A stable vertical reference for bathymetric surveying and tidal analysis in the high Arctic

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Abstract
The EM300 multibeam sonar mounted on the icebreaker CCGS Amundsen is one of the prime tools used for marine geomorphologic and hydrographic investigations as part of the ArcticNet research program. The area of operations for the Amundsen extends from the Labrador Shelf to the Beaufort Sea. Depths of interest range from ~ 20m to 2500m but the prime focus is on the Arctic Island Archipelago where depths are generally less than 300m and include zones of critical navigational interest. Within that area, whilst tidal predictions are available, there are insufficient active tide gauges to provide proper vertical control. The WebTide hydrodynamic model is available for predictions away from the active coastal sites but remains untested in many areas.
An alternate approach to a stable vertical datum is to adopt the ellipsoid as the reference. In doing so it completely bypasses the need for draft and squat measurements. As part of an experiment, almost all data acquired so far with the Amundsen has had synoptic measures of the vessel ellipsoid elevation derived using the CNav GcGPS service. To make use of the bathymetric data for hydrographic survey, however, an ellipsoid-geoid and ultimately geoid-chart datum model are required. At this time the EGM96 and the GPS-H models are being tested. EGM96 provides a separation model at 15 minute intervals from global spherical harmonics whereas the GPS-H is available at 2 minute intervals thereby providing shorter spatial wavelength undulations (higher spherical harmonics). Areas of particular concern, where the two might diverge, are those where the gradient in the ellipsoid-geoid separation is steep. This notably includes the Labrador Shelf and the east coast of Baffin Island.
An additional byproduct of this technology is that, as long as appropriate draft and squat models are applied, the same data can be used to examine the variations in the phase and amplitude of the tide at locations remote from the existing tides network. This will allow calibration of existing hydrodynamic models and even perhaps the establishment of viable chart datum interpolations for these remote areas.

Introduction
Canada has seen a recent increase in funding for research and mapping in the high Arctic. In order to support the associated bathymetric mapping operations, there needs to be a practical method of vertical referencing in these remote regions.
The primary bathymetric mapping platform at the moment is the CCGS Amundsen, a 97m, class 1200 icebreaker converted for scientific operations (Bartlett et al., 2004). The vessel operates a Simrad EM300 30 kHz multibeam sonar in depths typically ranging from 30 to 300m within the Arctic Island Archipelago.

Unlike the usual restricted extent of dedicated hydrographic surveys, the Amundsen is faced with acquiring the majority of her bathymetric data in transit between widely spaced oceanographic stations. Thus her area of operations is not usually focused within geographically constrained regions. It is therefore not practical to use fixed tide gauge instrumentation (assuming that it even existed).
As with all hydrographic mapping operations, the data need to be presented with as high as possible accuracy. Aspects of that accuracy that can be addressed for any vessel include calibration of the sensor relative accuracies. A particular concern in this case is the oceanic watermass variability that is difficult to map in ice-covered waters (Beaudoin et al., 2004a, 2004b). But ultimately the accuracy of all sea-surface referenced solutions is linked to confidence in either the sea-surface level, or more directly the sonar elevation with respect to a known datum.

Figure 1: Arctic Tide Gauges

The traditional approach of tides, draft and heave can be adopted. Heave is manageable, but the draft of the vessel varies significantly with loading (the vessel on and offloads ancillary craft, mooring hardware and large amounts of fuel and deliberately alters trim for icebreaking versus open ocean operations). Additionally speed-related dynamic draft considerations have not previously been explored for vessels of this class.

But most importantly, the tidal and other long period sea surface variations can affect accuracy. Tide ranges in the Western Arctic are v. weak (< 50cm) but can exceed 6m in the Eastern Arctic, particularly in Hudson Strait. Tide gauge locations in the Arctic are very sparse (Fig. 1) and thus one is forced for large regions to rely on hydrodynamic models such as WebTide (see below).

We have two main requirements for vertical control:

1. to reduce soundings to a meaningful and reproducible datum for the purpose of navigational safety.
2. to monitor seabed change from surveys, months or even years apart.

The first requirement necessitates reducing data to a datum tied to the geoid (such as a chart datum for example). But the second requirement frees us potentially to ignore a physically meaningful datum and to adopt a more convenient one such as the ellipsoid. One example of the second requirement is monitoring change in shelf break rotational slump fields known to exist on the outer edge of the Beaufort Sea shelf. The absolute depth is of lesser interest; rather it is the relative change in depth over time, at scales potentially of as little as several decimeters that is of concern.

An alternate approach to the tide, draft and heave model is to use the ellipsoid as a reference. This approach can serve the second requirement directly, and with sufficiently accurate geoid ellipsoid separation models can also serve the first requirement.

In this paper we explore the use of ellipsoid height referencing from a globally corrected GPS (GcGPS) service (C-Nav) as an alternate form of referencing and examine both its internal accuracy and the accuracy of available models to transfer from the ellipsoid to the geoid in the Canadian Archipelago.

WebTide
A hydrodynamic model of the Arctic Island Archipelago region, extending from the Beaufort Sea to the Labrador Sea has been developed by researchers within the Ocean Physics Group at DFO (DFO , 2004). The "arctic8" model (Dupont and Greenberg , 2004), is a 3D finite element, barotropic model, that is forced with sea surface elevation along distant boundaries in the Beaufort and Labrador Seas.

In addition, as the Amundsen's range of operations extends beyond the arctic8 model bounds, for the work in Hudson Bay, and the Labrador Sea, the "hudsonbay" Web tide model developed at IML and the nwatl" Web tide model developed at BIO were substituted. These models include constituents for the M2-S2-N2-K1-O1 and in the case of the Hudson Bay, also the M4-MS4.

