

**Developing Strategies to Facilitate Long Term Seabed Monitoring in the Canadian Arctic
using Post Processed GPS and Tidal Models**

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Abstract

As international shipping, interests in commercial activities and resource development increase in the Canadian Arctic, the impact of these stresses on the local environment must be monitored. The capability exists to repeatedly survey areas of interest using multibeam sonar, in an effort to detect changes over time and identify potential geohazards. The difficulty is that temporal changes in the seabed morphology are often hard to detect and measure due to complexities in the local tidal regime and inherent errors in high latitude GPS observations.

The head of the Oliver Sound fjord, on northern Baffin Island, was surveyed in September of 2006 using the Ocean Mapping Group's survey launch, the Heron, with an EM3002 and CNav Globally Corrected GPS. The head of the fjord was then resurveyed in September of 2008, again with the Heron. Changes in the seabed morphology are evident, but quantifying these changes requires improvement of the horizontal and vertical GPS positioning solutions. Steep fjord walls and the latitude of the site, at 72 degrees north, present conditions which obstruct the view of geosynchronous CNav correction satellites and the majority of the GPS constellation. Lack of tidal information at the head of the sound also results in a source of sounding error and prevents subsequent surveys from being compared and analyzed.

Methods of improving the external sources of error of GPS positioning and tidal influences have been investigated using post processed positioning solutions, such as PPP and PPK, and hydrodynamic tidal models. This will allow for detection of decimetre level changes in the seabed morphology and successful long term monitoring projects utilizing the capability and resolution of the available multibeam systems. With accurate geoidal models the post processed GPS can also be used to validate the amplitude and phase of local hydrodynamic models.

Introduction

The increasing melt of Arctic glaciers and decreasing sea ice coverage is transforming the Arctic landscape. A number of long term monitoring projects have been initiated on and off shore to determine the effects of the changing climate on the coastal environment. The Ocean Mapping

Group, at the University of New Brunswick, has been involved with collecting and analysing bathymetric data in the Arctic since 2003, as a partner in the Arcticnet research program. In 2006, a long term monitoring project begun in Oliver Sound, a fjord located in Sirmilik National park on the northern tip of Baffin Island Canada as shown in figure 1. A number of glaciers terminate in Oliver Sound and it is in these areas that change is predominantly occurring. The goal of the project is to determine changes to the local ecosystem over time, specifically at the site of the main glacial delta at the head of the fjord.

In 2006 multibeam surveys were performed from the CCGS Amundsen, Canada's primary Arctic mapping platform, and the Heron, the Ocean Mapping Group's survey launch, at the monitoring site in Oliver Sound [Bartlett et al., 2004]. The CCGS Amundsen is a 97 metre, 1200 class icebreaker which has been converted for scientific operations and was equipped with a Simrad EM300 30 kHz multibeam sonar, a 3.5 kHz sub-bottom echosounder and a MVP-300 Sound Velocity Profiler [Bartlett et al., 2004]. The Heron is 10 metre survey launch and is equipped to survey the shallow Arctic coastal 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.

In 2008 the Heron returned to Oliver Sound, thanks to the Canadian Hydrographic Service and Canadian Coast Guard, onboard the CCGS Henry Larsen. The 2006 study area was resurveyed, using the Heron's EM3002 multibeam system. A glacial delta in Navy Board Inlet was also surveyed in 2008 by the Heron to provide baseline information for a new monitoring site.

