The Princess of Acadia GPS Project: Description and scientific challenges

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Abstract

This paper describes the Princess of Acadia Project and overviews its scientific goals and challenges. The Princess of Acadia Project can be summarized as follows. A GPS rover receiver is on-board the ferry *The Princess of Acadia*. GPS reference stations are located on both sides of the Bay of Fundy, in Saint John, N.B., and in Digby, N.S. The base stations are at different distances from the ferry receiver as it moves, allowing the assessment of kinematic, differential carrier phase solutions through long / short baseline comparisons. Data from permanent stations around the Bay of Fundy are also be used in the processing. Meteorological stations have been collocated with the GPS receivers. A tide gauge has been installed in Digby; another one already exists in Saint John (operated by the CHS). Data are being collected for a one year period, covering different seasons, and periods of distinct weather conditions, with the aim of detecting effects coming from seasonal variations, daily variation, cold fronts, etc. in the GPS data processing. The objectives of the project are: (a) to investigate the performance of high-accuracy (cm-level) positioning and navigation using GPS carrier phase observations in terms of area coverage (i.e., distance from reference stations) and variability in weather conditions, in a marine environment; (b) to investigate the seamless representation of a vertical datum, by integrating data from tide gauges; (c) to investigate local effects associated with tides (tidal loading and sea surface topography) and site effects (multipath).

1. Introduction

A number of very important problems are addressed in this project: variability in positioning due to area coverage and due to weather fronts, issues related to seamless vertical datum and site dependent effects.

The problem of area coverage in the realm of kinematic positioning is primarily related to ambiguity resolution, which is typically possible up to some limiting distance from the reference station. Various ambiguity resolution techniques exist [*Han and Rizos*, 1997], but they start to fail after a certain distance from the base station, typically 10 km [*Santos et al*., 2000a]. One may want to try to fix the ambiguity no matter how far away the base station is (and may be punished by adopting as fixed ambiguity ones which are not fixed). Alternatively, one may accept the fact that fixing the ambiguity is more difficult with increasing distance to the base station [*Kim and Langley*, 2001], and treat it as float after a certain distance.

The incurrence of weather fronts can also disturb GPS observations. The troposphere's effect on GPS has been extensively discussed [e.g., *Dodson et al.*, 1996; *Mendes*, 1997; *Santos et al.*, 2000b] and it directly impacts the vertical component. The variability in weather conditions adds a factor to this problem [*Gregorius and Blewitt*, 1998; *de Haan et al.*, 2002; *Jensen*, 2002a; *Jensen*, 2002b]. The usual approach towards tropospheric effect is to rely on surface temperature and pressure measurements and/or rely on tropospheric prediction models. The drawbacks come from horizontal and vertical spatial variations not appropriately accounted for, specially the vertical profile of water vapour. Tropospheric effect is of even greater concern for marine positioning because it maps directly into vertical positioning uncertainties. Besides, tropospheric conditions are not as densely sampled at sea as over land. Infrastructures used in continental areas, such as the grid of GPS stations covering 40,000 km^2 described by *Zhang and Lachapelle* [2001] are much more difficult and expensive to implement at sea, if not impossible. The uncertainties coming from troposphere contaminate the cycle ambiguity resolution process, causing longer range kinematic positioning unreliable or impossible [*Wells et al.*, 2004].

The variability in positioning due to area coverage and due to weather fronts are problems studied in this project by making use of redundant observations, collected over one year by several base stations, ranging from 1.5 to 202 km in length, correlating area coverage and weather fronts.

Additionally, this project entails an investigation of vertical datums. The creation of a seamless vertical datum requires that proper relationships be established among the various vertical surfaces, being tidal, geoid and the reference ellipsoid [*Wells et al.*, 1996]. The ellipsoid is chosen as the basic transfer surface since its definition does not depend on data, like the other vertical surfaces. Analysis of simultaneously observed geodetic height and tidal time series, associated with information derived from a geoidal model, can be used for assessing the ability for establishing a vertical datum, methods of vertical height determination and vertical datum recovery.

Some early results from the projects have already been presented by *Wells et al.* [2004], *Bisnath et al.* [2004], *Cove* [2004] and *Santos* [2004].

2. The Princess of Acadia Project

Receivers have been collecting GPS kinematic data at reference stations, located on both sides of the Bay of Fundy, and by an onboard GPS rover receiver. Two base stations have been installed at the Canadian Coast Guard building in St. John and in Digby, at the Digby Regional High School. A total of four other permanent stations already in operation by other organizations have been used. Two stations are located in Fredericton: the IGS station UNB1, on UNB campus, and the Canadian Active Control

System (CACS) FRED run by the Geodetic Survey Division of NRCan. The other two stations are the US CORS station ESPT, in Eastport, Maine, run by NOAA, and the IGS station HLFX, in Halifax, run by NRCan. The rover receiver has been operating on board the ferry *The Princess of Acadia*. This ferry runs between Saint John, New Brunswick, and Digby, Nova Scotia and belongs to Bay Ferries Ltd. The Princess of Acadia is a car-ferry capable of accommodating up to 650 passengers, 155 automobiles and 33 tractor-trailers. The ferry has a length of 146 m, beam of 20.5 m and draft of 4.6 m. It was built in 1971. It travels between St. John and Digby between two to six times a day depending on the season. Figure 1 shows the relative location of all stations.

Figure 1 – Relative location of stations in Fredericton, St. John, Digby, Halifax and Eastport (indicated by the stars).

Stations in Fredericton, Halifax and Eastport are used in a network adjustment to estimate the coordinates of the ones in St. John and Digby. All stations, except ESPT and UNB1, collect data at a rate of 1 Hz. The ferry solution is relative to the high rate stations. Table 1 shows the distances among the baselines used in the network adjustment. Table 2 indicates the distances between base stations used to determine the position of the ferry. Two exceptions are shown in Table 2, in rows 2 and 3. In these rows we see the distances between the GPS base stations in Digby and St. John and the ferry docks. For example, whenever the ferry is docked in Digby, its distance from the GPS Digby station is 5 km. As it moves away from Digby, its distance grows to up to 74 km (distance between Digby and St. John).

Table 1 – Distance between base stations used in the network adjustment

Baseline	Distance (km)
Fredericton – St. John	87
St. John – Eastport	83
Halifax – Digby	167
Digby – St. John	74

Table 2 – Distance between base stations using 1 Hz rate GPS data

Baseline	Distance (km)
Ferry docked in St.John - St.John GPS stn.	1.5
Ferry docked in Digby – Digby GPS stn.	5
Digby – St. John	74
Fredericton – St. John	87
Fredericton – Digby	160
Halifax – Digby	167
Halifax – St. John	202
Halifax – Fredericton	250

Data collection has been designed in order to satisfy the following criteria:

(a) It should cover period(s) with distinct weather conditions, aiming at detecting effects coming from seasonal variations, daily variation, cold fronts, etc.

(b) Base stations should be located in such a way that they will be at different distances from the on-board receiver as it moves. Based on this spatial distribution of the base stations, there will always be two different GPS solutions for the on-board receiver. These solutions can be compared at any given time. It is expected that the GPS solution based on the closer base station will have a more reliable ambiguity fixing and can therefore control the solution computed from the farther receiver. Also, weather fronts or local weather effects would affect the receivers differently.

