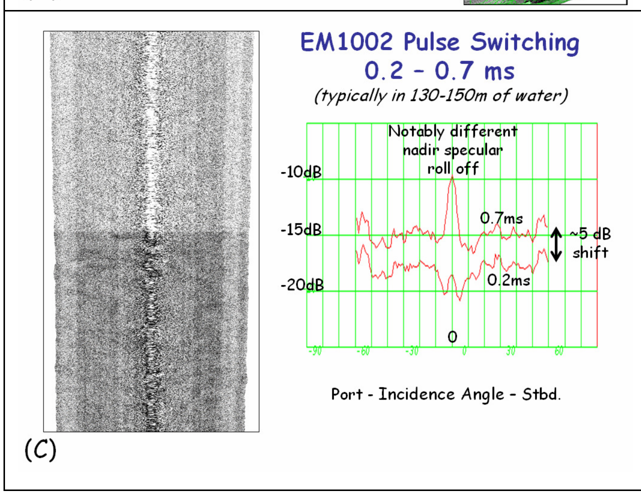


Figure 5:
A: EM1002 backscatter data, as acquired, showing abrupt, across-track shifts in BS level at the pulse length is changed.
B : after arbitrary 5dB drop in data using 0.7 ms pulse length. Note the remaining abrupt change in the character of the nadir stripe.
C: Showing change in mean BS and apparent angular response with changing pulse length. Note also that the spatial speckle texture is significantly different (coarser for 0.7 ms pulse).

In this case, the pulse length changes are unavoidable as the sonar is signal to noise limited at a certain depth and thus must switch pulse lengths to maintain bottom lock. The EM3000 and EM3002 normally only use one pulse length and thus are not affected by this (although there is an optional operator override for this).

The EM710 shares similar source level and attenuation characteristics to the EM1002 and thus also needs to change pulse length. An additional complication is that the EM710 changes sector frequency when the pulse length is changed. The EM710 has 30 kHz of available bandwidth (70-100 kHz) to accommodate several broad band pulses. In shallow water using a 0.2 ms pulse (5 kHz bandwidth) the full bandwidth is used with the three sectors set at : 71, 97 and 83 kHz (port to starboard). As one goes deeper, and uses longer pulses, the required pulse bandwidth reduces and thus the system can shift to the lower frequency (and thus lower attenuation) range. With a 0.5 ms pulse, the sectors are now 71, 83 and 77 kHz, and in the deeper water a 2.0 ms pulse is used with sector frequencies of 71, 77 and 74 kHz. All these changes in ensonified area, and centre frequency hold great potential for apparent shifts in BS if not properly compensated for.

In Figure 6a the EM710 coverage is presented, coded by used pulse length and frequency combinations. The system automatically adjusts mode to suit depth range. Unlike the EM1002 though, once in a mode, the EM710 is more likely to stay in that mode. In the deepest water (~200m) the EM710 switched to a 2.0ms pulse, unlike the EM1002 (which does have this option), resulting in a third mode.

Figure 6b illustrates a region with adjacent and overlapping regions where each of the three EM710 pulse length modes was used. As can be seen, unlike the EM1002, the BS levels for the EM710 modes are within ~ +/- 1dB (and averages are obtained from non overlapping areas) indicating that the pulse length corrections are reasonable. What one does clearly notice, however is a change in the apparent speckle texture for the three modes. The change would complicate using classification algorithms that in part rely on BS statistics (e.g.: Milvang et al., 1993; Preston et al., 2001).

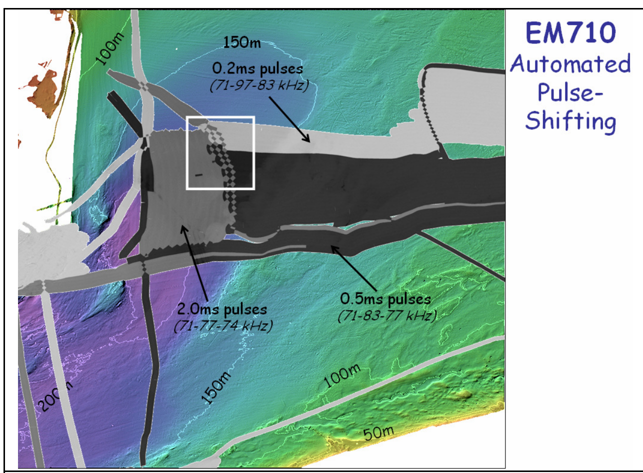


Figure 6a: EM710 coverage. Shades of grey represent the three discrete pulse length and sector frequency modes used.

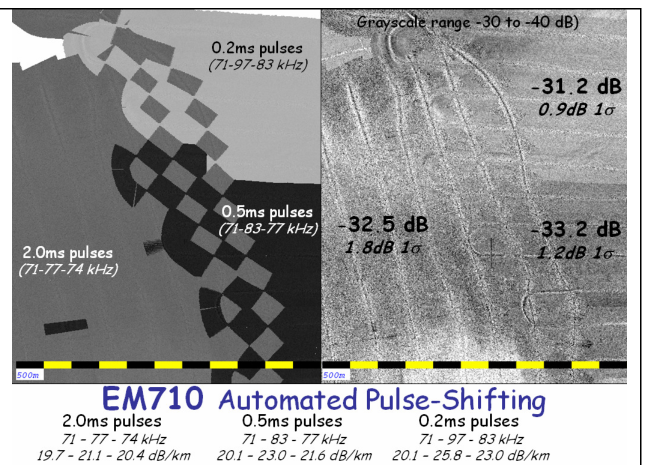


Figure 6b: zoomed area, showing detail of texture and slight BS shifts between pulse length and frequency sector changes.