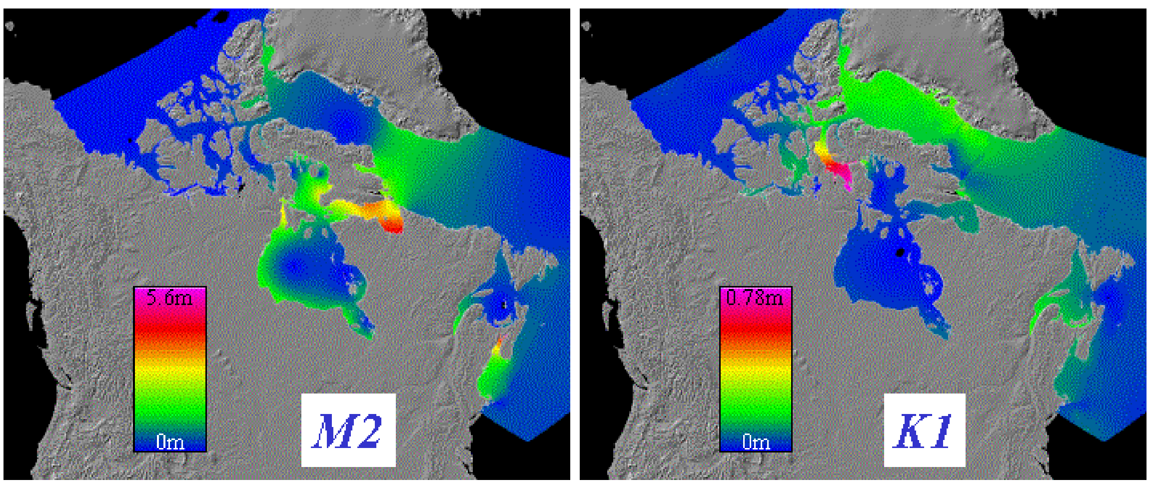

Figure 2: M2 and K1 tidal amplitudes from WebTides constituents (range –2x amplitude presented).

Interpolated elevations can be generated for any time at any location within the bounds of the 3 models. These elevations are used herein to test other estimates of sea surface topography.

C-Nav GcGPS
In partnership with NavCom Technologies Inc., a subsidiary of John Deere and Co., C & C Technologies has developed a Satellite Based Augmentation System marketed in the marine arena as C-Nav. This technology is designed to provide decimetre level positioning worldwide, for the hydrographic, offshore oil, construction, and geodetic survey industries [Roscoe Hudson and Sharp, 2001].

NavCom's Wide Area Correction Transform uses a dual frequency system to eliminate ionospheric effects and, extended carrier smoothing techniques, thus eliminating multipath effects at the receiver. The UNB3 model is used to account for tropospheric effects. C-Nav uses the GIPSY-OASIS II processing algorithms developed by the Jet Propulsion Laboratory that correct for satellite specific clock and orbit errors. GIPSY is implemented in real-time as the RTG correction software (Gregorius, 1996).

Chance et al., (2003) were able to demonstrate 30-40cm 95% confidence levels for the C-Nav in the vertical at static stations globally. They indicated that at this level, IHO Order 1 vertical accuracies could potentially be met worldwide. Wert et al. (2004) applied this for the first time in a micro tidal environment indicating that, with temporal filtering the tidal frequencies could be extracted with a 95% confidence level of as little as 10cm. That test however, was from an otherwise stationary platform (the Amundsen frozen into the icepack experiencing just tidal perturbations). These trials are the first to test the tidal signatures extraction capability of the C-Nav system for an underway platform, specifically in this case in the Canadian high Arctic where other forms of vertical referencing are not readily available.

Geoid-Ellipsoid Separation Models

In order to provide observations with respect to a surface meaningful to either mariners or oceanographers, the elevations need to be reduced to at least the geoid. For inshore work it would be nice also to have at least some estimate of a geoid-referenced chart datum (e.g. Zhao et al., 2004). Three geoid-ellipsoid separation models are herein examined. They include the C-Nav internal filtered version of EGM96, the full resolution EGM96 model and the GPS-H model from the Geodetic Survey Division of Canada. In all three cases, for the areas that are offshore all three solutions converge on near identical global satellite altimetry estimates (e.g. Sandwell and Smith, 1997).

For the EGM96 compilation (Lemoine et al., 1998) source data include major terrestrial gravity acquistions by NIMA since 1990 including airborne gravity surveys over Greenland and parts of the Arctic and the Antarctic, surveyed by the Naval Research Lab (NRL), NIMA also computed and made available 30'x30' mean altimeter derived gravity anomalies from the GEOSAT Geodetic Mission. EGM96 also included altimeter derived anomalies derived from ERS-1 by Kort and Matrikelstyrelsen (KMS), (National Survey and Cadastre, Denmark) over portions of the Arctic, Lemmoine et al., (1998) indicate that the model was used to compute geoid undulations accurate to better than one meter (with the exception of areas void of dense and accurate surface gravity data). Whilst this compilation is one of the best available, it is recognized that future work is needed to identify problems in model performance over certain regions that have been noted in the literature for instance over the Foxe Basin and Ungava Bay (*Sansò*, [1997]).

The GPS-H v2.01 (NRCan, 2004), developed through the Geodetic Survey Division, Natural Resources Canada, allows GPS users in Canada to convert their NAD83 (CSRS98) ellipsoidal heights to CGVD28 orthometric heights (heights above mean sea level). Overall accuracy of the height transformation is estimated as ± 5 centimetres (with 95% confidence) in the southern regions of Canada, but may amount to a few decimetres in remote or northern regions where there are few accurate CGVD28 heights to derive a reliable transformation GPS-H incorporates the CGG2000 scientific model of the geoid for North America (Véronneau, 2001) which was not available at the time of the EGM96 compilation. In GPS-H, CGG2000 is adjusted to the Canadian primary vertical control (CGVD28) by means of 1285 NAD83 (CSRS98) ellipsoidal heights throughout Canada. Significantly. Within GPS-H, EGM96 (Lemoine et al. 1998) defines the long wavelengths up to degree $l = 30$, while coefficients from degree 31 to 360 contribute to the shorter wavelengths of the gravity field. Thus, the two models should share the same long wavelength characteristics, differing only at shorter spatial wavelengths. This is reflected in the fact that the EGM96 is available on a 15 minute grid whereas the GPS-H is distributed as a 2 minute grid.

The solutions coming out of the C-Nav receiver utilize a generalized version of the EGM96. These are the same tables as the 'Morgen' Project (L1/WAAS receiver for FAA applications) i.e. a 2-deg grid synthesized from the finer 15-minute EGM96 grid. Thus the shortest wavelength undulations present in the full EGM96 are missing in the geoid model used inside the C-Nav receiver for real time solutions.

It is illuminating to examine and compare the shortest spatial wavelengths available in the EGM96 and GPS-H models (fig. 3).

