Monitoring temporal changes in seabed morphology and composition using multibeam sonars: a case study of the 1996 Saguenay River floods.

Kammerer E. and Hughes Clarke J.E. (Ocean Mapping Group, University of New Brunswick), Locat J. (Université Laval), Doucet N. and A. Godin (Canadian Hydrographic Service)

Abstract

In July 1993 and in august 1997 two collocated sonar surveys were conducted in the upper part of the Saguenay fjord. Between these two surveys a flood occurred in the summer of 1996 during which a considerable amount of material was both eroded and deposited on the fjord floor.

The data were collected on board of the Canadian Hydrographic Service (CHS) vessel Frederick G. Creed using a Simrad EM1000 imaging multibeam sonar. The swath data are used to map changes in both the morphology and surficial sediments close to the discharge points for the floodwaters. The high-density sounding and backscatter data potentially provide an opportunity to monitor fine-scale changes, previously unresolvable using conventional single beam and sidescan sonar methods. In order to do that, however, a number of limitations in the quality of the acquired data need to be assessed and compensated for.

These include limitations due to:

- imperfect compensation for the vertical displacement of the sensor due to tide, heave and dynamic draft errors,
- the local mixing of fresh and salt water in the fjord which introduces uncertainty in the refraction solution,
- bottom detection failures in regions of rapidly changing relief and
- uncertainty in the inter-survey signal strength calibration due to changes in hardware and software.

Methods for quantifying the extent of these limitations and approaches to removing these error sources are presented.

Résumé

En juillet 1993 et en août 1997 deux levés sonar successifs ont été réalisés dans la partie supérieure du fjord du Saguenay. Entre ces deux missions une crue a eu lieu durant l'été 1996 pendant laquelle une quantité considérable de matériel a été érodé et déposé sur le fond du fjord.

Les données ont été acquises à bord du navire du Service Hydrographique du Canada (SHC), le Frederick G. Creed, à l'aide d'un sonar multifaisceaux Simrad EM1000. Les données ont servi a cartographier les modifications morphologiques et sédimentaires près des points de décharge des eaux de la crue. La haute densité des sondages et de données de rétrodiffusion nous fournit l'occasion d'étudier les changements à petite échelle, qui étaient innaccessibles avec des techniques monofaisceau et sonar latéral. Dans cet objectif, cependant, un certain nombre de limitations dans la qualité des donnés acquises nécessitent détermination et correction.

Parmi ces limitations:

- imparfaite compensation du déplacement vertical du sonar du fait de la marée, de la houle et des erreurs d'attitude dynamique du navire,
- le mélange d'eau douce et d'eau de mer dans le fjord qui introduit des incertitudes dans les corrections de réfraction,
- des erreurs de détection de profondeurs dans des régions au relief variant rapidement et
- des incertitudes dans la calibration de l'amplitude du signal du fait du changement de matériel électronique et de logiciel entre les deux missions.

Des méthodes pour quantifier l'étendue de ces limitations et des approches pour supprimer ces sources d'erreurs sont présentées.

Introduction

In July 1993 and in august 1997 two collocated sonar surveys were conducted in the upper part of the Saguenay fjord near the cities of La Baie and Chicoutimi and also near l'Anse St Jean. Between these two surveys a flood occurred in the summer of 1996 during which a considerable amount of material was both eroded and deposited on the fjord floor by the rivers. The areas surveyed are those immediately adjacent to the river discharge points.
The survey in 1997 was a collaboration between the Canadian Hydrographic Service (Laurentian region), Université Laval (Quebec) and the University of New Brunswick (Fredericton).

Multibeam data were collected using the CSS Frederick G. Creed, a SWATH (Small Waterplane Area Twin Hull) vessel owned by the Canadian Hydrographic Service. The vessel was equipped with a Simrad EM-1000 [Simrad, 1992] multibeam bathymetric system, mounted in the starboard pontoon. The EM1000 works at a frequency of 95 kHz, producing a fan of 60 beams with 2.4° by 3.3° beam widths over a total angular swath sector of 150°. While the sonar can operate in water depths ranging from as little as 3m to up to 1000m, this system is most useful between about 10 and 600 metres of water. The depth of the survey area in the fjord ranged from 20 metres down to 200 metres.

The quality of bathymetric data collected varies across the swath. The data collected within the inner ~120° sector is usually within IHO standards [Hare et al., 1996], whereas those data within the wider part of the swath are generally limited by orientation and refraction uncertainty. While the sonar is capable of resolving depth changes of as little at 0.25% of the water depth, because of the finite footprint of the beams, only targets whose horizontal dimensions exceed about 10% of the water depth will confidently be identified. In addition to dense bathymetric coverage, the sonar provides an estimate of the seabed backscatter strength corrected for both radiometric and first order geometric effects [Hughes Clarke et al, 1996]. With this high resolution, changes in geomorphology and superficial sediments should be both observable and quantifiable by comparing the two sets. However a certain number of limitations makes this difficult.

In this paper we will first expose the method used to compare the two data sets; then review the different limitations brought by the system; and lastly try to distinguish between the real changes in the seafloor and those changes that are artifacts due to the imaging system. This study forms the first phase of a multi-year research project examining the geomorphic effect of the 1996 Saguenay floods lead by the third author. Only the data processing aspects necessary to derive information about the flood deposits will be discussed herein. This study uses some techniques first described as part of a similar study done by R. Courtney [Courtney and al, 1997] on the bottom subsidence above an offshore coal mine in Cape Breton, Nova Scotia. All the data processing has been done with the Swathed software developed by the second author at the Ocean Mapping Group.