Coping with Beam Pattern Uncertainty

Each EM model sonar has a designed array directivity on both transmit and receive. Some of these are vertically referenced beam patterns and some are sonar referenced. For those sonars with multiple sectors (e.g. EM1002 and EM710), each sector has its own roll-stabilized beam pattern (Kongsberg, 1998, 2005). For malfunctioning EM1002s it is possible to have both vertically referenced and sonar referenced beam pattern issues (Hughes Clarke, 2008). Any deviation from the designed beam pattern (reduced for by the Kongsberg standard algorithm) will show up as a series of residual variations in BS projected on the seafloor as a function of angle. As these small perturbations are unknown, an empirical estimate has to be made of these by stacking the average BS values recorded as a function of vertically referenced angle (Hughes Clarke et al., 1997). For multi-sector sonars, these statistics should be compiled separately for each sector (Llewellyn, 2005). Such a stack combines the beam pattern residuals as well as the combination of the true seafloor angular response and the Kongsberg compensation.

For an area of homogenous seabed type, this variation of BS by angle (e.g. Fig. 7a) can be used to normalize the BS estimates across track to a common reference angle. As the beam pattern residuals are unique to a hardware configuration, each vessel will have its own specific signature.

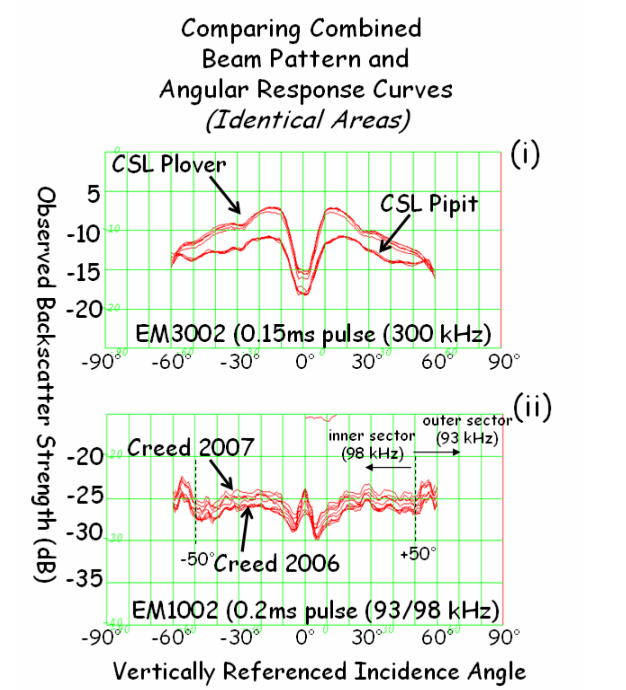


Fig 7a: Comparing reproducibility for systems and years.

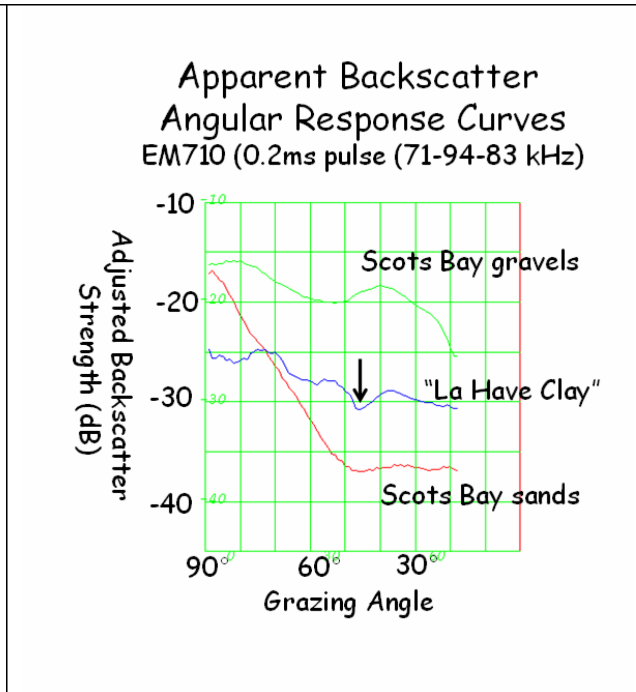


Fig 7b: Angular response curves derived accounting for the local seabed grazing angle (arrow indicates sector boundary).

In Figure 7a(i) the signature of two EM3002's collected on the same day in the same area shows a 2dB shift between the two installations that can be corrected for in the installation-specific offsets (table 2). Superimposed on the average offset, however, there is a smaller variation by angle that needs, also, to be accounted for. A common reference level for each profile is picked, (usually the average BS value at ~ 40°) and all BS observations at other angles, are adjusted by the average difference from that level.

