The Squamish Delta Repetitive Survey Program:
A simultaneous investigation of prodeltaic sedimentation and integrated system accuracy

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Abstract

The Squamish River discharges into the head of Howe Sound in British Columbia. The submerged section of the delta (the prodelta) extends from the low water line to over 200m depth. On average, the delta front progrades ~ 4m per year and the upper prodelta accretes 50cm to 1m each year. Superimposed on the long term accretion is very localized slumping and bedform translation in channels on the prodelta front.

Repetitive surveys conducted 6 to 24 months apart over the past 6 years, have clearly indicated that certain sections of the prodelta are intermittently active and inactive over such timescales. In order to better understand the short period evolution of the prodelta, a new program has been initiated which will use monthly surveys over the less active winter months, followed by semi-weekly surveys during the peak river discharge period.

While any gross change is easy to resolve, much of the scale of natural seabed change on the Squamish prodelta is close to the limits of the total propagated error in the integrated system. It is thus hard to distinguish real change from artefacts due to implementation biases. Therefore any experiment aimed at assessing seabed change must be able to quantify the nature of typical resulting errors (systematic biases and/or random errors).

Introduction

As multibeam surveys reveal the short wavelength morphology of the coastal zone and continental shelf, evidence is appearing of inferred active sedimentary processes such as sand wave migration, mass wasting, gas and fluid escape and ice scour. There is significant commercial and scientific interested in understanding how active the seafloor is. Of particular interest is quantifying the timescales and volumes involved. To best achieve that over large areas, repetitive multibeam survey differencing is an attractive option. In order, however, to confidently utilize the results of inter-survey difference maps, the achievable accuracy of each of the surveys needs to be assessed. That achievable accuracy will ultimately control the validity of apparent differences.

Scientific Aim of Surveys

One specific application of inter-survey difference mapping is the delineation of active mass wasting on the prodelta slope off active river mouths (Hill, 2011). For the project described here, there is a scientific interest in comprehending the mechanism for small scale landslides and bedform migration in depths from the low water mark to 285m on the prodelta of the Squamish River in British Columbia.

Analysis of historic records indicates that the delta front is advancing at ~ 4 metres per year (Bell 1975, Hickins 1989). Initial multibeam survey comparisons in 2004 and 2005 compared with 1981 (Prior and Bornhold, 1984) and CHS 1973 and 1990 single beam operations indicate that the average sedimentation rate on the upper delta (<50m) is ~1m/yr reducing to ~50cm/yr in depths of ~150m (Brucker et al. 2007). Superimposed on the mean growth rate of the delta are the local incision and refilling of large slump scars and channel complexes (Brucker et al. 2007). Using spring and autumn surveys, it is clear that the major activity occurs correlated with the summer freshet discharge of the river (Hughes Clarke et al., 2009).

The pronounced channel systems exhibit periodic transverse ridges which have been referred to as “crescentic” bedforms. The origins of these bedforms are enigmatic ,with one recently proposed model being listric faulting developed in grain flows involving the bulk sediment in the floor of the channels (Paull et al., 2010). Our over-winter observations, however, appear to indicate that these bedforms migrate upslope suggesting alternately a supercritical bedform analogous to an antidune. This project is aiming to use repetitive multibeam at time intervals of weeks to days to try and capture sequences of displacements of these bedforms or fault scarps. We therefore seek to resolve change at a scale of about a metre horizontally and a decimetre vertically.

Survey Design

After 6 years of survey, it is clear that there are abandoned sections of the delta that are receiving only a fine and uniformly distributed rain of sediment with an accumulation of ~ 10 cm/year. These regions are therefore used as a test of absolute integrated sensor accuracy. Any apparent lateral displacement of short wavelength relief therein is only a result of systematic biases in one (or both) of the surveys. In this manner we can quantify how small a displacement we can actually discriminate.

Using our estimates of minimum detectable displacement, we hope to examine the activity of the mobile sections of the delta front. Because it is clear that significant change happens over periods shorter than 6 months, we are implementing a year long program where we undertake resurveys every month during the winter low discharge period and semi-weekly during the summer high discharge period. The survey is being conducted using an EM710 (1°x2°) mounted on a 10m launch (CSL Heron). The expected seabed displacements over such short time periods will challenge the achievable accuracy limits. Using redundant coverage, successively orthogonal line orientation and dense MVP profiling, the source and scale of systematic biases will be explored.

The hope is to capture the spatial pattern of seabed change as the delta grows. In this manner we can, for the first time, directly observe deltaic mass wasting processes which are an excellent analog for deep sea mass wasting processes.

Geomatics Aim of Surveys

In order to meet the scientific objective of the Squamish Delta surveys, we have to comprehend the limits of achievable accuracy and resolution of our integrated survey instrumentation (Hughes Clarke, 2011). Based on a compilation of uncertainty in the components sensors of our integrated systems and their potential time, position and angular offsets, it is possible to come up with total propagated uncertainty estimates (Hare et al., 1995). Such estimates however, assume that the component error contributions are random rather than systematic.

A typical survey in this area involves a series of parallel lines with an interval of no more than 10 minutes. Over a time period as short as 10 minutes, many of the error sources will be almost constant. For example, a refraction bias due to a dated sound speed profile, will probably manifest in a very similar way over such a short time period. Similarly, the GNSS space vehicle constellation geometry will change only slightly over a period of a few minutes. Error contributions due to integration problems (e.g. patch test imperfections) will generate biases that are azimuth and speed dependent.

Thus for a survey that consists of a series of sub-parallel lines, the map of depth difference errors due to that survey will not show randomly distributed false changes. Rather, the map of the errors will be manifest as corridors in which the error sense will be common. By examining the spatial patterns of the errors over areas that are not changing, characteristic signatures may be identified.