Method

Bathymetric Data Reduction

Once the data has been collected, a variety of corrections need to be applied. For the bathymetry, the data is immediately reduced for the instantaneous position and orientation of the vessel together with the input model of the watermass. Subsequent bathymetric processing requires reduction due to the simultaneously collected tidal information and correction for any miscalibration of the orientation and positioning sensors [Herlihy et al., 1989]. The tide data have been collected every fifteen minutes at the harbour tide gauge at La Baie. Without other information about the watermass (besides the sound speed profiles collected discretely during the cruise) little can be quantitatively done to correct for imperfections in the refraction solution. For the refraction corrections in the 1997 survey, two Sound Velocity Profiles (SVP) have been taken before and after the data collection.

In order to compare the data between the two years easily, we must build identically registered Digital Terrain Models (DTM) for each of the data sets. We will then subtract the depth values in one DTM from the other to estimate the magnitude and spatial variation in depth changes tha occurred in August 1996.

The rule-of-thumb in DTM generation is to choose for the grid cell size one half to one third of the typical minimum horizontal spatial resolution of the sonar [de Moustier, 1997]. For the EM1000 this corresponds to about 10% of the water depth on average (actually varying from about 4% near nadir to more than 15% in the outer part of the swath). Choice of an optimum grid size is made more difficult because the depth is varying significantly between the shallow parts of the fjord (30 metres average depth) and the bottom of the fjord (200 metres average depth). The grid size was chosen to correspond to the smaller dimension resolved in the shallower water. A dynamically adjusting weighted filter was used to allow for the decreasing resolution with depth. The filter used is a Butterworth filter defined by the width of a flat area around the node, the power of the outer inverse power law and the cutoff limit [Hughes Clarke, 1997]. After gridding, a simple subtraction has only to be done between the two coregistered DTM's to obtain the variation between the two years.

In the figure presented of the DTM differences, dark zones are positives variations (material addition, deposition), light zones are negatives ones (removal of material, erosion). We are going to look in more detail in the next part at the different zones which can be interpreted as real changes in depth between the two surveys and those which are artifacts due to some misfunctions or limitations of the multibeam system.

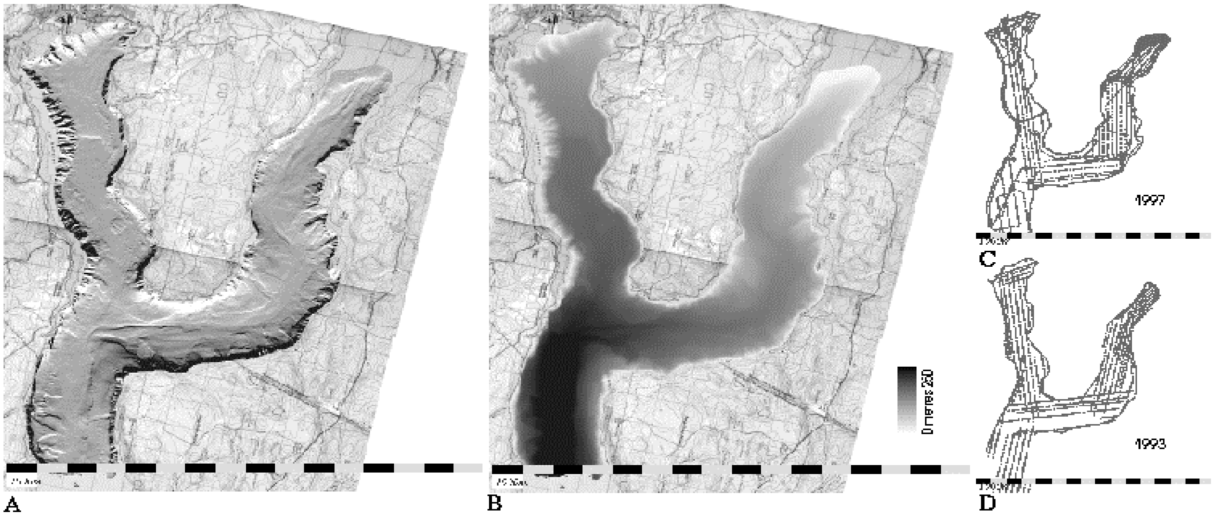

Figure 1 - View of the total area of the survey in 1997. (A) artificial sun illumination, (B) depth, (C) navigation tracks for 1997 and (D) for 1993.

Backscatter Data Reduction

For the seabed backscatter data, geographic mosaics are created of the spatial variation in seabed backscatter strength. In order to take out the first order variation in backscatter strength due to grazing angle, the angular response is assumed to vary in a Lambertian manner and thus all data is normalised to vertical incidence through the division by the inverse of cosine squared of the grazing angle. In order to remove uncompensated residual variations in the sonar source level as a function of incidence angle, an empirical estimate is made of these residuals and removed globally from all the data [Hughes Clarke et al, 1997].

If all the data reduction has been done correctly we should be able to compare the local backscatter strength levels between the two surveys. In practice, because the electronic hardware has been significantly modified over the intervening 4 years, while we can monitor relative changes of less than 2dB within a single survey, we cannot be confident in the absolute values of the backscatter strength to better than about ~5dB. In order then, to tie the two surveys together we have chosen to select the deep -distal part of the fjord floor at the furthest distance from the point of flood discharge in 1996 and assume that this region has not changed. In the figures presented the data have the same range in dB, but one image has been shifted in absolute signal level so that the distal backscatter in the digital regions is identical. A description of the geology of the fjord floor can be found in [Perret et. al, 1995].