To satisfy the design criteria, we have implemented a data collection scenario having one GPS receiver running continuously, for a period of one year (therefore, covering the four different seasons), on board *The Princess of Acadia*. The position of this on board receiver is determined with respect to the high rate stations.

Meteorological stations are collocated with the receivers in St. John and in Digby. They are gathering pressure, temperature and relative humidity. These are Campbell Scientific stations operating at a scan rate of 15 seconds and logging rate of 10 minutes. Pressure is logged at every hour. Other sites with meteorological data are available: a SUOMI network station at UNB (2 km away from the CACS station), in Fredericton, and at the IGS Halifax GPS station.

Besides the surface meteorological data, we have access to meteorological data through the Canadian Meteorological Center (CMC). These data is part of the Global Environmental Multiscale (GEM) model (see Section 3).

To allow the investigation on vertical datums, tidal information is required. For this purpose, we have installed one tide gauge at the ferry terminal in Digby. Our intention was to have this tide gauges running continuously for one year. A storm, in December 2003, provoked an interruption which lasted until April. The tide gauge in Digby belongs to Dalhousie University and was installed by the CHS. We have been using information collected by the tidal gauge, in St. John run by the Canadian Hydrographic Service, which is also located at the ferry terminal.

The data collection operation has been designed to provide redundancy and reliability. Data processing and analysis will exploit this fact. Data processing and analysis has been carried out by comparing solutions for the rover generated from the various base stations to investigate effects from different inter-frequency data combinations, and from allowing or not allowing ambiguity resolution, combining with the effects of variability in weather conditions at the base stations, and at the boat, including the input of weather fronts.

The processing engine to be used will be DynaPos, from The XYZ's of GPS and GrafNav, from Waypoint Consulting.

The data collected (GPS data, surface meteorological data, GEM data) has been stored in an ftp site. It is our intention to have this data made available for researchers in the future. A project website also exists at http://gge.unb.ca/Research/PrincessOfAcadia/.

The basic idea behind the Princess of Acadia project was a fruit of conversations between the first two authors of this paper, and inspired in early experiments by Dr. L. Huff (University of New Hampshire) and Dr. B. Remondi (The XYZ's of GPS). Its basic idea: to study long-range kinematic GPS positioning in a marine environment, and to study the effect of weather fronts on high-accuracy positioning. It is an example of a project that integrates several disciplines, geodesy, hydrography, meteorology, oceanography and geodynamics, with each discipline feeding the other with useful information. The basic idea was extended to study relationships among vertical frames, local effects provoked by the Bay of Fundy's highest tides in the world, such as tidal loading and sea surface topography, and specific site dependent effects such as GPS multipath. This project looks like a birth place of ideas!

3. Scientific Challenges

The synergy among various disciplines allows us to look for answer to different scientific challenges in the next years to come. A number of scientific challenges have given the tone of the Princess of Acadia Project. Within the context of this paper we will refer to 5 of them as the most comprehensive, without closing the window of opportunity for other challenges to be identified.

The first scientific challenge is related to long-range kinematic positioning. We investigate the performance of high-accuracy (cm-level) kinematic positioning and navigation using GPS carrier-phase in terms of area coverage (i.e., distance from reference stations) in a marine environment.
GPS position results are affected by baseline length mostly due to decorrelation of atmospheric errors [*Han*, 1997]. As baseline length increases, position results degrade due to the difficulty to correctly fix the carrier phase ambiguity to its integer value. Carrier phase fixed ambiguity solutions are more accurate than float ambiguity solutions. It is generally accepted that carrier phase can be successfully fixed for baselines of up to 10 km. After that, fixing ambiguities becomes more difficult and risky, being the worst situation when one believes that ambiguity is correctly fixed when it is not. It would be certainly more advantageous to have a reliable float solution rather than an unreliable fixed solution.

Mitigation strategies for the several error sources affecting kinematic positioning are well known and effective [e.g., *Hofmann-Wellenhof et al.*, 2001]. Clocks offsets can be eliminated by double differencing GPS observations. To solve for ionospheric delay, an ionospheric-delay free inter-frequency combination can be used. This alternative comes with a price: ambiguity is not an integer number any longer. Orbital errors are greatly minimized by using IGS products. Multipath can be reduced by using special antennas. In kinematic positioning, multipath is less likely to occur. Concerning the effect coming from neutral atmosphere (troposphere), the usual approach is to use tropospheric model. But tropospheric delay remains a problem (more on this later in this Section).

To tackle the long-range kinematic positioning we have designed the following strategy, shown in Figure 3. In this figure, 3 base stations are shown by stars. The ferry docks appear as crosses. The circle indicates a distance of 10 km from the GPS station in St. John. The best ambiguity fixed solution of the ferry (while docked or moving) can be obtained within this circle, having the St. John GPS station as base station. Within this distance, kinematic positioning is usually considered as reliable and uncontaminated by differential tropospheric conditions. This short baseline solution can be used as an accurate "reference" or "ground truth" in evaluating the long baseline solutions from the other GPS stations in Digby, Fredericton and Halifax (not shown in the figure), which can be based on various L1 and L2 inter-frequency combinations (e.g., ionosphere-free, wide lane, narrow lane, or other blends of L1 and L2 carrier phase measurements). The same strategy is valid when the ferry is within a 10 km distance from Digby GPS station: the short baseline solution is used to evaluate the long baseline solutions from the other GPS stations. During the time the ferry is away the 10 km circle, from both St. John and Digby stations, the reliable ionospheric-delay free seems as the best option as ground truth. For this analysis, we build on previous experience described in *Cove et al*. [2002].