Herein we examine the component sensors in isolation and look for potential sources of systematic biases.

Horizontal Positioning

Using a variety of GNSS based positioning solutions, we can examine the potential contributions to the error. On board the CSL Heron, there are two sources of real-time horizontal positioning. The first is the CNav Real-Time Gypsy solution. The CNav system feeds an RTCM correction to the POS/MV v.4 GPS aided inertial navigation system. The POS thus generates an inertially smoothed differential solution. The CNav raw observables are then logged for post processing either as a Precise Point Positioning solution (PPP) or Post Processed Kinematic (PPK) solution. A Cansel Can-Net base station is used for the PPK solutions.

The plot below (Fig. 1) illustrates the relative differences between the 4 available positioning solutions. All solutions have been reduced from the antenna to the vessel Reference Point.

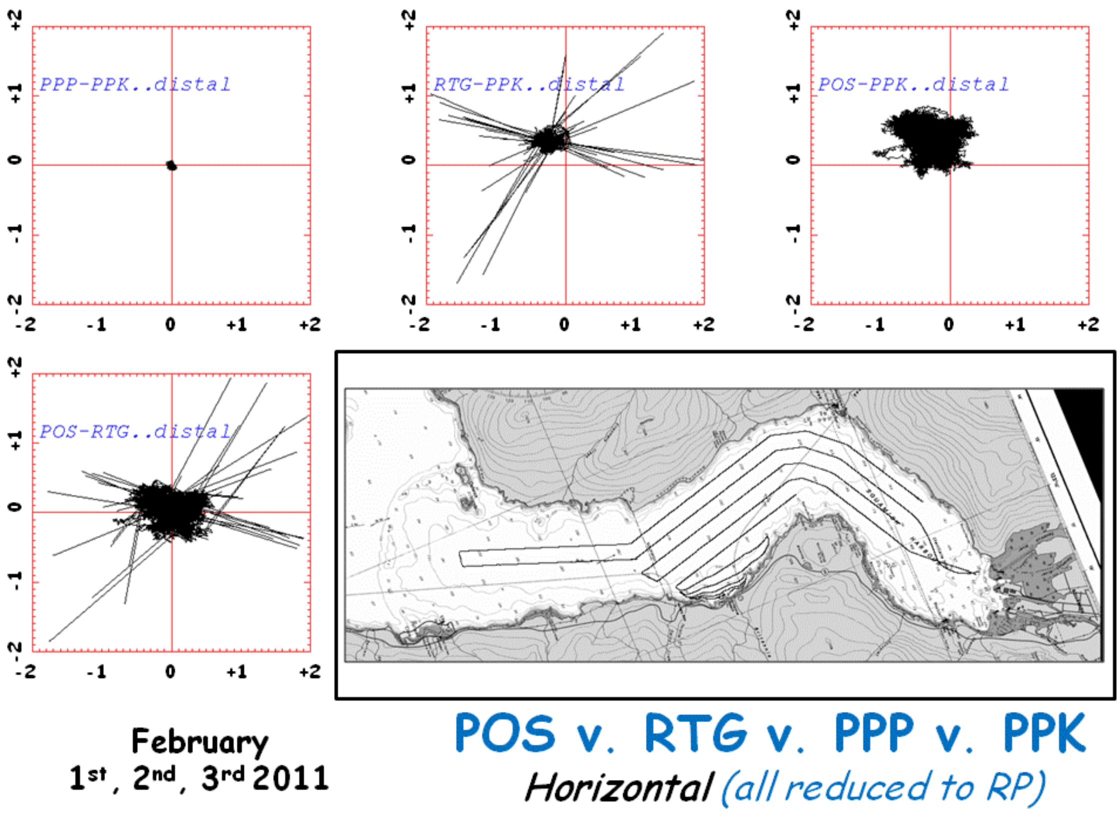

Fig 1: cross plotting the POS/RTG/PPP/PPK solutions to observe their relative agreement. All solutions are reduced to the vessel RP. All plot axes represent +/-2m. The navigation plot indicates the position of the vessel for the period used to compile the difference statistics.

As can be seen in Fig. 1, the PPP and PPK solutions (derived from the same antenna and pseudo-range observations) agree horizontally within 10cm (2 sigma). The RTG solutions agree within ~ 30cm (2 sigma) but with occasional outliers. The POS solutions (fed with an RTCM solution from the CNav receiver) provide a slightly larger horizontal uncertainty, but due to the benefit of inertial smoothing have no outliers.

Vertical Positioning

We have observed tides, predicted zonal adjustments, and GNSS ellipsoid-based height solutions. Superimposed on this we have options for utilizing bandwidth limited high frequency vertical motion histories based on inertial sensing (heave). There are multiple possible ways of combining these sensors to try and minimize different systematic biases.

For initial processing, a predicted tide for Point Atkinson (35km away) is used. Observed tides from the DFO MEDS online service is used subsequently. In both cases the real-time heave from the POS/MV is applied directly. As we post-process the GNSS solutions described above, we intend to use them for both horizontal and vertical control.

