

Use of a nested finite-element hydrodynamic model to predict phase and amplitude modification of tide within narrow fjords

Ian Church, John E. Hughes Clarke and Susan Haigh

Dept. Geodesy and Geomatics Engineering, University of New Brunswick

Abstract

A long term monitoring project to measure the inter-annual change in pro-glacial deltaic sediments has been initiated in Oliver Sound, one of a cluster of fjords that lie off Eclipse Sound along Baffin Island, Canada. In order to confidently identify the decimetre-level change, from multibeam surveys, adequate tidal control is required. Surveying in such remote locations presents conditions, logistics and time constraints that prohibit the installation of tide gauges. Even if one could be established, the individual deltas are spread out over several 10's of kilometres along constricted waterways and there is no prior knowledge of the likely propagation of the tidal wave.

Globally Corrected GPS observations (CNav) obtained during the survey are available, but for the requirements of these surveys are not accurate enough and suffer from severe reliability issues due to the steep fjord walls. The Arctic-wide WebTide model would be an option for the more open waters, but does not resolve the fjords. Predicted tides from nearby stations could also be used, but they are far from the survey area and separated by complex and restricted bay geometries. In order to overcome these hurdles, a nested hydrodynamic circulation model has been developed. The model can be tested against CNav (which can confirm correct phasing of high and low water) and predictions from constituents obtained at other locations within the model domain.

While the comparisons will be referenced to mean-sea-level, the same data is forwarded to the CHS for inclusion in charting. For that purpose, chart datum to MSL separation has to be established. Given the significant modeled variation in tidal range within the fjord complex, a single datum offset is unacceptable. Therefore a continuously varying datum offset is generated for the whole region based on using the local sum of major constituent amplitudes together with a scaling factor that reflects the ratio between that sum at observed stations and the used LLWLT there.

Introduction

A long term monitoring project has begun using multibeam bathymetry within the Oliver Sound fjord on the northern tip of Baffin Island, Canada. One goal of the project is to measure decimetre level changes in the seabed morphology over time. In order to monitor these changes, stable vertical control is required to relate subsequent survey datasets. The major limitation to this objective is attaining a measurement of the tidal phase and amplitude at the time of survey.

The primary focus of the project is on the pro-glacial deltas within the fjord. Examining the deltas provide an indication of environmental changes due to processes such as ice scouring, tidal scouring, mass wasting and bedform migration. A number of pro-glacial deltas have been identified for study within the fjord and multibeam surveys will be performed annually or biannually to observe transformations on the seabed in this region.

For comparisons to be constructed between subsequent survey datasets, large systematic errors associated with the bathymetry must be removed. To achieve this objective, tidal control must be established to provide knowledge of the tides. Tidal control is sparse, at best, within the Canadian Arctic and reaching the ageing benchmarks to set up a tide gauge can be time consuming and hazardous. In the event that a traditional tide gauge could be erected, the nearest vertical benchmark is over 100 kilometres from the survey site and the amplitude and phase modification of the tidal wave as it propagates between deltas, up the fjord, is unknown.

Each summer the CCGS Amundsen travels from Quebec City, Canada up into the Canadian Arctic Archipelago as part of the Arcticnet research program. The CCGS Amundsen is a 97 metre, 1200 class icebreaker which has been converted for scientific operations [Bartlett et al. 2004]. The vessel is equipped with a Simrad EM300 30kHz multibeam sonar and a 3.5 kHz sub bottom echosounder. During the journey to the Canadian Arctic, the Eclipse Sound region, off which lies Oliver Sound, is visited each year. Arcticnet has teamed up with Parks Canada to take advantage of the presence and capabilities of the Amundsen by starting a long term monitoring project within Oliver Sound, which is located in the Sirmilik National Park. The summer of 2006 was the first year that the CCGS Amundsen ventured into the Oliver Sound fjord to establish baseline information on oceanography, biology and seabed morphology. 2006 was also the first year that the CCGS Amundsen was accompanied by the Ocean Mapping Group's survey launch, the CSL Heron. At 10 metres in length and with a draft of 1.15 metres, the CSL Heron is equipped to survey the shallow Arctic deltas with the use of a Simrad EM3002 300kHz multibeam sonar, 200kHz Knudsen Sidescan, 3.5kHz Sub bottom echosounder and a MVP-30 Sound Velocity Profiler. While the CSL Heron surveys the shallow deltas, the CCGS Amundsen surveys the remainder of the fjord, where depths reach up to 400 metres.

Globally corrected GPS observations (CNav) were obtained on both the CCGS Amundsen and the CSL Heron during the Oliver Sound survey. Under normal circumstances these observations could be used to determine the amplitude and phase of the tides during the survey [Hughes

Clarke et al, 2005]. The CNav correction signals were only received intermittently during the Oliver Sound survey; however, due to poor satellite visibility caused by the steep fjord walls, the accuracy of the GPS signal was not sufficient to detect tidal signatures for the majority of the survey.

Predicted tides could be extracted for the survey from the Arctic wide WebTide model, but the resolution of the model is not sufficient to delineate the fjords in the survey region [Dunphy et al., 2005]. The resolution of the WebTide model is not sufficient to model the effects of the fjord and nearby islands on the tide as it reaches the head of the fjord. Predicted tides could also be obtained from nearby historic tide stations, but they are far from the survey area and separated by complex and restricted bay geometries.

To overcome the hurdles posed by these options, a nested hydrodynamic circulation model has been developed to encompass the Oliver Sound fjord and surrounding regions. The model is nested within the WebTide Arctic grid and provides the resolution required to observe alterations to the tidal wave as it propagates up the narrow fjords in the region. The hydrodynamic model can predict the phase and amplitude of the tide for any point within the model domain, including the head of the Oliver Sound fjord.