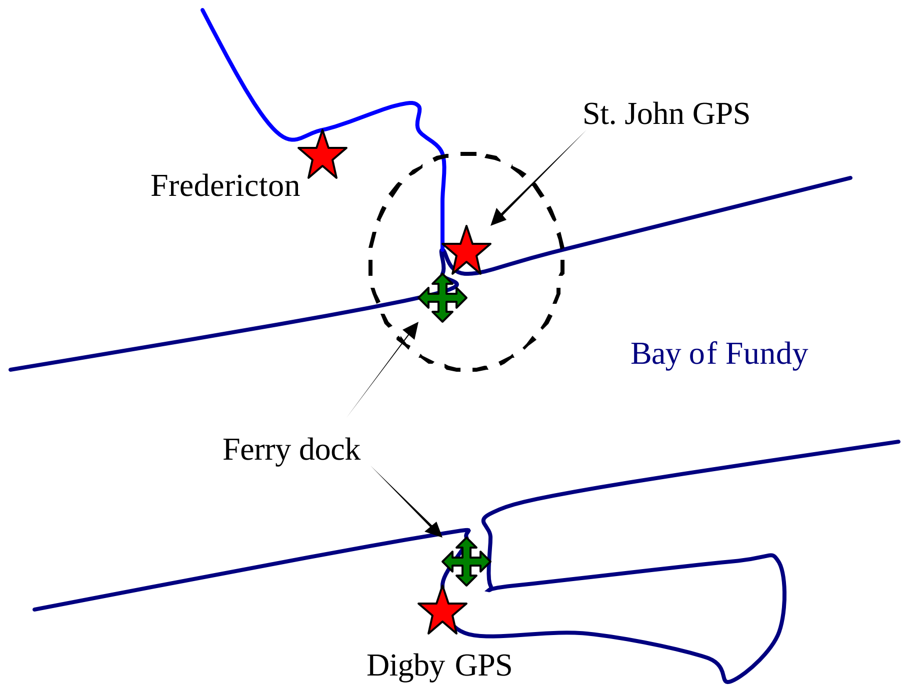

Figure 3 – Long-range kinematic positioning analysis strategy

Another scientific challenge is related to the variability in weather conditions. We want to investigate performance of high-accuracy (cm-level) kinematic positioning and navigation using GPS carrier-phase in terms of variability in weather conditions at each site (caused, for example, by incoming weather fronts). The GPS signal is affected by weather as it passes through neutral atmosphere, affecting primarily the vertical component. As weather front approaches, and depending on the way it is propagating, it will affect one base station before the other. The residual difference in tropospheric delay between two stations is referred to as differential troposphere. Temperature inversion and other dynamic coastal weather phenomena degrade the effectiveness of tropospheric delay models [*Gregorius and Blewitt*, 1998]. The inability to have the behaviour of differential troposphere well described may hampers or even prevents a successful ambiguity resolution process as baseline length increases. One of our goals is to improve upon existing tropospheric models and have such improvements integrated in PPK software.

As the GPS data will be collected in different seasons it will cover periods with distinct weather conditions allowing the detection of effects coming from seasonal variations, daily variation, cold fronts, etc.

An example on the variability in weather conditions one may encounter in shown in Figures 4, 5 and 6. They show the difference in surface pressure, temperature and relative humidity between measurements taken in St. John and Digby on the 18th of February, 2004. On this day (and the following) the Maritimes were hit by a "weather bomb" (see Figure 7). A variation of 2 mbars, 6°C and up to 50% in relative humidity is seen.

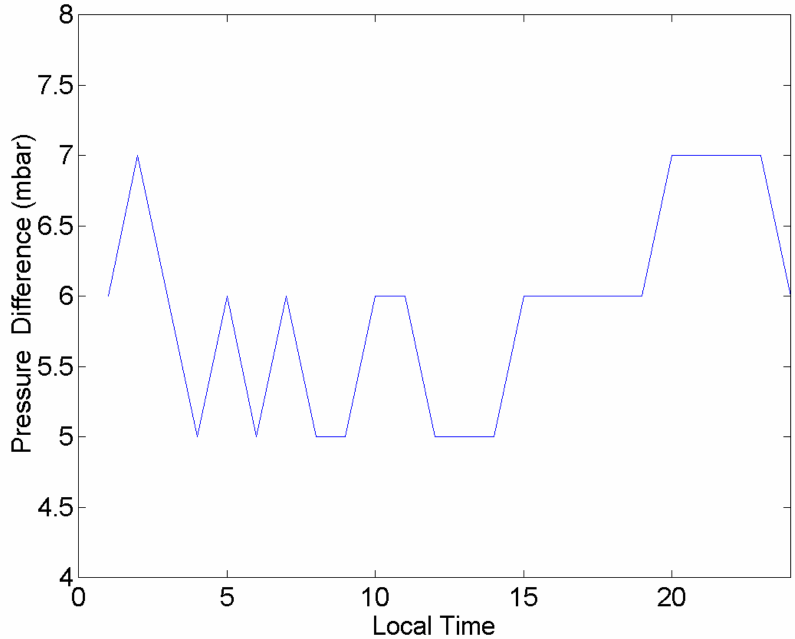

Figure 4 – Difference in measured surface pressure between St. John and Digby

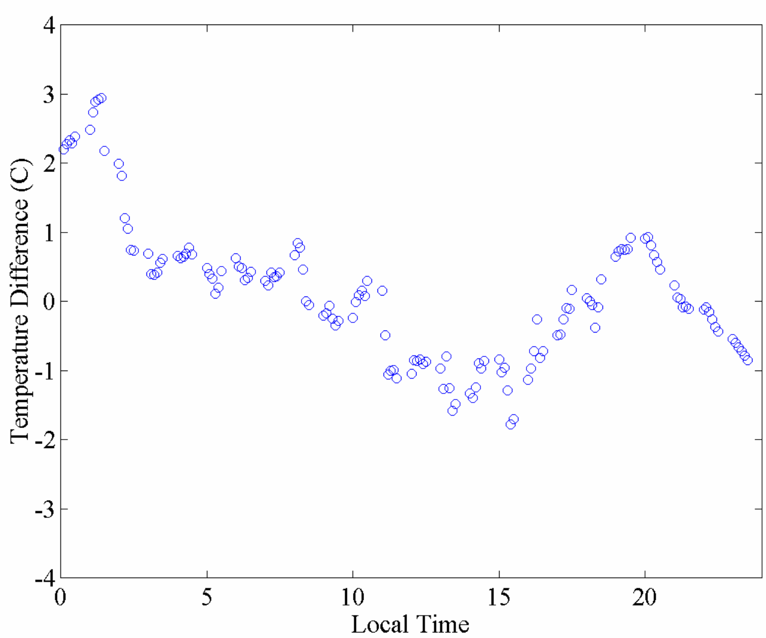

Figure 5 – Difference in measured surface pressure between St. John and Digby

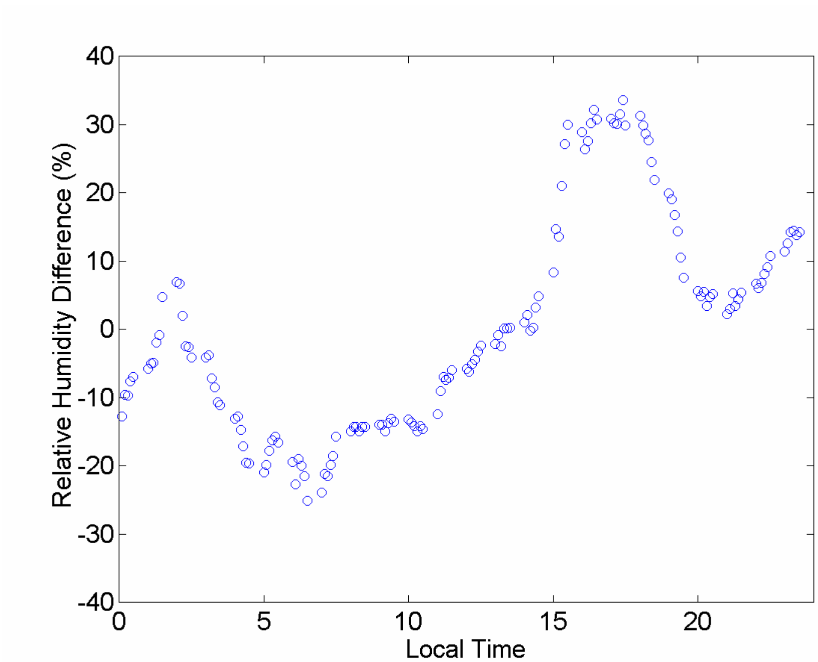

Figure 6 – Difference in measured surface pressure between St. John and Digby

An attempt to have a better representation of the neutral atmosphere along the path of a GPS signal is to use Numerical Weather Prediction (NWP) model GEM provided by the Canadian Meteorological Center (CMC). GEM model is composed of an analysis (post-fit) and a forecast representation. The analysis field corresponds to the best fit to the data available for the analysis. These data includes, for example: aircraft over a path, radio sonde, satellite data and surface observations. The GEM model is the engine used to produce the prediction. A full cycle would be composed of: analysis, forecast based on the analysis, data fit, new analysis. Temperature, pressure and relative humidity are provided in 28 isobaric levels. Grid nodes are at 20 km spacing. Figure 8 show a representation of the model.