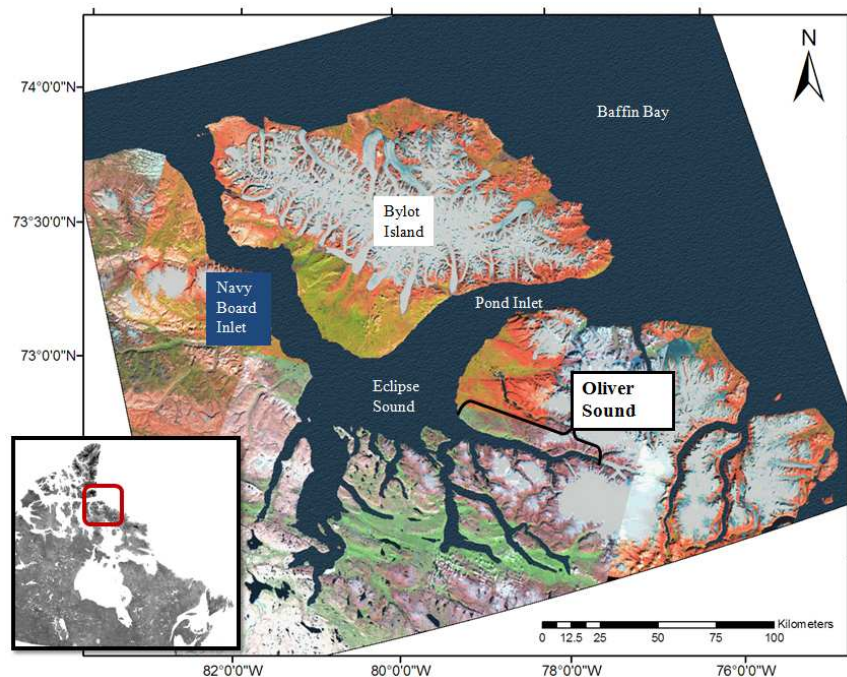


Figure 1 - Long Term Monitoring Project Area

For comparisons to be constructed between the 2006 and 2008 survey datasets in Oliver Sound, large systematic errors associated with the bathymetry must be removed. To achieve this objective, tidal control needs to be established to provide knowledge of the tidal regime and horizontal positioning errors must be minimized. Achieving these objectives is hindered by the logistics, time constraints and challenges of working in a remote Arctic environment.

GPS Positioning in the Canadian Arctic

There are a number of difficulties in using GPS for three dimensional positioning while working in the Arctic. At high latitude sites, such as Oliver Sound, the GPS constellation geometry is not optimized to provide the best solution. Due to the inclination in the polar orbit of the GPS satellites they will never appear directly overhead and will rest mainly on the horizon which results in poor satellite geometry and reduced visibility while working in areas of rough topography. An aided or post processed GPS solution is required to obtain positioning accuracies this would allow for decimetre level changes in seabed morphology to be detected.

The Amundsen and the Heron were both equipped with CNav GPS systems for the 2006 and 2008 surveys. The CNav system, by C&C Technologies, provides Real Time Gypsy (RTG) corrections to the vessel through geosynchronous satellites [C & C Technologies, 2008]. Under ideal conditions the CNav GPS system will provide decimetre level horizontal accuracies as long as corrections are received from the satellites [Wert et al., 2004]. When working in fjords, such as Oliver Sound, the steep walls can block the CNav corrections from reaching the vessel, which puts the GPS receiver back into traditional single point mode. In Oliver Sound, the CNav corrections are rarely received as the fjord runs predominantly east-west and the fjord walls can reach over 1 kilometre in height completely blocking the northern and southern skies.

The CNav RTG GPS alone is not sufficient to detect decimetre level changes in the seabed at the survey site within Oliver Sound when corrections are not received. Post processed GPS solutions have been investigated to achieve this goal. Post processing can be done using the raw dual frequency GPS observations that were collected during the 2006 and 2008 surveys from the CNav GPS. Two types of post processed solution were investigated; Precise Point Positioning (PPP) and Post Processed Kinematic (PPK) differential positioning. PPP is a method of post processing GPS data using measured satellite clock and orbit corrections which can be obtained through a variety of agencies, such as the International GNSS Service (IGS), to minimize satellite orbit and clock errors. This method does not require the use of a second receiver and works in a kinematic setting. PPK requires multiple receivers, with one at a known fixed location, observing the same satellites at the same time as the roving receiver. PPK is otherwise known as differential positioning as the satellite orbit and clock and receiver clock errors are essentially eliminated through differencing. PPK processing also eliminates a major component of the tropospheric error [Waypoint Products Group, 2008]. In this survey area PPK baselines will extend beyond the ideal limit of 10 km and a floating ambiguity solution is used [Santos et al., 2004].

Setting up a base station to attempt PPK GPS in remote locations, such as Oliver Sound, can be extremely difficult. The weather conditions and tremendous topographic variations inhibit reaching locations suitable for stable antenna installations. For the 2008 surveys, GPS base station data was obtained from the nearby community of Pond Inlet (70 km from the Oliver Sound survey site) for testing of a PPK solution. The base station was setup in 2008 as part of the

Canadian High Arctic Ionospheric Network (CHAIN) whose purpose is to study the Solar Wind-Magnetosphere-Ionosphere coupling within the Canadian Arctic using GPS and ionosonde technology [Jayachandran et al., 2009]. The CHAIN GPS data includes 1 Hz Rinex GPS files for each of their base stations and is freely available for download through their website (<http://chain.physics.unb.ca/chain/>).

GPS data processing was performed primarily using Waypoint GrafNav, a GNSS post-processing package that computes PPP and PPK differential solutions developed by Novatel. Data was imported in Rinex format and text files were output for analysis in Ocean Mapping Group software.

Tidal Information

Bathymetric surveys from multiple years must be related to a common vertical datum for comparison. As vertical accuracies with GPS are still upwards of 3 times worse than horizontal, especially with the majority of the GPS satellites sitting close to the horizon at the working latitude, it would not be possible to achieve the decimetre level vertical accuracy requirement using GPS alone. Therefore, any deviations in the survey data from Mean Sea Level (MSL) must be determined and removed from the dataset. This can include the water level information, which predominantly comprises tides and the inverse barometer effect; vessel squat and heave artefacts. The tidal influence is the major component of the data to be removed to allow comparisons.