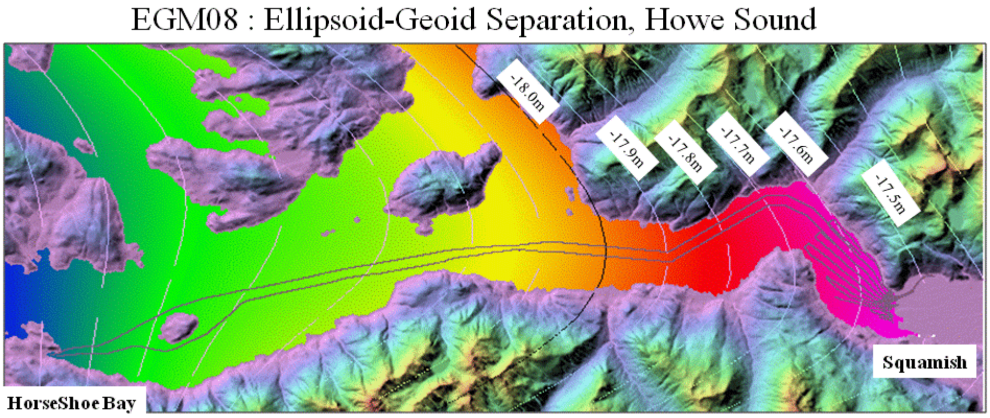

Fig 2: showing contours of the EGM08 Ellipsoid to Geoid separation surface along Howe Sound.

In order to compare the GNSS Ellipsoid height solutions to observed water levels, a separation model needs to be selected. For this program, the EGM08 model has been adopted. Fig. 2 illustrated the separation surface along the length of Howe Sound. Over the region considered for the study, the separation surface shifts by over 50cm.

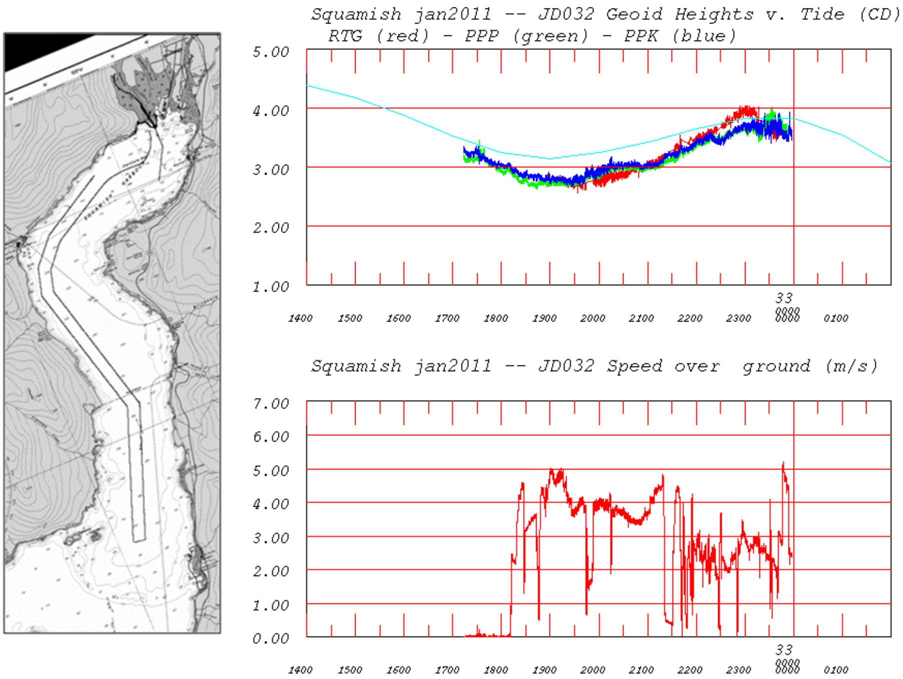

Fig 3: illustrating the antenna height profile derived through RTG, PPP and PPK methods relative to the observed tide at Point Atkinson. The vessel speed is plotted at the same time scale to indicate whether squat related characteristics can explain some of the observed vertical perturbations over periods shorter than tidal periods.

Fig. 3 compares the three GPS-derived height solutions, shifted to the geoid. They are plotted with respect to the observed tidal signal. The PPP and PPK solutions match each other within a decimetre. The RTG height solution, however, clearly diverges by up to 30cm at times over periods of several tens of minutes.

Notably, both the PPP and PPK solutions exhibit matching short-period shifts in the apparent vertical position of up to 15cm that do not appear to correlate with any change in speed of the vessel. The cause of these vertical shifts is not at this time understood.

Angular measurements.

For all surveys conducted in the Squamish delta, POS/MV v.2, 3 and 4 have been used to measure instantaneous angles. Long standing testing of the POS sensors since 1996 have clearly established that they meet angular accuracies of better than 0.05° (better than that is hard to prove operationally). For the purposes of heading and pitch displacements, this falls well inside sonar beam dimensions and thus is not a significant contributor to the total propagated error.

For roll however, such angular accuracies could compromise low grazing angle bottom detections. However, for al l surveys run, 200% coverage with a +/-65° sector has been used and the weighted grid surface generated is strongly biased to those data within +/-45°. At those reduced incidence angles, the roll sensitivity is much lower.

For total angular uncertainty, alignment errors grossly exceed the component sensor accuracies and thus the major focus is on the integration.

Sensor Integration

Irrespective of the positioning and orientation sensor component accuracies, errors due to imperfect integration, including inter-sensor timing, offsets and alignments can always compromise the data sets. The signatures of these integration imperfections can normally be identified looking at overlap characteristics. Traditional patch test methods can be employed to try and minimize these integration errors. As, however, the real time positioning is imperfect, a patch test line sequence is performed for every epoch of the survey so that, once the navigational post-processing is complete, the patch test can be revisited.

Sound Speed Variability

Working in an estuarine fjord environment and in the proximal plume of a river, the spatial and temporal variability in sound speed is an obvious source of uncertainty. To manage this uncertainty we utilize underway sound speed profiling with an MVP-30. Representative longitudinal sections along the fjord axis and up the river mouth are undertaken for each survey. In less than 10m depth, the profiles are taken every 70m and in the deeper fjord where penetration to ~ 35m at 8 knots is feasible, the profiles are acquired about every 700m.

Due to the widespread presence of floating and submerged logging debris, however, the MVP cannot be deployed at all times. Thus these representative sections are used to select representative profiles for real time application and are available for post-processing re-ray tracing.