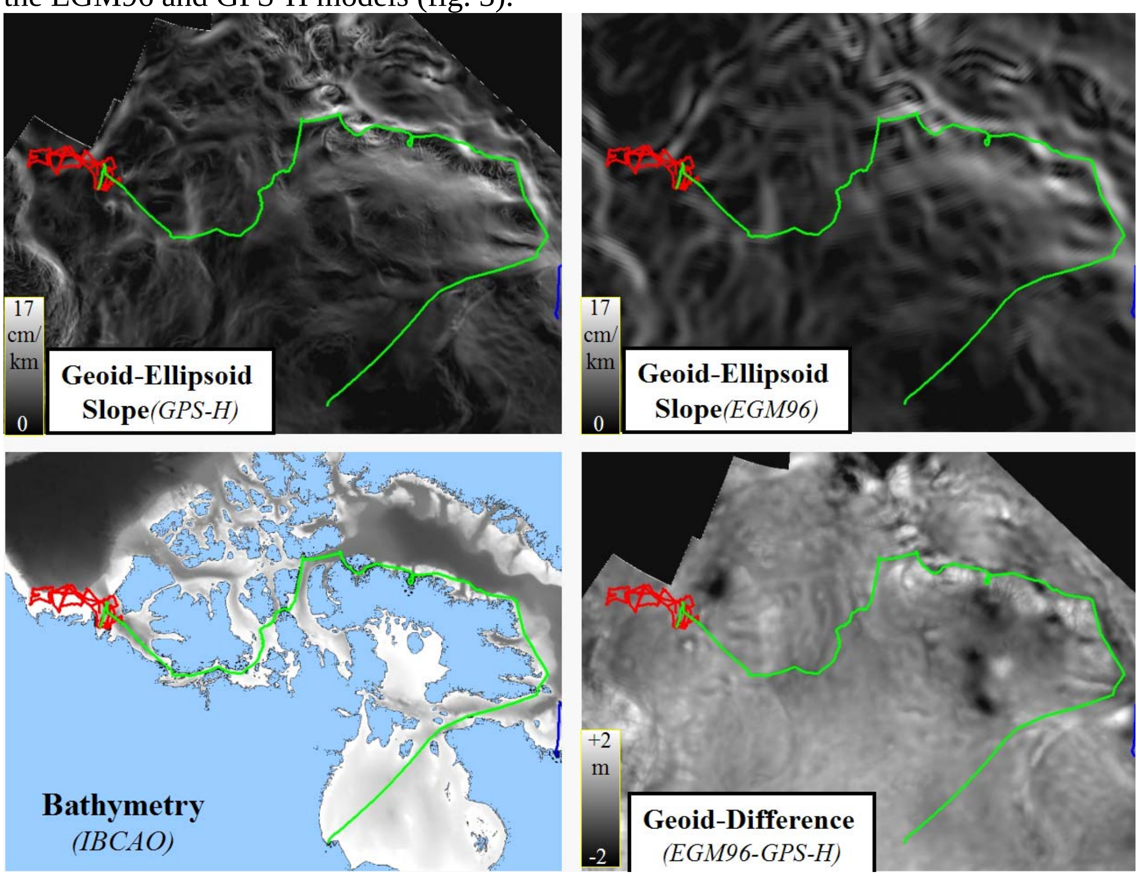

Figure 3: comparing the shortest wavelength undulations through slope and differnce maps for the EGM96 and GPS-H models.

If the EGM96 and the GPS-H geoid models are compared, spatially, the main observation is that the GPS-H contains much higher spatial frequencies, as expected with a 2 minute grid (Fig 3 top left) versus a 15 minute grid (Fig 3 top right). When the two surfaces are subtracted (Fig 3. bottom right), the difference for all of Canada has mean of 33cm and a standard deviation of 84 cm. Significant negative anomalies are seen in the Foxe Basin (-1.8m), Banks Island (-2.0m), a positive anomaly ridge along the east side of Baffin Island (+1.6m, presumably in part a reflection of the particularly steep gradients seen at that site) and in Ungava Bay (+2.0m).

The three geoid-ellipsoid separation models are applied in turn to the C-Nav derived ellipsoid heights to see the characteristics of the resulting geoid time series and compare them to the WebTide hydrodynamic model solutions as the vessel transits around the Arctic Island Archipelago.

Squat Calculations

In order to look at tidal signatures derived from antenna height solutions, we need to remove the non-tidal motions from the spectrum. Heave motions are zero mean and thus simply removed by low pass filtering. Squat in contrast, appear and disappears over typical time scales of speed alterations which commonly occur several hour apart as the vessel transits between coring sites (3-24 hour transits commonly) and then sits at those sites for a similar period. Thus an estimate of the vessel squat characteristics as a function of speed through the water needed to be established to remove these non-tidal squat–related signatures.

Squat tables do not exist for Class 1200 icebreakers. An opportunity to do either RTK or Reference Surface squat tests did not present itself and thus squat was attempted using CNav itself.

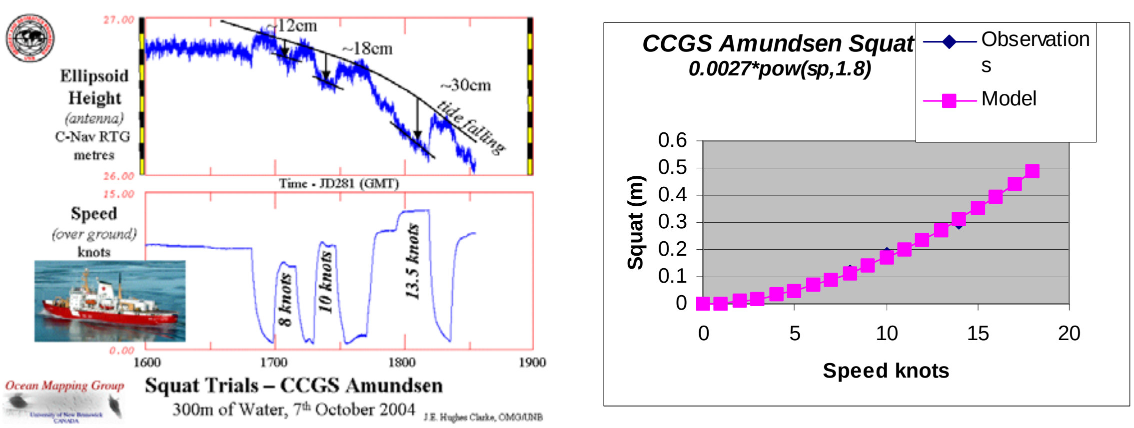

Figure 4: showing the C-Nav height time series during a falling tide, being perturbed as a result of periods of steaming at different speeds. The experiment was repeated both in 300 and 20 m of water. The results were very similar indicating that a single, second-order squat model (right) would suffice for most of the regions the vessel operated in.

Note the squat is used herein to take out speed dependent shifts in the antenna that would corrupt a tidal estimation. In contrast, it should be recognized that, for the purposes of sounding reduction to the ellipsoid, no squat correction is reduced or even wanted.