In Figure 7a(ii) we see the patterns for a single system (Creed EM1002) in two years (2006 and 7) calculated in the same location. Characteristically the EM1002 has a much greater degree of rippling in the beam pattern residuals than the EM3002 since the transmitter consists of multiple staves and each roll-stabilized receiver channel has a separate amplifier. Notice too that there is an abrupt step up of ~2-3 dB at + and – 50° that reflects the sector shift from the central 98 kHz sector to the outer 93 kHz sectors. Interestingly the beam pattern ripples are stable from year to year (as neither the transducer nor the transmitter and receiver electronics board have changed). There is a 1dB apparent shift in the mean BS level, but this is probably due to the day to day changes that were illustrated in Figure 3.

All these empirical beam pattern corrections implicitly assume that the shape of the seabed angular response curve remains the same for different sediment types. The derived BS AR curves for three common sediment types in the Bay of Fundy (Fig. 7b) show that the variation with grazing angle is actually very pronounced and thus the empirical combined beam pattern and AR curves will change with sediment type. A method needs to be put in place to account for that.

Coping with variable shape of Angular Response

Figure 8a illustrates a survey line of BS data observed across contrasting sediment types. The location of the line is indicated in Figure 10. Figure 7b shows the strongly contrasting angular response of the sands and gravels where there is both a significant drop in mean BS (averaged over all grazing angles) but also a strong change in the shape of the AR. The sandy sediments are notable in that there is a particularly pronounced roll-off in BS from vertical incidence to 40° incidence. From the regional BS mosaic presented in Figure 1 we note that the La Have Clay regions (A) appear on average to have similar mean BS to the mobile sand sheets (C). When compared over the full range of grazing angles though (Fig. 7b) it is seen that the La Have Clay regions have a much flatter angular response curve. The two sediment types are thus clearly separable based on their AR, even though their mean BS is very similar. This is important information for seabed characterization, but needs to be suppressed for the purposes of regional mean BS maps as the along-track striping is due to grazing angle, not sediment type changes away from nadir.

When interpreting a map of mean BS (e.g. Fig. 10 showing the Scots Bay sand wave field), the geologist would like to be able to delineate the bounds of the two sediment types. In the original data, (Fig. 8a) one can see both the changing angular response (the bright zone at nadir only present on the sand) as well as the system beam pattern (the sector boundaries most apparent in the gravels at the mid range). If the method described previously, involving stacking the average BS by vertically referenced angle, were utilised, the correction would depend on the seafloor type used to acquire the stack. If the stacked data is collected within the gravel region, then the reduced data will present an even grey level across the swath for sediment with an AR shape similar to the gravels (left side of Fig. 8b). But the same empirical correction would leave a strong BS stripe in the nadir regions of the sand area (right side of Fig. 8b). Inversely if the empirical combined beam pattern and angular response estimate is made predominantly within the sand areas (Fig. 8c), the sand seafloors will present an even grey level across the swath, whereas the gravel regions will be over compensated, resulting in an artificially low apparent BS in the near nadir regions.

