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Prospects for Extended-Range Marine PPK

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Abstract

In this paper we use the term Post-Processing Kinematic (PPK) to refer to the process of deriving 3D ambiguity-resolved carrier phase differential GPS positioning results without the use of a real-time data link. PPK is crucial for vertical positioning in hydrographic surveying. Positioning system performance often involves a tradeoff between positioning uncertainty and effective coverage (range). PPK is at the uncertainty end of this tradeoff, with restricted coverage due in significant part to problems in modeling differential tropospheric delay, particularly the wet component. Tropospheric delay is of concern for marine vertical positioning for three reasons: (1) Tropospheric uncertainties map primarily into vertical position uncertainties. (2) Tropospheric conditions are less densely sampled at sea than over land. (3) Tropospheric uncertainties contaminate the cycle ambiguity resolution process, making extended-range marine PPK positioning difficult to achieve. This paper describes initial results from a three-pronged campaign to overcome this limitation:

(1) Collection of a marine PPK database, under varying tropospheric conditions with seasonal variations in different climates. Initially data are being collected from the Princess of Acadia ferry repeating the same route 4 times daily across the Bay of Fundy (the Lagrangian approach), and from a stationary moored buoy in the Gulf of Mexico (the Eulerian approach).

(2) Development of better tropospheric models, based on analysis of precipitable water vapour associated with the PPK database, determined from (a) GPS measurements, (b) local weather measurements, and (c) regional weather models. The tool we use to assess the success of a PPK tropospheric model is the comparison between short baseline (less than 10 km) PPK solutions (for which PPK is reliable and uncontaminated by differential tropospheric uncertainties), and simultaneous position solutions from longer PPK baselines over which the tropospheric models are being assessed.

(3) Implementation of these models into better algorithms for four independent software packages, each capable of PPK processing, developed by Ben Remondi and Kendall Ferguson of XYZs of GPS Inc.; by Don Kim at UNB; by Sunil Bisnath at UNB and USM; and by Dave Dodd at UNB and USM.

Introduction

In this paper we discuss initial results from a three-pronged campaign to better determine and apply tropospheric delay corrections to extended range marine fixed-integer and floating-point cycle ambiguity-resolved carrier phase differential GPS positioning measurements.

In our campaign we are not attempting to use a real-time data link to supply differential corrections to measurements made on platforms at sea. All raw data are recorded and all processing is done afterwards. We use the term Post-Processing Kinematic (PPK) to refer to this process, in contrast with the term Real-Time Kinematic (RTK), which infers the use of real-time data links. In our experience the accuracy provided by RTK or PPK is required during final data processing, and not for survey track control, although under-keel clearance navigation applications would require RTK.

The goal of our campaign is to advance the science of modeling microwave tropospheric delay over coastal areas, and to test, apply, and demonstrate these advances to obtain higher accuracy (centimeter-level) positions at greater distances (10s to 100s of kilometers) from differential reference stations than is now possible, using the Global Positioning System in a post-processed fixed-ambiguity carrier-phase differential mode (PPK).

Once achieved, this will make possible marine vertical positioning (actually 3-D positioning) accurate enough for vertical control in the measurement and modeling of offshore tidal and other water level variations, offshore determinations of the geoid-ellipsoid separation, hydrographic surveying (including airborne LIDAR bathymetry), ground truth calibration of satellite altimetric sensors of sea level, and will contribute to realizing the goal of seamless vertical datums.

Our campaign consists of four activities

1. The collection of a **database of PPK data** that can be used to test, evaluate, and improve tropospheric models and algorithms. This coastal PPK dataset will be collected under varying tropospheric conditions with seasonal variations in different climates. We are employing two methods:

   (1a) **The Princess of Acadia Project:** This project involves instrumenting a car ferry that travels the 74 km route between Saint John, New Brunswick, and Digby, Nova Scotia between two and six times per day (depending on the season). The project is located in a temperate climate (the Bay of Fundy) with significant seasonal tropospheric variations (e.g. temperatures between – 30°C and + 30°C). We refer to this data collection strategy as the Lagrangian approach (spatial sampling). While the ferry is in port, it also permits data collection using the Eulerian approach (temporal sampling at a “fixed” location).

   (1b) The Central Gulf Ocean Observing System (**CenGOOS**): This project involves the development, deployment and operation of a data buoy outfitted with a PPK receiver, motion sensors, and sensors to monitor air temperature, air humidity, wind speeds, water temperature, surface salinity and currents, air pressure, velocity profile, and sea bottom pressure. This buoy is located in a subtropical climate (the Gulf of Mexico), also with significant seasonal tropospheric variations (e.g. temperatures between +5 °C and 35°C). This data collection strategy is the Eulerian approach.