Lever Arm Reduction

The CNav solutions are strictly from the antenna and thus to be applicable to bathymetric sounding reduction need to be lever armed to the ships reference point (RP). This is a trivial task, requiring only the instantaneous ships orientation and lever arms at the time of each epoch. Two surveys (Koksoak Approaches and Makkovik Bank) have already been reduced in this manner. But for the tidal analysis, which includes long periods when the vessel is not logging orientation as it is on station (orientation currently only being logged through the multibeam system), it is not possible to do that data reduction properly (a zero roll and pitch have to be assumed). For the tidal analyses, the high frequency antenna motion due to the lever arm is actually inconsequential as it will be lost in the low-pass filtering. What will remain, however, is any effect of long period ship list and trim changes. Looking at the logged orientation, however, it is clear that there are no large list or trim effects associated with changes in speed. The one concern is during coring (or mooring) operations when the vessel lists whilst the 3 ton corer (or mooring weights and cabling) is deployed on one side. For most core sites in less than 200m, this period of list (qualitatively estimated at this time at 3-5°) could be up to 30 minutes at a time. Until we log continuous (1 Hz at least) orientation, this limitation will have to be accepted.

Operational Trials

The vessel has collected 1Hz C-Nav solutions at the antenna for over 80 days of operations in the Canadian Arctic Archipelago in 2004. The two prime areas of operations are shown:

- Beaufort Sea, (CASES Leg 8)
- NW Passage Transit, Baffin and Hudson Bays (CASES Leg 9).

Specific data are presented from these two areas.

Northwest Passage, Baffin and Hudson Bay Operations

An intermittently conducted transit was carried out from the Beaufort Sea, through the Northwest Passage and Baffin Bay into Hudson Bay to the Port of Churchill (Fig. 5, upper). The vessel steamed from a micro tidal region with significant diurnal component into a macro tidal region, dominated by semi-diurnal tides (Fig. 2). The vessel traversed up and down over a 50m elevation difference in ellipsoid (Fig. 5 lower), stopping intermittently for sampling and conducted icebreaking for a period of 2-3 days.

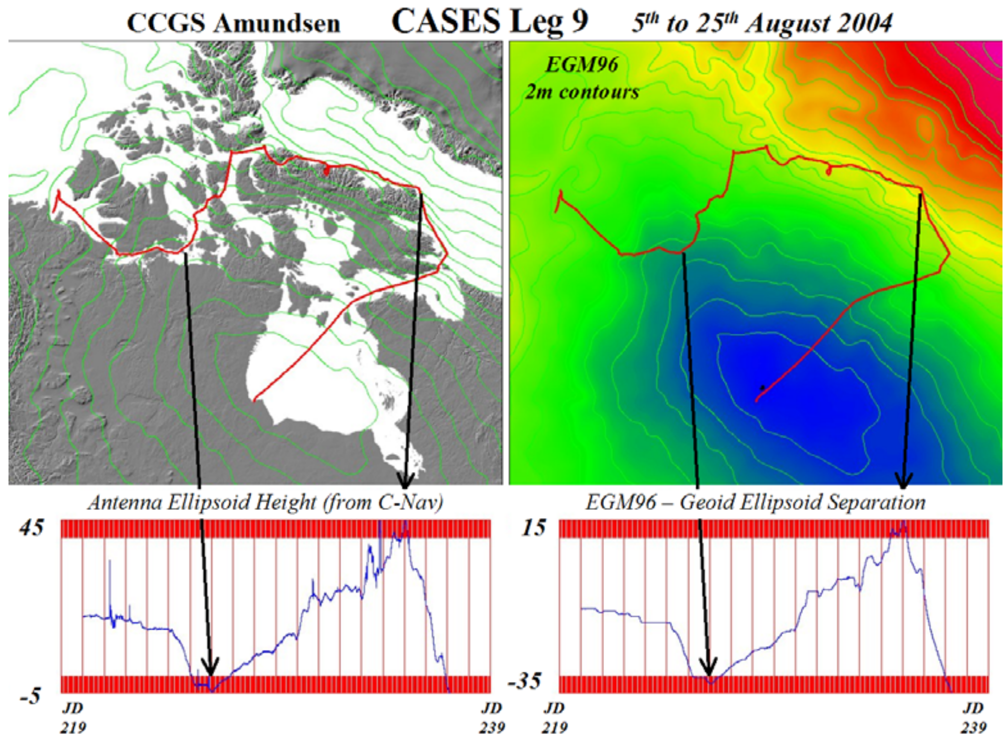

Figure 5: showing the shiptrack for Leg 9 with respect to the EGM96 surface.

In order to examine the vessel motions with respect to mean sea level, the ellipsoid height solutions had to be reduced to the geoid by one of the three available separation models Figure. 6 contrasts the three solutions, plotting inter-model differences along the track.