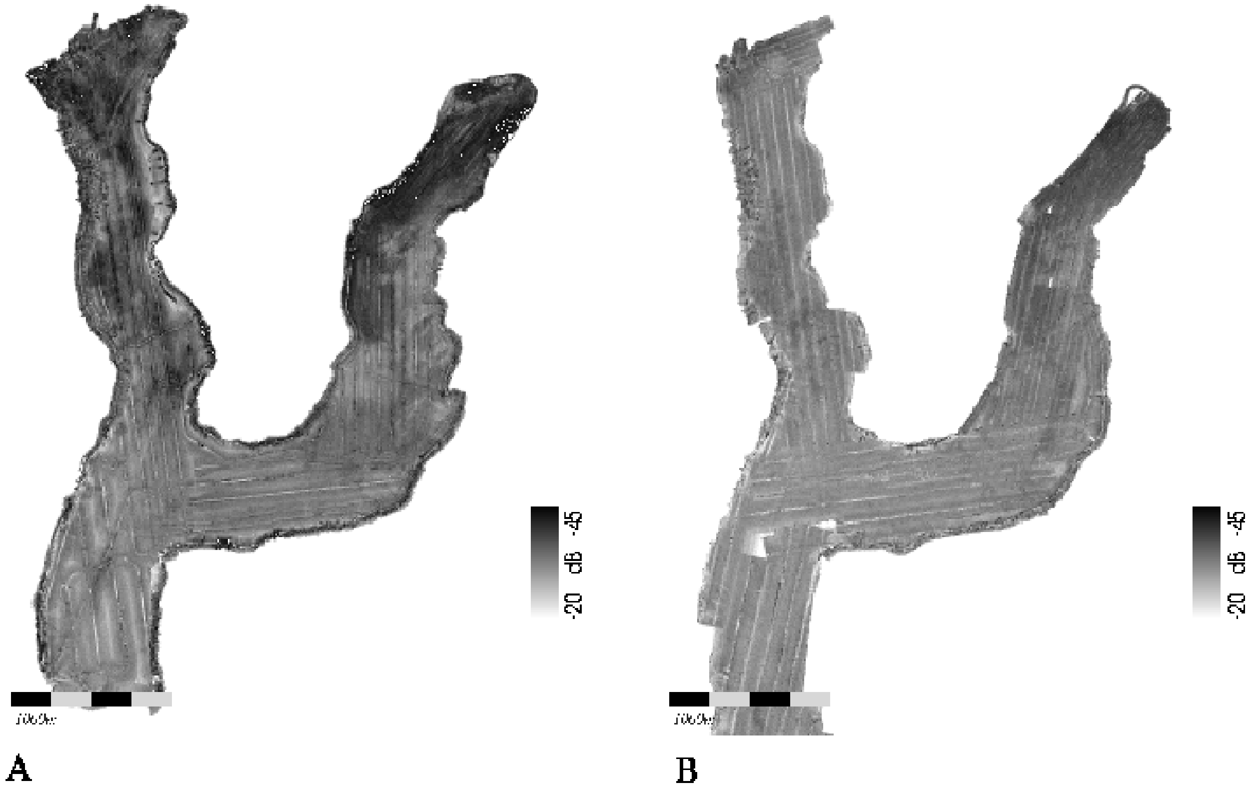

Figure 2 - Sidescan imagery of the two surveys. (A) 1997; (B) 1993.

<u>Problems involved in Bathymetric DTM comparison</u>

Beam pointing angle calibration problem:

This is an EM1000 specific malfunction. For every individual transducer array, each beam-pointing angle deviates from the design angle by a small shift. The manufacturer normally measures these shifts in controlled conditions and a calibration table is used on board the vessel to compensate for these deviations. In the case of the EM1000 on the F. G. Creed, the calibration table used was not appropriate resulting in a characteristic angular distortion to the across track profile. This results in the near nadir detects come in about 1.25% too shallow with respect to the outer swath detects. It produces a swath parallel artifact observable in a square uplift of the central part of the swath. It can be corrected by a systematic upward angular rotation of all outer swath beams. The angular shift was empirically estimated through averaging of large volumes of data on near flat seafloors.