Tidal control is sparse, at best, within the Canadian Arctic and reaching the ageing tidal benchmarks to set up a gauge can be time consuming and hazardous. At the Oliver Sound survey site the nearest vertical benchmark, at Pisiktarfik Island, is over 100 kilometres away and the amplitude and phase modification of the tidal wave as it propagates between deltas and up the fjord is unknown.

Water level data had not been collected during either the 2006 or 2008 surveys due to time restraints and restrictions in safely accessing a suitable setup location. An alternative was required to account for water level changes. Predicted tides exist at the Pisiktarfik Island benchmark just over 100 kilometres from the survey site, but the tidal constituents which make up the predicted tide were developed from just 15 days of data in the 1960's and the reliability of the data is unknown. Predicted tides could also be obtained from the WebTide tidal prediction interface which accesses a hydrodynamic model entitled Arctic8c which covers the entire Arctic Archipelago [Dunphy et al., 2005]. The problem with using the Arctic8c model is that resolution of the model is not sufficient to delineate the fjords in the survey region. The effects of the fjord and nearby islands on the tide as it reaches the head of the fjord are unknown. A new hydrodynamic circulation model was developed to encompass the Oliver Sound fjord and surrounding regions nested within the Arctic8c grid [Church, 2008]. It provides the resolution required to observe alterations to the tidal wave as it propagates up the narrow fjords and is

entitled the Bylot model. Figure 2 shows the extents and M2 tidal amplitude of the Arctic8c and Bylot models within the survey area.

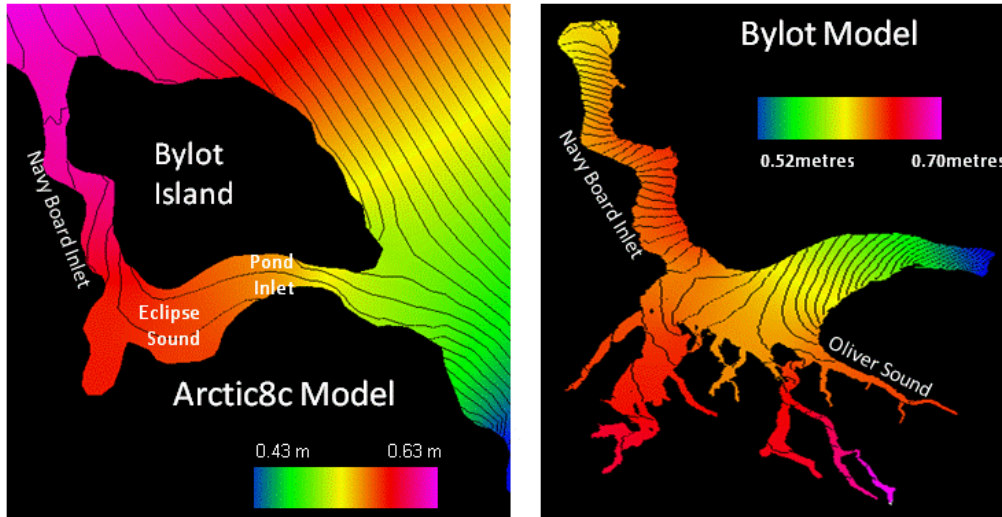


Figure 2 – Arctic8c and Bylot Model Extents and M2 Tidal Amplitude

Post processed CNav data (PPP) from a search and rescue mission completed by the Amundsen in 2008 was used to investigate the validity of the Arctic8c and Bylot models within the Eclipse Sound region, an area common to both models. In order to compare the height record from the CNav GPS to the output of a tidal model, the geoid-ellipsoid separation must be accounted for. The EGM08 separation model was used to relate the GPS observations from the Amundsen to the geoid. The geoid-ellipsoid separation is complex in this region and has a steep slope. Figure 3 shows the separation throughout the survey area, which ranges from 10 metres below the ellipsoid to 12 metres above the ellipsoid.

As the separation model is crucial in comparing the height record from the CNav GPS to the output of the hydrodynamic tidal model, alternate methods of establishing this relationship will be investigated in upcoming surveys. A simple GPS buoy is under construction which can be quickly and easily installed in the survey area. This will provide water level information during a

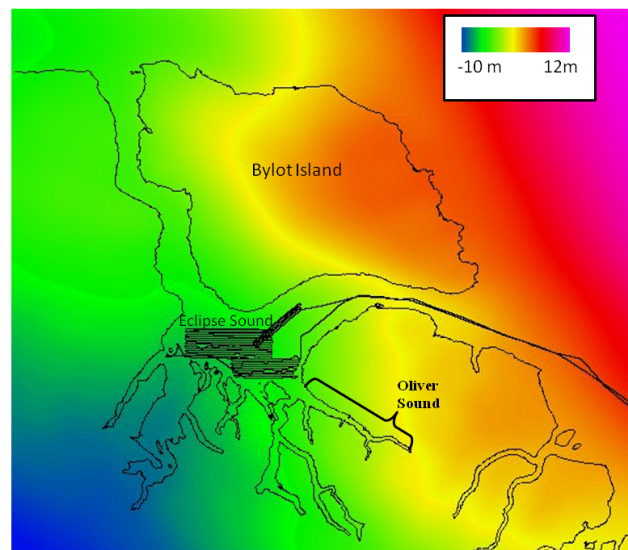


Figure 3 – EGM08 Geoid-Ellipsoid (WGS84) Separation with 2008 Amundsen Search and Rescue Navigation Track

survey and when installed for an extended period of time will provide information on the local geoid-ellipsoid separation.