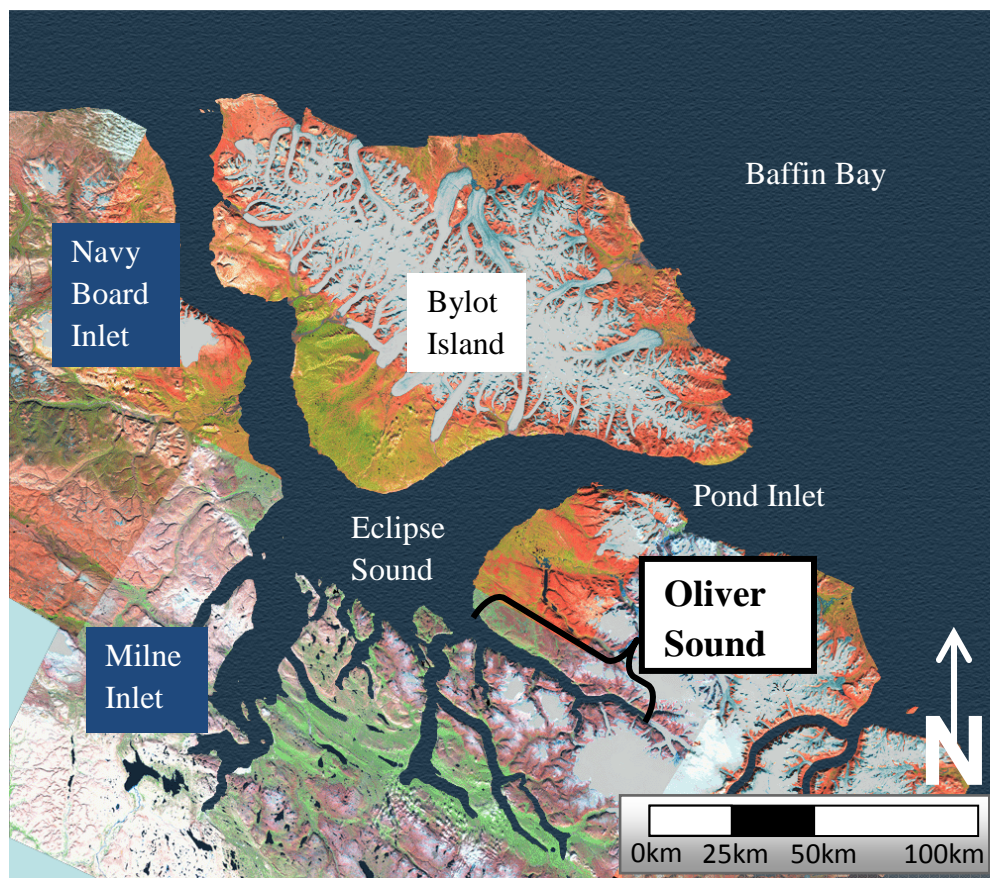


Figure 1: Hydrodynamic Model Region

Source Data

A hydrodynamic Model has been developed for the constricted waters of Bylot Island, including Pond Inlet, Eclipse Sound, Navy Board Inlet (Figure 1) and the many fjords which branch off these waters. The purpose of the model is to predict the change in phase and amplitude of the tide as it propagates up to the head of the Oliver Sound fjord.

In order to create the model, two primary sources of data were required. The first was an accurate coastline of the area which resolved the fjords and islands in the region. The second was the best available bathymetry for the model domain to ensure that the effects on the tide from changes in bathymetry were accurately reproduced.

A coastline for the model was digitized using Ocean Mapping Group software and Landsat 7 orthorectified satellite imagery. The Landsat imagery has a resolution of 30 metres and is freely available from Natural Resources Canada through the GeoGratis Website [Earth Sciences Sector NRCan, 2006]. The resolution of the satellite imagery was sufficient to accurately represent the coastlines of the islands and fjords within the model domain.

Bathymetry for the area was obtained from the Canadian Hydrographic Service (CHS) and the Ocean Mapping Group (OMG). The OMG has been collecting data since 2003 on the CCGS Amundsen through the constricted waters behind Bylot Island. Data collected by the OMG include multiple transits through the region (2003, 2004, 2005 and 2006), a survey of Pond Inlet (2005) and a survey of Oliver Sound (2006). The CHS have performed multiple surveys within the region of the model domain. The CHS have performed surveys at the entrances of Pond Inlet and Navy Board Inlet, within Milne Inlet, a single beam line of data down each of the fjords and evenly spaced soundings over the entire region for navigational charts.

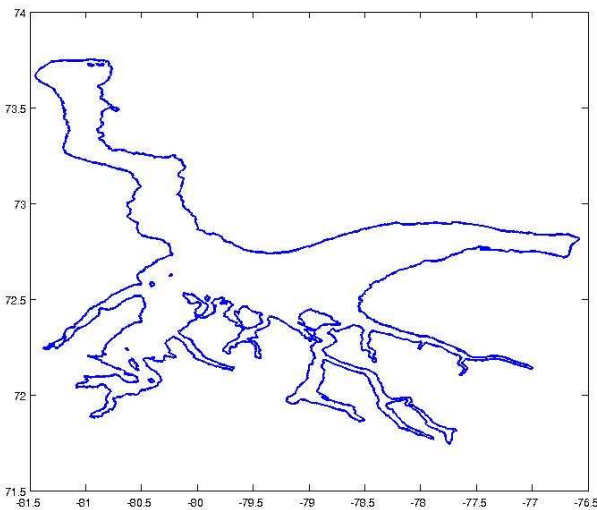


Figure 2: Hydrodynamic Model Boundary

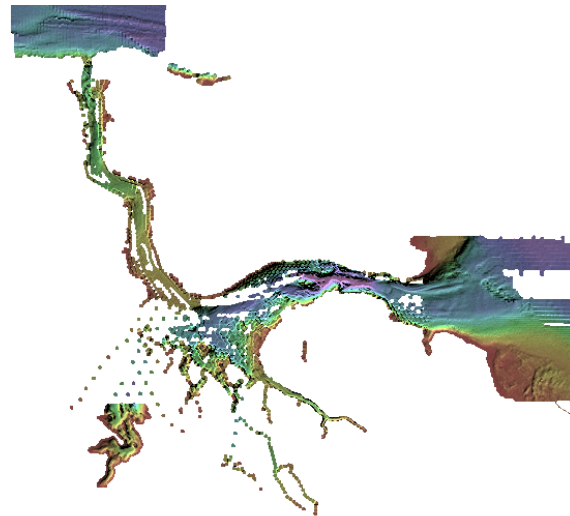


Figure 3: Source Bathymetry

WebTide

A hydrodynamic model of the Arctic Island Archipelago has been developed by researchers within the Ocean Physics Group at the Department of Fisheries and Oceans (DFO) [Dunphy et al., 2005]. The model covers the entire Arctic region and provides a good estimate of predicted tides. The limitation of the model is that due to its size and coverage, it was created using a low resolution approximation of the coastline and depth distribution. All fjords and small islands within the model domain were ignored for developmental and computational simplicity; therefore the model does not take into account the modifications to the tide caused by the shape and depth distribution of islands and fjords within the constrained waters behind Bylot Island. The model does however provide a good approximation of the tides for open water within the domain and has been used to reduce the tides for the majority of the CCGS Amundsen transit data through Arctic waters.

