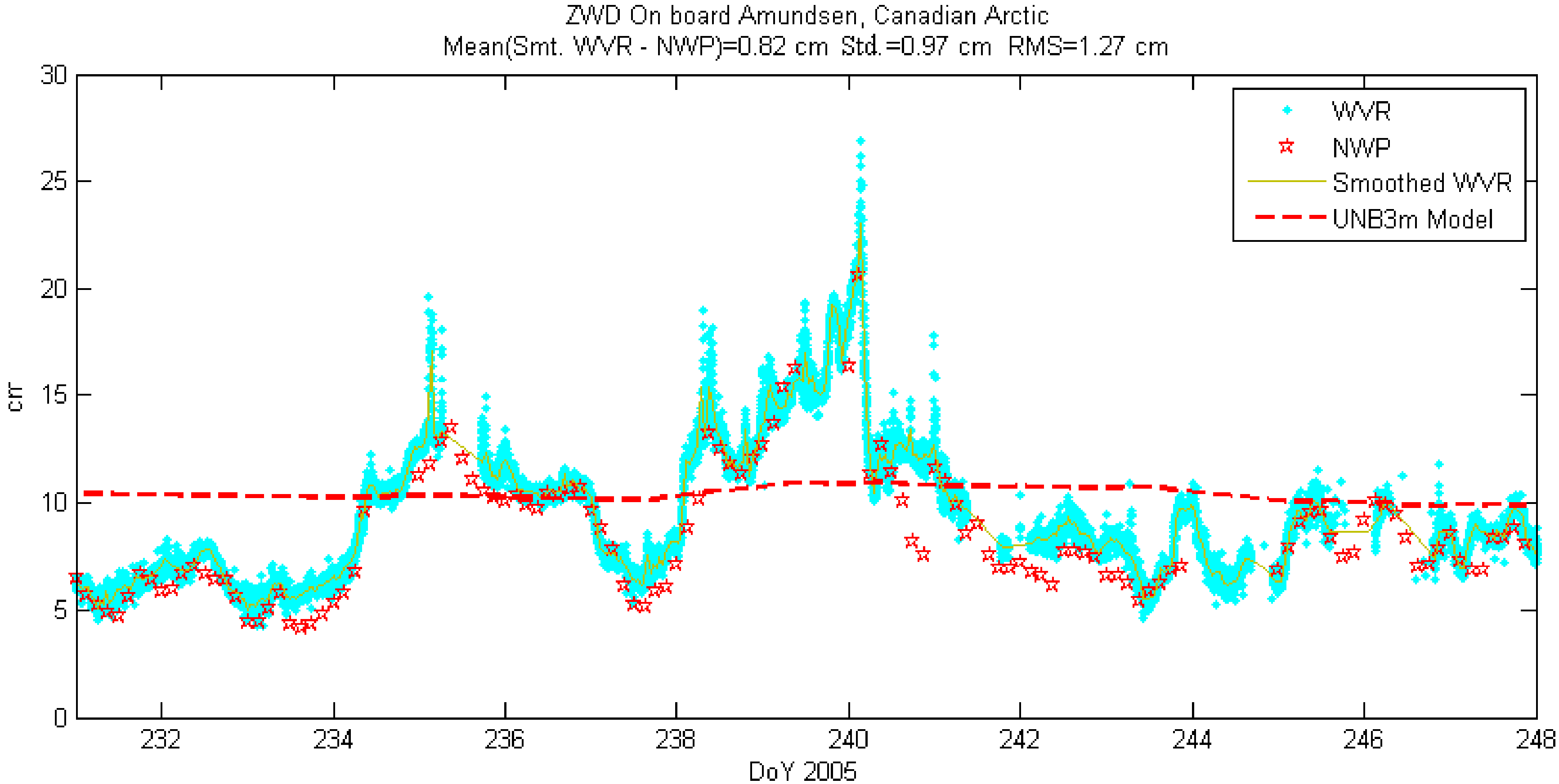
Measurements, Water Vapour Radiometer, and applications

Presented at the UNB workshop on Numerical Weather Models for Space Geodesy Positioning

October 24-25, 2011

Peter Dare

- The water-vapour radiometer delivers an atmospheric path-length correction based on integrated water vapour.
- Variable azimuth and altitude



ZWD On board Amundsen, Canadian Arctic
Mean(Smt. WVR - NWP)=0.82 cm Std.=0.97 cm RMS=1.27 cm
WVR
NWP
Smoothed WVR
UNB3m Model
cm
DoY 2005
0
5
10
15
20
25
30
232
234
236
238
240
242
244
246
248

- A **radiosonde** is a unit for use in weather balloons that measures various atmospheric parameters and transmits them to a fixed receiver.
- Modern radiosondes measure or calculate the following variables:
  - Pressure
  - Altitude
  - Geographical position (Latitude/Longitude/Height)
  - Temperature
  - Relative humidity
  - Wind (both wind speed and wind direction)
- Typically to altitudes of approximately 30 km
- http://www.youtube.com/watch?v=jGQWUFEMxT8
- http://www.youtube.com/watch?v=oPf-4XsxQlg

ION paper

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Comparing Various GPS Neutral Atmospheric Delay Mitigation Strategies: A High Latitude Experiment

Reza Ghoddousi-Fard and Peter Dare
Geodetic Research Laboratory, Department of Geodesy and Geomatics Engineering
University of New Brunswick

BIOGRAPHY

Reza Ghoddousi-Fard is a Ph.D. student at the University of New Brunswick (UNB). He obtained a B.Sc.E. in Geomatics and a M.Sc.E. in Geodesy in 1995 and 1999 respectively from K.N.Toosi University of Technology, Tehran, Iran. He has been involved in Geomatics projects since 1995. His current research focus is on GPS meteorology in the Canadian Arctic.