2. The development of **better tropospheric models**. Building on experience in designing the tropospheric model for the Wide Area Augmentation System (WAAS) for the FAA

(Collins, 1999), we are using our PPK database to test existing methods of dealing with PPK tropospheric uncertainties, and investigating the improvements that result from using various combinations of tropospheric delays determined from (a) GPS measurements, (b) local weather measurements, and (c) regional weather models.

3. The implementation of these models into **PPK GPS software algorithms**. We are using five software packages which already process carrier-phase differential kinematic GPS data in sophisticated ways, and which provide platforms for tropospheric modeling research and algorithm development. These are two commercial packages, **DynaPos**, supplied by XYZs of GPS, Inc., and **GrafNav**, available from Waypoint Navigation, and three academic software packages, **UNBRTK** provided by Dr. Don Kim, **PCPOS** developed by Sunil Bisnath, and **USMOTF** under development by Dave Dodd. These programs will be adapted and used to evaluate the effectiveness of new approaches to tropospheric models.

Any research and development into extending the range of PPK capabilities must anticipate the changes expected from the GPS Modernization program:

1. An improved GPS ground tracking network, and inter-satellite ranging. This is expected to improve the accuracy of predicted GPS orbits and clocks.
2. The addition of two new civilian GPS frequencies (C/A signal on L2 at 1227.60 MHz, and new L5 signal at 1176.45 MHz). This is expected to (a) improve the multi-frequency estimation and removal of ionospheric effects on GPS signals, (b) drastically lower the cost of civilian dual-frequency receivers (since proprietary methods to obtain L2 signals are no longer needed), (c) except for the limitations due to tropospheric contamination, greatly simplify carrier phase integer ambiguity resolution, since the L2/L5 widelane combination has a lane width of 5.8 m, in comparison with 0.86 m for the L1/L2 widelane.
3. The possibility of a new GPS constellation design (GPS III). It is possible that a new constellation could be optimized for height determination.

Even though these are important considerations for extending PPK baselines in the future, none of these improvements are expected to directly address the problem of tropospheric modeling uncertainty, which we expect to be the dominant remaining source of carrier phase differential GPS positioning uncertainties.

One of the tools we use to assess the success of a PPK tropospheric model is the comparison between short baseline (less than 10 km) PPK solutions (for which PPK is generally regarded as reliable and uncontaminated by differential tropospheric uncertainties), and simultaneous solutions from longer baselines over which the tropospheric models are being assessed, using several different combinations of the GPS observables (e.g. ionosphere-free, widelane, narrow lane, and other blends of L1 and L2 carrier phase measurements).

In this paper we concentrate on initial results from activity (1a) – the Princess of Acadia project, and in particular an analysis of the consistency being achieved among the GPS, tide, and meteorological sensors we are using. However we start with an overall description of the entire campaign.

Background

Over the past decade, positioning at sea for hydrographic surveying, navigation, and other operations, has been revolutionized by the use of the Global Positioning System (Wells et al., 1986, Parkinson and Spilker 1996, Wells 1998). There are several modes in which GPS can be used, yielding a progression of improving three-dimensional position accuracies (at the 95% confidence level): single receiver (autonomous) mode – 10-20 meters; differential code (standard DGPS) mode – 1-5 meters; differential carrier-phase with floating-point cycle ambiguities – 0.2-0.8 meters; and differential carrier-phase with fixed-integer cycle ambiguities (PPK or RTK) mode – 0.01-0.05 meters. All these modes are in common use.

Sub-decimeter marine vertical positioning accuracies are required for the measurement of water level variations (tides, etc.), hydrographic surveying, navigation and other operations. For shallow water hydrographic surveys, modern multibeam sonar echosounders are capable of delineating seabed features at the centimeter level (see Figure 1). This capability is damaged unless the 3-D georeferencing of the echosounder transducer has an equivalent accuracy. Other sensors (notably modern heave-pitch-roll sensors) can contribute to achieving such 3-D georeferencing accuracies, but non-periodic and very low frequency vertical transducer motions, such as due to tides, squat, long-period heave, and other dynamic draft effects, are adequately measured only by PPK or RTK GPS.