The hydrodynamic model developed for the constricted waters of Bylot Island will be nested within the WebTide Arctic model and the constituents from WebTide will be used to power the model at open boundaries. WebTide includes constituents for the M2, S2, N2, K1 and O1 tidal harmonics.

The WebTide tidal amplitude and phase for the M2, S2, K1 and O1 constituents, along the open boundaries of the model, were extracted for input to the developed hydrodynamic model. Open boundaries include those sections of the digitized model coastline that border water instead of land. It is these sections of the model that are driven to begin the tidal simulation.

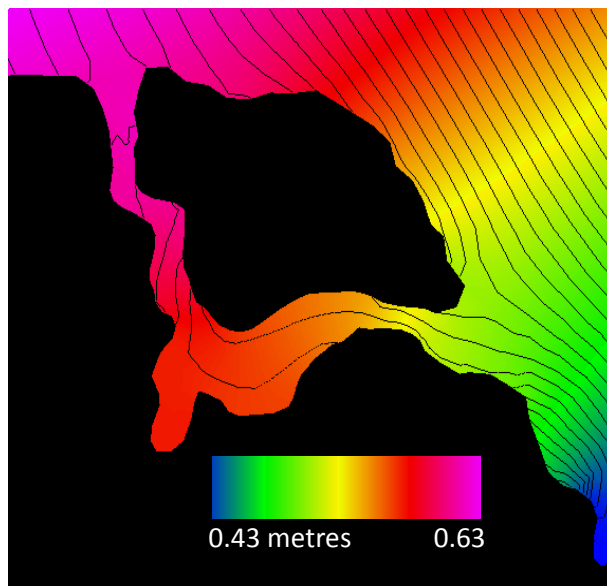


Figure 4: WebTide M2 Amplitude with cotidal lines. Phase contours at 0.5 degrees which equates to approximately 1 minute.

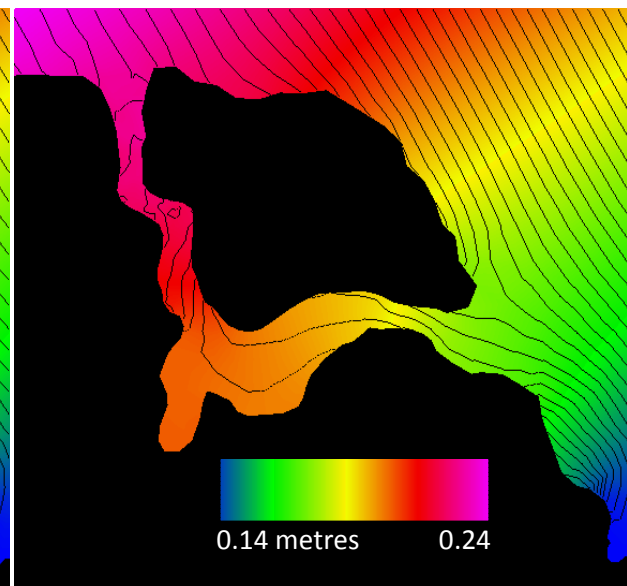


Figure 5: WebTide S2 Amplitude with cotidal lines. Phase contours at 0.5 degree which equates to approximately 1 minute.

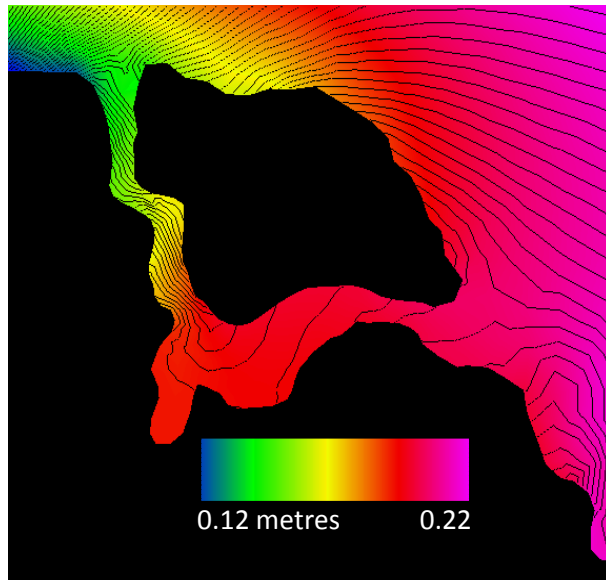


Figure 6: WebTide K1 Amplitude with cotidal lines. Phase contours at 0.5 degree which equates to approximately 2 minutes.

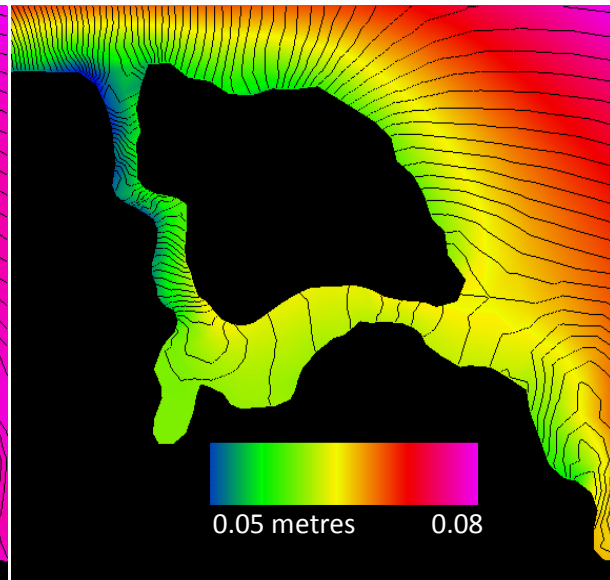


Figure 7: WebTide O1 Amplitude with cotidal lines. Phase contours at 0.5 degree which equates to approximately 2 minutes.