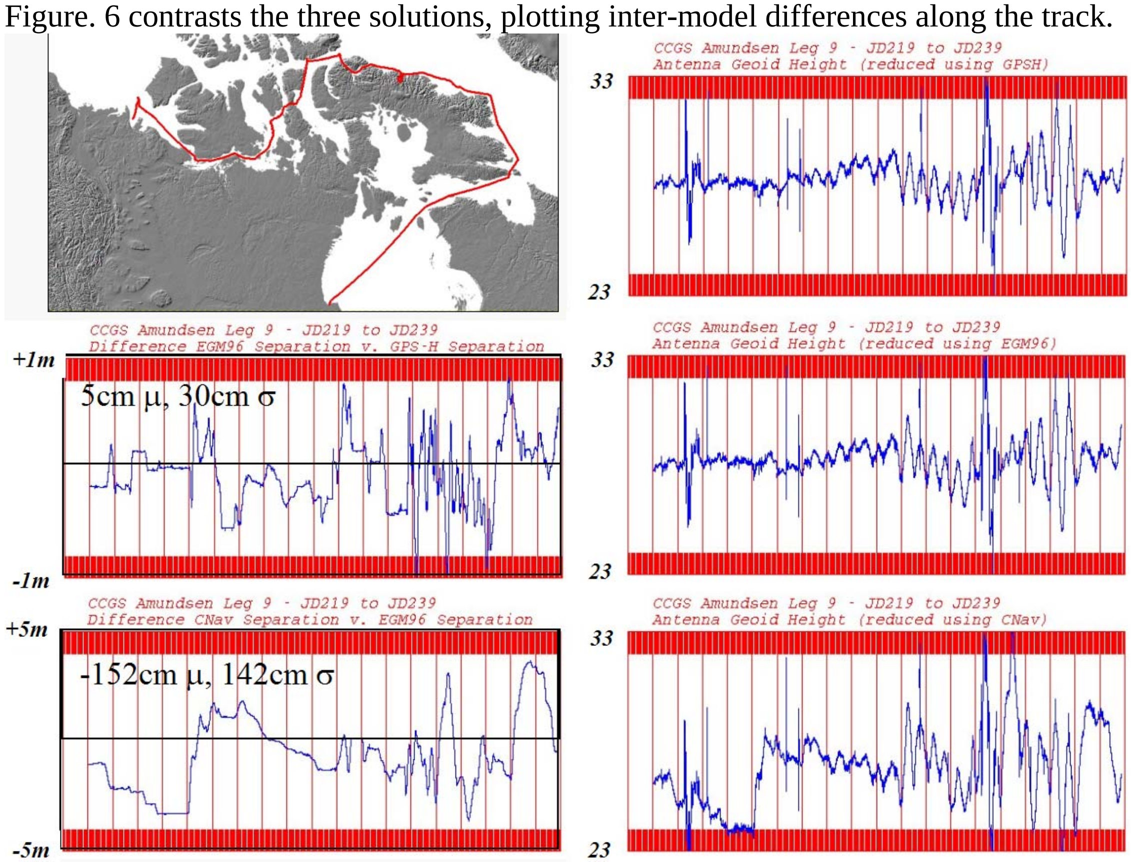

Figure 6: Comparison of the the three (top: GPS-H, middle: EGM96, bottom: C-Nav internal) antenna geoid height solutions for CASES Leg 9 in the NW Passage, Baffin and Hudson Bays. Left hand plots show time series of inter geoid model height differences.

The geoid height profile produced using the C-Nav internal separation model (Fig 6 bottom right) clearly contains, unrealistic vertical motions. Those motions are almost exactly mimicked in the C-Nav internal (EGM96 reduced to 2° grid) to full resolution EGM96 model differences (Figure 6, lower left). In contrast, the EGM96 and GPS-H profiles appear almost identical, with their differences (Fig. 6 left centre) very minor. Both solutions, however, indicate an apparent multi-day drift of the antenna solution that cannot adequately be explained by tidal signals or vessel dynamics (discussed further below).

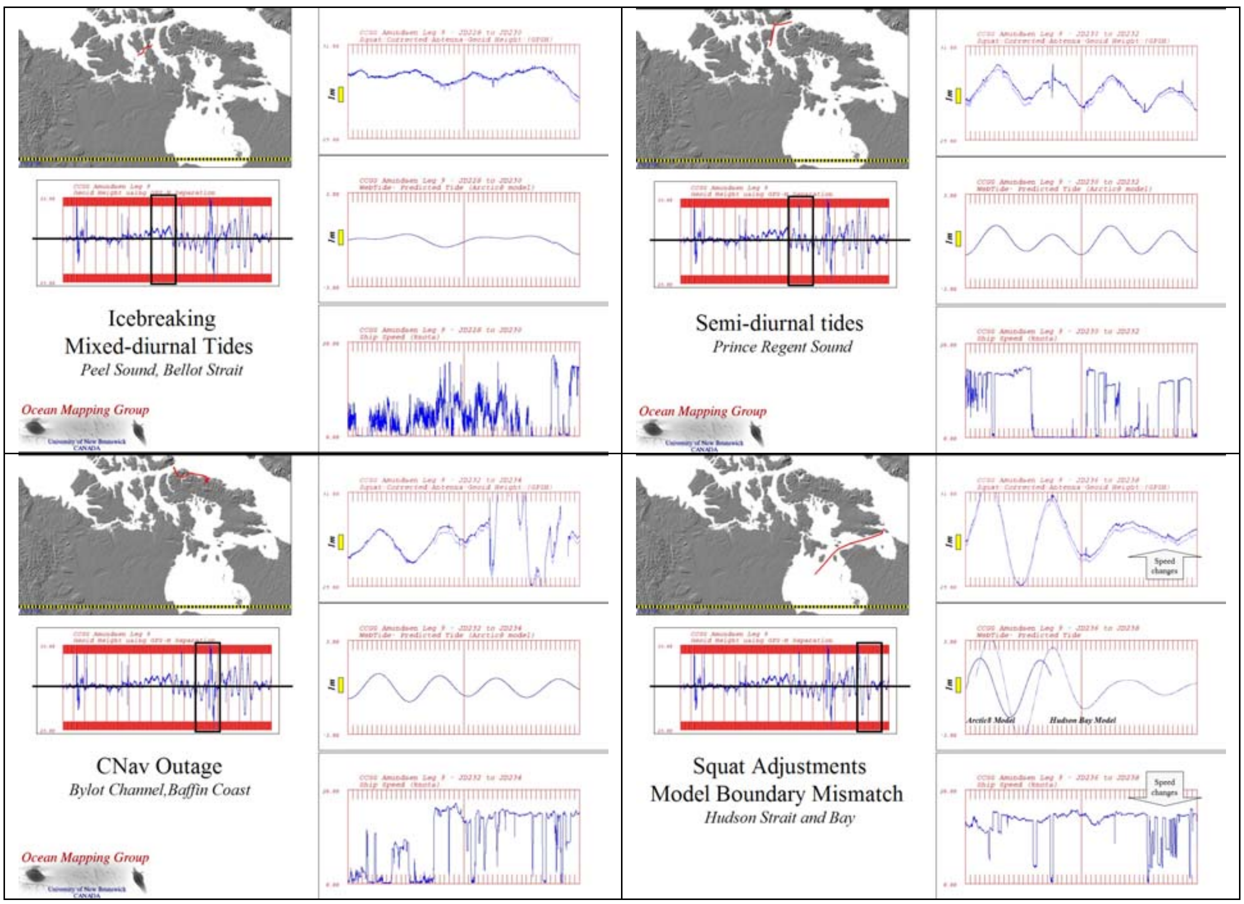

Figure 7: For each of the four 48 hour time series plots, three windows are presented:

- top – the squat-reduced antenna height (dark blue) is plotted over the raw height (light blue)
- middle – the WebTide predicted tide for that time window
- bottom – the vessel speed (that controls the squat model).

Within the transit, selected windows are presented showing characteristics of the antenna height profile as compared to the WebTide predicted model (Fig. 7).

Fig. 7 - Top-left – This example shows that antenna noise (as seen in minute averages) is not noticeably corrupted by icebreaking activity (sustained periods of variable speeds generally below 6 knots). The mixed tides in Peel Sound (with significant diurnal component) are clearly visible.
Fig 7 - Top-right – Once through Bellot Strait, a markedly different, larger amplitude, predominantly semidiurnal time is experienced, confirming the WebTide predictions.
Fig 7- Bottom-left – This example shows the onset of a Cnav "outage" event. Within the 20 day leg, during two periods of ~6-12 hours, the C-Nav solutions diverge abruptly by several metres. The quality indicators associated with the RTG string do not indicate the cause of the effect.
Fig 7 - Bottom-right – This example shows how the C-Nav results clearly indicate that the model results at the extreme boundaries of the Arctic8 model, that extend part-way into Hudson Strait, are poorer than the overlapping Hudson Bay model itself (whose boundaries lie out in the Labrador Sea.). In addition this example provides a particularity nice demonstration of how the squat adjustment, improves the fidelity of the tidal surface measurements (by removing the high frequency vessel –speed induced vertical perturbations).