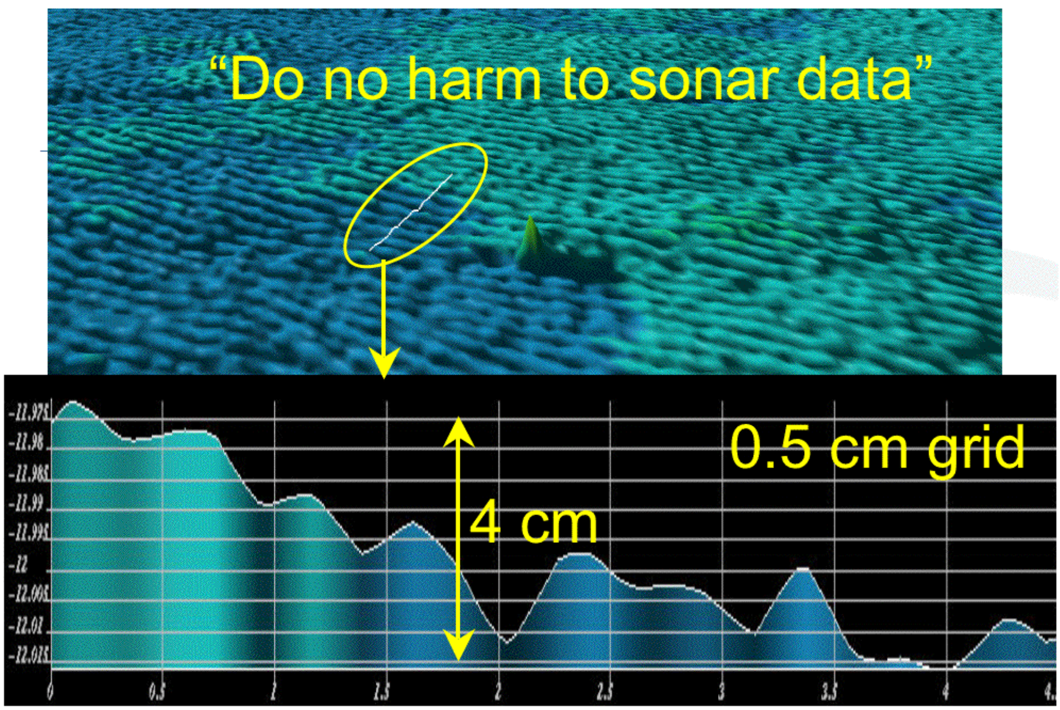


Figure 1. Sub-centimeter sandwave heights measured by Reson 8125 multibeam sonar near Martha's Vineyard (IVS Fledermaus image courtesy of Larry Mayer, Center for Coastal and Ocean Mapping, University of New Hampshire). This image demonstrates that modern multibeam sonars are capable of delineating features of centimeter and sub-centimeter size. Combining data from adjacent survey lines that are georeferenced less accurately (i.e., without PPK) will smudge the overlapping coverage, rather than sharpening it.

Airborne LIDAR hydrography (ALH) also requires centimeter-level vertical positioning for two reasons: (a) to accurately correct LIDAR bathymetry for water level variations; and (b) to provide the only vertical referencing possible for hybrid bathymetric / topographic LIDAR systems (such as Optech's new SHOALS-1000 system) designed to provide continuous bathymetric / beach topography to support coastal zone management and amphibious operations.

The availability of high density, high-resolution topographic and bathymetric datasets and digital elevation models (DEMs) has highlighted the difficulties in representing topography and bathymetry in a common vertical reference frame (Hess 1994, Wells et al., 1996, Milbert and Hess 2001). The problem of determining the detailed relationships among **orthometric heights** (related to the geoid and other gravity-based surfaces), **geodetic heights** (related to the ellipsoid), and hydrographic **depths** (related to Chart Datum, a particular statistic of water level variations) requires the construction of several "separation models"; the familiar geoid-ellipsoid separation model, and a family of separation models relating various water levels (mean sea level, mean lower low water, etc.) to the ellipsoid, based on hydrodynamic modeling.

The term "seamless vertical datum" has come to refer to the set of separation models and other transformations which permit referencing DEMs from different data sources (e.g., topographic and bathymetric) seamlessly with respect to whichever of the vertical reference surfaces (geoid, ellipsoid, specific water level) is most appropriate for a particular application. The ellipsoid is chosen as the fundamental transfer surface (by relating all separation models to a common ellipsoid) since it is simple and defined by convention, rather than being data-dependent. Seamless DEMs provide critical decision support for many applications, such as amphibious operations, coastal erosion studies, and determining shipping under-keel clearances.

PPK is the technology that permits the ellipsoid to play this role, since PPK heights are related to the ellipsoid. PPK-controlled topographic LIDAR, flown along beaches and waterlines, provide a crucial "stitching layer", facilitating the development of appropriate hydrodynamic models to create the required separation models.