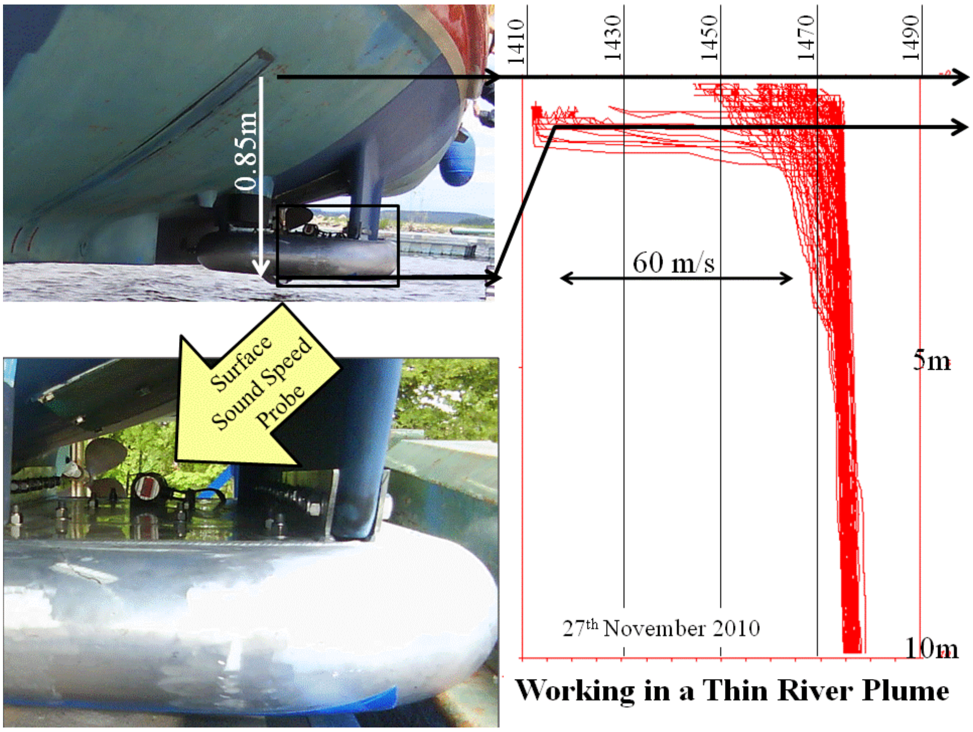

Fig 4: Illustrating the massive gradient in sound speed close to the location of the transducer.

The MVP profiling clearly illustrates the spatial variability of the river plume. The most notable problem, however, is that the plume is unusually pronounced within the top ~ 1.5m (Fig. 4). The transducer face lies at ~ 85cm depth, very close to the region of maximum sound speed gradient. The surface sound speed probe is mounted for safety on the top of the gondola, approximately 20cm higher than the transducer faces. There is often a 60m/s shift over that same distance.

Initial results indicate that the movement of the vessel through the water probably perturbs the fresh water plume. Within a few minutes of receiving the last sound speed profile, the surface probe often will mismatch the corresponding value from the archived profile by more than 15m/s.

Sound Speed Extrapolation

While we have reasonable control on the variability of the upper water mass, the MVP-30 does not allow us to sample below ~ 80m (cable length limitations). We thus have to use extrapolations based on archived sound speed information. To date, this extrapolation has been ignored for many of our coastal situations where the MVP approaches to within 5-10m of the seabed. In such fjord environments, however, the extrapolation represents the majority of the water column.

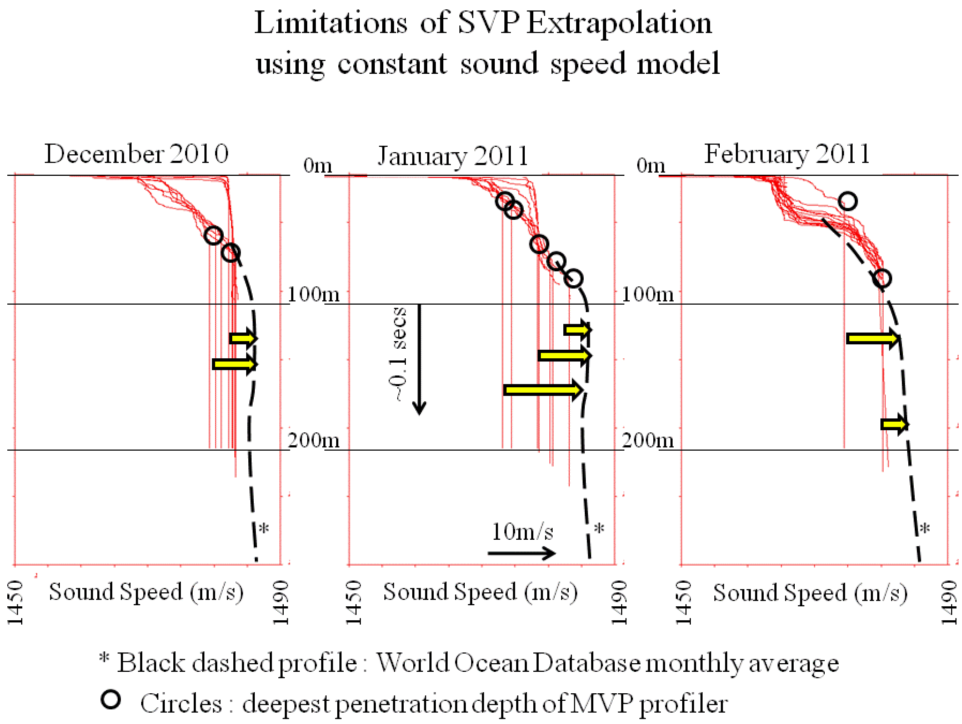

Fig 5: illustrating the bias induced by the SIS default extrapolation of the deepest sound speed value, when compared to the archived deep water mass characteristics typical of the region at that time of the year.