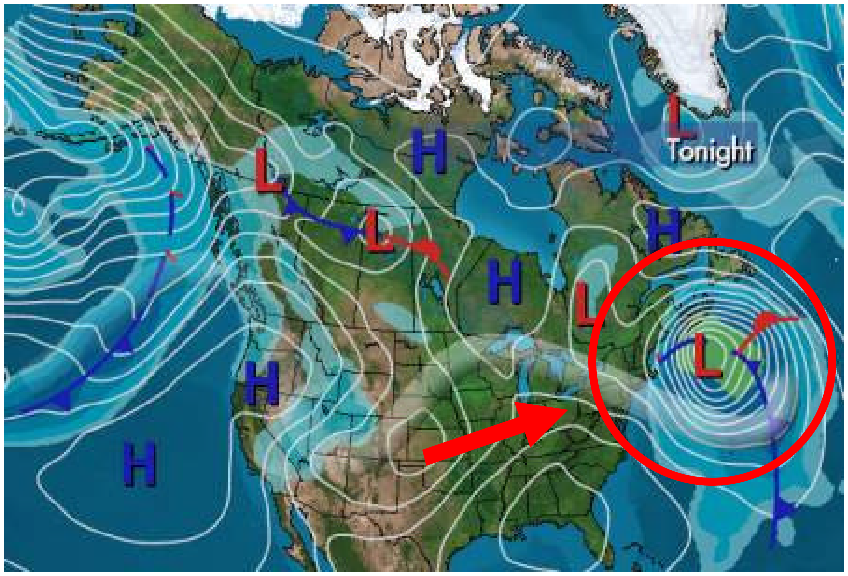

Figure 7 – Weather map showing the storm arriving at the Maritimes, on February 18, 2004 (courtesy of The Weather Network).

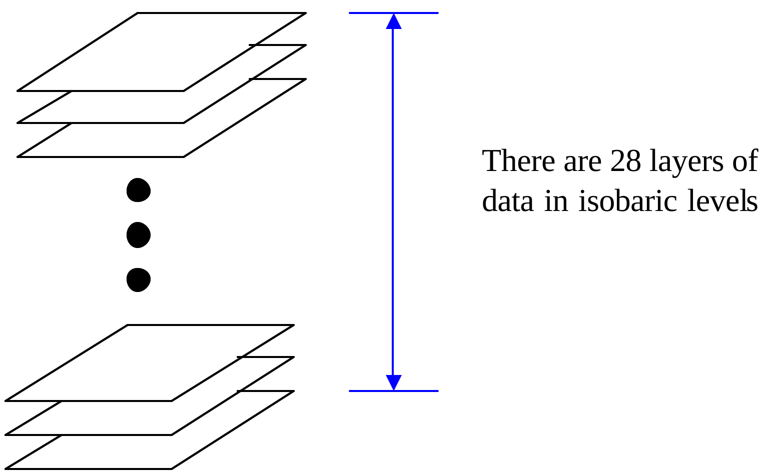

Figure 8 – NWP model.

Depending on the effectiveness of using NWP model for dealing with differential troposphere, we foresee its use in a service since these models, such as the GEM model, are typically is available on line.

Another scientific challenge is related to the investigation on the <u>connections among vertical reference systems</u>. At the sites where GPS receiver and tide gauge (at

both ferry docks) are collocated we have: geodetic height *h* (from GPS), orthometric height *H* (from vertical geodetic network), geoidal height *N* (from a geoidal model or *h* - *H*), instantaneous sea level from the tide gauge observations, mean sea level from long term records (from St. John tide gauge), chart datum (given), sea surface topography (*SST*) and sea surface height (*SSH*). It is also known the antenna height with respect to the water level and the static draft of the vessel. As the ferry moves away from the docks, the on-board receiver maintains track of the geodetic height over the instantaneous sea level. Due to the high tides in the Bay of Fundy, the ferry will effectively either go up or down the tidal hill by as much as 8 metres. There should
be good agreement between the geodetic and the tidal gauge derived heights when the ferry is at either one of the docks. But a disagreement will show up as the ferry moves. We expect to benefit from the year long time series.

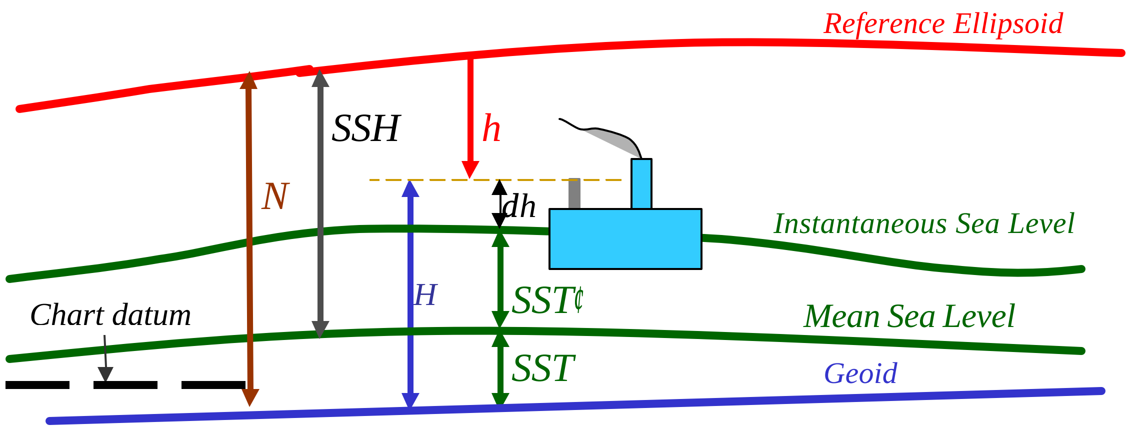

Figure 9 - Ferry as a moving gauge

Another scientific challenge deals with the investigation on the effect due to ocean tide loading and body tide on the base stations, notably St. John and Digby, and what such effect would impact kinematic position and if so how to account for it. Processing of hourly and daily sessions using in-house Differential Positioning Package program (DIPOP). Two models are being contemplated: *Pagiatakis* [1988] and *Scherneck* [1991] models. Theoretical values from models will be compared with the ones estimated from GPS. Figure 10 shows a snapshot of ocean tide loading on the Bay of Fundy, as derived from *Scherneck*'s model. Figure 11 portrays a variation due to ocean tides at station St. John.