Peter Dare is the Chair of the Department of Geodesy and Geomatics Engineering at UNB. He obtained a B.Sc. (Hons) in Land Surveying Sciences from North East London Polytechnic in 1980, an M.A.Sc. in Civil Engineering from the University of Toronto in 1983 and a Ph.D. in Geodesy from the University of East London in 1996. He joined UNB in 2000 and became the Chair of the Department in 2002. He was elected a Fellow of the Royal Institution of Chartered Surveyors (RICS) in 2000.

ABSTRACT

Numerical Weather Prediction (NWP) models have been used by researchers for neutral atmospheric delay mitigation on GPS measurements. However, in high latitude regions, the performance of both NWP and GPS may be degraded. Lack of enough meteorological sensors in the Arctic may affect initialization of NWP models. The need for using low elevation satellites and hence increasing the associated errors may also be the consequence of the problematic GPS constellation in high latitude regions.

During the 2005 Canadian research icebreaker CCGS Amundsen's mission in the Arctic an experiment was carried out to investigate the performance of the Canadian regional NWP model both in observation and position domains. Wet delay measurements using a Water Vapour Radiometer (WVR), surface pressure measurements from a precise barometer, and data from geodetic quality GPS receivers (including C-Nav) were recorded during most of the sailing. Zenith hydrostatic and non-hydrostatic delays from the NWP model are compared with the WVR and barometer measurements. Long baseline kinematic positioning performance under various neutral atmospheric mitigation strategies such as field measurements, climatic and NWP models are investigated.

INTRODUCTION

There have been a number of strategies developed to deal with the neutral atmosphere delay on GPS signals including:

- Using an a priori tropospheric model with surface meteorological measurements or climatic based meteorological look up tables
- Estimation of the tropospheric delay as an extra unknown in the GPS processing procedure
- Retrieving refractivity profiles and tropospheric delay estimation (zenith or slant) from a NWP model
- Using a WVR to measure the slant or zenith wet delay and estimate the zenith hydrostatic delay using surface pressure measurements.

Estimation of tropospheric delay in GPS processing is a common practice in static scenarios with long observation periods. However, in kinematic scenarios (where the solutions are usually required for every epoch), the positioning results might be significantly affected by uncertainties in the a priori tropospheric model. In these cases, considering the tropospheric delay as an extra unknown may degrade the positioning solution due to the lack of enough redundancy.

WVRs have been used as a device for validation of other sensors and methods in wet delay estimation. NWP models for assisting GPS processing have also been

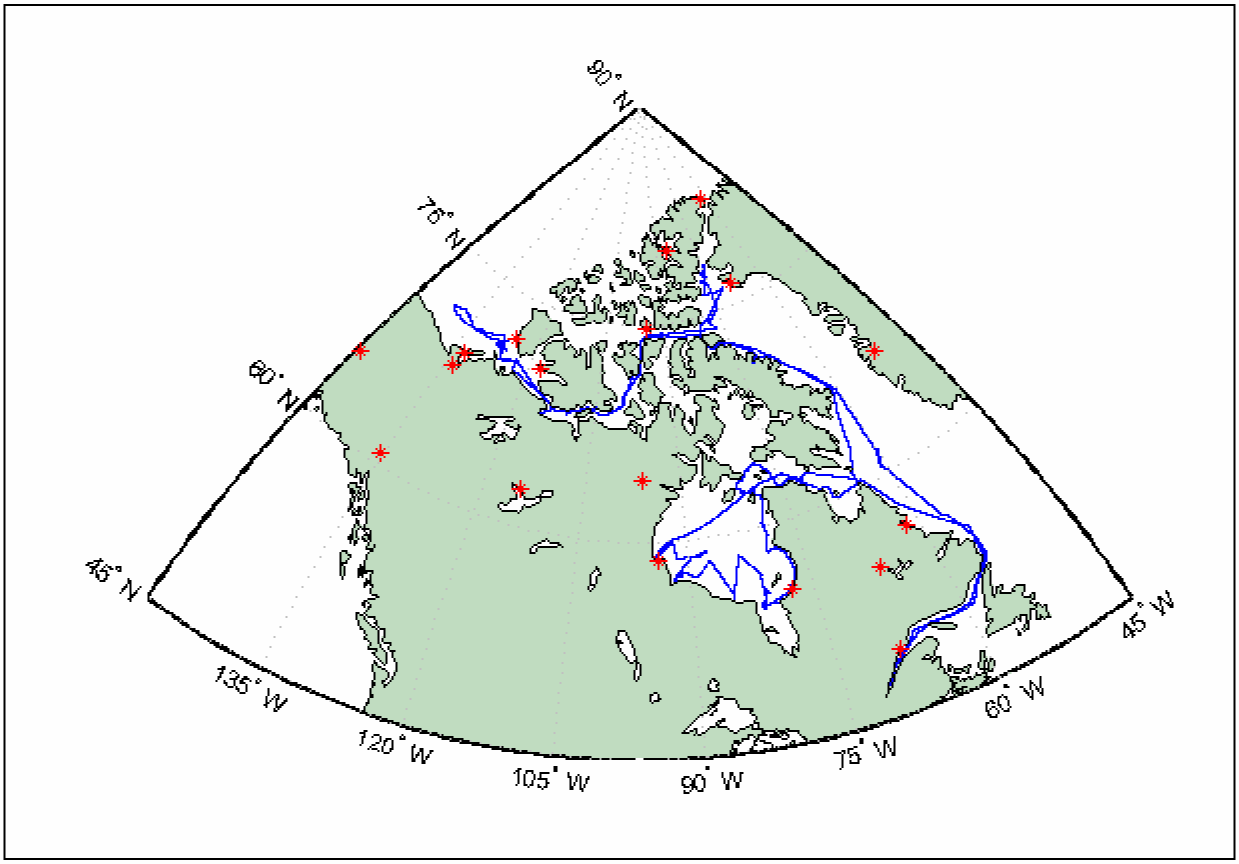

Figure 1- Amundsen expedition track on her 2005 mission. Stars show the location of GPS stations.

investigated by several researchers in recent years. While the effectiveness of NWP models in tropospheric delay mitigation has been shown by researchers in some experienments, (see e.g. Jupp et al. [2003], Cucurull et al. [2002] and Hann and Marel [2004]) these should be validated in the Arctic as the lack of sufficient initial data might degrade the performance of NWP models.