A quick lesson learnt in this project is not to accept the default extrapolations. Using the SIS system, a default sound speed structure to 12000m is always substituted. The user has the option to alter the default file used for extrapolation, but the details of the extrapolation (how far the deepest observed value is replicated and when is a gradient introduced beyond the observed profile) appears to change with the range of the input file. As shown in Fig. 5, the default extrapolation of the deepest value is a poor representation of the deeper water mass. All data is being re-ray traced using the archived database of the deeper sound speed structure of the fjord.

BACKSCATTER

While the traditional focus of repetitive multibeam surveying has been on bathymetric change. In the case of the distal prodelta where average rates of less than a centimetre per month are common, it is clear that such change will be beyond the achievable discrimination limits. An alternate approach to detecting sedimentation is to examine changes in the seabed backscatter strength.

On the shallower delta, significant effort has been undertaken to remove the grazing angle signature in the backscatter data due to the strong relief (Brucker et al., 2007) in order to separate the textural (sediment driven) rather than topographic signature in the imagery. Imagery in less than 150m of water obtained over the 2006-2008 period indicate no pronounced seasonal variability in the seafloor signature.

In contrast to the shallower (< 150m) section of the delta, at greater depths lower frequency (95 kHz) imagery for the two times the delta was surveyed (Fig. 6) clearly indicate a marked change in the seafloor backscatter angular response with season.

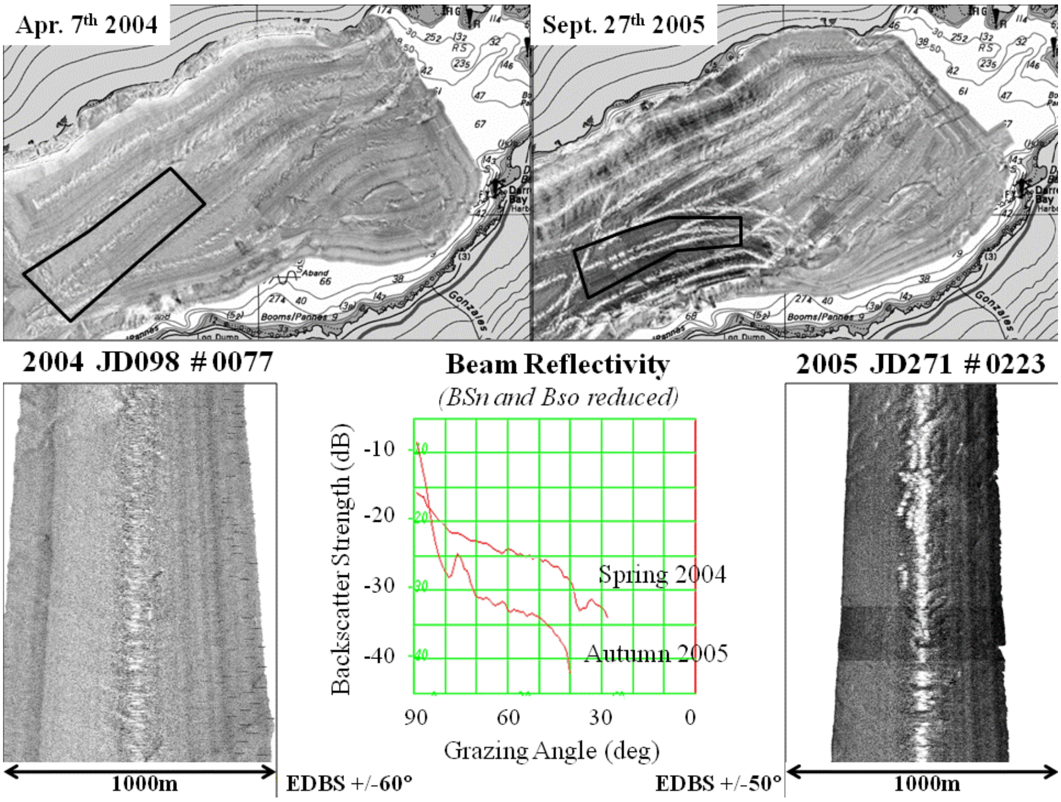

Fig 6: Illustrating the marked change in the angular response of the seabed backscatter strength at 95 kHz between EM1002 surveys acquired in the spring and the fall.

Fig. 6 shows a marked change in the angular response of backscatter data acquired with the identical system (an EM1002 on CCGS Vector) 18 months apart. In the spring of 2004, before the river was very active, the distal prodelta exhibited a flatter angular response. By the fall of 2005, after the summer discharge maximum, the same seafloor now exhibits a much more pronounced angular response. If these data are reasonably inter-calibrated, this might suggest a drop in the surface roughness after the summer.

Urgules et al. (2002) observed very similar phenomena from EM1000 data collected before and after the 1996 Saguenay floods. Pronounced bathymetric change had previously been reported from the same EM1000 multibeam surveys (Kammerer, 1998). Urgules et al. (2002) proposed that the decrease in the backscatter might be a result of a fresh turbidite layer over the bottom of the fjord, suppressing the roughness that would naturally develop through bioturbation.

At this time, without bottom photography, such a hypothesis cannot be tested in Howe Sound. However, on a monthly basis the entire distal basin, extending down to the Porteau Cove sill is being surveyed to see if any change in the backscatter angular response (at 70-80 kHz with the EM710) can be identified.