Model Construction

The digitized coastline, bathymetry and open boundary conditions were combined to begin the process of creating a hydrodynamic model. A number of processing steps were required to

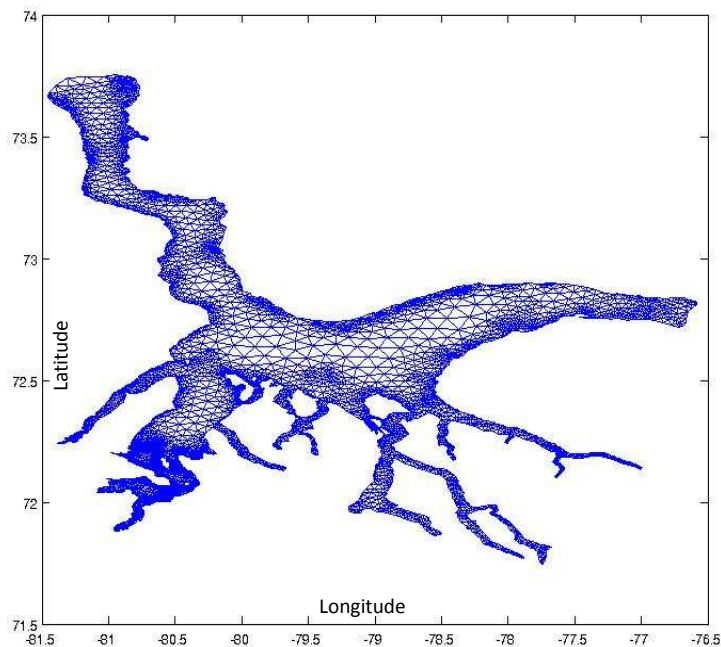


Figure 8: Hydrodynamic Model TIN

construct the model. The first was to create a triangulated irregular network (TIN) based on the coastline and depth data using a program entitled resolute [Chaffey and Greenberg, 2003]. The second was to edit the TIN to improve triangle geometries and distribution.

The model TIN and the boundary conditions from WebTide were input to a program titled QUODDY. QUODDY was developed at the Numerical Methods Laboratory at Dartmouth College and is designed for 3D coastal ocean circulation modelling [Ip and Lynch, 1995]. It is a free-surface, tide resolving model based on 3D shallow water equations.

QUODDY interprets the user input grid and depth information to construct a 3D mesh of the model. The horizontal grid, as shown in figure 6, is projected down to the seabed. The walls of each of the new 3D elements are vertical and each is divided into an equal number layers.

Model Results

The development of a hydrodynamic model for the enclosed waters of Bylot Island is a work in progress. Results from the model are constantly being improved though optimizing the depth and node distribution and boundary shapes and conditions.

Initial results have shown that the amplitude and phase do vary significantly throughout the model domain, especially within the fjords and through narrow channels within which the main focus of survey interest lies.

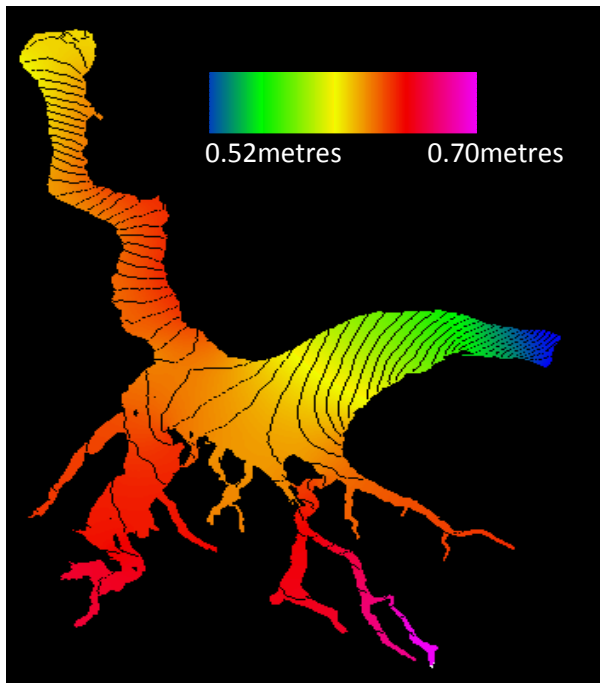


Figure 9: M2 Amplitude with co-tidal lines. Phase contours at 0.5 degrees which equates to approximately 1 minute.

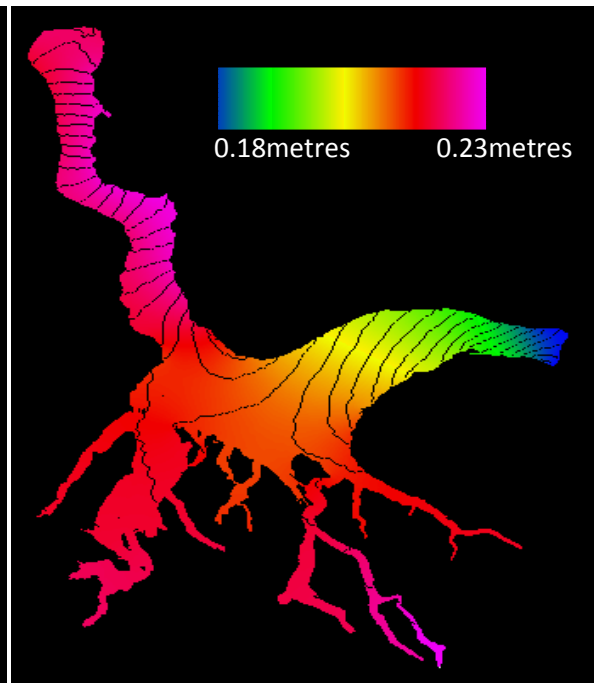


Figure 10: S2 Amplitude with co-tidal lines. Phase contours at 0.5 degree which equates to approximately 1 minute.

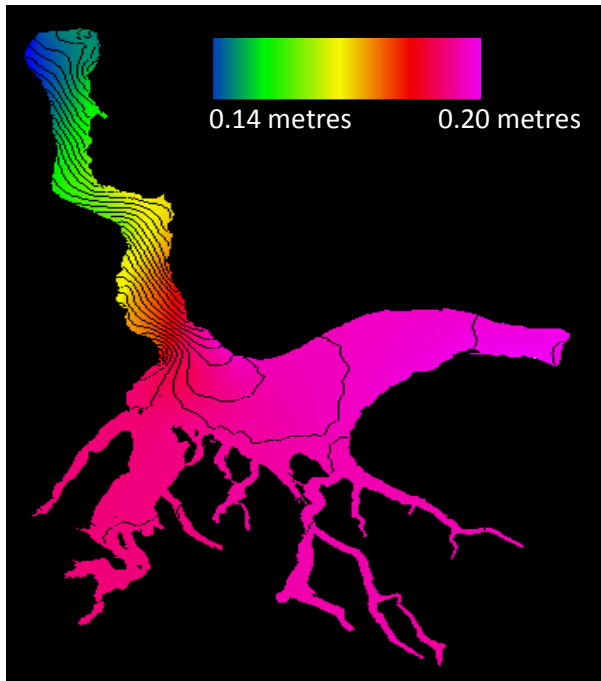


Figure 11: K1 Amplitude with co-tidal lines. Phase contours at 0.5 degree which equates to approximately 2 minutes.