Beaufort Sea Operations

For a period of 42 days, the Amundsen steamed between oceanographic stations on the Beaufort Shelf and Amundsen Gulf. The vessel speed varied from 5-15 knots in transit interspersed with periods of over a day whilst stationary on station. As the geographic extent of the leg is much more restricted, the geoid-ellipsoid undulations are much reduced.

As with the Leg 9 results, a comparison is provided of the three methods of estimating antenna geoid height profiles (Fig. 8). Again the real time C-Nav internal separation model provides clearly unrealistic motions (Figure 8, lower right). Those motions are again almost exactly mimicked in the C-Nav internal model to EGM96 difference profile (Fig 8, lower left). They probably reflect the lack of high order harmonic coefficients in the lower resolution 2° model. As for leg 9, the two profiles generated using either the EGM96 or the GPS-H models show only minor differences. The blocky nature of the EGM96-GPS-H difference profile is merely a reflection of the fact that the vessel was stationary for long periods, during which the separation model differences would of course remain identical.

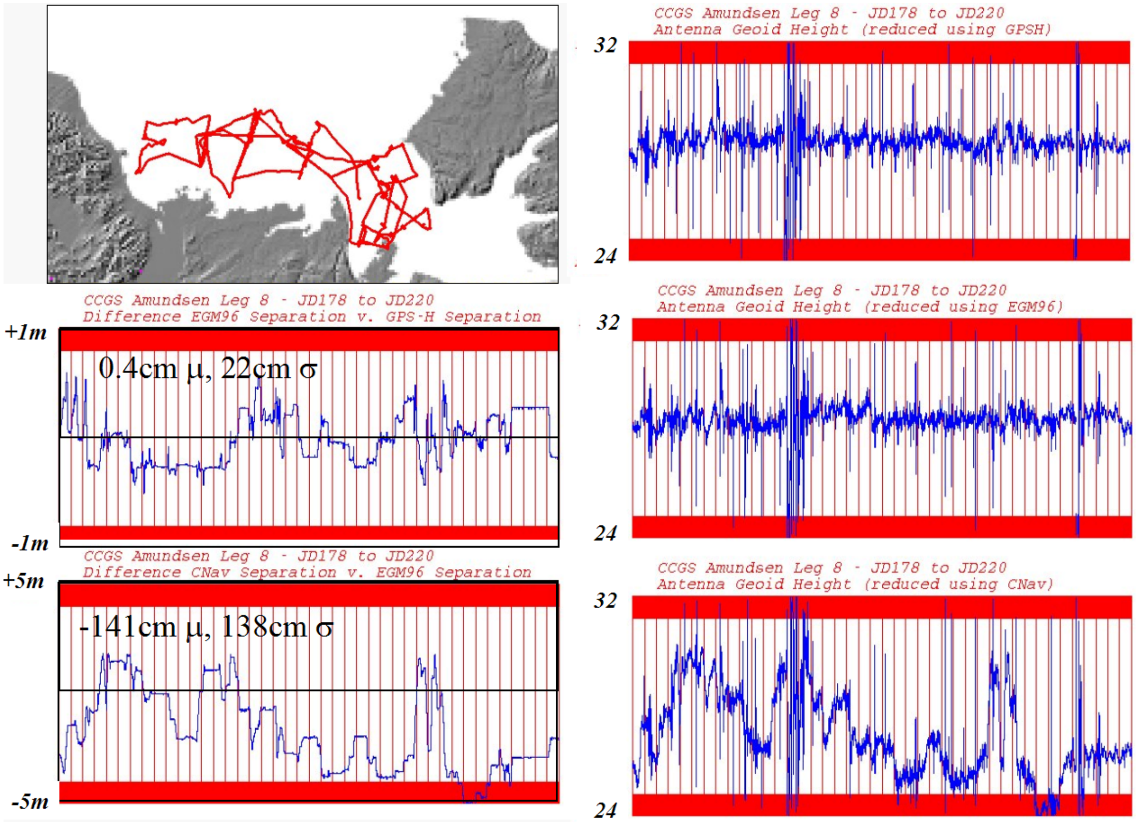

Figure 8: Comparison of the three (top: GPS-H, middle: EGM96, bottom: Cnav internal) antenna geoid height solutions for CASE leg 8 in the Beaufort Sea. Left hand plots show time series of height differences.

In Figure 9, four 48 hour windows are presented, illustrating the greater difficulty recognizing the weaker tidal signatures superimposed on the C-Nav noise characteristics.

One of the main concerns with the Beaufort Sea data is that, given that the tidal amplitudes are so small (always less than +/-20cm often less than +/-5cm), the coherent residuals in the geoid height solutions show up clearly. In figure 9, the top left plot shows the clear regional trends in geoid height bias as the vessel transects across the Beaufort Shelf. This indicates a local error in the regional geoid-ellipsoid separation in this region (When long transits are made in such a region, the antenna height (and by inference the sealevel) appears tilted (e.g. from B to D and back up again from D to F) as the vessel steams up or down the erroneous separation model. .

As with the NW Passage data, there were 3 discrete periods of sustained C-Nav height anomalies. When this would happen, although the receiver reported valid solutions, they would clearly drift several metres for periods of over 12 hours (Figure 9, bottom left). The timing of these anomalies needs to be compared to constellation and sun-spot activity to see if they can be explained.

Where the tidal amplitudes were above ~ +/- 0.2m, the signature could just be discerned in the C-Nav height solutions (Figure 9, top and bottom right plots).