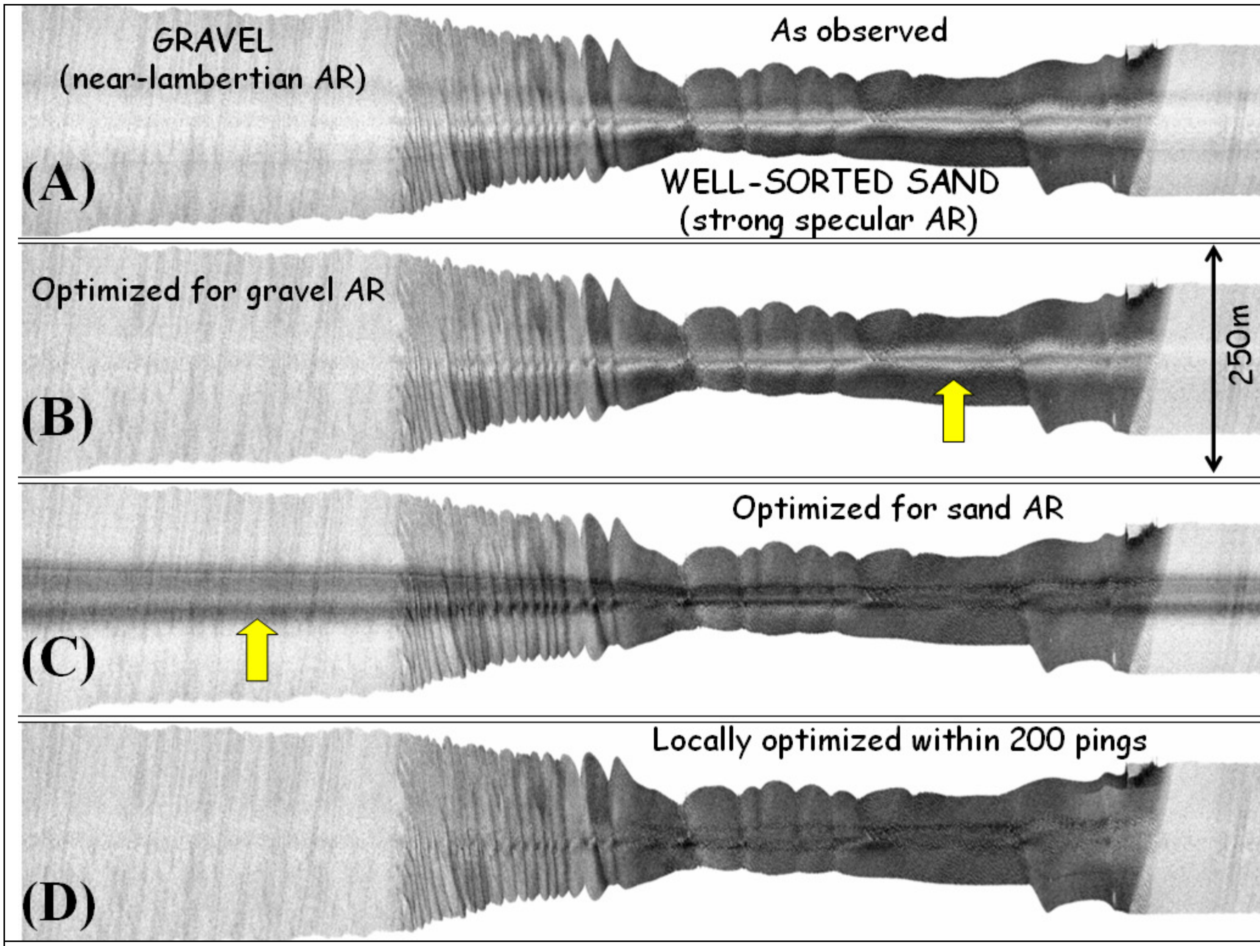


Figure 8 : Illustrating empirical approaches for suppressing combined beam pattern and angular response (AR) signatures.

(A) - as observed using Kongsberg default TVG.
(B) - Using statistics of gravel region – undercompensated sand AR (arrow).
(C) - Using statistics of well-sorted sand region – overcompensated gravel AR (arrow)
(D) - Using statistics derived from local 200 ping rolling average.

The solution to this is to acquire the empirical corrections locally, ideally within the same sediment type. The problem here is that the method is circular. One needs to know the sediment boundaries to define similar sediment types, yet the data reduction method is for the very purpose of defining the sediment boundaries. Herein, a rolling local average is used that responds to sediment variations within a few 100 pings of the region of interest (Iwanowska, 2005; Hughes Clarke, 2008). This method is applied for the same data (Fig. 8d). It generally works well (the image in Figure 10 used this approach), but can fail in regions where there is a local (i.e. maintained within the few 100 ping averaging) abrupt across-track boundary in sediment type.

Whether to reference to the local level or the local surface?

All the previously-described empirical approaches, compiled the BS with respect to the vertically-referenced beam angle. For flat seafloors this closely approximates the grazing angle. But where there are strong seafloor slopes, the two can differ. A common example of this is in the presence of steep bedforms (Fig. 9) where much of the variation in the BS level is controlled by slope rather than sediment type changes.