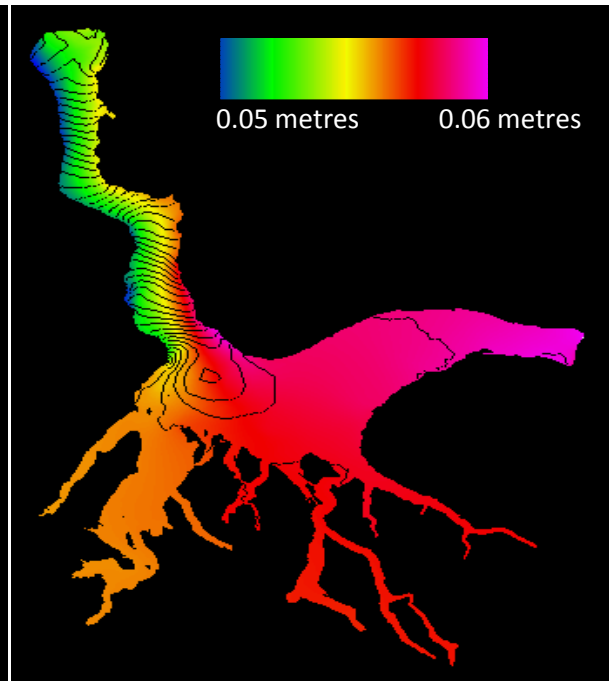


Figure 12: O1 Amplitude with co-tidal lines. Phase contours at 0.5 degree which equates to approximately 2 minutes.

Predicted Tides

Predicted tides can be estimated for three locations within the model domain. Tide stations are located at Pisiktarfik Island, Koluktoo Bay and Milne Inlet. The amplitude and phase of each of the major constituents is available for all three stations. The constituents can be compared to the results of the hydrodynamic model at similar locations within the grid.

The Milne inlet station was established in 1965. The tidal predictions were created using two months of hourly tide level observations from the summer of 1965. The Koluktoo Bay station was established in 1964. The tidal predictions were created using one month of hourly tide level observations from the summer of 1964 and 1965. The Pisiktarfik Island tide station was established in 1966. The tidal predictions were created using only 15 days of tide level observations from the summer of 1966. The short time series and the age of the original observations for each of the predicted tide stations infer that the accuracy of the prediction at each of the stations might be questionable. The predicted tides at these stations should therefore not be relied upon for precise surveys in the region.

The closest of these tide stations is over 100 kilometres away from the head of the Oliver Sound fjord. The predicted tidal stations are also separated by complex and restricted bay geometries from the survey site.

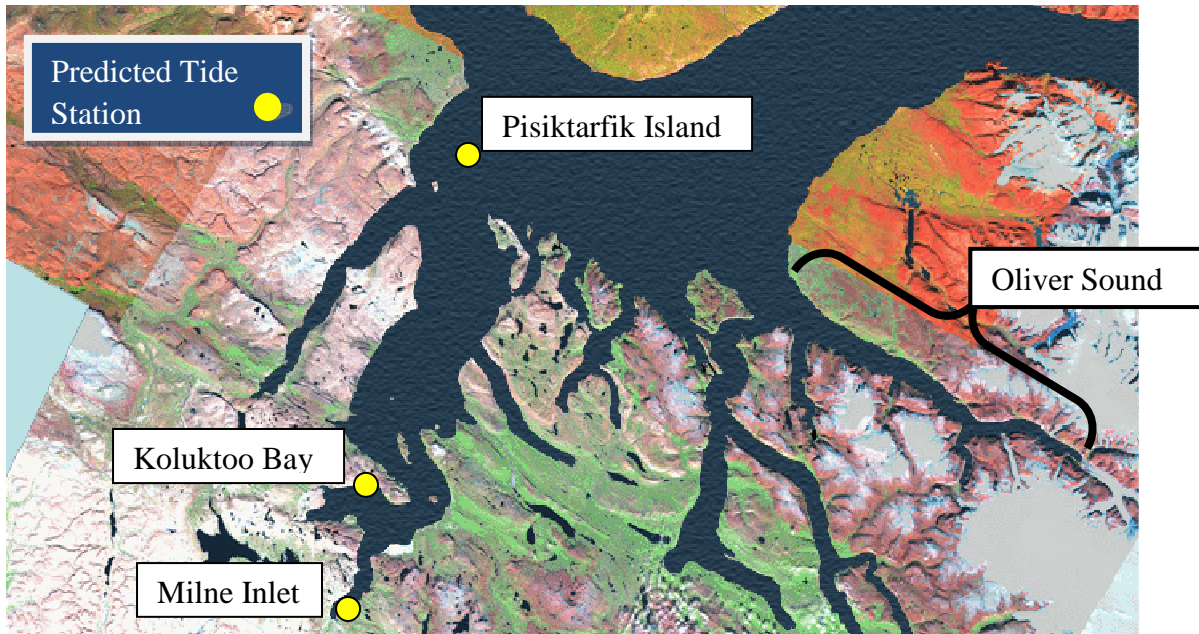


Figure 13: Predicted Tide Stations within Model Domain

Station		Pisiktarfik Island		Milne Inlet		Koluktoo Bay	
		Amp	Phase	Amp	Phase	Amp	Phase
M2	Model	0.64	113°	0.66	111°	0.66	111°
	Prediction	0.55	134°	0.56	132°	0.57	140°
S2	Model	0.22	163°	0.22	163°	0.23	163°
	Prediction	0.18	174°	0.23	181°	0.20	184°
K1	Model	0.19	240°	0.19	242°	0.19	241°
	Prediction	0.33	244°	0.25	246°	0.26	248°
O1	Model	0.06	203°	0.06	203°	0.06	203°
	Prediction	0.08	215°	0.08	201°	0.08	210°

Table 1: Tidal Constituent Comparison (Amplitude in metres). Hydrodynamic Model vs. CHS Predicted Tide

Similarities can be observed when the output harmonic constituent magnitudes from the hydrodynamic model for each constituent are compared to the constituents that form the predicted tides. The amplitude and phase for each constituent is similar between the predicted tide and the model, with the largest variation existing with the M2 constituent.