Before, however we may be confident that a perceived change in logged backscatter intensity values is a real change in seabed physical properties, we need to establish that our data reduction procedures have been implemented correctly. The major components to consider include:

- Source level (by sector)
- Attenuation coefficients
- Pulse lengths
- Frequencies (per sector, per swath)

Source Level : As noted by Hughes Clarke et al. (2008) the absolute source level of specific Kongsberg sonars can shift by several dB from installation to installation. In this case, a single sonar, without firmware upgrades is being used.

Attenuation Coefficients : The EM710 has three options for estimating attenuation coefficients (Kongsberg, 2005) : manual input; or based on a fixed salinity (deriving temperature by inverting from the measured sound speed); or through direct input of a pressure, temperature and conductivity profile. Initial surveys used the default fixed salinity value (35ppt). On adjusting to the average salinity of the fjord (31 ppt), the attenuation coefficient change by an average of 3dB/km. This however is actually a depth dependent variable. Thus a CTD profile was generated for automatic calculation. However, the same problem exists as with the sound speed profiling. How to extrapolate measurements from the deepest depth achieved by the MVP? At this time it is clear that the default extrapolation algorithm is imperfect and thus all backscatter data is being reprocessed using archived CTD profile data to come up with an optimum, depth dependent (and sector frequency dependent) attenuation coefficient.

Pulse Lengths: In going from the delta front to the deepest part of the basin, the pulse length switches from 0.2ms to 0.5ms to 2.0ms. Had the depths exceeded 300m, FM pulses of 20ms would have been substituted. Viewing the backscatter data at the pulse length shift locations (~100m from 0.2 to 0.5ms and ~200m from 0.5 to 2.0ms) it is clear that the change in ensonified area is not perfectly being reduced in the default Kongsberg model (Hammerstad et al., 2000). To overcome this, data in which the three pulse lengths have been manually selected has been collected over the same seafloor to attempt an intercalibration.

Frequencies by Sectors and Swath : In dual swath mode, the EM710 utilizes 6 sectors in total with three sectors per swath. For each swath the outer sectors share the same bandwidth so that 4 frequency ranges are utilised for a given depth range. As one moves into the deeper water and longer pulse length modes, the centre frequencies of all the sectors shift to the lower end of the 70-100 kHz range available from the EM710 transducers. As a result, when comparing backscatter strength measurements, and their angular response, it is important to establish what the centre frequency of the specific observation is. It is not currently possible to view the full range of grazing angle (90° to 25°) within a single frequency range.

Survey Design to Isolate Systematic Error Sources

Given the likelihood of having systematic biases in the data, we have designed successive surveys with orthogonal line geometry. In this manner we can recognise, and potentially isolate the signature of specific error sources. 200% coverage is acquired at all times using a +/-65° sector.

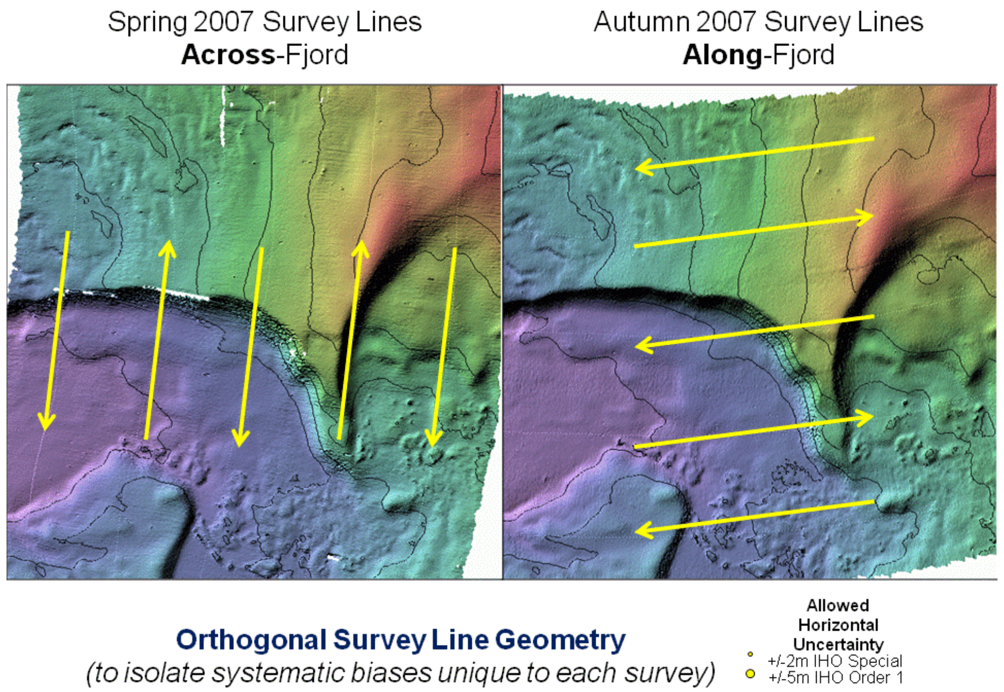

Fig. 7: Example of a pair of sequentially orthogonal surveys acquired over a part of the Squamish Delta that is not currently active. The surveys were both acquired using RTK GPS positioning and represent the best navigated of all the archived surveys in existence.

To illustrate the pattern of errors that commonly are manifest in the presence of a systematic bias, a synthetic example is presented (Figs. 7,8,9). In this case a well navigated pair of surveys is deliberately distorted with a known systematic bias. The data sets chosen are a successive pair of surveys and examine a part of the delta that has experienced no morphological change in the 5 years of multibeam surveys. It is gradually being buried, however, through the rain of silt fraction from the overlying river plume (~ 10cm year).