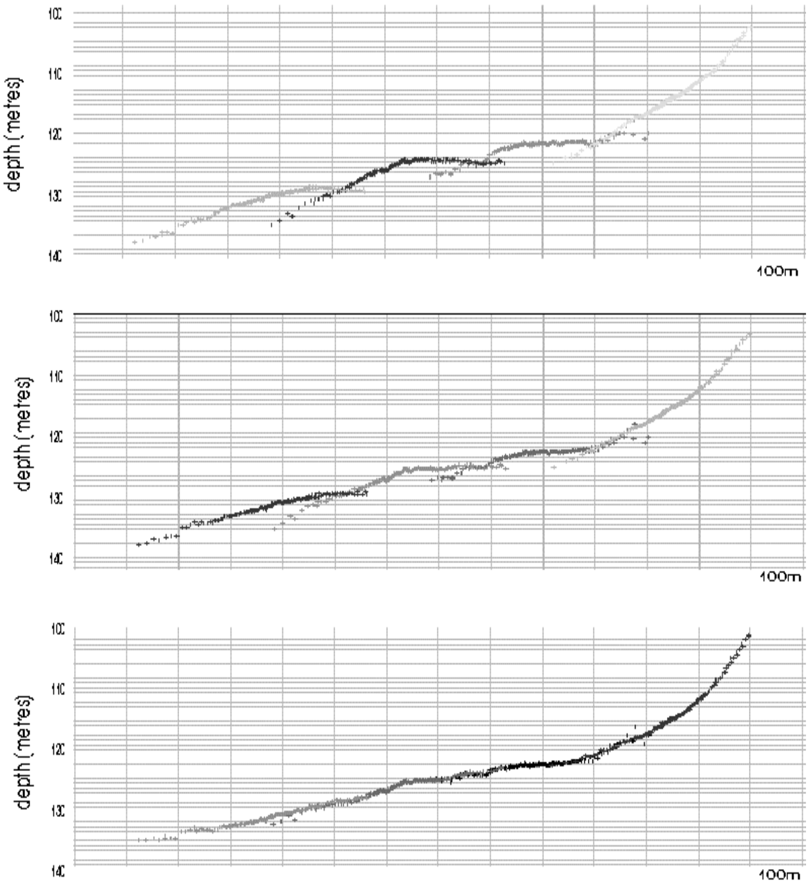

Figure 3 - Profiles across-track of the superposition of different lines; (A) DTM without any correction; (B) correction of beam pointing angle calibration problem; (C) correction of refraction problem.

Refraction problems

Wide swath coverage like the Simrad EM1000 multibeam system (150°) makes depth measurement quality very sensitive to the variation of sound velocity through the water column. Sound velocity varies with temperature, salinity and pressure of the water. In the Saguenay fjord we are in the particular situation of a very narrow sea arm (i.e. without important mixing of the water masses made by currents) where several rivers are pouring out fresh water which cannot circulate as easily as in the open ocean. The spatial variations of the salinity bring errors in the refraction corrections applied to the data. These errors curve the swath by bringing up (or down) the outer beams. The result of this imperfection can be seen by the stripes showing high differences in the overlapping zones between two lines, the outer beams being more affected by refraction than the inner beams. This is due to the low grazing angle of the outer beams.

To correct this problem we can apply on each line at small space intervals an empirical refraction correction that will bring a curved swath to a more realistic one. Estimating this empirical correction requires regions of weak topography, this is therefore quite impossible to be achieved in the Saguenay fjord because the topography is so rough that it is difficult to know which correction apply and what would be a realistic swath. The method applied in order to resolve this is described below:

First, we separated the different lines corresponding to the different sound velocity profiles (SVP) taken during the survey; for the Baie des Ha!Ha! and Bras Nord areas two different SVP's have been used (the two parts have been done on two different days), so we have two sets of lines, one for each day. We distinguished then geographically within each of these two sets, the lines which are in the two main different areas (assuming that the water masses are affected differently so requiring different refraction coefficients). We applied to each of these four groups of lines distinct (empirically estimated) refraction corrections that reduce (as well as possible) the curvature of the swath. Figure 4 shows the differences.

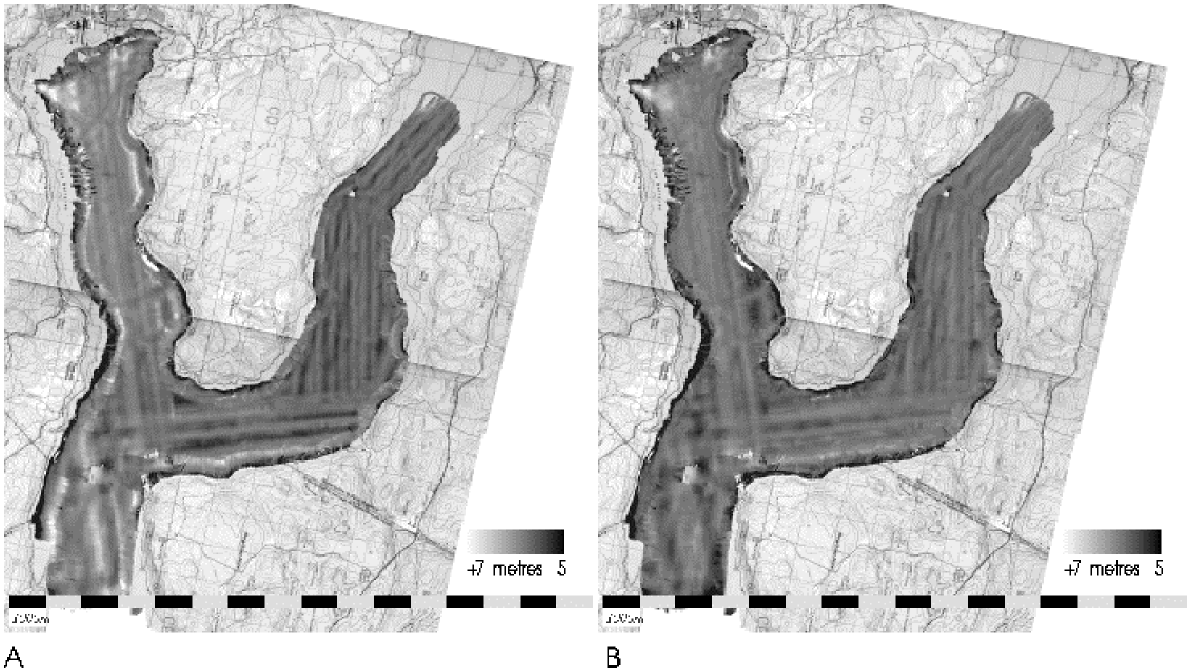

Figure 4 - Differences between the two DTMs before(A) and after (B) to the refraction correction.

Bottom detection failures

When we refer to bottom tracking failure (or bottom detection failure) we are describing situations when a part of the swath looses track of the bottom whereas the rest of the swath keeps tracking it. In our situation of DTM's difference study, as long as the orientation of the original survey lines are retained, it is relatively straightforward to detect when this phenomenon occurs.