CNav Vessel Elevations

CNav globally corrected GPS utilizes technology from the Jet Propulsion Laboratory to provide a worldwide GPS positioning solution with accuracies of the order of a few decimetres [Roscoe Hudson and Sharp, 2001]. It was developed as a partnership between C&C Technologies and NavCom Technology Inc. to aid hydrographic and offshore oil field exploration, survey and construction industries [Roscoe Hudson and Sharp, 2001]

Wert et al. (2004) and Hughes Clarke et al.(2005) demonstrated that CNav observations may be used to observe tidal signatures during a hydrographic survey. The issue that is encountered in surveying a site similar to the head of the Oliver Sound fjord is that the steep fjord walls hinder the ability of the CNav correction signals from reaching the vessel. The fjord walls also limit visibility of the GPS constellation. CNav observations are therefore insufficient for observing the signature of the tides within the Oliver Sound fjord, but they can be used to confirm the phasing of high and low water at various sites within the model domain where visibility was sufficient to receive corrections.

Tidal signatures can be observed in the CNav elevation data if it is referenced to mean sea level. Therefore our CNav elevation data must be reduced to the best available approximation of mean sea level, the geoid. Large geoidal undulations exist in the area of Oliver Sound and the filtered version of the EGM96 geoid ellipsoid separation model delivered in the CNav signal is not sufficient to account for them. As the undulations are quite short in wavelength, the GPS-H v2.01 separation model, developed through the Geodetic Survey Division of Natural Resources Canada, will be used to transform ellipsoid heights to geoid heights [NRCan, 2004]. Hughes Clarke et al. (2005) demonstrate that very little difference exists between using the full EGM96 or the GPS-H separation models when processing CNav elevations to observe tidal signatures.

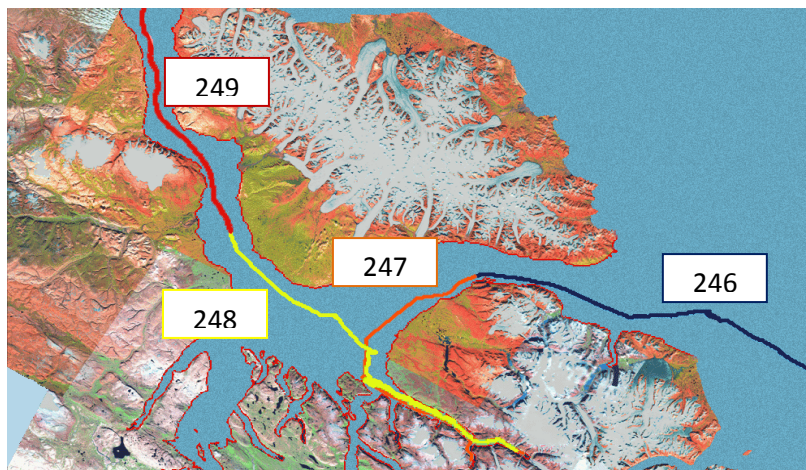


Figure 14: Navigation Track of CCGS Amundsen through the Model Domain (2006). Labels indicate day of the year and correspond to the horizontal axis in figure 15.

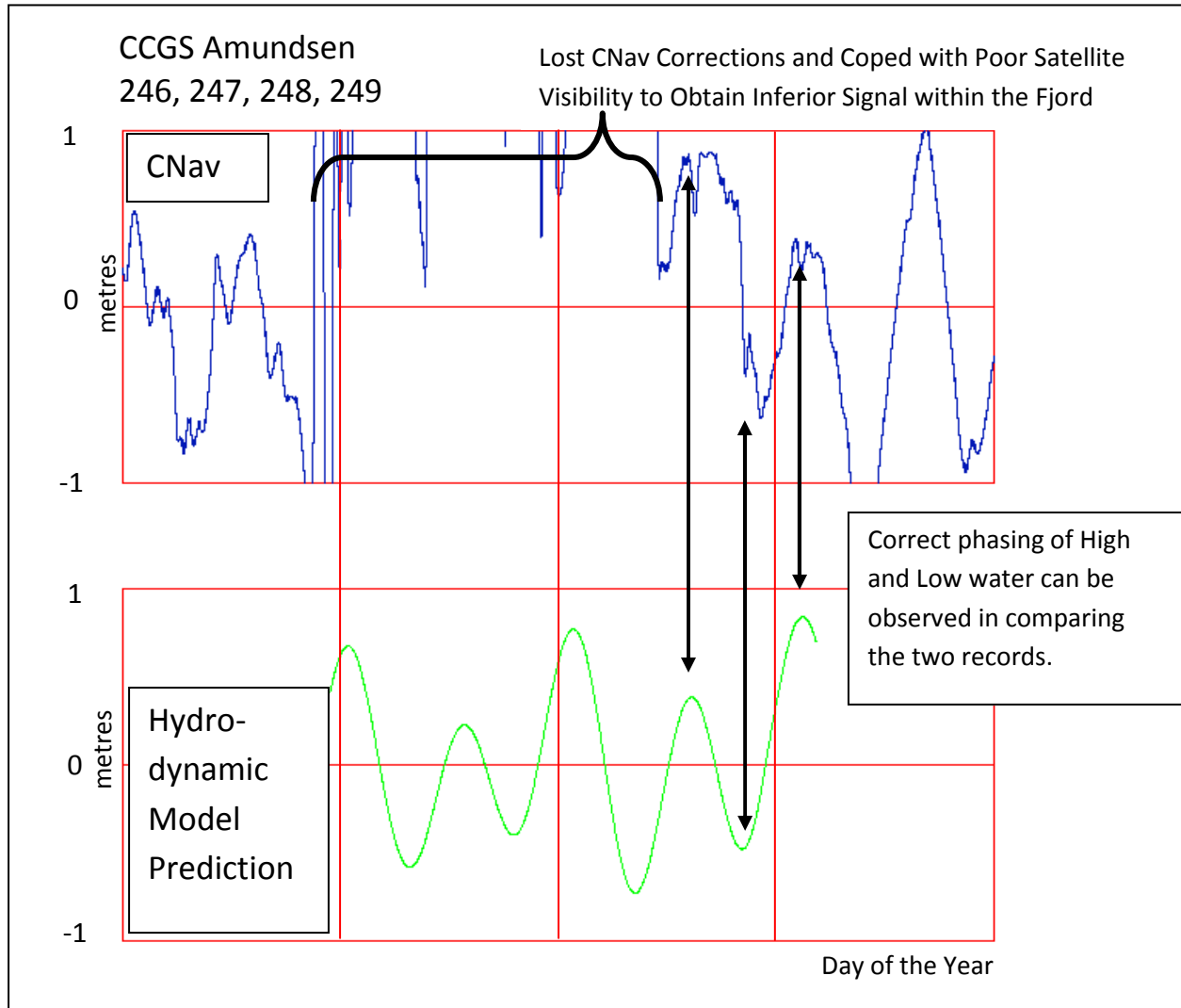


Figure 15: (Top) CNav elevation record for the 2006 Amundsen Ship track through figure 14, smoothed hourly. Elevations in the CNav record are above the Geoid using GPS-H Separation Model. (Bottom) Tide output following the 2006 Amundsen Ship Track through the developed hydrodynamic model.