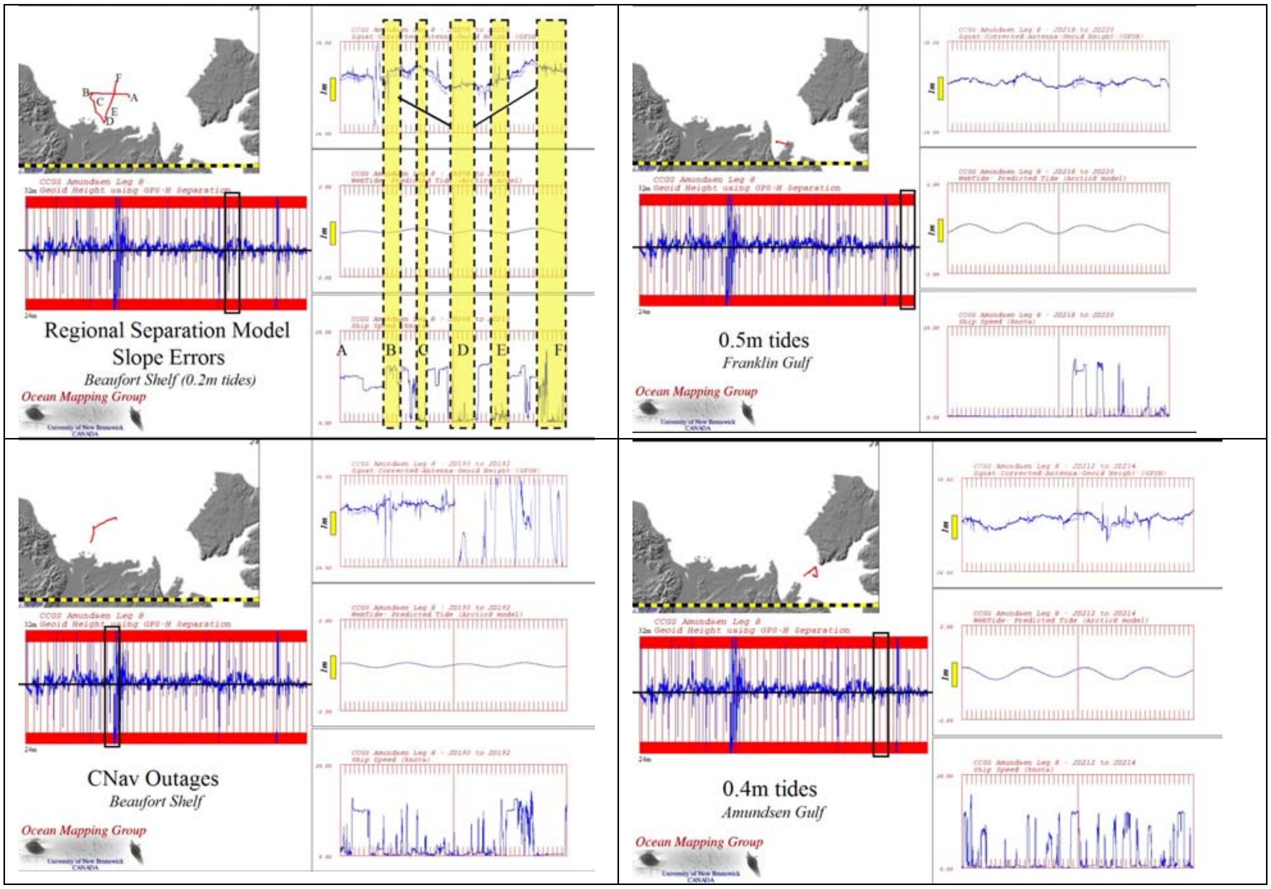

Figure 9: four 48 hour windows comparing C-Nav-GPS-H and squat reduced antenna profiles to WebTide predictions.
For each 48 hour time series plot, three windows are presented:

- top – the squat-reduced antenna height (dark blue) is plotted over the raw height (light blue)
- middle – the WebTide predicted tide for that time window
- bottom – the vessel speed (that controls the squat model).

Discussion

From the example data presented, when tidal amplitudes are above ~ +/-25cm, we can note a reasonable correlation of the C-Nav geoid height predictions to the WebTide model results. One cannot definitively provide accuracies estimates, as the hydrodynamic model itself has unknown errors. Nevertheless it provides a clear indication of the likely magnitude, phase and spectral characteristics of the tides to be expected.
In order to provide a time series that is predominantly reflecting the tidal signature, more work needs to be done to filter the data. Results presented above include all solutions reported valid, averaged down to a minute. In order to remove the prevalent spike-like noise characteristics, a combination of median and longer period (hourly) averaging would need to be developed. Figure 10 below shows an example of a data set reduced to hourly samples in this manner. The tidal components are now far more visible. What remains however for both surveys is a clear longer period (several days) drift in the mean antenna profiles (dotted lines in Figure 10). The cause of these longer period drifts need to be examined.

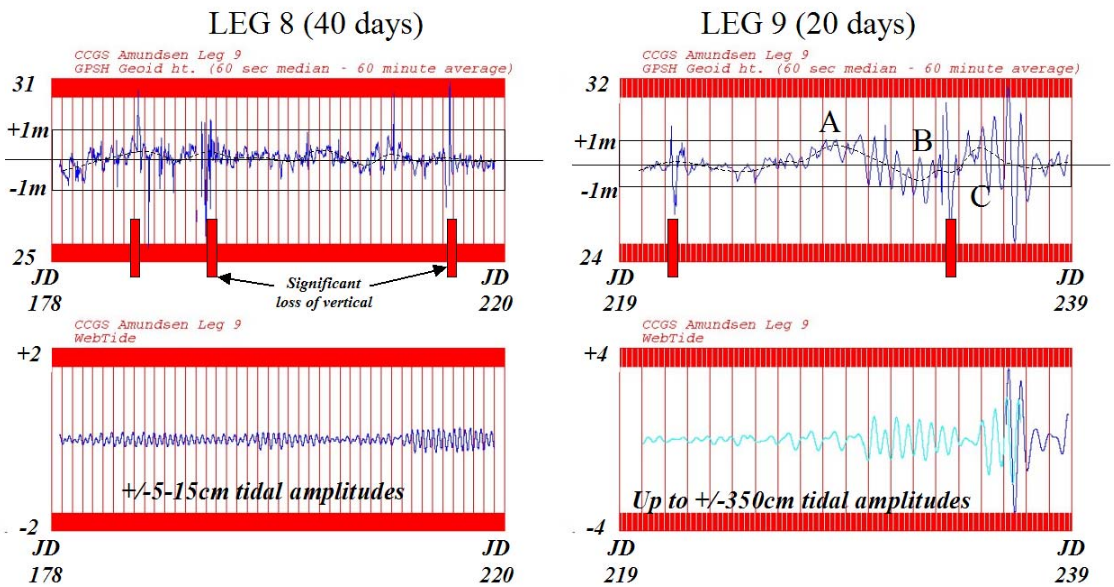

Figure 10: Comparison of best reduced antenna time series (median filtered for each minute, then averaged for each hour), against WebTide predictions for time and location of CCGS Amundsen Leg 8 and Leg 9 ship track
For each antenna time series, the dotted line indicates an approximate tide-free error trend.