During the 2005 Canadian research icebreaker (CCGS Amundsen) mission in the Canadian Arctic and Hudson Bay, a field experiment was carried out to investigate the performance of different neutral atmosphere mitigation strategies in the observation as well as position domains. The mission was carried out during part of the summer and fall. The expedition track is shown in Figure 1. This paper includes a review of the field observation procedure, comparison of Canadian high resolution NWP model zenith delay products with field observations, and an investigation on the effect of different neutral atmosphere mitigation methods on long baseline kinematic positioning results.

FIELD MEASUREMENTS

The CCGS Amundsen is equipped with a C-Nav antenna, other GPS receivers and navigation devices. The multi function C-Nav antenna receives the L1 and L2 GPS frequencies as well as the StarFire GcGPS corrections that are transmitted over the Inmarsat L-BAND frequency band. The gain pattern of this antenna is designed to be relatively constant even at lower elevations and hence efficient when the antenna is operated at high latitudes [C-Nav, 2002]. The antenna was setup at the top of the mast which is the highest point of the ship and has the best sky visibility. In addition to the real time corrected NMEA (National Marine Electronics Association) sentences, dual frequency raw GPS data was recorded. A WVR-1100 was set up on the ship's deck (see Figure 2)

Figure 2 - WVR onboard CCGS Amundsen

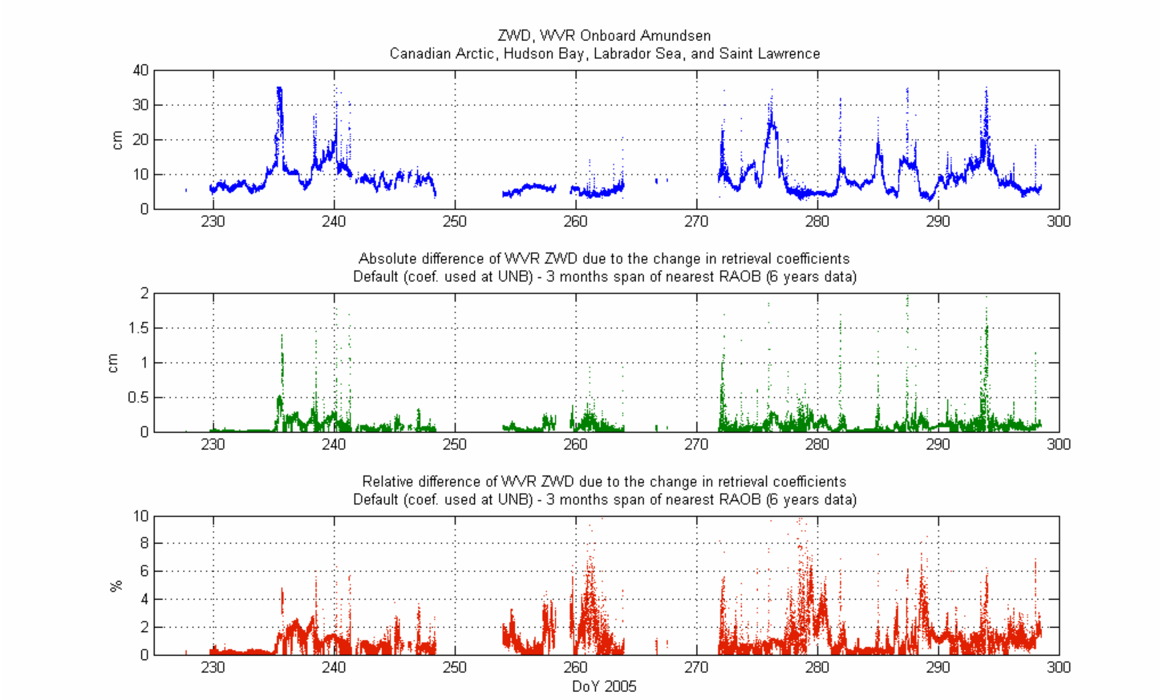

Figure 3 – ZWD during the expedition (upper plot); absolute difference between ZWD from scenarios 1 and 2 (middle plot); relative difference between scenarios 1 and 2 (bottom plot)

and was programmed to record zenith as well as some specific slant measurements. A precise barometer was setup at a known height difference from the GPS antenna and was continuously recording the surface atmospheric pressure. GRIdded Binary (GRIB) files of pressure, temperature and humidity from the Canadian high resolution NWP model were also saved during most of the expedition.

WVR ON A MOVING PLATFORM

There are very few experiences on the performance of the WVR on a moving platform. Researchers at the University of Miami set up a WVR on the "Explorer of the Seas" ship [Minnett, 2004]. The experiment was also used to compare WVR and GPS results [Rocken et. al., 2005].

WVR measures brightness temperature which has a strong correlation with wet delay. Wet delays from WVR are actually obtained from the observed brightness temperature and the estimated retrieval coefficients. These coefficients can be estimated from long term radiosonde measurements in the same climatological region that the WVR operates. A retrieval program provided by Radiometrics Corporation has been used in this experiment. In order to investigate how different coefficients might affect the final WVR Zenith Wet Delay (ZWD) three scenarios have been considered:

1- Default retrieval coefficients derived from a radiosonde near UNB at a latitude of ~46 N.
2- Retrieval coefficients from the nearest radiosonde considering just 3 months of data that span the date of measurement. Different sets of coefficients (from 6 years of data of 10 nearby radiosondes) were derived and used based on the proximity of the ship to a radiosonde site during the expedition.
3- Same as 2 but using the entire (12 months every year) 6 year radiosonde data set.

The difference between the results from scenarios 2 and 3 was found to be negligible (about 0.04 cm on average). Figure 3 shows the measured ZWD during the expedition as well as absolute and relative difference of ZWD resulted from scenarios 1 and 2. As can be seen in Figure 3 the change of retrieval coefficients affect the resultant WVR ZWD by less than 4% in most cases. The result from scenario 2 has been selected as the final WVR ZWD in this study.