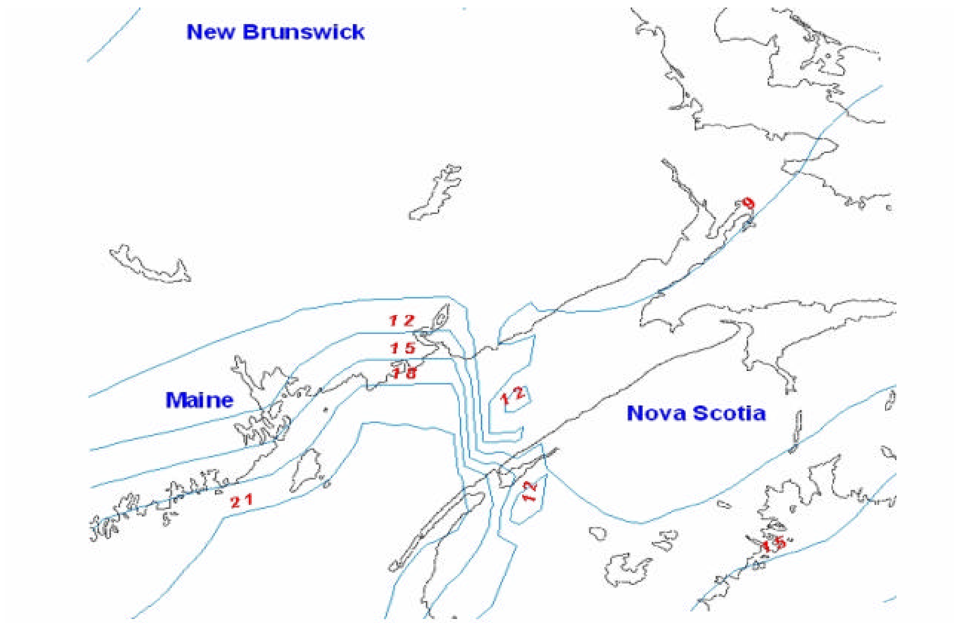

Figure 10 – Ocean tide loading M2 amplitude (values in mm)

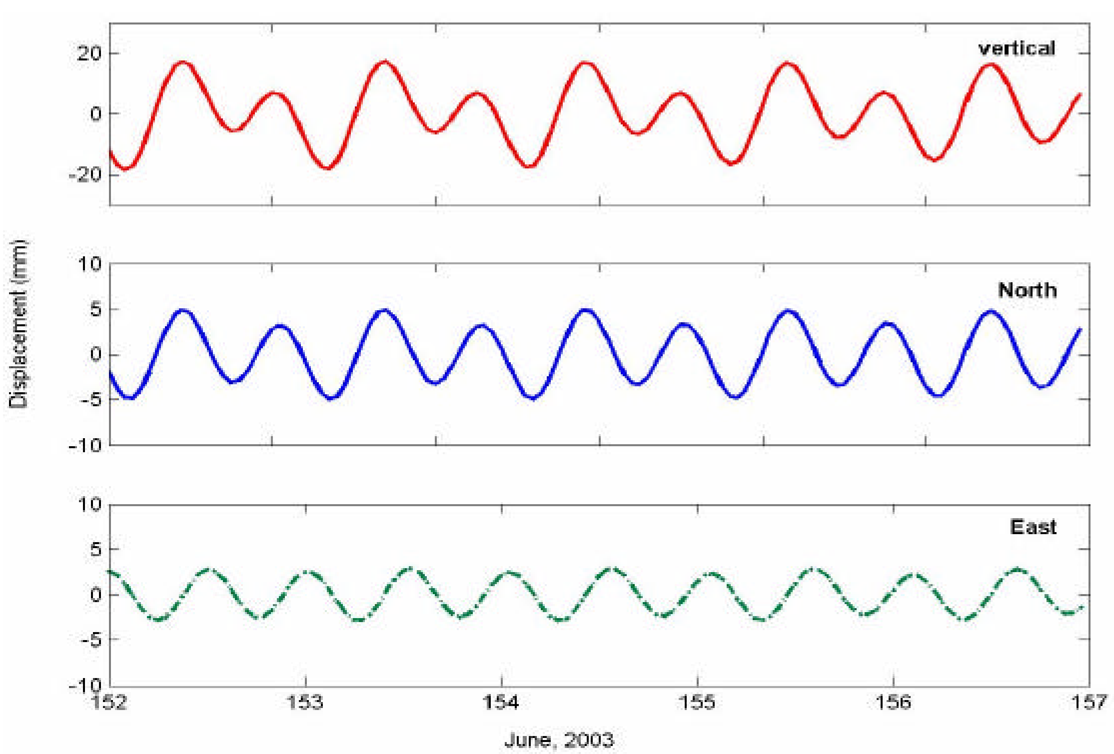

Figure 11 – Time series of theoretical ocean loading in St. John

The last scientific challenge we want to mention deals with site effects, specifically multipath effect on base stations and on rover receiver. Multipath is the remnant effect on GPS observations, since all are accounted for (and troposphere is being investigated). A daily evaluation of pseudorange multipath using TEQC [*Estey and Meerten*, 1999] is taking place and a special look into carrier-phase multipath is underway. We intend to further up investigation on multipath mitigation effect on rover by combining dual-frequency observations collected by the base station receivers [*Santos and Farret*, 2002].

4. Campaign status and preliminary results

The one year of data collection started on 27 November 2003 planned to last until December 2004. GPS OEM DL4 Novatel receivers [*Novatel*, 2003], installed in St. John, Digby and on the ferry, are continuously logging at 1 Hertz. Campbell scientific meteorological sensors [*Campbell Scientific*, 2000] are logging temperature and relative humidity at every 10 minutes, with a scanning rate of 30 seconds, and pressure at every hour. Tide gauges are recording at every 15 minutes.

Figure 12 shows the receiver and meteorological station setup on board the Princess of Acadia. Figure 13 shows the tide gauge in Digby. This tide gauge was destroyed late last year by a storm and has been place back in operation in April of this year.

Figure 12 – GPS receiver and meteorological station on board


Figure 13 – Tide gauge station in Digby

Software suites used for kinematic GPS data processing used so far have been Dynapos, from *The XYZ's of GPS* [2001], Grafnav, from *Waypoint Consulting* [2003] and UNB RTK [*Kim and Langley*, 2003], which has been modified to work with long baselines. Quality control has been performed using Unavco's TEQC. Static data processing has been carried out with UNB's DIPOP.