The two surveys differenced reveal no discernable net change other than associated with local slopes. The changes measured were locally a maximum of within +/-50cm whenever the slopes exceed about 25° particularly about the channel flanks. The inactive bedforms in the top left of the image do not show up in the difference map at this point. Even at this low level, a faint rectilinear pattern of differences, matching the orthogonal line orientation can be discerned. The surveys were in 100-125m of water and this is a small fraction of the IHO Special Order accuracy requirements (Fig. 8).

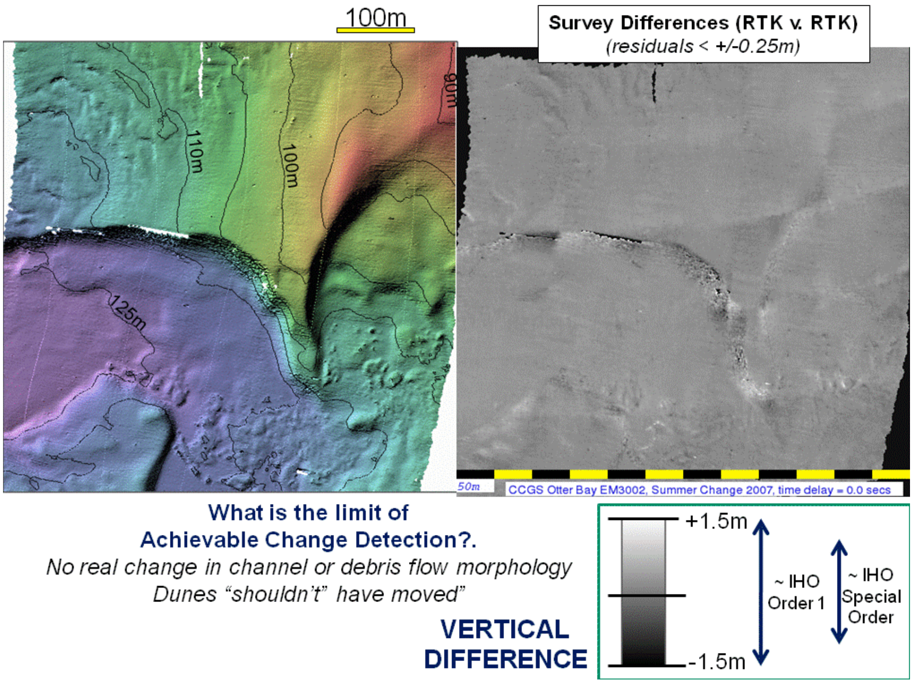

Fig. 8: Actual inter-survey differences revealed before additional systematic bias is introduced.

We can induce a shift due to a modelled systematic bias. In the example shown (Fig. 9) we assume a 0.5 second time latency in the positioning. At 7 knots survey speed this is equivalent to 1.75m horizontal shift along track.

As would be intuitively expected, the scale of the apparent vertical difference is correlated with the slope of the seafloor. Peak apparent seabed vertical change is over 1.5m locally on the steepest slope of the channel flanks. The pattern of the apparent differences reflects the orthogonal line orientation. With this introduced systematic bias, the bedforms in the upper left of the image now appear to have moved.

Thus our tolerance of horizontal positioning biases is obviously a function of the local seafloor slope. The false apparent depth difference dz due to a horizontal displacement bias of dx is :

$$dz = dx \tan(slope)$$

where the slope is measured along the displacement azimuth.

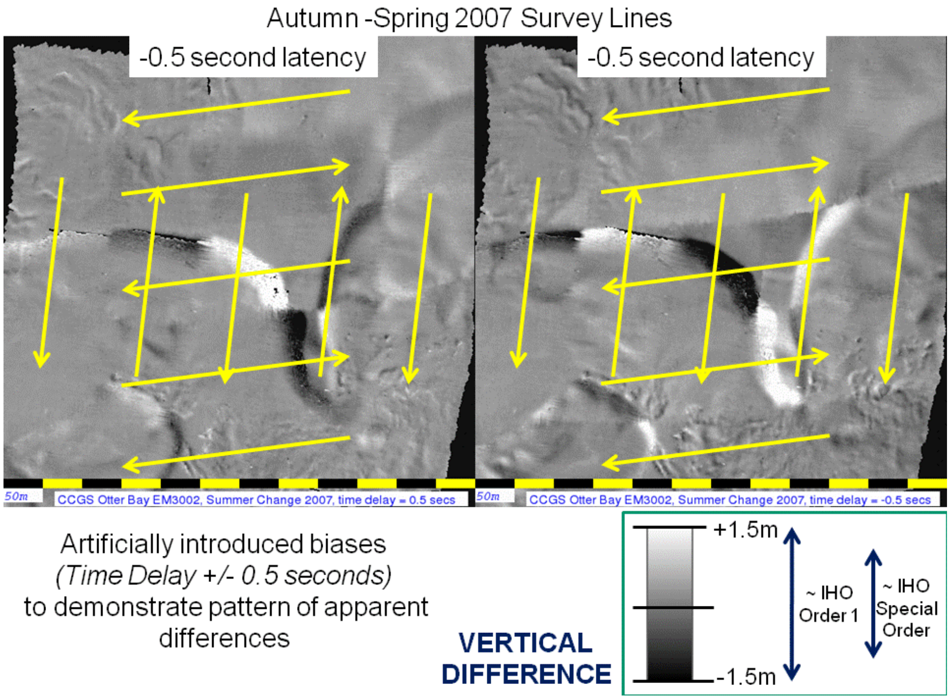

Fig .9: map of inter-surface differences when a time latency of +0.5 and -0.5 seconds is introduced.

For typical unconsolidated sediments an angle of repose is < 5°. In contrast, consolidated bedrock (such as the flanks of the fjords) will routinely exhibit slopes in excess of 30°. The surprising result (Fig. 10) is that, on the actively failing front of the Squamish Delta, slopes of > 45° are common and even the lee faces of the crescentic bedforms observed in the channel axes are over 20°.