In order to carry out the tip curve calibration of the WVR noise diode injection temperatures, the WVR needs to be accurately levelled which was not possible onboard the vessel. Therefore the calibration values obtained before the expedition were used.

NWP NEUTRAL ATMOSPHERE DELAY RETRIEVAL

A number of studies have focused on the use of various NWP models for neutral atmospheric correction to the GPS signal. In this study the high resolution Canadian NWP model has been evaluated using field measurements.

A software package has been developed to retrieve appropriate refractivity profiles from the nearest 4 grid points of the NWP model to the point of interest (in this case the GPS antenna onboard the CCGS Amundsen). The 4 profiles were then interpolated to the GPS antenna position (see Figure 4) using a bi-linear interpolation method following the approach of Schuler [2001]. The resultant profile for each location was then input to our ray tracing program in order to derive zenith delays. In this paper the NWP data from initialization times (00 and 12 UTC) as well as 3 hour forecasts are used.

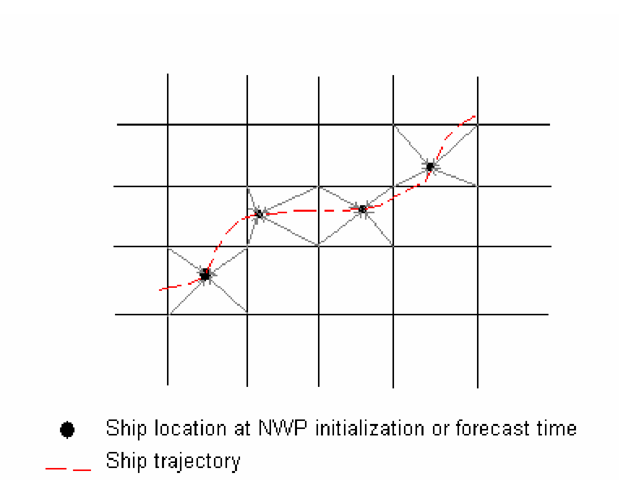

Figure 4 – A schematic view of ship trajectory and NWP grid

COMPARISON OF ZENITH DELAYS

It has been shown that the Saastamoinen model [Saastamoinen, 1972] is able to estimate Zenith Hydrostatic Delay (ZHD) with sub-millimeter level accuracy (see e.g. Mendes [1999]) provided that an accurate surface pressure measurement is available. Therefore a comparison between observed pressure onboard the CCGS Amundsen and that retrieved from the NWP model at the GPS antenna position might be an accuracy measure of our NWP ZHD retrieval procedure.

Figures 5 and 6 show a comparison between NWP and barometer pressure measurements corrected to the GPS antenna height during parts of the expedition (Canadian Arctic, Sub Arctic and mid-latitudes). The RMS of the differences is less than 1 hpa for the compared data series. Assuming no error in the Saastamoinen model, height and latitude, an uncertainty of less than 1hpa in surface pressure measurement will result in less than 2.3 mm error in the ZHD. The figures also include the predicted pressure from UNB3 [Collins, 1999] (a climatic based neutral atmosphere model). The models and measurements are in better agreement in Figure 6 (mid-latitudes) than in Figure 5 (high latitude). However, in the case of NWP, this may partly be due to the fact that only initialization data were used in Figure 6.

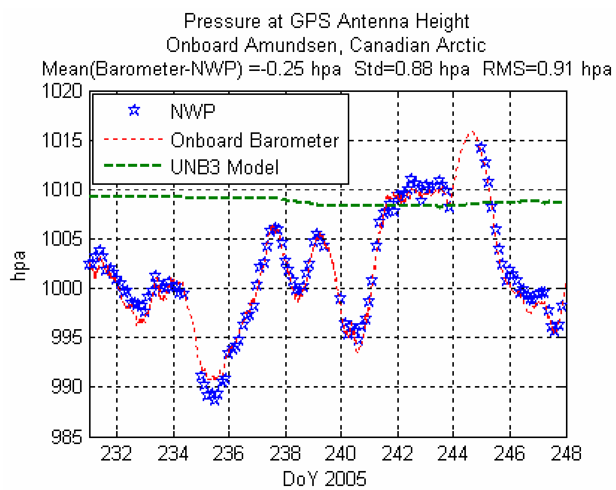

Figure 5 – Measured and NWP pressure values in the Canadian Arctic

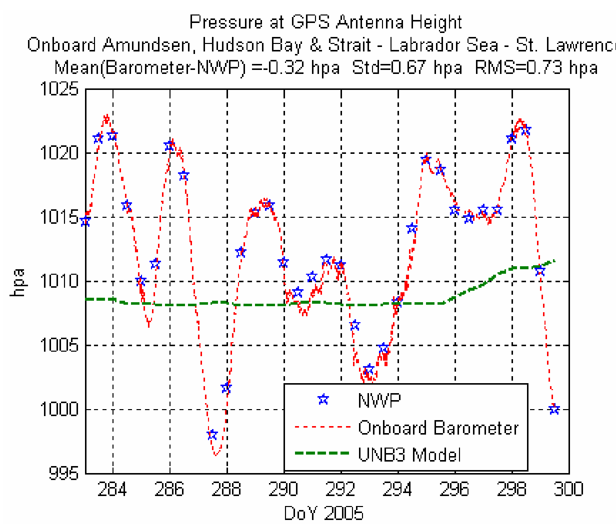

Figure 6 – Measured and NWP pressure values in the Canadian Sub Arctic and mid-latitudes

Figures 7 and 8 show the WVR ZWD results compared with those calculated from the NWP. The RMS of the difference between the smoothed WVR (using a low pass filter) and NWP are at the cm level. The figures also include the ZWD from the UNB3m model [Orliac, 2002], a modified version of UNB3 for ZWD. As expected, the uncertainty in retrieving the wet delays in this study is about 1 order of magnitude larger than those of the hydrostatic delays. Liquid water or ice on a WVR antenna degrades the accuracy of brightness temperature measurements [Ware et al., 2004]. Therefore recorded data with liquid water values above 0.05 cm were removed before comparison. However, the largest difference usually occurs during the time of rapid change in wet delays at peak values. Apart from systematic and random errors that might exist in both the WVR and NWP, the larger differences at peak values might be due to local effects on the WVR measurements and small scale weather phenomena which might not be detectable by the NWP with a 15 km resolution.