Preliminary results from baseline comparisons are shown in Figures 14, 15 and 16, for the 18th of February. Three types of comparisons are shown, all based on a short baseline solution compared to a long baseline solution. The red lines represent the ferry in motion. The green line represents the period of time considered as good enough to be used for comparison, when formal errors do not exceed 20 cm, and summarized in Table 3. Converge time was not included in the analysis. Figure 15 shows the difference between short baseline ionospheric-delay free solution and long baseline ionospheric-delay free solution using standard meteorological parameters for a 24 hours period. Figure 16 shows the difference between short baseline narrow-lane solution and long baseline ionospheric-delay free solution using standard meteorological parameters, for a 12 hours period. Figure 17 shows the difference between short baseline narrow-lane solution and long baseline ionospheric-delay free solution using average meteorological parameters for a 12 hours period. Table 3 summarizes the results by showing the differences in latitude ϕ, longitude λ and height h for solution comparisons with 95% confidence region values after convergence. Preliminary results show improvement in position results by adding averaged surface meteorological parameters to prediction model in processing for some days. The magnitude of the improvements may be related to the type of weather that is in the area ie., passing of weather fronts had a negative effect on the model. These results may become more significant with changes in the weather in spring and summer

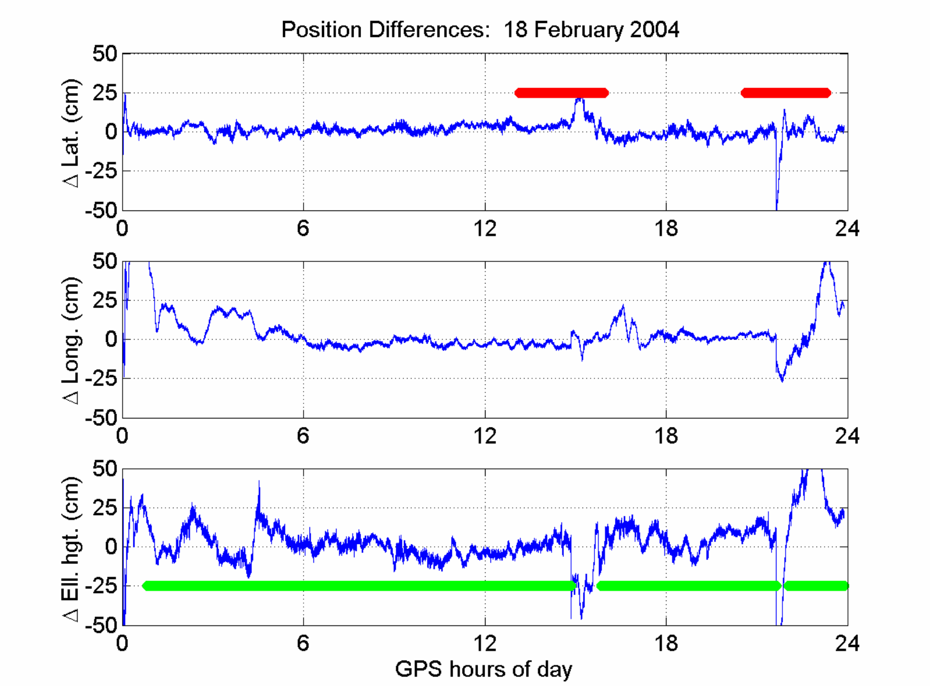

Figure 15 – Difference between short baseline ionospheric-delay free solution and long baseline ionospheric-delay free solution using standard meteorological parameters

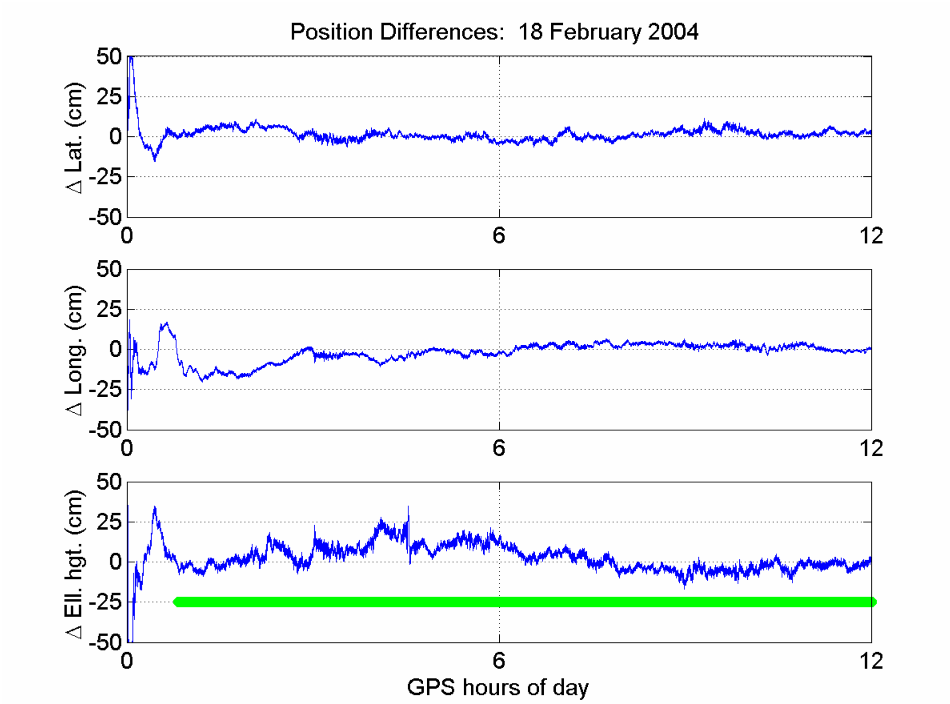

Figure 16 – Difference between short baseline narrow-lane solution and long baseline ionospheric-delay free solution using standard meteorological parameters

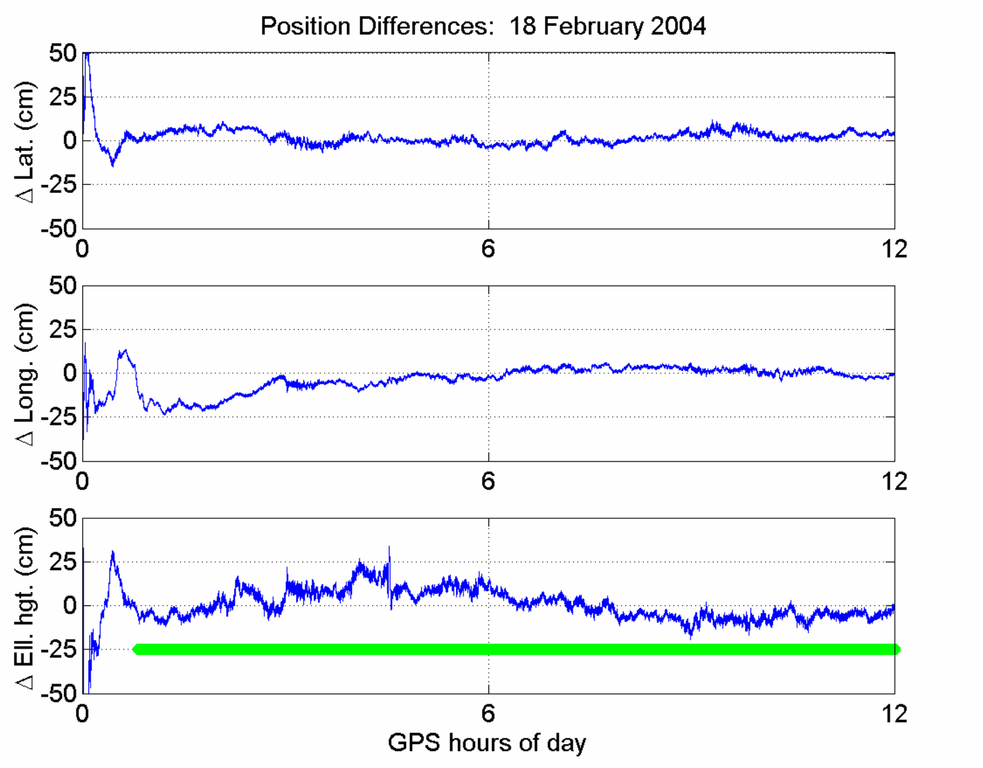

Figure 17 – Difference between short baseline narrow-lane solution and long baseline ionospheric-delay free solution using average meteorological parameters