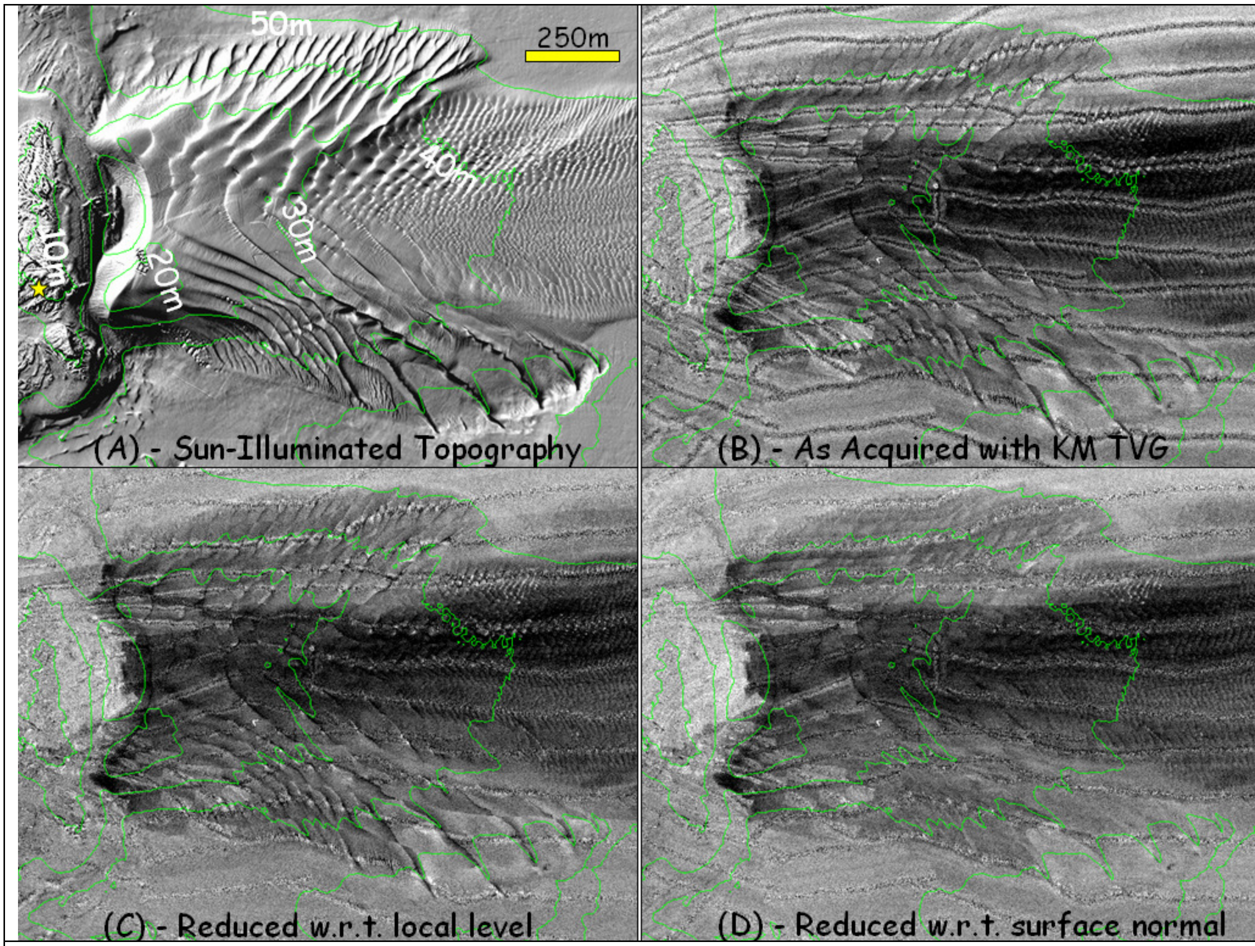


Figure 9: Showing progressive reduction of the backscatter data over the Quaco Ledges Sand Wave field.

- *A: sun-illuminated topography – showing true bathymetric relief (10m contours, superimposed).*
- *B : showing data as acquired using the Kongsberg real-time time-varying gain that assume a locally flat seafloor, and a model beam pattern.*
- *C: after empirical reduction using a 500 ping moving average of the variation in BS as a function of vertical referenced angle.*
- *D : after empirical reduction using a line-averaged estimate of the variation by 3D local grazing angle.*

When using textural analysis, whether through grey-level occurrence matrixes (e.g. Reed and Hussong, 1989) or directional spectra (e.g.: Pace and Gao, 1988), much of the apparent texture in very low aspect ratio sidescan systems is a mixture of true patchiness in sediment types and changes in seabed slope. Particularly for the case of bedforms, or rock outcrop, the presence of shadows and the variation in the grazing angle strongly contribute to the apparent texture of a backscatter image. For the case of sidescan imagery, there is no unambiguous way of separating the slope effect from sediment type. For multibeam data, however, we have the opportunity to separate out the two. This is of particular value when we wish to examine the distribution of sediment types across large bedforms.

Figure 9 illustrates the observed BS variability about large scale bedforms. It is clear that much of the BS pattern correlates with the bedform relief. By stacking the BS values with respect to the local seabed slope rather than the vertically referenced angle, we can generate an improved estimate of the angular response. We can then apply this estimate according to the local seabed slope. As a result (Fig. 9d), we can see textural (sediment patchiness) variation about the bedform independently of the slope. Significantly, the visibility of the bedform crests is markedly reduced and the new image would exhibit different textural statistics.

This method only works well for those sonars that have weak beam pattern ripples, the signature of which does not migrate with seafloor slope, as the ripple pattern would overprint the real slope signal. The EM3000 and EM3002 have single line transmitters and single sectors and are thus well suited to this.

Coping with imperfect Attenuation Coefficients.

As part of the data reduction steps described by the sonar equation (Urick, 1983), one has the propagation terms including spherical spreading and path length attenuation. While the first is environmentally invariant, the second strongly depends on temperature and salinity (and depth). Thus for a given range and sediment type, the received intensity will vary as a function of the water column properties. The Kongsberg data reduction scheme relies on a user-supplied attenuation coefficient. The issue is then whether the correct attenuation coefficient is used.

	April 4.5°C 32 ppt	**June** 6.5°C 31.5 ppt	**August** 11°C 32.5ppt	**October** 11°C 33ppt
300 kHz	63.2	64.1	71.7	72.4
100 kHz	25.9	27.5	32.1	32.5
70 kHz	19.6	20.3	22.1	22.4

Table 3: Attenuation coefficients (dB/km) in seawater for the range of frequencies used in the surveys. Calculated using the formulas of Francois and Garrison (1982). Values used are from 30m depth, at Station Prince 5 in the outer Bay of Fundy.

Table 3 illustrated typical attenuation coefficients for the range of frequencies used in the Bay of Fundy multibeam surveys. The coefficients are calculated for four times of year during which the data were acquired. For a depth of 100m, at an incidence angle of 60°, the two way travel distance is approximately 400m. Thus the received echo could be in error by 0.4 dB for 1 dB/km mismatch in the applied attenuation coefficient.

As one can see, between winter and summer conditions in the Bay of Fundy, there is a 9 dB/km variation for 300 kHz, but only 3 dB/km variation at 70 kHz. Thus having the correct value is far more important at the higher frequencies.

For the EM710 sonar system, there is an option to self-calculate the depth-integrated attenuation coefficient if the user supplies a profile of temperature and salinity rather than just sound speed. Since the CCGS Matthew routinely operates an MVP-200 CTD profiling system this was done automatically. This is of particular importance for this system as the attenuation coefficient changes by sector and the sector frequencies, in turn, change with pulse length.

For the EM3000/3002/1000/1002 sonar systems, however, determining the attenuation coefficient is the responsibility of the operator. Unless adjusted, it is normally set to the default of ~30 dB/km for 95 kHz and ~65 dB/km for 300 kHz. This was the case for most of the surveys performed. Thus where the EM3002 was used in deeper waters (> 100m), the resulting BS data would appear as stronger in the spring and weaker in the fall. To date this has not been corrected for these data sets.