CNav observations depict that the model interprets the phasing of high and low water correctly. The CNav observations continue outside of the model domain on day of the year 249, but the observations depict a mixed semi-diurnal tide with a very similar signature to the model tides.

Varying Vertical Datum

The shape and complexity of the narrow channels and fjords within the model domain cause variations in tidal phase and amplitude throughout the model. Therefore, using a single chart

datum based on historical tidal records in the region to reduce bathymetric data is not appropriate. A chart datum based on historical records at existing predicted tide stations will not sufficiently represent a level below which the tide rarely falls within the model domain.

A proposed solution is to use a modification of the Indian Spring Low Water as a vertical datum. The Indian Spring Low Water is a level for chart datum suggested by Sir George Darwin for Indian waters [Great Britain Hydrographic Office, 1969]. It is constructed by subtracting the sum of the amplitudes of the principal semi-diurnal and diurnal tidal harmonic constituents, M2, K1, S2 and O1, from Mean Sea Level.

A hydrodynamic model outputs tidal amplitudes for each input constituent at every node in the model mesh. The four major constituent amplitudes can then be summed to provide a value for the Indian Spring Low Water at each node within the hydrodynamic model. Therefore; instead of creating a vertical datum represented by a plane based on a single tide station, a constantly varying datum can be constructed for the entire survey area with the Indian Spring Low Water value at each node.

Tide Station	Pisiktarfik Island
M2 Amplitude	0.551 metres
S2 Amplitude	0.179 metres
K1 Amplitude	0.332 metres
O1 Amplitude	0.077 metres
Sum	1.139 metres
Chart Datum	1.262 metres
Multiplier	1.11

The Indian Spring Low Water chart datum should be related to the existing chart datum evaluated at the historic tide station for the area. A historic tide station must be selected within the model domain and the ratio between the Indian Spring Low Water chart datum at that station and the existing chart datum, lower low water large tide, should be determined. The resulting multiplier can be applied to the Indian Spring Low Water determination at each node within the model.

The result is a continuously varying chart datum, based on Indian Spring Low Water, which covers the entire model domain.

Table 2: Indian Spring Low Water and Chart Datum Separation Multiplier

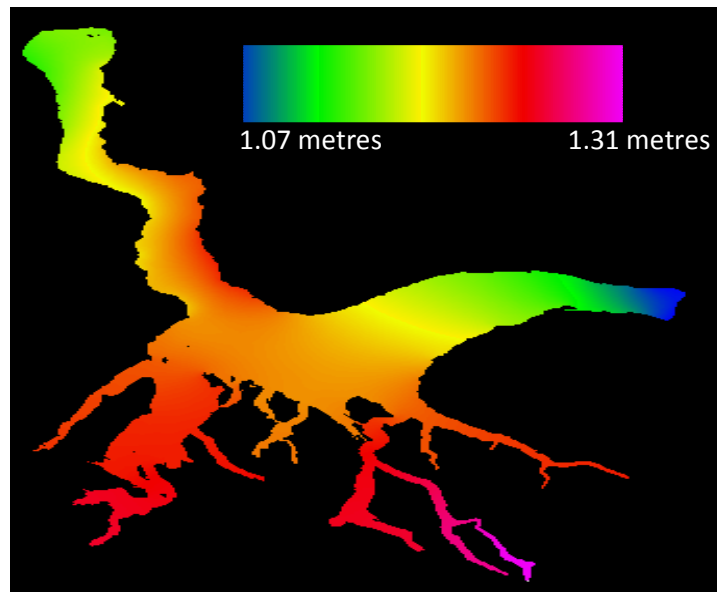


Figure 16: Modified Indian Spring Low Water Vertical Datum

Discussion

The initial hydrodynamic model results show that the phase and amplitude of the tides within the model are affected by the size and shape of the regional fjords. In figure 9, the resulting amplitude map for the M2 constituent, it can be seen that the maximum amplitude of the tide, for the entire model, exists within the fjords off Eclipse Sound. The fjords are not modeled in WebTide and are therefore ignored in the WebTide tidal prediction.

The WebTide model results may not provide adequate representation of the varying tides within the model region. The differences in phase and amplitude, for the M2 constituent, between the developed hydrodynamic model (Figure 9) and the WebTide model (Figure 4), within Eclipse Sound (Figure 17), show average differences of 12 degrees in phase and 0.05 metres in amplitude. A phase difference of 12 degrees equates to a time difference of 24 minutes for the M2 constituent. The differences most likely exist because of the low resolution bathymetric data used in the construction of the WebTide model. Bathymetric data used in WebTide was obtained from the International Bathymetric Chart of the Arctic Ocean (IBCOA) [Dunphy et al., 2005]. With a resolution of approximately 2.5 kilometres, the IBCOA bathymetry is insufficient for detection of some of the tremendous regional variations in the seafloor topography [Macnab, 2003]. The comparison of the S2 constituent between the developed hydrodynamic model and WebTide displays similar characteristics as the M2 constituent with a difference in phase of 7 degrees (14 minutes) and 0.02 metres. The output from the developed hydrodynamic model for the diurnal constituents, O1 and K1, are almost identical to the WebTide output. This suggests that the short wavelength semi-diurnal constituents are more affected by the increased resolution of the bathymetry and coastline.

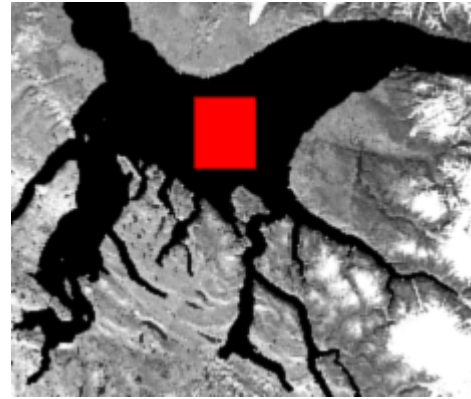


Figure 17: Hydrodynamic Model and WebTide Comparison Region

Comparisons with predicted tidal constituents, at the three CHS predicted tide stations, show confirmation of the model results in terms of the magnitude and phase of the tidal amplitudes (Table 1). The largest discrepancies exist in the phase difference for the M2 constituent between the predicted tide and the hydrodynamic model result. Peculiarities can be observed in examining the predicted phase for the M2 constituent between the three tide stations. The prediction implies that an 8 degree (16 minute) phase lag exists between Milne Inlet and Koluktoo Bay station and that the M2 tide reaches the Milne Inlet station 4 minutes before the Pisiktarfik Island station.