The bottom detection failure example shown here occurred during the survey of Anse Saint-Jean downstream of the rest of the survey. It happened at different times along a line where the topography was changing rapidly. In Figure 5.C, one can see that for smooth slopes the two DTM's stay well aligned. But three times when the seabed abruptly rose the nadir beams kept tracking an apparent flat seafloor (equivalent to the slant range back to the flatter seafloor at the base of the slope) for a while before again joining the 1993 topography. The difference between the two years is not a real change because these new features do not appear on the outer beams of the two adjacent lines. This anomaly is affecting the inner beams (those where the amplitude bottom detection method is used) while the outer beams (with phase bottom detection method) stay unaffected.

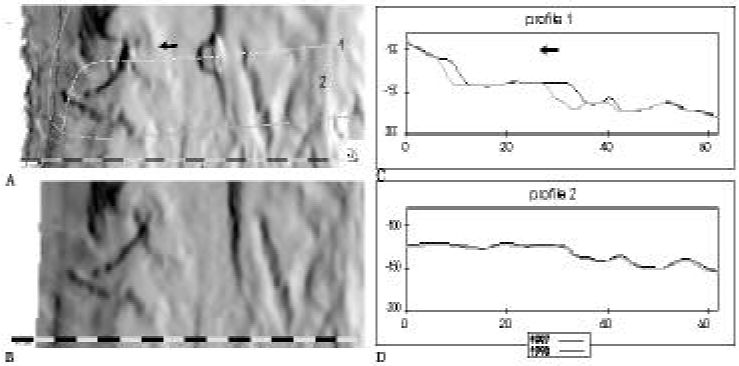

Figure 5 - Bottom detection failure example; (A) sun illuminated topography in 1997 with the navigation; (B) sun illuminated topography in 1993, (C) profile at nadir showing several examples of mistracking of the seafloor; (D) profile in the outer beams showing perfect concordance between the two surveys

Imperfect horizontal and vertical compensations

Horizontal

The edges of the fjord are very steep and composed in certain places by a dense network of very narrow, steep sided canyons. These areas are very sensitive to horizontal position shifts, which result in a series of apparent positive and then negative depth differences on the flanks of the canyons. The sense of the depth difference depends on the orientation of the horizontal position shift (whether due to datum shifts, time delays or incorrect antenna offsets) with respect to the seabed slope azimuth.

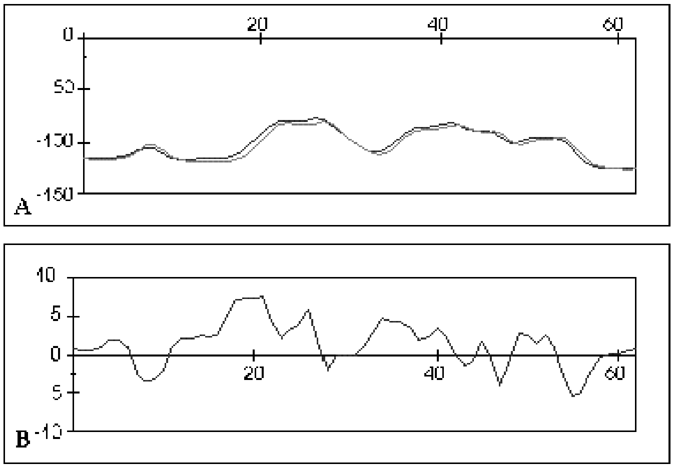

Figure 6 - (A) Superposition of two profiles on a series of canyons in the Baie des HA!HA! area; (B) Difference between the two profiles above, note the oscillation between +5 and -5 metres.

Note that while an apparent vertical depth difference is observed it is actually due to a horizontal misalignment in position between the two surveys. This can be confirmed by noting that the difference is always positive on slopes facing one direction and negative on slopes facing in the inverse direction. The scale of this shift can be used to recalibrate the sonar to estimate the unresolved datum shift, time delay or false antenna offset (in a manner equivalent to the patch test described in Herlihy et al., 1989).

Vertical

A variety of sources of vertical error are possible including tidal uncertainty, long period heave errors and vessel squat. For the case of these comparisons no convincing examples were seen. We feel that this is a result of a number of factors. Long period heave (Hughes Clarke, 1995) would only show up in the presence of significant swell periods that are unheard of in the Saguenay Fjord. Squat effect should be minimised as all surveys were run at a constant vessel speed (~14 knots). Tidal offsets of a few decimetres may be present but, as most of the region is in excess of 100m, they represent only a very minor percentage of the water depth (in contrast, the refraction errors scale with water depth).

Changes in hardware and software between the two surveys

The implementation of the position and orientation system POS-MV [Woolven et. al, 1996] on the Creed (since 1994) has made the data collection during the turns of the vessel possible. This was not the case for the 1993 data in which an older TSS-335B was used which was extremely sensitive to cornering [Hughes Clarke and Godin, 1993]. In order to minimise this problem for 1993 data, only data collected after the vessel had completed turning and was on line for about 3 minutes were used.

Reasons for these horizontal positioning displacements mentioned above can be traced to a variable clock drift that was present in older versions of the sonar software in the earlier survey (corrected in later versions). This introduced a varying +/-1 to 2-second positioning clock offset which, at speed of about 14 knots resulted in 7-14 m horizontal positioning shifts. Because the time delay was itself varying with time, it was not possible to systematically back out this uncertainty from the data.