The compared values in Figures 7 and 8 are zenith measurements and not the slant-mapped-to-zenith values. This is of concern on a moving vessel as the true elevation angle of the WVR's line of sight may change due to the roll and pitch of the vessel. However, a 7 degree roll or pitch which was the case during a few periods of the expedition does not have a significant effect on WVR zenith measurements. Calculating the Neill mapping function [Neill, 1996] for an 83 degree elevation angle shows that a 7 degree roll or pitch can cause about 0.75% error on the WVR ZWD results and is, therefore, insignificant.

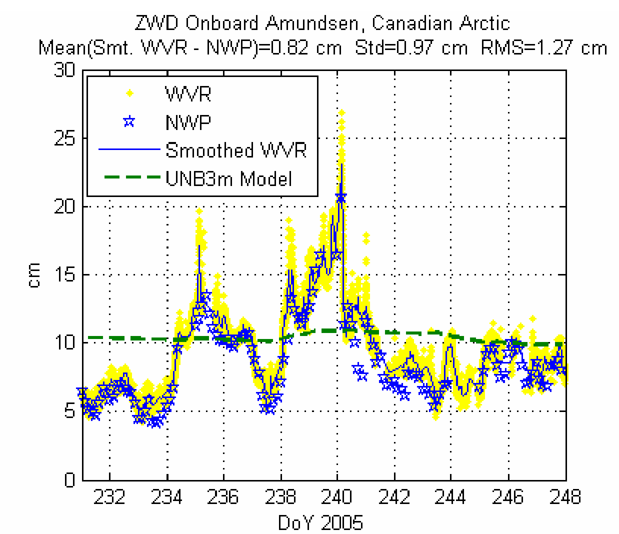

Figure 7 – WVR and NWP ZWD in the Canadian Arctic

EFFECTS ON KINEMATIC POSITIONING

While position validation in a kinematic scenario such as a moving vessel is difficult, the effect of different tropospheric models on positioning can be investigated.

In order to investigate the effect of different neutral atmosphere mitigation methods on long baseline kinematic results, the Bernese GPS software Version 5.0 [Hugentobler et al, 2006] was employed. Major processing steps which were employed in this experiment follow from the diagram shown in Figure 9.

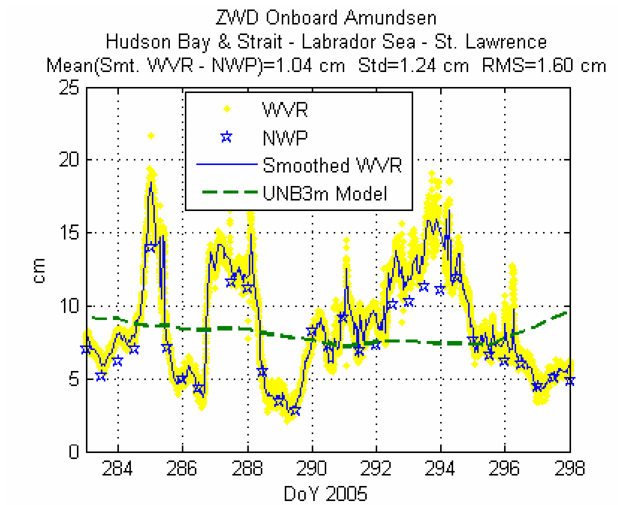

Figure 8 – WVR and NWP ZWD in the Canadian Sub Arctic and mid latitudes

As can be inferred from Figure 9, the change in resultant coordinates from the last step are expected to show the effect of different neutral atmosphere scenarios because these scenarios are employed with similar estimated ambiguities from the previous step in all cases.

The resultant kinematic solution of the onboard antenna has been compared under a number of neutral atmospheric mitigation methods. These include:

1- Default: the Saastamoinen zenith delay models with constant meteorological values (interpolated to the height of the antenna) and Niell mapping functions as implemented in the Bernese GPS software version 5. This strategy hereafter is refered to as Saas. (Bernese).
2- UNB3m: The same as above but using a meteorological lookup table rather than constant values and a different height interpolation method.
3- NWP: the zenith delays derived from the Canadian high resolution NWP at the location of antenna together with Niell mapping functions.
4- WVR: ZWD from WVR measurements, ZHD from Saastamoinen model with surface pressure measurement and Niell mapping functions.

One way to validate the accuracy of the kinematic solution is processing static stations in kinematic mode and comparing the solutions with the static results (see e.g. Kim & Langley [2005] and Schuler [2006]). A long baseline (about 745 km) between two IGS stations in the

Canadian Arctic (namely Reso and Thu3, see Figure 10) has been chosen to investigate the effect of different neutral atmospheric models on the kinematic positioning results.