The second component to the water level data is the inverse barometer effect. This is the affect of the changing atmospheric pressure on the water level. Atmospheric pressure data observed hourly at Pond Inlet by Environment Canada was used to calculate the inverse barometer effect which was then removed from the GPS height record of the Amundsen.

Squat effects were also removed using a squat model defined for the Amundsen in Hughes Clarke et al., (2005).

With the effects of the geoidal deviations from the ellipsoid, atmospheric pressure and squat removed from the Amundsen height record it could then be compared to the output of the Arctic8c and Bylot hydrodynamic models, as shown in figure 4. The figure shows that within Eclipse Sound, either the Arctic8c or Bylot models follow the tidal signature outlined by the PPP GPS solution from the Amundsen, but there are still low and high frequency undulations which are not being accounted for. High frequency effects are likely from noise in the PPP solution and the low frequency effects could be from errors in the EGM08 separation model or a low frequency tidal constituent not accounted for in the models.

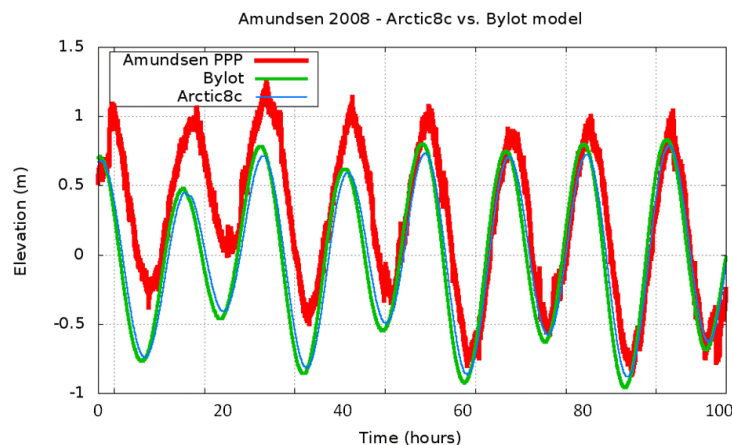


Figure 4 – Amundsen GPS vs. Arctic8c and Bylot Models

Navy Board Inlet

The Navy Board Inlet survey site is a new monitoring project area with only the baseline multibeam bathymetric survey completed in 2008. At this site a PPK GPS base station was setup on a nearby ridge less than 10 kilometres from the survey site. The Heron was logging CNav RTG GPS solutions during the survey and a comparison can therefore be made between the original RTG solution and post processed PPP and PPK solutions.