Problems involved in Sidescan mosaic comparison

As described above, in addition to the system radiometric compensation (for source level, pulse length, predicted radiation pattern, and TVG) all backscatter data has had three steps applied:

1. lambertian compensation for grazing angle (in Simrad software)
2. empirical residual beam pattern compensation and
3. empirical inter-year absolute source-level shift.

Each one of these steps makes some simplifying assumptions about the nature of the data.

For **step (1)**, one has to assume that the shape of the backscatter angular response is invariant between all the different data types on the fjord floor. Recent studies however, [Hughes Clarke et al., 1997] have shown that the variations in the shape of the angular response are significant for common sediment types. Without however, prior knowledge of these changes little can be done for single pass surveys. The result of this is that, as the angular response changes, shiptrack parallel stripes tend to appear in the backscatter map. These can be seen throughout the survey.

For **step (2)** one has to assume that these residual beam patterns (which show up as a series of along track stripes in the uncompensated sidescan data) do not change. This has previously been shown to be adequate for the EM1000 within a single mode (a mode is a particular pulse length and the beam spacing combination). However, in the Saguenay fjord, the mode has to be continuously changed because of the large range of water depths. Generally longer pulse lengths and tighter beam spacing modes are used in the deep water.

For **step (3)** it seems reasonable to assume that the distal sediments would be the least affected. Given the known presence of turbidity current channels on the fjord floor however, distal sediment transport is possible. An additional problem that is significant in the Saguenay region is that the salinity is highly variable, resulting in changing attenuation conditions. At 95 kHz, the attenuation coefficient varies from about 3 to 30 dB per km from fresh to salt water. Usually in shallower water where salinity changes are most extreme, the slant ranges propagated are too small for the changing path length attenuation to be significant. In 200m of water with slant ranges in excess of 500m, however, small variations in the attenuation coefficient will result in several dB variation in the apparent seabed backscatter strength. Without more frequent watermass monitoring (e.g. Dinn et al., 1997) little can be done to minimise this uncertainty.

Actual changes in the depth at the river mouth

We have looked most closely at the two river mouth (rivière des Ha!Ha! and rivière à Mars in the Baie des Ha!Ha!, the lower arm of the fjord) and the Bras Nord area (the upper arm of the fjord). We notice three significant white zones corresponding to areas where large scale deposition of material occured. Figure 7 shows those three zones:

Figure 7 - White areas highlighting three major deposition zones. (A) detail in baie des Ha!Ha!; (B) details in the upper part of the North Arm.

Figure 8 shows in detail the changes for the rivière des Ha!Ha!. The deposition takes the form of a triangle and the quantity of deposition decreases as we go away from the shore (in the first profile the maximum of deposition is of 7 metres).

For the rivière à Mars, Figure 9, in the DTM difference a dark zone is present close to the shore corresponding to a removal of material between the two years and then as we move further, offshore there is deposition (white zones). The flux of material seems to have been taking two channels, the topographic changes in these two channels are shown in the two small boxes Figure 9A1 and 9A2 (up to 5 metres of deposition in these channels). In the 1997 image one can see transverse features developed on top of the new deposit that resemble either bedforms or rotational slump ridges. Furthermore, the two channels join together to form one large area of thin deposition.

The third zone (in the Bras Nord area, Figure 10) is very linear. If you look to the bathymetry and topography corresponding to this zone, you will notice the a flat shallow area (10 metres depth) and then a 20 to 30 metres high cliff, followed by a slope going deeper. Two profiles have been taken across the cliff and one in the flat shallow area. In profiles 1 and 2 in Figure 9 the top of the cliff seems to have been eroded and there is some deposit present at the bottom of the cliff. In the sun illuminated topography of 1993 there is a network of sand waves in the shallow area, they do not appear in the topography of 1997. Profile 3 shows that the sand waves have been buried during the flood.

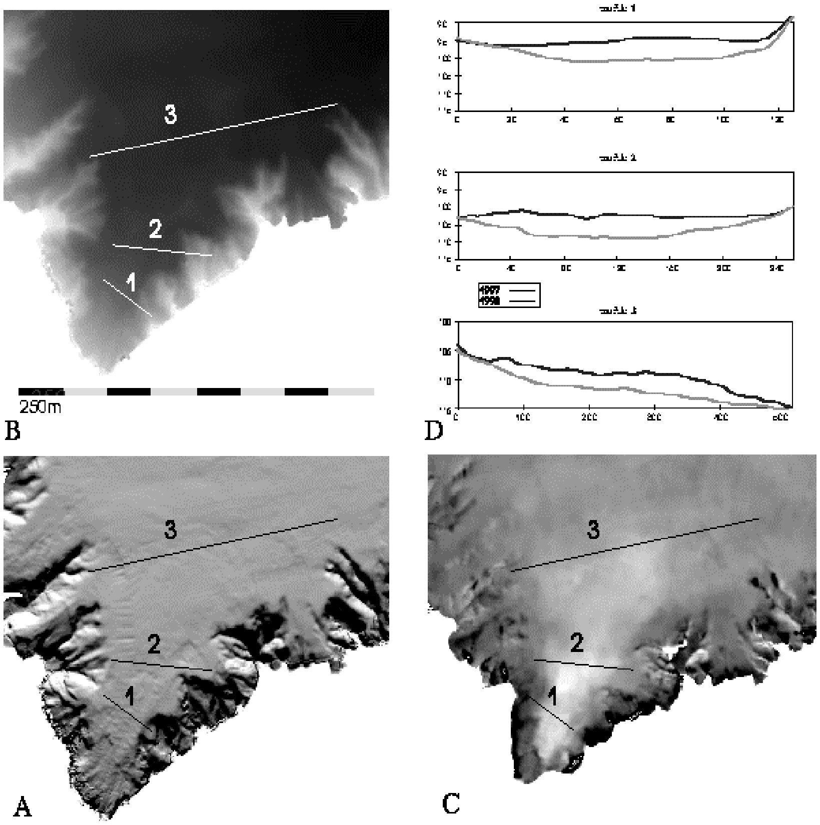

Figure 8 - Detailed view of the area close to the rivière des Ha!Ha! mouth; (A) sun illuminated topography (1997); (B) bathymetry (1997); (C) DTM difference (white areas correspond to places where 1997 data is above 1993 data); (D) three profiles showing the amount of deposition.