Table 3 - Differences in latitude ϕ, longitude λ and height h for solution comparisons 95% confidence region values after convergence

Processed with …		Feb 17	Feb 18	Feb 19	Feb 20
Standard meteorological parameters	$\Delta\phi$ (cm)	7.6	6.7	5.9	7.3
	$\Delta\lambda$ (cm)	13.2	15.5	17.7	12.8
	Δh (cm)	12.0	16.1	13.2	17.2
Averaged meteorological parameters	$\Delta\phi$ (cm)	7.7	7.3	6.2	6.6
	$\Delta\lambda$ (cm)	15.9	19.0	14.0	12.2
	Δh (cm)	10.1	14.7	14.4	11.9

A daily monitoring of the data quality has been performed using Unavco's TECQ. Figure 18 shows the mean values for L1 code multipath (MP1) and L2 code multipath (MP2) for station in Digby. Station St. John has shown higher values for MP2 than shown here.

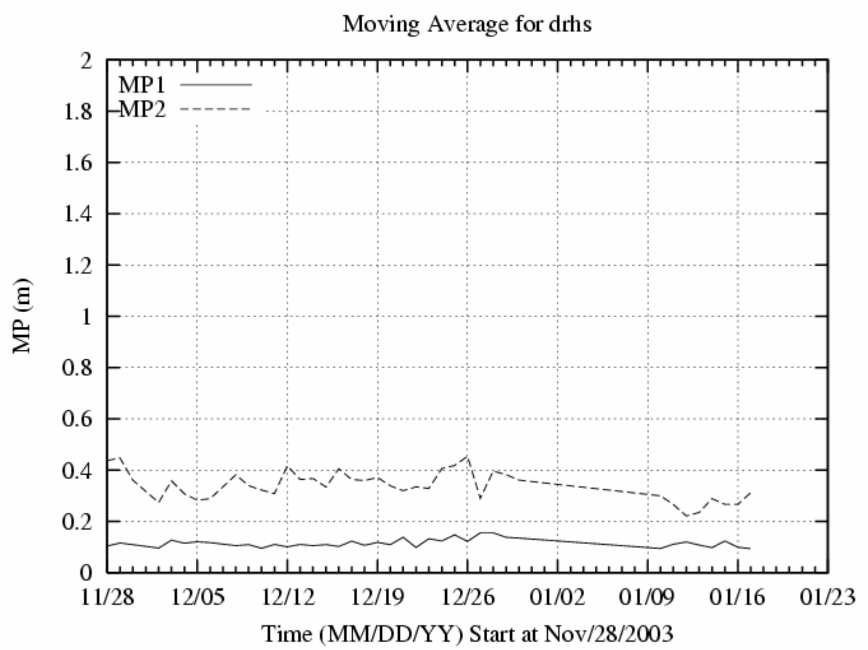

Figure 18 – Mean MP1 and MP2 values for station Digby (drhs)

Figure 19 shows interesting features coming from the comparison of GPS-derived heights with the ones observed with the tidal gauges and those derived from tidal prediction model. Deep blue and red show the results obtained by the on board GPS receiver with respect to St. John and Digby, respectively. Yellow line shows the tide as observed in St. John. The light blue shows the predicted tide for Digby. At 22:00 hours the ferry is in St. John. The GPS heights agree with the tidal measurement at St. John, but disagree with the predicted tide in Digby. As the boat moves away from St. John and (up) to Digby the GPS derived heights depart from St. John and gets closer to the predicted tide for Digby, coinciding with it as the boat docks in Digby. Predicted tides for Digby are used because this preliminary analysis covers a period when the tide gauge in Digby was not in operation.

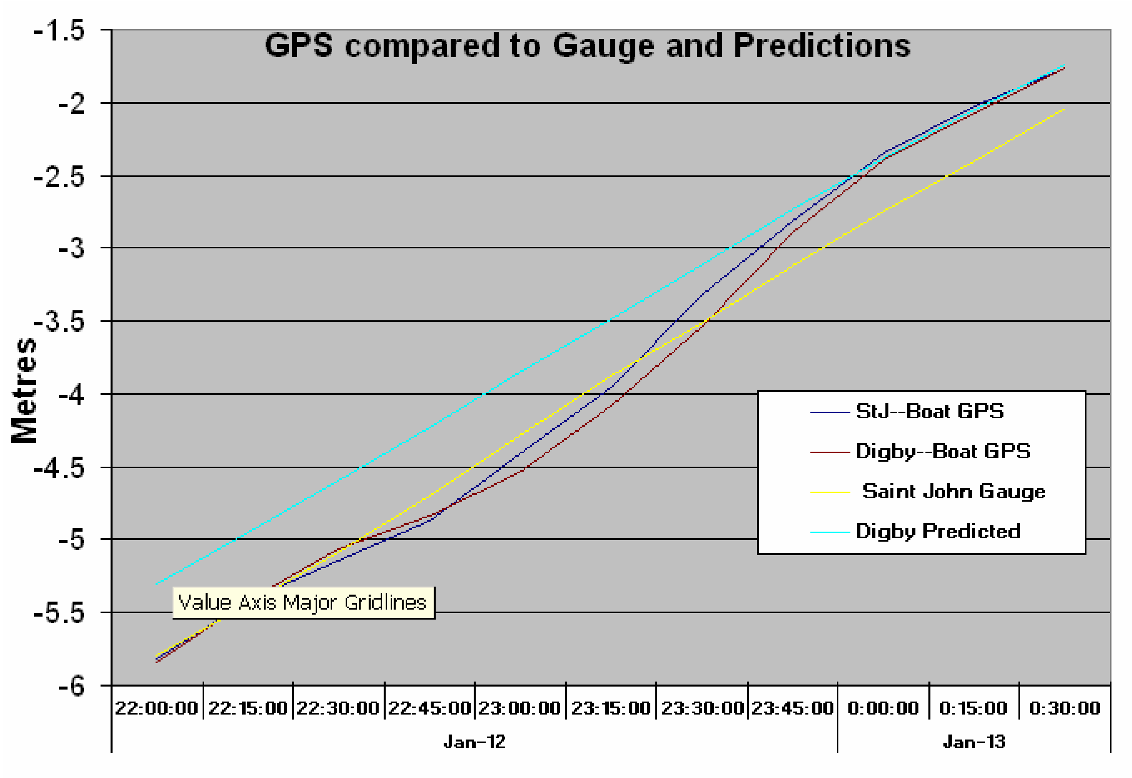

Figure 19 – GPS heights compared to tide gauge and tide predictions.

5. Concluding Remarks

This paper describes the design and objectives of the Princess of Acadia Project and presents some initial results. We expect that this project will yield analysis related to distance limitations of marine kinematic GPS under various climatic conditions. A major driving force behind it is due to the still present problem of how properly account for differential troposphere in a marine environment. Novel ways will be investigated, including the use of a Numerical Weather Prediction model. The outcome should contain indicators to support critical kinematic positioning decisions (that could be applied for both PPK and RTK), providing procedures on what to do under similar circumstances. It may provide answers to questions such as how to deal with ambiguities for an increasingly long baseline between base station and rover (try to fix it or move to a float solution), expected effects from an incoming weather system, what to do in such situations, and what to expect as far positioning performance and reliability goes.