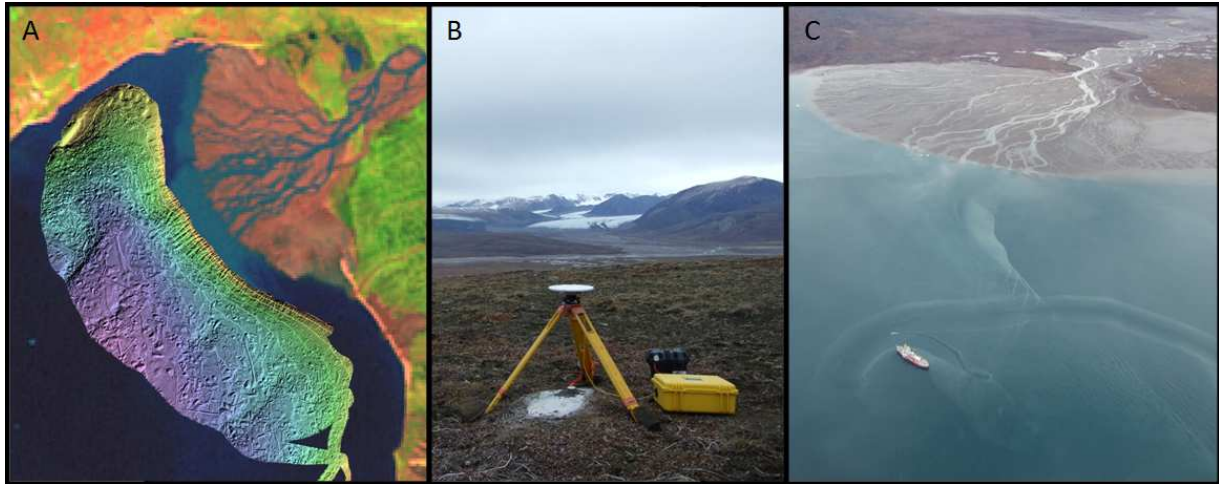


Figure 5 – Navy Board Inlet A) Multibeam Grid B) PPK GPS Basestation C) Delta

Figure 5 shows the resulting bathymetric grid, the basestation setup and an aerial view of the delta. The grid shows that the region is heavily influenced by iceberg scours in the deeper waters and erosion and accretion closer to shore. The Navy Board inlet survey site is different from the Oliver Sound site in that it is in an open environment and there are no obstructions to block the view of either the GPS constellation or the CNav geosynchronous correction satellites.

Figure 6 shows the CNav RTG GPS elevation during the Navy Board inlet Survey with the PPP solution. At this site the CNav RTG solution is very similar to the PPP solution, but there are a number of spikes present in the RTG solution that do not appear in the smoother PPP solution and RTG is noticeably noisier than the PPP solution.

A comparison between PPP and PPK is shown in figure 7. The PPP and PPK solutions are very similar although the PPK solution is less noisy than the PPP result. The standard deviation associated with the PPP and PPK solutions with respect to the vertical and horizontal direction is shown in figure 8. While the standard deviation of the PPP solution is almost twice that of the PPK solution, it is still generally within 10 cm in the horizontal direction and 20 cm in the vertical. The increase in standard deviation for the horizontal and vertical solutions, in figure 8, at the 1 and 3 hour marks correspond to a drop in the number of visible satellites during that time period from 9 to 7 as shown in figure 9.