Where a slightly imperfect attenuation coefficient is used, an apparent depth dependence in the BS data is generated. This has been a particular complication for the matching of relative BS levels between the high and low frequency systems. If the source level offsets (Table 2) are calculated at one depth, the two sonar system results may not match at other depths, either shallower or deeper.

Coping with changing frequency of scattering

Even when all the above limitations are taken into consideration, there is still no particular reason why the backscattering strength of a given seabed type should be independent of the acoustic frequency. The scattering is strongly controlled by the relative scale of the wavelength with respect to the dominant roughness scales on the surface (Ogilvy, 1991). For frequency shifts of less than an octave such as those within EM1000/1002/710 family (all within 71-98 kHz – 2.1-1.5 cm λ) it would be expected that the only fractional change in the wavelength would not make the scattering strength vary significantly. But for the case of the 300 kHz family (EM3000, EM3002 – 0.5cm λ), in which the wavelength changes by a factor of 3 to 4 over the EM1000/1002/710 systems, the assumption is less likely to hold true.

As an example of where the scattering strength clearly do not map well, Figure 10 illustrates the variation in BS from the deflated gravel pavements onto the mobile sand sheets across the Scots Bay sand wave field (Swift et al., 1966; Miller and Fader, 1990). At 71-97 kHz (EM710) there is clearly a strong contrast in BS (and the AR as shown in Fig. 8) between the two sediment types. Note that where a subset of the sand wave field was surveyed at 300 kHz, the BS at 300 kHz matches in the gravel regions but is different by more than 15dB in the mobile sand region.

Presumably either the surface or the volume scattering of the sand surface is markedly different at 0.5cm v. 2.0cm wavelengths.

Interestingly, other lower BS sediment types such as the La Have Clay, appear much more similar at the two wavelengths. Thus the frequency dependence is sediment type dependent. If both frequencies were acquired in all areas, this would add a degree of freedom to the characterization routines (equivalent to multi-spectral classification in remote sensing). In practise this is not possible due to attenuation limits at the higher frequency in deeper water and the inability of the small launches to carry the larger, lower frequency arrays.