In addition to these questions, other issues regarding the vertical component are addressed such as the relationships of various vertical surfaces via a seamless datum and local tidal effects.

The project can also be of benefit to navigation in general and in particular to navigation in the Bay of Fundy.

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To finish with, we would like to lay down the names of those who have been technically involved with the Princess of Acadia Project. From the University of New Brunswick: Dave Wells, Marcelo Santos, Don Kim, Karen Cove, Julie Baglole, Mohammed Al-Shahri, Mazhar Rafiq, Christian Solomon and Rodrigo Leandro. From the University of Southern Mississippi: Dave Wells, Sunil Bisnath, Jamie Davis, David Dodd and Steven Howden.

References

Bisnath, S., D. Wells, M. Santos and K. Cove (2004). “"Initial results from a long baseline, kinematic, differential GPS carrier phase experiment in a marine environment” Position Location and Navigation Symposium, IEEE PLANS 2004, Monterrey, Ca., 26-29 April, 2004.

Campbell Scientific (2000). SM4M/SM16M storage module instruction manual. Campbell Scientific Inc., Logan, Utah.

Cove, K., M. Santos, L. Huff, B. Remondi and D. Wells (2003). “Assessment of performance of ionospheric delay-free GPS carrier phase kinematic relative positioning with varying baseline lengths”. *Proceedings of the HYDRO 2003*, Biloxi MS 25-27 March 2003.

Cove, K. (2004). “Initial results and future goals for Princess of Acadia Project.” Carrier Phase and GPS Navigation for Hydrographic Surveys and Seamless Vertical Datums, University of Southern Mississippi, Gulfport, Ms, 16-18 March 2004.

De Haan, S., H. van der Marel and S. Barlag (2002). “Comparison of GPS slant delay measurements to a numerical model: case study of a cold front passage.” *Physics and Chemistry of the Earth*, Vol. 27, pp. 317-322.

Dodson, A. H., P. J. Shardlow, L. C. M. Hubbard, G. Elgered and P. O. J. Jarlemark (1996). “Wet tropospheric effects on precise relative height determination.” *Journal of Geodesy*, Vol. 70, pp. 188-202.

Estey, L. H. and C. M. Meeertens (1999). “TECQ: the multipurpose toolkit for GPS/GLONASS data.” *GPS Solutions*, Vol. 3, No. 1, pp. 42-49.

Gregorius, T. and G. Blewitt (1998). “The Effects of Weather Fronts on GPS Measurements.” *GPS World*, Innovation Column, May issue, pp.52-60.

Han, S. (1997). *Carrier Phase-Based Long-Range GPS Kinematic Positioning*. School of Geomatics Engineering UNISURV Report S-49, The University of New South Wales, Sydney, Australia.

Han, S., and C. Rizos (1997). “Comparing GPS ambiguity resolution techniques.” *GPS World*, Vol. 8, No. 10, pp. 54-61.

Hofmann-Wellenhof, B., H. Lichtenegger, and J. Collins (2001). *GPS Theory and Practice*. 5th. ed., Springer-Verlag.

Jensen, A. O. (2002a). “Numerical Weather Prediction for Network RTK.” Ph. D. Thesis. Publications Series 4, Volume 10, National Survey and Cadastre, Denmark.

Jensen, A.B.O. (2002b). “Investigations on the Use of Numerical Weather Predictions, Ray Tracing, and Tropospheric Mapping Functions for Network RTK.” *Proceedings of Institute of Navigation GPS 2002*, Portland, OR, September 24-27, pp.

Kim, D. and R. Langley (2001). “Estimation of the stochastic model for long baseline kinematic GPS applications.” *Proceedings of Institute of Navigation 2001 National Technical Meeting*, Long Beach, CA, U.S.A., 22-24 January, pp. 586-595.

Kim, D. and R. Langley (2003). “A New Dual-Mode GPS Real-Time Kinematic System for Seamless Ultahigh-Precision Positioning and Navigation.” *Proceedings of Institute of Navigation 2003GPS/GNSS 2003*, Portland, OR, 9-12 September 2003; pp. 2120-2128.

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, Fredericton, New Brunswick, Canada, 353 pp.

Novatel (2003). *OEM4 Family of Receivers: User Manuel*. Accessed off the World Wide Web on 21 April 2003. (http://www.novatel.ca/Documents/Manuals/om-20000046.pdf) Novatel Inc.

Pagiatakis, S. (1988). *Ocean tide loading in a self-gravitating, compressible, layered, anisotropic, visco-elastic and rotating earth with solid inner core and fluid outer core*. Ph.D. Thesis, Department of Geodesy and Geomatics Engineering Technical Report No. 139.

Santos, M. C., C. B. Souza and S. R. C. Freitas (2000a). "A practical evaluation of the fast static method." *Geomatica*, Vol. 54, No. 4, pp. 504-512.

Santos, M. C., N. C. C. Silva and L. C. Oliveira. (2000b). "An assessment on the effect of tropospheric delay on geodetic positioning using GPS data collected by the RBMC network." *Advances in Space Dynamics*, Antonio F. B. A. Prado (Ed.), National Institute of Space Research, São José dos Campos, SP, Brazil, pp. 447-455.

Santos, M. C. and J. C. F. Farret (2002). "Analysis and generalization of a dual-antenna multipath mitigation technique." *Proceedings of the Institute of Navigation GPS 2002*, pp. 487-492.

Santos, M. C. (2004). "The Princess of Acadia GPS Project." Carrier Phase and GPS Navigation for Hydrographic Surveys and Seamless Vertical Datums, University of Southern Mississippi, Gulfport, Ms, 16-18 March 2004.

Scherneck, H.-G. (1991). "A parameterized solid earth tide model and ocean tide loading effects for global geodetic baseline measurements." *Geophysical Journal International*, Vol. 106, pp. 677-694.

The XYZs of GPS (2001). "DynaPos™ GPS Real-Time Dynamic Positioning Software User's Manual." The XYZs of GPS, Inc., Dickerson, MD.

Waypoint Consulting (2003). GrafNav / GrafNet, GrafNav Lite, GrafMov Operating Manual Version 7.00, Waypoint Consulting Inc. Calgary, Alberta.

Wells, D, A. Kleusberg, and P. Vanícek (1996). *A seamless vertical-reference surface for the acquisition, management, and ECDIS display of hydrographic data*. Final contract report for the Canadian Hydrographic Survey, Technical Report No. 179 of the Department of Geodesy and Geomatics Engineering, University of New Brunswick, Fredericton, N.B., March, 64 pp.

Wells, D., S. Bisnath, S. Howden, D. Dodd, M. Santos and K. Cove (2004) "Prospects for extended-range marine PPK." The International Navigation Conference MELAHA 2004, Cairo, Egypt, 15-15 April, 2004.

Zhang, J., and G. Lachapelle (2001). Precise estimation of residual tropospheric delays using a regional GPS network for RTK applications. *Journal of Geodesy*, Vol. 75, 255-266.