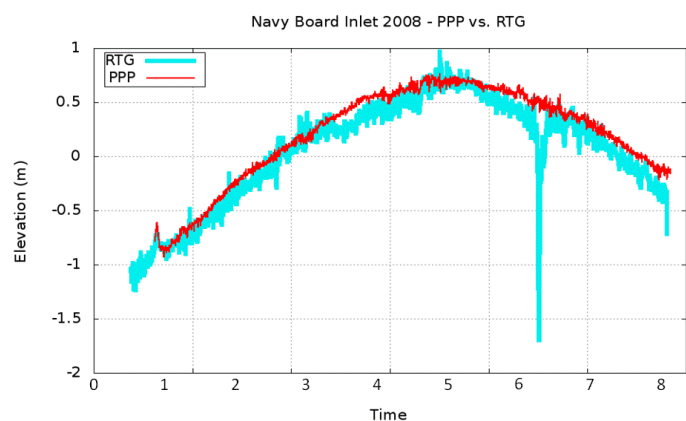


Figure 6 -- CNav RTG and PPP Solutions in Navy Board Inlet

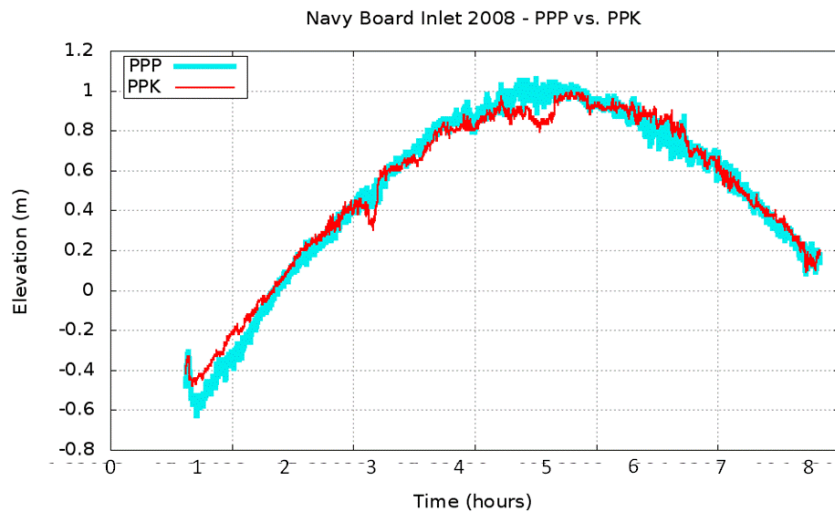


Figure 7 – PPP and PPK Solutions in Navy Board Inlet

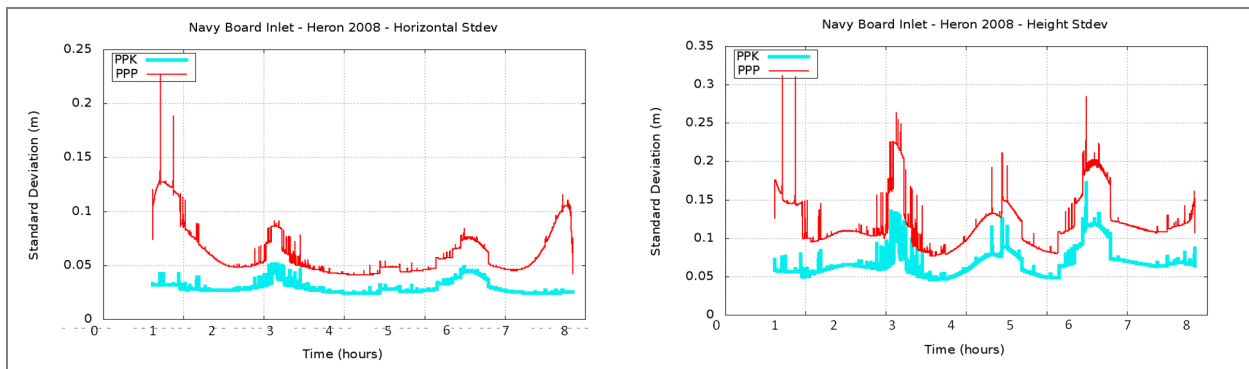


Figure 8 -- Horizontal and Vertical Standard Deviation at Navy Board Inlet

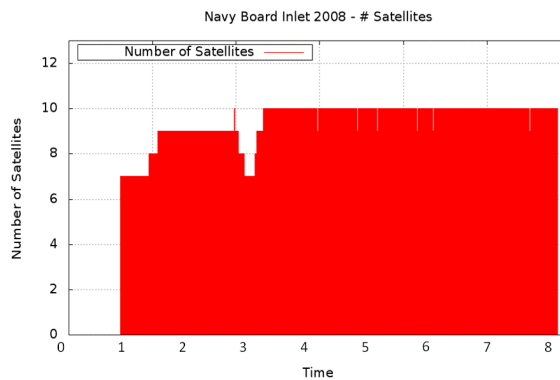


Figure 9 – Number of Visible GPS Satellites at Navy Board Inlet

Oliver Sound

In 2006 the Heron did the initial survey of the head of the Oliver Sound Fjord. In 2008 it returned and resurveyed the area to observe changes in the seabed morphology. The glacial terminus which sits at the head of the sound originates from the Oliver Ice Cap and inputs fresh water to the survey area. This fresh water stream alters the near shore seabed and, as the glacier recedes, creates a coastal delta. Changes in the seabed at the base of the delta over time can indicate the strength of the melt water flow and the location of the principal channel within the delta.

The processing strategy with the 2006 and 2008 Heron data was to use GPS for horizontal positioning and predicted water levels for vertical. The predicted water level includes the tides from a hydrodynamic tidal model and the inverse barometer effect from nearby atmospheric pressure gauges. This strategy allows for traditional errors associated with GPS to be present only in the horizontal solution.

The main obstacle to surveying within the Oliver Sound fjord is the steep fjord walls which restrict the view of the CNav and GPS satellites. Figure 10 shows the original vertical RTG and PPP solutions for the Heron from 2006 and 2008. The 2006 RTG solution varies in the vertical by over 30 metres and by over 10 metres in 2008. As can be noted in figure 10, the PPP solution is much improved over the original RTG solution.