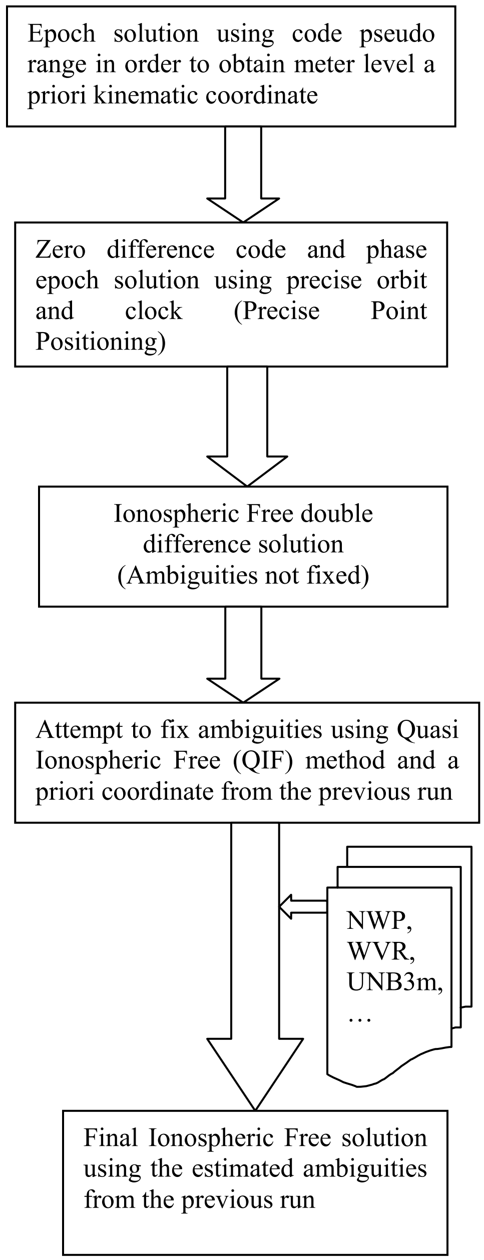

Figure 9 – Employed steps for kinematic processing using Bernese GPS Software Version 5

Figure 11 shows the comparison between the resultant kinematic coordinates (from different tropospheric models) with the combined cumulative solution of IGS. Table 1 shows the statistics of the plots in Figure 11. Assuming the cumulative IGS solution is the true value, the RMS of this comparison may be a measure of accuracy and the standard deviation may be a measure of precision. As can be seen in Table 1, there is an unexpected improvement in the longitude component achieved by using the NWP model. Furthermore, improvement in the height component can be seen in the NWP results. Whether the longitude change is due to wrong ambiguity resolution, GPS constellation or the azimuth of the baseline (mainly in an East-West direction) is not known and requires further investigation.

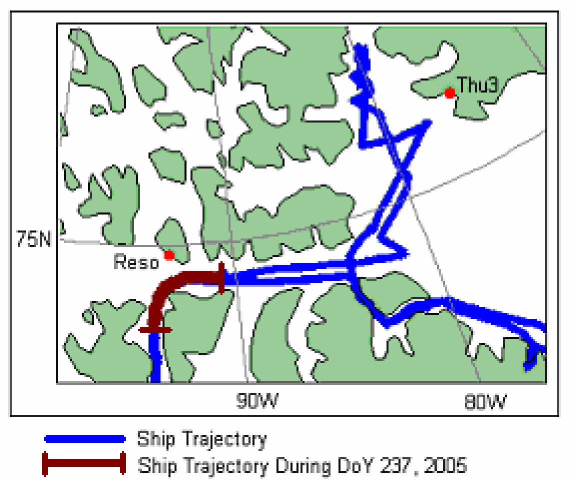

Figure 10 – Investigated static baseline and part of the ship trajectory

Table 1 – Statistics of thu3 kinematic solution (Unit: mm)

	Solution Using					
	Saas.(Bernese)		UNB3m		NWP	
	RMS	Std	RMS	Std	RMS	Std
Lat.	14.4	13.6	14.7	13.7	13.9	13.6
Lon.	37.5	15.1	38.9	15.1	19.4	15.0
h	37.0	33.3	42.7	35.8	35.5	24.9

A real kinematic scenario is investigated during DoY 237, 2005, using double difference solution with Reso as a fixed station. The baseline length during this investigated period varies from about 52 km to 109 km. ZTD from different strategies at both Reso and the moving antenna onboard the CCGS Amundsen can be seen in upper and middle plots in Figure 12.

The double difference tropospheric parameter in the GPS carrier phase observable can be written as:

$$STD_{DD} = ZTD_i\left(M(\alpha_i^m) - M(\alpha_i^n)\right) - ZTD_j\left(M(\alpha_j^m) - M(\alpha_j^n)\right) \quad (1)$$

where ZTD_i and ZTD_j are ZTD at points i and j respectively, α_i^m and α_i^n are elevation angle from point

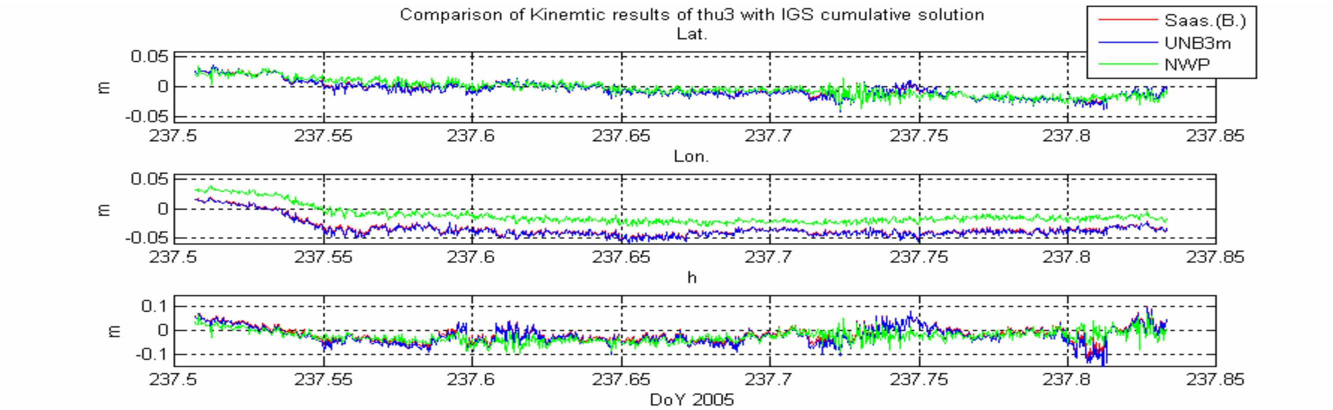

Figure 11 – Comparison of thu3 kinematic result of three neutral atmosphere strategies with IGS cumulative solution

i to satellites m and n respectively, α_j^m and α_j^n are those from point j to satellites m and n respectively and M is a mapping function. For baseline lengths shorter than 100 km and small height differences the elevation angle to the same satellite from the both ends of the baseline can be assumed identical (see e.g. Santerre [1989]). Therefore the double difference tropospheric parameter in the GPS carrier phase observables (equation 1) can be simplified as:

$$STD_{DD} = (ZTD_i - ZTD_j)(M(\alpha^m) - M(\alpha^n)) \quad (2)$$

at each epoch. Hence the difference between the double difference tropospheric parameter is just the difference between ZTDs at the reference and rover stations (first parenthesis in equation 2). The lower plot in Figure 12 shows the difference between the ZTD at the reference