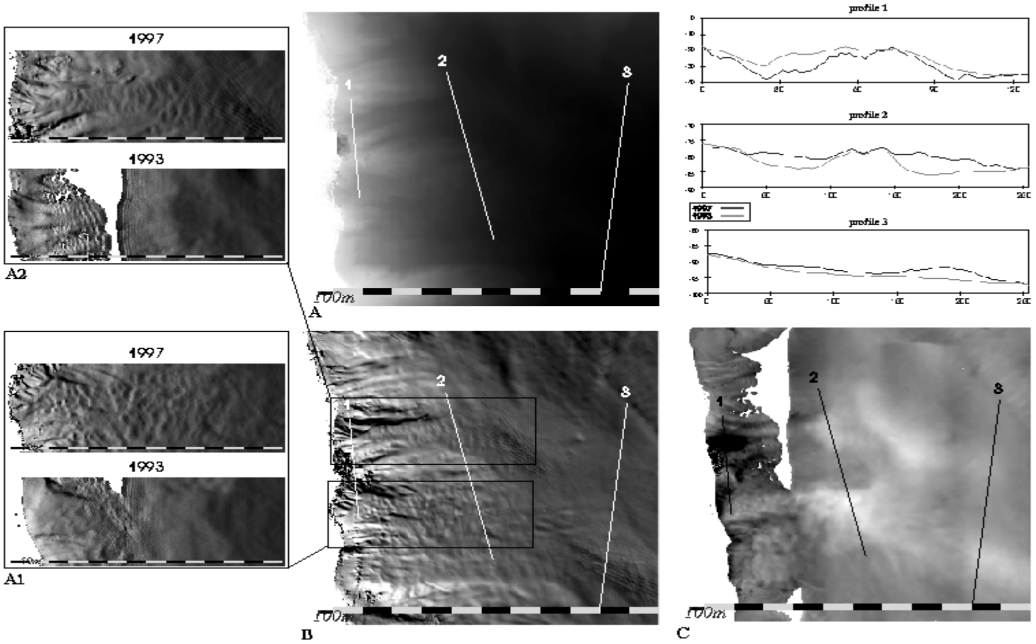

Figure 9 - Detailed view of the area close to the rivière à Mars mouth; (A) sun illuminated topography (1997); (B) bathymetry (1997); (C) DTM difference (white areas correspond to places where 1997 data is above 1993 data); (D) three profiles quantifying this difference, note an erosion in the profile 1 and a deposition in the two others.

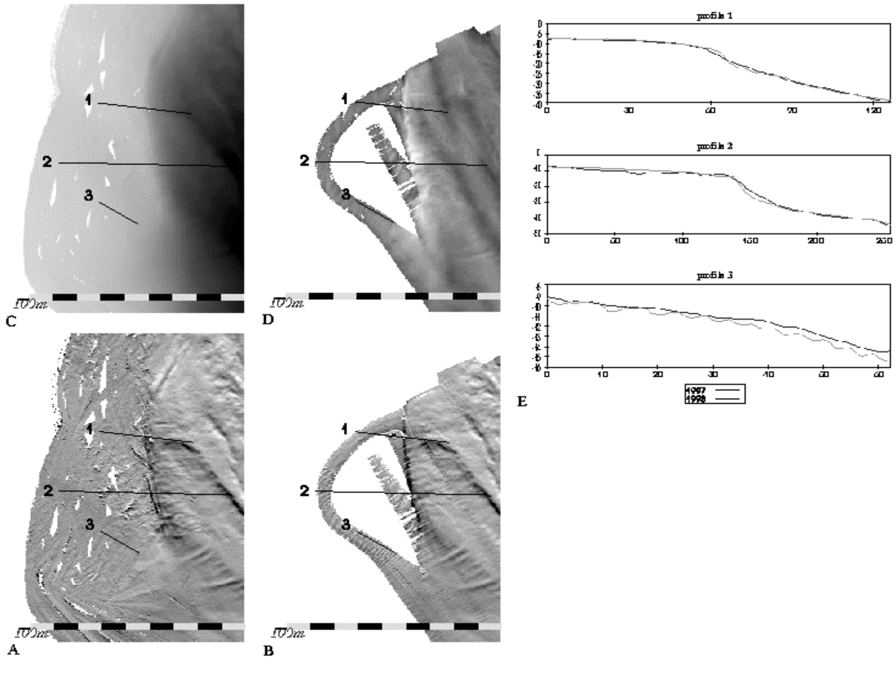

Figure 10 - Detailed view of the area close to the rivière du Moulin mouth; (A) sun illuminated topography in 1997; (B) sun illuminated topography in 1993; (C) bathymetry (1997), (D) DTM difference (white areas correspond to places where 1997 data is above 1993 data); (E) three profiles showing deposition at the bottom of a cliff an sand waves erosion.