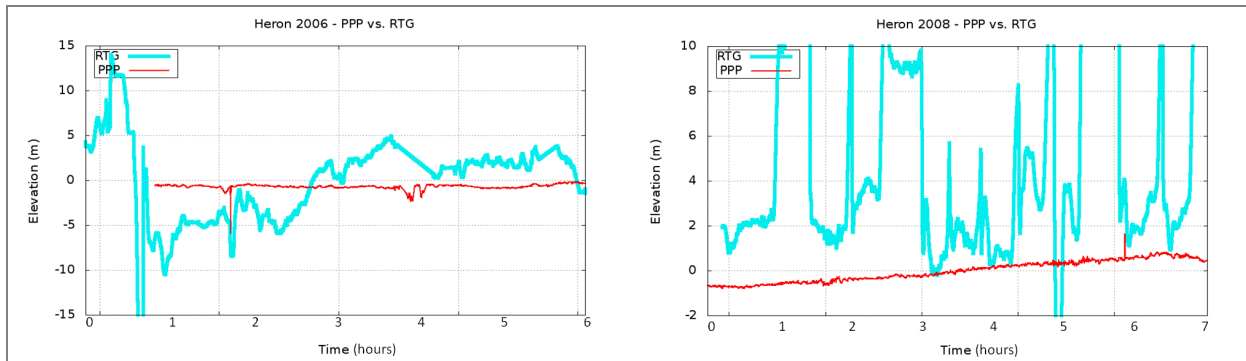


Figure 10 -- Heron 2006 and 2008 RTG vs. PPP

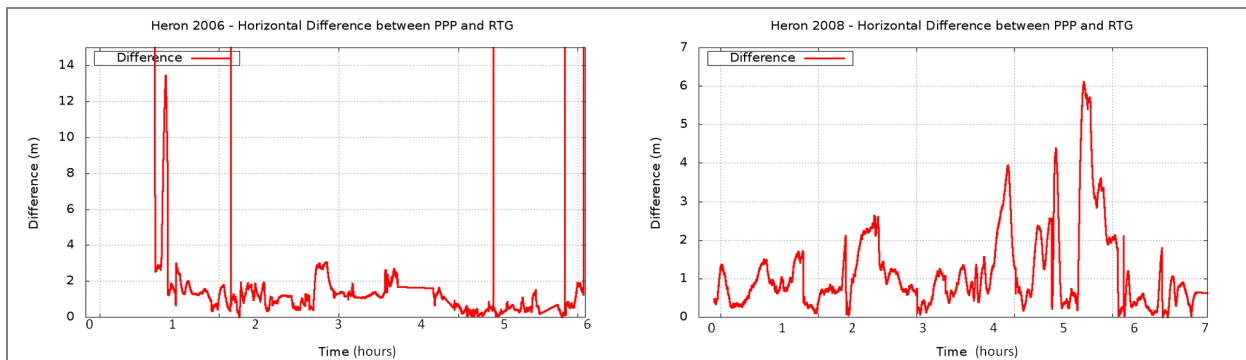


Figure 11 – Horizontal Difference between PPP and RTG Solutions at Common Epochs for 2006 and 2008

The horizontal distance between positions processed with PPP and the original RTG solutions at a common epoch is shown in figure 11 for the 2006 and 2008 surveys. The 2006 data exhibits horizontal differences up to 13 metres at the beginning of the time series with the remainder less than 4 metres. Differences reach a magnitude of 6 metres for the 2008 survey.

A PPK solution was also constructed for the 2008 survey using the Pond Inlet CHAIN GPS basestation, at approximately 70 kilometres from the survey site. After examining the GPS height record for both the long range PPK solution and the PPP solution, in figure 12, it was determined that PPP provided a smoother more precise solution over the PPK.

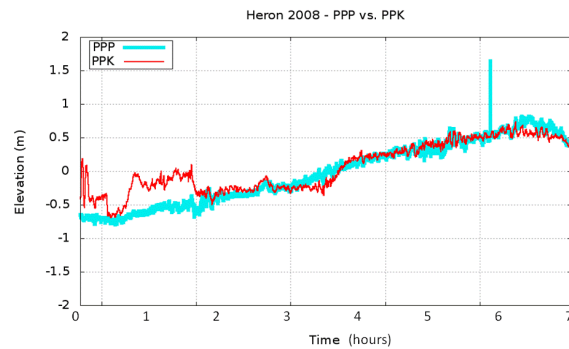


Figure 12 – Long Range PPK vs. PPP for Heron 2008 Survey

The difference between the 2006 and 2008 bathymetric grids was first constructed using the multibeam bathymetry collected with CNav RTG GPS positioning. The result of this comparison is shown in figure 13. The figure shows that there is a large variation in the seabed along the top right edge of the grid which follows the ship track and indicates a swath positioning problem. Smaller variations throughout the figure, with differences larger than 1 metre, are also present at many of the seafloor undulations. The edges of the fjord basin are steep and any horizontal positioning error will translate to an apparent error in a vertical direction which accounts for the strip along the top right of the figure. It is very difficult to determine from figure 13 which features within the difference map are due to accretion or erosion and which are a result of horizontal positioning errors.

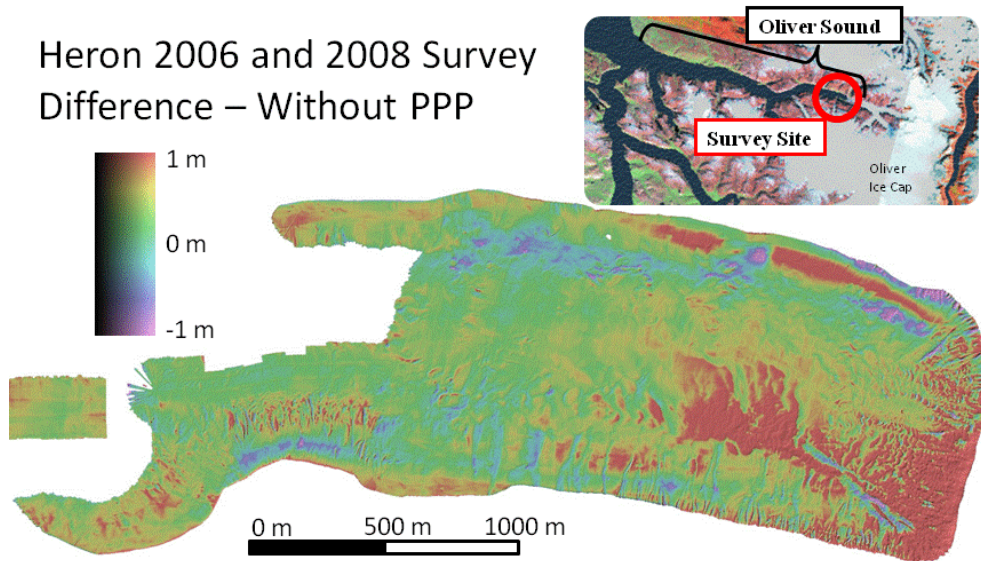


Figure 13 – Difference between 2008 and 2006 Heron Multibeam Surveys Positioned using RTG