The CNav height record of the vessel demonstrates the proper phasing of high and low water for the hydrodynamic model tidal prediction. Examining the continuation of the CNav record outside of the model domain, for day of the year 249, demonstrates an apparent mixed semidiurnal tide, which is very similar to the mixed semidiurnal tidal signal constructed within

the model. Further analysis and an extension of the model into regions where CNav corrections were obtained should provide verification of the observed similarities.

The development of a spatially varying chart datum from a modification of the Indian Springs Low Water provides an improvement to the alignment of multiple datasets within the survey region and improves safety of navigation. It also compensates for the lack of tidal control within the large survey region. If the CHS chart datum established at Pisiktarfik Island were used throughout the model domain, it would under compensate for the level below which the tide rarely falls in some regions, especially within uncharted fjords. Differences between the CHS chart datum at Koluktoo Bay and the developed chart datum grow to approximately ± 0.25 metres in the Milne Inlet region for example. The spatially varying chart datum provides a smooth alternative to the traditional horizontal chart datum and is based off the model predicted tide for every region within the domain.

Conclusions

The development of a hydrodynamic model for the constricted waters behind Bylot Island has shown the effects of the narrow fjords, within the region, on the amplitude and phase of the tide. When performing a survey within one of the fjords, using tidal predictions outside of the survey area may not be sufficient to accurately represent the tidal modification caused by the nature of the fjord. The use of a nested finite-element hydrodynamic model, to predict the tides within the narrow fjords off Eclipse Sound, will allow for the removal of tidal artefacts within survey data. Comparisons between subsequent multibeam surveys, to monitoring changes in seabed characteristics, will then be possible.

As the construction of a hydrodynamic model for the constrained waters behind Bylot Island is a work in progress, a number of future research directions have been identified.

- Continue to run model simulations to obtain improved results.
- Examine model construction methods to simplify the process of developing a hydrodynamic model in other locations where similar limiting circumstances may exist.
- Attempt to install a tide gauge within one of the fjords to measure multiple tide cycles for comparison to model results. Obtain tide gauge data from CHS surveys performed in the region since the 1960's and compare to model results.
- Inspect overlapping survey lines within the region and reduce the survey data using hydrodynamic model predictions to check model accuracies.
- Consider the effects of non-tidal residuals in the area by examining atmospheric pressure gauge readings from Environment Canada at Pond Inlet or from measurements taken onboard the Amundsen.

Acknowledgements

The first author and the field component of this research (CCGS Amundsen and CSL Heron) have been supported by funding through the ArcticNet NCE (project 1.6, the opening NW Passage). The Heron reincarnation, the third author and OMG software development are all supported by the sponsors of the Chair in Ocean Mapping at UNB (U.S Geological Survey, Kongsberg Maritime, Royal (U.K.) Navy, Fugro Pelagos, Rijkswaterstaat and the Route Survey office of the Canadian Navy). CNav instrumentation was provided by C&C Technologies.

References

- Chaffey, J. D., and D. A. Greenberg (2003). "resolute: A Semi-Automated Finite Element Mesh Generation Routine." Canadian Technical Report of Hydrography and Ocean Sciences 225, Ocean Sciences Division, Bedford Institute of Oceanography, Department of Fisheries and Oceans, Dartmouth, N.S., Canada.
- Dunphy, M., F. Dupont, C.G. Hannah and D. Greenberg (2005). "Validation of a Modeling System for Tides in the Canadian Arctic Archipelago." Canadian Technical Report of Hydrography and Ocean Sciences, Ocean Sciences Division, Bedford Institute of Oceanography, Department of Fisheries and Oceans, Dartmouth, N.S., Canada.
- Earth Sciences Sector, NRCan, (2006). *Geogratis Datasets Search*. [On-Line] 10 August 2006. <http://geogratis.cgdi.gc.ca/geogratis/en/product/search.do?locate=true>
- Fisheries and Oceans Canada (2007). *DFO WebTide Tidal Prediction Model*. [On – line] 26 February 2007. <http://www.mar.dfo-mpo.gc.ca/science/ocean/coastalhydrodynamics/WebTide/webtide.html>
- Geodetic Survey Division, NRCan, (2004). *The GPS-H v2.01*. [On-Line] 5 March 2007. http://www.geod.nrcan.gc.ca/software/gpsht_e.php
- Great Britain Hydrographic Office (1969). "Tides and Tidal Streams." Chapter Two in *Admiralty Manual of Hydrographic Surveying*, Vol. 2, Somerset, England, 118pp.
- Hughes Clarke, J., P. Dare, J. Beaudoin, and J. Bartlett (2005). "A stable vertical reference for bathymetric surveying and tidal analysis in the high Arctic." Proceedings of the United States Hydrographic Conference 2005, San Diego, California.
- Ip, J. T. C., and D. R. Lynch (1995). "Comprehensive Coastal Circulation Simulation using Finite Elements: Nonlinear Prognostic Time-Stepping Model." Thayer School of Engineering, Dartmouth College, Hanover, New Hampshire, U.S.A.

Macnab, R. (2003) *IBCAO Version 1 – 2001*. International Oceanographic Commission (IOC) and the International Hydrographic Organization (IHO) [On-Line] 1 April 2007. <http://www.ngdc.noaa.gov/mgg/bathymetry/arctic/ibcaoversion1.html>

Ocean Processes Numerical Modeling Laboratory (2005). *OPNML User's Guide*. University of North Carolina at Chapel Hill, Department of Marine Sciences. [On-line] 5 December 2006. http://www.opnml.unc.edu/OPNML_USERS_GUIDE/OUG_driver.html

Roscoe Hudson, J., and T. Sharp (2001) "Globally Corrected GPS (GcGPS): C-Nav GPS System." *Proceedings of the Dynamic Positioning Conference*, Houston, Texas, U.S.A.

Wert, T., P. Dare, and J. Hughes Clarke (2004). "Toward Real-Time Tides from C-Nav GPS in the Canadian Arctic." Paper submitted to the ION GNSS 2004 Conference, Long Beach, CA., U.S.A., 21-24 September.