Quantitatively assessing errors in geoid undulation models is strictly not possible from this data as one cannot unambiguously separate tidal components from short wavelength geoid undulations. For periods longer than 24 hours however (equivalent to maximum wavelengths of ~300nm at transit speeds), it is conceivable that one could unambiguously identify geoid undulation residual errors. In this manner, one could assess the tide-free residuals (thin dotted line in figure 10). For Leg 8, one sees that this long period trend is no worse than +/-30cm. Bear in mind that for Leg 8, the vessel operates within a restricted region, where geoid undulations are generally quite benign. In contrast for Leg 9, that tide-free residual varies from ~+80cm to –60cm. For Leg 9, the profile is taken across a much larger geographic extent over which there are greater and steeper changes in the geoid-ellipsoid separation model. One can note a significant positive anomaly (fig. 10, A) when the vessel is in the vicinity of Peel Sound, and passing through the Boothnia Peninsula. A negative anomaly (fig. 10, B) exists whilst the vessel is in Lancaster Sound and a second positive anomaly (fig. 10, C) appears on the east coast of Baffin Island (where strong geoid gradients are present).

Looking at the tidal-period vertical motions about these longer period trends, it is apparent that for tidal amplitudes greater than ~60cm (peak to peak) the C-Nav results can be used to assess tidal signatures. Lesser amplitudes are not reliably visible within the C-Nav noise characteristics. Whilst RMS residuals may be within the 2-4 decimetre range, and thus may meet the hydrographic vertical uncertainty requirements, it does not allow confident tidal signature extraction. This is because there are clearly non-tidal error sources that have correlation lengths of several hours that thus will overprint and distort the tidal spectral solutions.

One aspect not considered here are real non-tidal variations in sea-level. At this time vessel–derived sea-surface air-pressure is not yet available to see how this could contribute to the sea surface anomalies. The long period drift in the tide-free residuals may in part reflect atmospheric forcing. As a substitute for the vessel readings, atmospheric pressure readings from the closest terrestrial weather stations (maintained by Environment Canada) are plotted in figure 11. There appears to be a reasonable correlation between the low pressure periods and the long-period positive antenna height anomalies. However, the antenna height anomalies are about a factor 6 too large (assuming 1 millibar is worth ~ 1cm sea surface elevation difference).

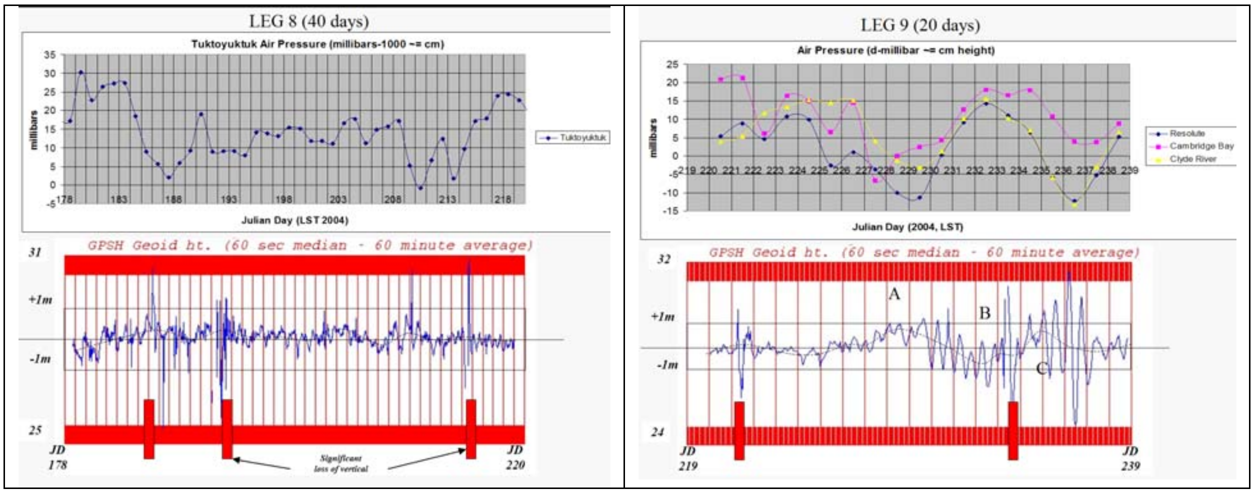

Figure 11: comparison of Environment Canada midday atmospheric pressure readings at Arctic coastal communities closest to the vessel path.

An alternate possibility is that the atmospheric electromagnetic propagation conditions correlate with the atmospheric pressure readings. Other authors (Wert et al., 2004) have noted a correlation between water vapour radiometer readings and C-Nav vertical height solutions. This may in part help to explain the long-period tidally-averaged drifting of the apparent sea surface.

An alternate, but less likely reason for the long period drifting of the apparent vertical could be common errors in the EGM96 and GPS-H models. Both sources have known limitations and share the same long wavelength spherical harmonics. However, the worst anomalies are seen along the narrowest sections of the NorthWest Passage, presumably close to terrestrial observation sites making it unlikely.

An additional contributor to the apparent residual sea-surface topography could be a result of dynamic oceanic circulation. For example there is believed to be a net residual drift from the west to the east through the Archipelago (Melling et al., 1984), which could induce long wavelength barotropic sea surface slopes. One possibility to look at the scale of these effects would be to examine PGM2000A (Pavlis et al., 2000) which combines the EGM96 model with the two year mean (1993-1994) Dynamic Ocean Topography (DOT) field implied by the POCM_4B circulation model.

Conclusions

C-Nav GcGPS ellipsoid height solutions are capable of resolving > +/-0.3m amplitude tidal signals under operational survey conditions in the Canadian Arctic Archipelago. In the absence of other available vertical datums this currently represents the best available means of vertical referencing away from the sparse network of tidal gauges.

A C-Nav derived squat mode is seen to significantly improve the usefulness of the antenna height solutions for the purposes of tidal analysis. The results seen here help corroborate the WebTide hydrodynamic models available for the Arctic Archipelago. Slight mismatches seen can be used for future refinement and testing of the model.

Multi day period drifting of the apparent sea surface elevation is seen in the data. Possible causes include: atmospheric forcing of sea-level; correlated variations in atmospheric propagating conditions; and long wavelength residual errors in the existing geoid-ellipsoid separation models. The current data cannot yet be used to unambiguously separate the relative importance of these three potential contributions.

Future intended research directions include:

- comparing archived 2003 and future 2005 transit antenna height series to see if the apparent long period antenna height anomalies are time variant (implying atmospheric) or invariant (implying geoid separation model residual errors).

- Adding a continuously logging orientation system that provides lever arm orientations even when the shipboard multibeam sonar system is not logging. This will improve the antenna height solutions when the vessel in on station.

- Installing a water vapour radiometer to for the 2005 field season to see if the long period anomalies and "outage" periods can be correlated with atmospheric conditions.

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