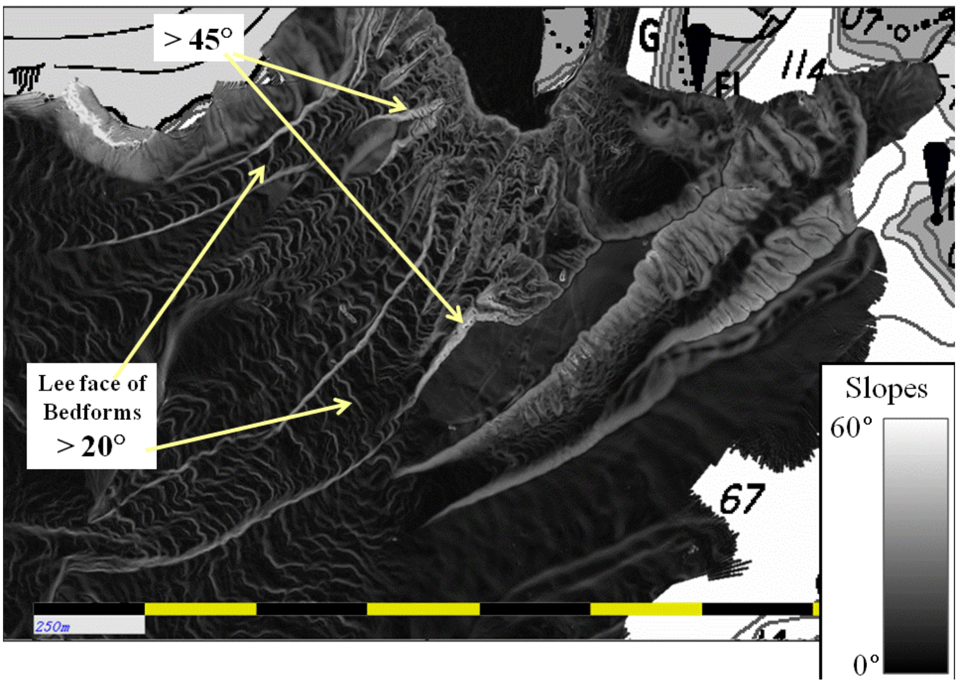

Fig. 10 : Slope map of the upper prodelta, illustrating the range of slopes commonly present. Note the channel flanks, even though developed in unconsolidated sediments, commonly exhibit slopes comparable to the bedrock flanks of the fjord.

Thus in order to distinguish real bedform translation or scarp accretion or collapse from false apparent change due to horizontal uncertainty, we must minimise those uncertainties. As the positioning solutions above (Fig .1) indicate, PPP and PPK solutions should meet this requirement. It is far more likely that the residuals in the difference maps will be a result of integration problems.

Results

At this time (end March 2011) the Squamish program has been operational on a monthly basis for the period November 27th 2010 to March 27th 2011. This corresponds to the over winter discharge low when little is expected to have happened. As such it represents an excellent test of the repeatability.

Throughout this period, there has been one minor surge in the river discharge due to a mid January melt event. The example is illustrated in Fig.11, where the lip of the delta top is clearly seen to prograde. Superimposed on this progradation are four sites of collapse. Downslope of those collapse points, a clear train of bedform displacement events can be seen which extend over 1000m from the collapse point.

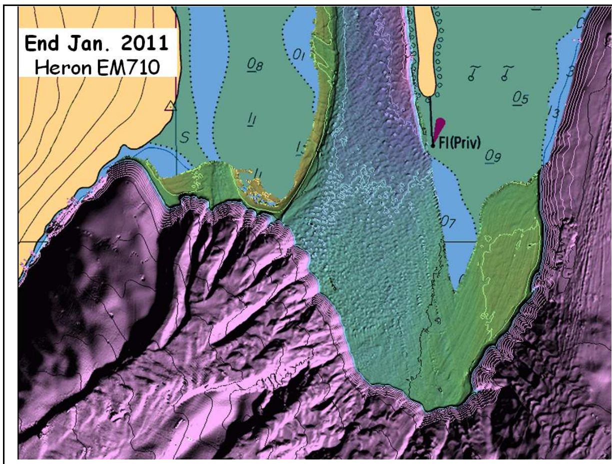

Fig 11left: Terrain Model : Delta Front
Black contour is the drying line and 10m levels below that. White contours are at 1m intervals

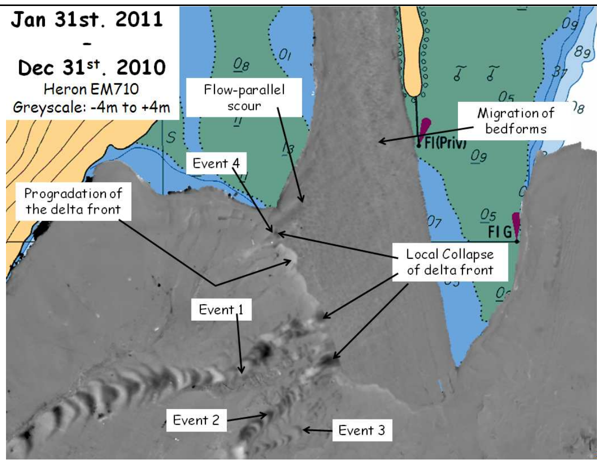

Fig 11 right: Difference Map : Delta Front.
Greyscale represents +/-4m of apparent vertical change.

The river discharge is expected to rise through the month of May and maintain a level of > 500 m^3/s until mid August. During this period, the delta will be surveyed twice weekly to monitor the potential seabed change. An essential part of the analysis will be attempting to minimize the potential sources of systematic bias outlined in this paper.

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