The 2006 and 2008 grids were also differenced using the PPP solution, as shown in figure 14. This difference map shows that the linear feature in the top right of the grid, along the steep slope at the edge of the fjord basin, has been removed as have many smaller features throughout the grid. This indicates that many of the difference features shown in figure 13 are the result of horizontal positioning errors from using the original RTG solution during processing.

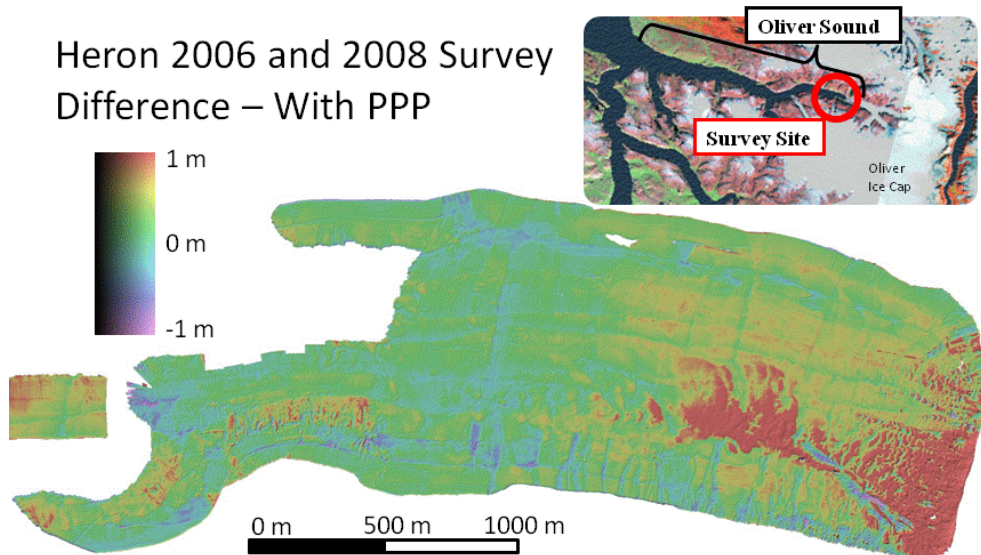


Figure 14 – Difference between 2008 and 2006 Heron Multibeam Surveys Positioned using PPP

Figure 14 shows how the seabed has changed over the 2 years between the multibeam surveys. The major feature within the difference grid is the addition of sediment at the head of the fjord, at the right side of the grid, and the mound of sediment in the centre of the fjord basin. The centre mound is over 2 metres higher than it was in 2006 while the additional sediment at the head of the fjord reaches over 7 metres.

Conclusions

One can now infer the most active face of the delta, the manner of slope progradation, the extent of erosion of the main channel and the central location of distal deposition from repeat multibeam surveys using GPS and tidal models in remote locations thanks to advancements in PPP and PPK GPS. If conditions enable the installation of a GPS basestation within 10 km of the survey site, as in the Navy Board Inlet survey, then PPK is likely the best option for positioning, otherwise PPP out performs PPK in long range applications, as shown in the Oliver Sound survey. PPP also eliminates the time, resources and risks associated with establishing a PPK basestation. PPP GPS solutions were sufficiently accurate to remove the majority of the positioning errors in the 2006 and 2008 Oliver Sound surveys in conjunction with hydrodynamic tidal models.

High resolution hydrodynamic tidal models are facilitating the construction of predicted tides in remote areas. Predicted tides are sparse throughout the Arctic and modifications to the tidal wave between stations are unknown. Tidal models help determine these alterations especially in complex coastal regions. As the precision of post processed GPS continues to improve, bathymetric data at long term monitoring sites will likely be related to either an ellipsoidal or geoidal datum rather than MSL, but today tidal models continue to provide the best solution when working with noisy vertical positioning data in remote regions. Validation of tidal models continues to evolve and the future applications of easily deployable GPS buoys to measure water levels will further improve modelling efforts.

The bathymetric grids from the 2006 and 2008 surveys at the head of the Oliver Sound fjord could not have been reliably compared without the use of a post processed GPS solution and hydrodynamic tidal models. The post processed GPS grid comparisons can be used to determine areas of erosion and accretion along with quantitative volumes of sedimentation. Future surveys at the Oliver Sound and Navy Board Inlet sites, and others throughout the Canadian Arctic, will allow for further testing and refinement of GPS processing methods and tidal model implementations.

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