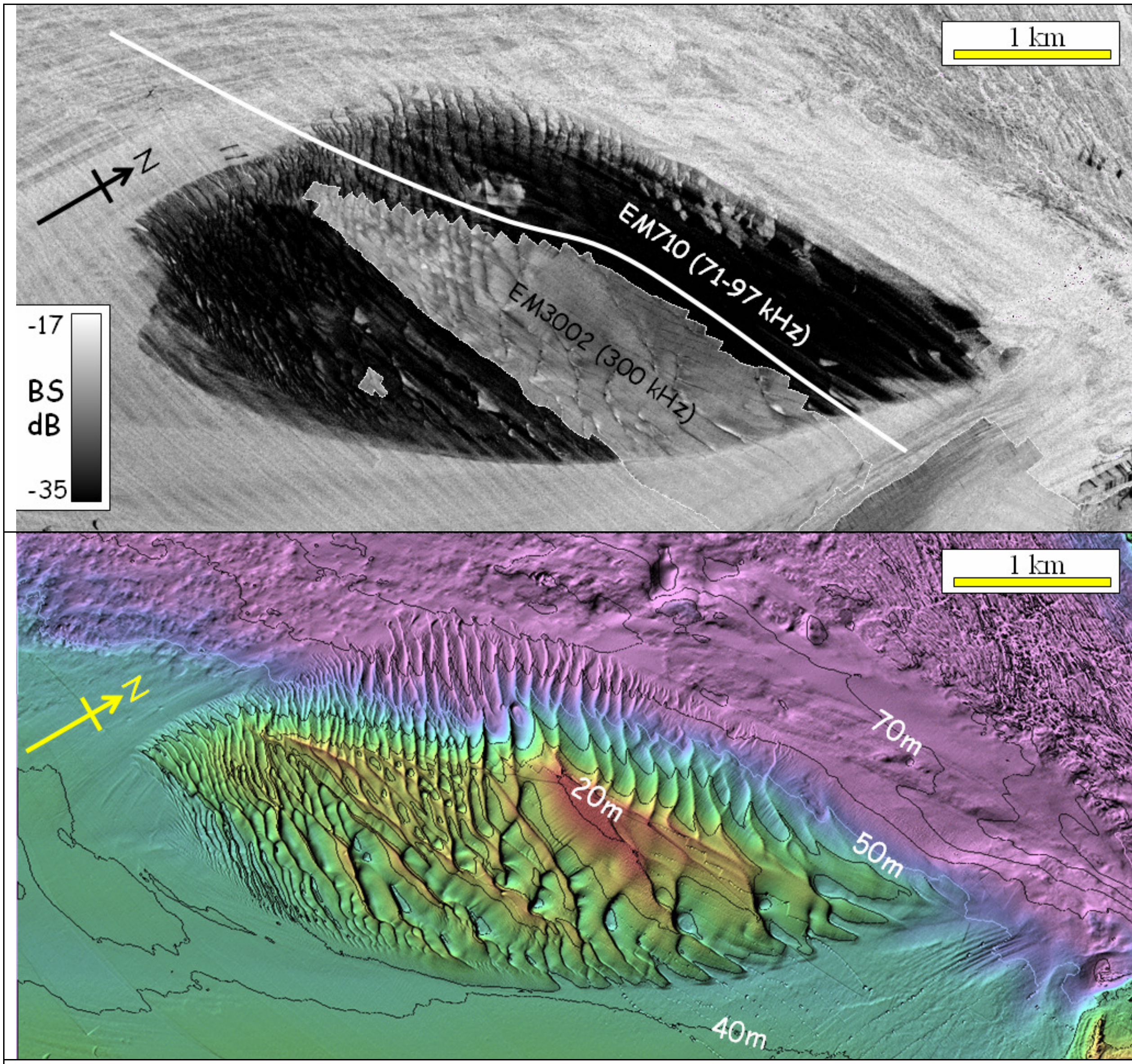


Figure 10: showing backscatter strength estimates from 300 kHz and 71-97 kHz over a transition from gravel to sand on the Scots Bay sand wave field. The white line represents the corridor of data displayed in Fig. 8.

Conclusions

Multi-year, multi source multibeam acoustic backscatter data has been integrated into a single regional coverage map. To do so has required a range of theoretical and empirical corrections. Each one of these corrections has limitations and often depend on the fidelity of other corrections.

Even after empirical matching between sonar systems, the relative level of confidence in the mean backscatter strength is only likely to be within +/- 2 dB. As such, apparent subtle shifts in apparent seabed physical properties that lie at survey boundaries should be treated with suspicion. Because of slight variations in the residual beam pattern artefacts that are linked to specific sonar configurations, classification schemes that rely on the shape of the angular response curves must proceed with caution. The use of textural classification methods that rely on the spatial statistics of the instantaneous backscatter strength values are also compromised by the changing pulse lengths required to cover the range of depths in the Bay.

Due to the ship-time economies inherent in multiplatform deployment and the need for the launches to work in the shallower regions, much of the Bay has been surveyed alternately with 100 or 300 kHz sonars. This creates a significant problem for data interpretation. Unless the user’s attention is drawn to the patchwork quilt of sonar sources, they risk interpreting a frequency switch as a potential sediment boundary.

Whilst these limitations will challenge the efficacy of automated seabed characterization algorithms, with a proper understanding of the nature of the inter survey uncertainty, subjective interpretation by trained marine geologists can still proceed. The reality of hydrographic survey operations dictate that this imperfect situation will continue for many years. This is a result of the fact that over 15 years of shallow water multibeam data has now been collected in Canadian waters and the sonar systems used have been, and will continue to be, continually upgraded. We can therefore expect to have these issues in compilation of seabed backscatter strength maps for many years to come.

Future Directions

In 2008, the mapping program will continue using EM710, EM1002 and EM3002 multibeam sonars. As well as adding on to the existing coverage there will be several instances where repeat surveys will be performed to monitor both topographic and sediment variations over an annual or multi-annual period. The confidence with which we can say whether the surficial sediment distribution has changed will be strongly limited by the ability to match backscatter strength estimates across different platforms and sensors.

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References

Applied Physics Laboratory, 1994, High Frequency Ocean Environmental Acoustic Models Handbook, Applied Physics Laboratory-University of Washington TR 9407-AEAS 9501, Oct 1994.

Byrne, T., Hughes Clarke, J.E., Nichols, S. and M-I, Buzeta, 2002, The delineation of the seaward limits of a Marine Protected Area using non-terrestrial (submarine) boundaries – The Musquash MPA : Canadian Hydrographic Conference Proceedings CDROM.

Campbell.J.W.M., Gray,A.L., Mattar,K.E., Hughes Clarke,J.E. and van der Kooij, M.W.A., 1997, Ocean Surface Feature Detection with the CCRS Along-Track InSAR: Canadian Journal of Remote Sensing, v.23, no. 1, p.24-37.

de Moustier, C. , 1985, "Beyond bathymetry: Mapping acoustic backscattering from the deep seafloor with Sea Beam", Journal of the Acoustical Society of America, Vol. 79, No. 2.

de Moustier, C. , Alexandrou, D. , 1991, "Angular dependence of 12-kHz seafloor acoustic backscatter", Journal of the Acoustical Society of America, Vol. 90, No. 1, pp. 522 - 531.

Ogilvy, J.A., Theory of wave scattering from random rough surfaces, Institute of Physics Publishing, 1991, 273 pp.

Fader, G. B., L.,H, King and B,Maclean, 1977, Surficial geology of the eastern Gulf of Maine and Bay of Fundy, Geol, Survey Can, Paper 76-17, 23 **p.**

Francois R. E., Garrison G. R., 1982a, "Sound absorption based on ocean measurements: Part I:Pure water and magnesium sulfate contributions", Journal of the Acoustical Society of America, 72(3), 896-907.

Francois R. E., Garrison G. R., 1982b, "Sound absorption based on ocean measurements: Part II: Boric acid contribution and equation for total absorption", Journal of the Acoustical Society of America, 72(6), 1879-1890.

Hagerman, G., G. Fader and R. Bedard, 2006, EPRI North American Tidal Flow Power Feasibility Demonstration Project, Phase: 1 – Project Definition Study Reports: EPRI - TP- 003 NB Rev 1 and EPRI - TP- 003 NS Rev 1

Hammerstad, E. (2000). "EM Technical Note: Backscattering and Seabed Image Reflectivity":

Kongsberg Technical Documentation.