Actual changes in backscatter over the region

Because of the uncertainty due to grazing angle and beam pattern variations, small area changes in the backscatter strength must be treated with suspicion unless they are gross (>5dB). Nevertheless on a regional scale, these uncertainties are less important. Examining the two maps, it is clear that the axial fjord floor over distance of several 10's of kilometres has a drop in backscatter strength that is most intense close to the source of the flood waters and dies away distally. To produce such a change requires only a minor change in the seabed physical properties [Jackson et al., 1986] such as a shift in the bulk density, sound speed, or roughness of the upper few centimetres. Thus we may be seeing far wider reaching effects of the flood, expressed as a change in just the top few centimetres, due perhaps to deposition of fine sediment from suspension.

We note thus that the backscatter has a potentially far more sensitive capability because deposition need not be on scales of several tenths of a percent of the depth, merely a change in centimetre scale bottom physical properties.

Conclusions

Small-scale temporal changes in the morphology and composition of the seafloor may be detected using swath sonar systems. The ability to do so, however, is strongly dependent on the fidelity of the original data. Such data is routinely degraded through imperfect calibration, instrumental limitations and inadequate knowledge of the water mass. Although this sonar has a precision allowing it to potentially resolve features of as little as a few tenths of a percent of the depth, only absolute depth changes of more than ~2% of the depth can be confidently stated to be real changes. For the depths covered in the Saguenay Fjord this means that several metres of deposition must occur in the deeper (100m+) floor before it can be confidently detected.

In contrast to the metre-scale changes that can be detected from direct depth differencing, even if the erosion/deposition is on scales only of a few decimetres or less, it may still be possible to detect the changes through variation in the surficial backscatter strength. This relies on changes in the surficial physical properties rather than the absolute depth. For this method to be feasible, however, adequate calibration of the sonar is required and variations due to grazing angle and changes in the shape of the angular response must be adequately compensated. For the case of the Saguenay fjord, such changes are clear and are currently being quantified as part of an extensive seabed-sampling program designed to establish the magnitude and composition of the distal flood deposits.

Acknowledgements

This work would not been possible without the assistance and expertise of the crew of the NSC Frederick G. Creed. The Creed survey time was funded through an NSERC research grant to J. Locat. The first author is supported by a NSERC Research Grant. The second author is supported through the Chair in Ocean Mapping Group at UNB, (Chair sponsors include: Canadian Hydrographic Service, PetroCanada, NSERC, Kongsberg Simrad Mesotech, Seabeam Instruments, Naval Research Laboratory, NOAA, Naval Oceanographic Office, Nautronics, C & C Technologies, MBARI, US Geological Survey, Nortech-Jacques Whitford, James Cook University and International Submarine Engineering).

References

Courtney, R., D. Forrester, S. Forgeron (1997), *The use of multibeam methods in the offshore coal industry*, 10^{e} congrès annuel de l'association professionnelle des géologues et des géophysiciens du Québec.

Dinn, D.F., Furlong, A., Loncarevic, B.D., Penny, M. and Dakin, D.T. (1997). *Controlling multibeam sonar errors*: Sea Technology, v.38, no.8, p.75-80.

Hare, R., Godin, A. and Mayer, L. (1995). *Accuracy estimation of Canadian Swath (multibeam) and Sweep (multi-transducer) sounding systems* : Canadian Hydrographic Service, internal report, 95pp.

Herlihy, D.R., B.F. Hillard, T.D. Rulon (1989). *National Oceanic and Atmospheric Administration Sea Beam "Patch Test" Manual* : Ocean Mapping Section, Office of Charting and Geodetic Services, 34 pp.

Hughes Clarke, J.E. and Godin, A., 1993, Investigation of the roll and heave errors present in Frederick G.Creed - EM1000 data when using a TSS-335B motion sensor, DFO Contract Report FP707-3-5731.

Hughes Clarke, J.E., 1995, Accuracy and Operational Constraints for POS/MV-EM1000 integration aboard NSC Frederick G. Creed, Nov, 94- April 95, DFO Contract Report F5184-5-3001.

Hughes Clarke, J.E. (1997). Data Thinning for Chart Production Purposes In *1997 Coastal Multibeam Training Course* , Ocean Mapping Group, Department of Geodesy and Geomatics Engineering, University of New Brunswick, Fredericton, NB, 26pp.

Hughes Clarke, J.E., Danforth, B.W. and Valentine, P., (1997). *Areal Seabed Classification using Bacscatter Angular Response at 95kHz* : NATO SACLANTCEN Conference Proceedings Series CP-45, High Frequency Acoustics in Shallow Water, p.243-350.

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, p607-629.

Jackson, D.R., Winebrenner, D.P. and Ishimaru, A., (1986), *Application of the composite roughness model to high-frequency bottom backscattering*, : J. Acoust. Soc. Am., 79, 1410-1422.

de Moustier, C. (1997). DTM Generation Methods and Pitfalls In *1997 Coastal Multibeam Training Course* , Ocean Mapping Group, Department of Geodesy and Geomatics Engineering, University of New Brunswick, Fredericton, NB, 6pp.

Perret, D., Locat, J. and Leroueil S. (1995). *Strength development with burial in fine-grained sediments from the Saguenay Fjord*, *Quebec* : Can. Geotech. J. 32 : p. 247-262.

Simrad, (1992). *SIMRAD EM1000, Hydrographic echo sounder, Product Description* : Simrad Subsea A/S, Horten, Norway, #P2415E.

Woolven, S., Scherzinger, B., (1996) *The Benefits of a Tightly Coupled Inertial/GPS Integration for Seafloor Mapping with Multibeam Sonars*: Proceedings of the Canadian Hydrographic Conference in Halifax, June 1996, pp.74-79.