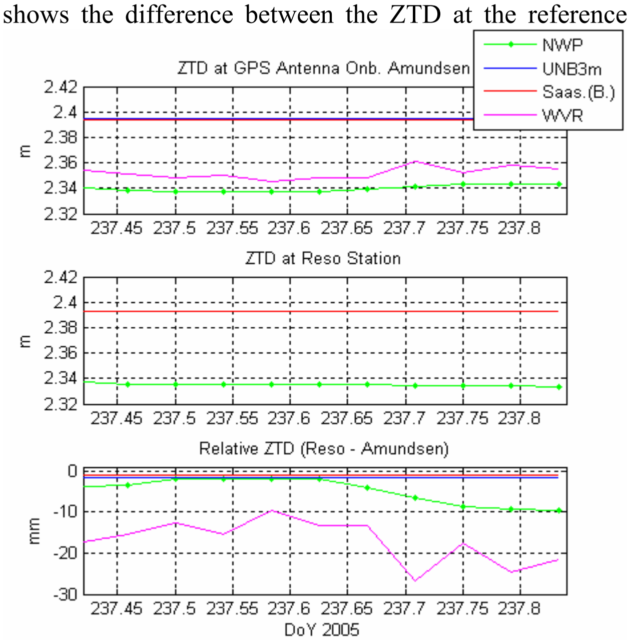

Figure 12 – ZTD at moving antenna (upper plot); ZTD at Reso station (middle plot); relative ZTD (lower plot)

and moving antennas for four different neutral atmospheric mitigation strategies. One should note that as there was no WVR available at Reso station; the NWP result at this station was also used for the WVR scenario. Table 2 gives the mean relative ZTD between Reso and the moving antenna as shown in Figure 12.

Table 2 – Mean relative ZTD and differences for the investigated kinematic baseline

Strategy	Mean relative ZTD	Difference From Saas. (Bernese)
NWP	-4.8mm	3.9mm
UNB3m	-1.7mm	0.8mm
WVR	-17.1mm	16.2mm
Saas. (Bernese)	-0.9 mm	---

The positioning results as compared with the default solution (Bernese implementation of Saastamoinen zenith models and Niell mapping functions) can be seen in Figure 13. Table 3 shows the statistics of the plots in Figure 13.

Table 3 – Statistics of kinematic solution differenced from default solution (unit: mm)

	Solution difference from default (Saas. Bernese)					
	UNB3m		NWP		WVR	
	RMS	Std	RMS	Std	RMS	Std
Lat.	0.2	0.2	1.9	0.9	2.2	2.1
Lon.	0.1	0.1	0.9	1.0	1.6	1.8
h	3.3	0.7	10.3	8.9	43.5	15.5

As can be seen in Table 3 and Figure 13, the height component has a high correlation with the tropospheric modeling scenario. The trend of the variation in h in the lower plot of Figure 13 almost follows the relative ZTD shown in the lower plot of Figure 12.

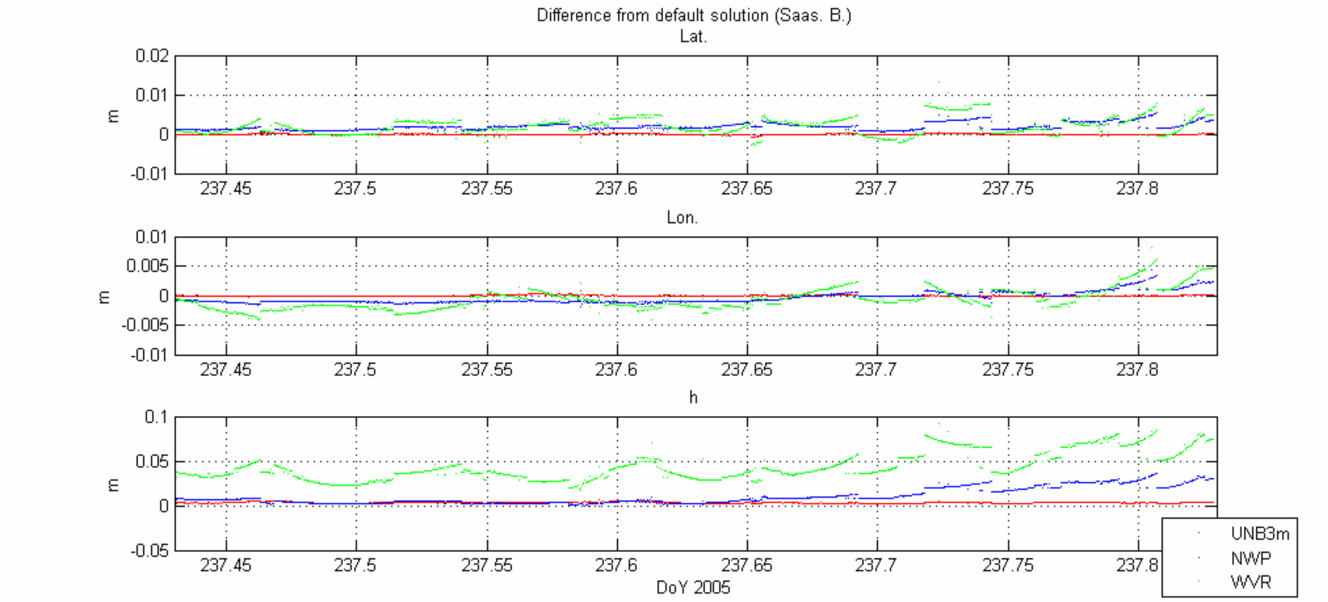

Figure 13 –Positioning difference from default solution (moving antenna onboard)

This is expected as the change in the solution is mainly due to the change in the tropospheric modeling. The WVR result in this specific period shows a 16.2 mm (Table 2) mean relative difference from the default scenario and this has caused a 43.5 mm (Table 3) difference (RMS) in the height component results which is about 2.7 times the ZTD difference. This is in agreement with the rule of thumb that a 1 cm relative ZTD bias leads to a 3 cm error in the height component.