Hughes Clarke, J.E, 1993, The potential for seabed classification using backscatter from shallow water multibeam sonars, in Pace, N. and Langhorne, D.N., Acoustic Classification and Mapping of the Seafloor, Proc. of the Inst. of Acoustics, v. 15, pt. 2, p. 381- 388.

Hughes Clarke, J.E., 1994, Toward remote seafloor classification using the angular response of acoustic backscattering: a case study from multiple overlapping GLORIA data: IEEE Journal of Oceanic Engineering v.19, no.1, p.364-374.

Hughes Clarke, J.E., Mayer, L.A. and Wells, D.E., 1996, Shallow-water imaging multibeam sonars: A new tool for investigating seafloor processes in the coastal zone and on the continental shelf: Marine Geophysical Research, v.18, p.607-629.

Hughes Clarke, J.E., Danforth, B.W. and Valentine, P., 1997, Areal Seabed Classification using Backscatter Angular Response at 95 kHz: NATO SACLANTCEN Conference Proceedings Series CP-45, High Frequency Acoustics in Shallow Water, , p.243-250.

Hughes Clarke, J.E., 2008, Optimal use of multibeam technology in the study of shelf morphodynamics : Sedimentology – Special Publication , Shelf Morphodynamics, Editors, Hill, Li and Sherwood, reviewed.

Iwanowska, K., Hughes Clarke, J.E., Conway, K.W. and Barrie, V., 2005, Managing systematic residual errors in multibeam backscatter data: GEOHAB 2005, Conference Victoria, Abstracts and poster.

Jackson, D.R., Winebrenner, D.P. and Ishimaru, A., 1986, Application of the composite roughness model to high-frequency bottom backscattering: Journal of the Acoustical Society of America, v.79, p.1410-1422.

Kongsberg Simrad A/S 1998, EM1002 Multibeam Sonar Operators Manual, Horten, Norway.

Kongsberg Simrad Maritime, 2004, EM3002 Multibeam Sonar Operators Manual, Horten Norway

Kongsberg Maritime, 2005, EM710 Multibeam Sonar Operators Manual, Horten Norway.

Llewellyn, K, 2005, Corrections for Beam Pattern Residuals in Backscatter Imagery from the Kongsberg-Simrad EM300 Multibeam Echosounder MScEng Thesis, UNB.

Miller, R O; Fader, G B J , 1990, Phase C - Sand Wave Field - Scots Bay, F.R.V. Navicula: Geological Survey of Canada, Open File 2298, 28 pages Bedford Institute of Oceanography, Cruise Report 89-009.

Milvang, O, Huseby, R.B., Weisteen, K. and Solberg, A.S., 1993, : Feature extraction from backscatter sonar data. Acoustic Classification and Mapping of the Seabed. International

Conference. Proceedings.

Mitchell, N. C., Somers, M. L. (1989) Quantitative Backscatter Measurements with a Long-Range Side-Scan Sonar *IEEE Journal of Oceanic Engineering* **14**(4), 368-374

Pace, N.G. and Dyer, C.M., 1979, “Machine Classification of Sedimentary Sea Bottoms”, IEEE Transactions on Geoscience Electronics, vol. GE-17, no. 3, p. 52–56.

Pace, N.G. and Gao, H., 1988, “Swathe Seabed Classification”, IEEE Journal of Oceanic Engineering, vol. 13, no. 2, p. 83–90.

Parrott, D.R., Cranston, R., Li, M., Parsons M.E. and Kostylev V.E., 2002, Monitoring and Evaluation of Conditions at the Black Point Ocean Disposal Site Operations to March 2001. Report to Environment Canada by Natural Resources Canada Geological Survey of Canada (Atlantic). 165 pp.

Preston, J.M., A.C. Christney, S.F. Bloomer and I.L. Beaudet, 2001, "Seabed Classification of Multibeam Sonar Images", MTS/IEEE Oceans 2001 Conference Proceedings, p. 2616-2623.

Reed, IV, T.B. and D. Hussong. 1989, Digital image processing techniques for enhancement and classification of SeaMARC II side scan sonar imagery. Journal of Geophysical Research 94(B6): 7469-90.

Swift, D.J.P., A.E. Cok and A.K. Lyall, 1966, A Subtidal Sandbody in the Minas Channel, Eastern Bay of Fundy: Maritime Sediments, v.2, p.175-180.

Swift, D. J. P., B. R. Pelletier, A. K. Lyall, and J. A. Miller, 1969. Sediments of the Bay of Fundy, A Preliminary Report. Maritime Sediments, 5: 95-100.
.
Urick, Robert J., 1983, Principles of underwater sound: New York, McGraw-Hill Book Company.

Wildish D.J., Fader G.B.J., Lawton P. and MacDonald A.J., 1998, The acoustic detection and characterization of sublittoral bivalve reefs in the Bay of Fundy. Continental Shelf Research 18, 105–113.

Wildish, D.J., Hughes Clarke, J.E., Pohle, G.W., Hargrave,B.T., Mayer,L.M. 2004, Acoustic detection of organic enrichment in sediments at a salmon farm is confirmed by independent groundtruthing methods: Marine Ecology Progress Series, v.267, p.99-105

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Jon Griffin is a hydrographer with the CHS-Atlantic, and is currently a Chief Hydrographer aboard the CCGS Matthew for the 2008 survey season. Jon joined the CHS in 1991, and has been primarily involved with field programs in support of science and hydrography since then. He has a Masters of Engineering from UNB.