CONCLUSION

The result from field experiments onboard the CCGS Amundsen in the Canadian Arctic seem satisfactory. WVR and NWP results (as two independent sources of ZWD information) were in the expected range of agreement. The performance of the WVR onboard an icebreaker seems reasonable, although some practical difficulties and accuracy limitations were faced. The ZHD from NWP in the Canadian Arctic seems to be sufficiently accurate for precise GPS applications as the results are in good (~2 mm) agreement with the precise pressure measurements in the marine areas of the Canadian Arctic.

As expected, the change in the neutral atmospheric modelling strategy mainly affects the height results. However, the investigated static case processed in kinematic mode shows an unexpected improvement in longitude results due to the use of the NWP model. Further investigation is required to find out whether this is because of wrong ambiguity resolution, the GPS constellation, or geometry of the baseline. Changing the neutral atmospheric model in the investigated kinematic baseline mainly affected the height component. The change in the height component may be more significant in abnormal weather conditions where the models significantly differ from reality. For high accuracy applications a more realistic neutral atmospheric model may seem necessary. Although the amount of the ZWD in the Arctic is lower than mid and low latitudes, the effect of bias in the relative ZTD in a double difference scenario may be significant for some applications due to a problematic GPS constellation.

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REFERENCES

C-Nav (2002). C-Nav GPS Systems Operations Manual, C&C Technologies, Inc, GPS Services Group, Lafayette, USA

Collins, J.P. (1999). *Assessment and Development of a Tropospheric Delay Model for Aircraft Users of the Global Positioning System*. M.Sc.E. thesis, Department of Geodesy and Geomatics Engineering Technical Report No. 203, University of New Brunswick, Fredericton, Canada, 174 pp.

Cucurull L., P. Sedo, D. Behnard, E. Cardellach and A. Rius (2002). "Integrating NWP Products into the Analysis of GPS Observables", Physics and Chemistry of the Earth, Vol 27 (2002) pp. 377-383.

Haan S. and H. Marel (2004). "The influence on GPS estimates of NWP-derived mapping functions" *Physics and Chemistry of the Earth,* Vol. 29, pp. 159-166

Hugentobler U., R. Dach, P. Fridez and M. Meindl (2006). Bernese GPS Software Version 5.0 Draft, Printing office of the University of Bern, Feb. 2006

Jupp, A., S. Healy , M Powe ,J. Owen , J. Butcher (2003) . "Use of Numerical Weather Prediction Fields for the Improvement of Tropospheric Corrections in Global Positioning Applications" ION GPS/GNSS 9-12 September, Portland OR, USA.

Kim D. and R.B. Langley (2005). Nullification of Differential Inospheric Delay for Long-Baseline Real-Time Kinematic Application. ION 61st Annual Meeting, Cambridge, Massachusetts, June 27-29.

Mendes, V.B. (1999). *Modeling the neutral-atmosphere propagation delay in radiometric space techniques*. Ph.D. dissertation, Department of Geodesy and Geomatics Engineering Technical Report No. 199, University of New Brunswick, Canada, 353 pp.

Minnett P.J. (2004). WVR on a moving vessel. [On line] to R. Ghoddousi-Fard <c447j@unb.ca> from <pminnett@rsmas.miami.edu>, 31 December.

Niell, A.E. (1996). "Global mapping functions for the atmosphere delay at radio wavelengths." *Journal of Geophysical Research,* Vol. 101, No. B2, pp. 3227-3246

Orliac E. (2002). *Troposphere Delay Models for Satellite Navigation Applications.* Diploma thesis, École Polytechnique Fédérale de Lausanne, Lausanne, Switzerland.

Rocken C., J. Johnson, Teresa Van Hove, and T. Iwabuchi (2005). Atmospheric water vapour and geoid measurements in the open ocean with GPS, *Geophys. Res. Lett*., 32, L12813, doi: 10.1029/2005GL022573.

Santerre R. (1989). *GPS Satellite Sky Distribution: Impact on the Propagation of Some Important Errors in Precise Relative Positioning*. Ph.D. dissertation, Department of Surveying Engineering, University of New Brunswick, Canada, 200 pp.

Saastamoinen, J. (1972). "Atmospheric correction for the troposphere and stratosphere in radio ranging of satellites." In *The Use of Artificial Satellites for Geodesy*, Geophysical Monograph Series, Vol. 15, American Geophysical Union, Washington DC, pp 247-251.

Schuler T. (2006). Impact of systematic errors on precise long baseline kinematic GPS positioning. GPS Solut (20060 10 -108-125 DOI 10.1007/s10291-005-0012-6

Schuler T. (2001). *On the Ground_Based GPS Tropospheric Delay Estimation*. Ph.D. dissertation, Universitat der Bundeswehr Munchen. [On line] 14/11/2004 http://forschung.unibw-muenchen.de/info.php?&id=591

Ware R., D. Cimini, P. Herzegh, F. Marzano, J. Vivekanandan and E. Westwater (2004). Ground-based Microwave Radiometer Measurements During Precipitation. Presented at the 8th Specialist Meeting on Microwave Radiometry, 24-27 Feb 2004, Rome, Italy. [on-line] August 16, 2006 http://www.radiometrics.com/ware_microrad04.pdf