However, PPK is often limited to maximum ranges of 5-10 kilometers from the nearest differential base station, due to inadequate modeling of a number of error sources, including tropospheric delay of the GPS signals. For example, current ALH surveys using the SHOALS system require the deployment of many PPK base stations distributed along the survey route, in order to not to exceed the maximum 5-10 kilometer range from the nearest base station (Lillycrop, 2002). Even this (expensive) strategy is not available for operations more than 10 km from land, or under covert conditions.

There are effective mitigation strategies for all sources of PPK uncertainty, except tropospheric delay. Clock errors are eliminated by double-differencing the GPS range measurements (Wells et al., 1986). Ionospheric delay uncertainty is almost completely eliminated by two-frequency estimation. GPS satellite orbit errors can be eliminated by post-processing with precise ephemeredes (and have little effect for baselines up to a few 100 kilometers). Multipath uncertainties can be reduced by using special equipment: choke-ring and other multipath-resistant antennas, and receivers with multipath-estimating tracking loops. Multipath is less likely for antennas in motion as on buoys and boats at sea, and has a smaller signature for GPS carrier phase measurements than for GPS code measurements.

Tropospheric delay is usually estimated based on either surface pressure and temperature measurements (at the GPS receivers being used) and/or model atmospheric predictions. This approach often inadequately accounts for horizontal and vertical spatial variations in atmospheric conditions, in particular the vertical profile of water vapor. Tropospheric delay is of greatest concern for marine vertical positioning for three reasons: (1) Tropospheric uncertainties map primarily into vertical position uncertainties. (2) Tropospheric conditions are less densely sampled at sea than over land. (3) Tropospheric uncertainties contaminate the cycle ambiguity resolution process, making longer range PPK positioning unreliable or impossible.

Much work is being done on advancing the modeling of tropospheric delay over continental areas for GPS applications in land and air transportation and precision agriculture. For example, a network of 16 differential GPS base stations spaced 50 km apart on a 200 x 200 km grid has been established for just this purpose (Zhang and Lachapelle 2001). Establishing such an infrastructure at sea would be much more difficult and expensive, if not impossible.

Less PPK tropospheric delay modeling research is being done for marine applications. The marine climate and tropospheric conditions are quite distinct from those over land. Also coastal and marine climates differ widely between temperate and tropical areas, leading to wide differences in the temporal and spatial variability of microwave tropospheric delays. One of the goals of this campaign is to address the need for better GPS tropospheric uncertainty modeling at sea in order to achieve longer ranges for reliable PPK vertical positioning.

One of the goals of this campaign is to create the necessary infrastructure and start to assemble a database of high quality carrier phase short / long baseline datasets, obtained in both temperate and tropical climates, and under all seasonal and weather conditions. We have analyzed one such data set from Chesapeake Bay where the short baseline was of order 1 km, and the long baselines varied from 47 to over 200 km (Cove et al., 2003).

Long range PPK Database

A comprehensive database of diverse high quality coastal and marine PPK data has not so far been available. The ideal data series would be one with baseline distances up to 200 km, with data collected in all weather conditions, in various climates, and all seasons. Such a database could be used to not only validate new tropospheric modeling approaches, but also aid in driving the evolution of long baseline, marine differential models. The collection of this database is a goal of this campaign, and is a collaborative effort. Once assembled, access to the database will be made available to other researchers working on tropospheric problems. It is expected to eventually contain a several hundred Gigabytes of data.

The procedure proposed for initial population of the PPK database relies on two complementary data collection strategies: a commercial ferry (low cost vessel of opportunity, firm data collection schedule, year-round operation), and a data collection buoy (ideal platform of opportunity as it can be transported to and deployed at practically any near-coastal and offshore locations).

1. **Ferry data collection**. Data collected on a regularly scheduled ferry have the advantages of spatial and temporal diversity. The varying distances from each PPK base station during the ferry crossing is repeated for each crossing, so that sampling under similar PPK geometries can be repeated under widely varying tropospheric conditions. Control for the ferry crossing data comes from long / short baseline pairs, where base stations are located at both ends of the ferry route to allow for verification of the long baseline solutions (between the ferry and the far terminus) using those from the short baseline (between the ferry and the near terminus).

   UNB negotiated agreements with **Marine Atlantic** (who operate *The Princess of Acadia*, a car ferry, all year on the 74-km route across the Bay of Fundy between Saint John New Brunswick and Digby Nova Scotia); the **Canadian Coast Guard** (who operate a

DGPS base station in Saint John); the **Atmospheric and Environmental Service of Canada** (who measure, interpret, and distribute meteorological information), and the **Canadian Hydrographic Service** (who operate tide gauges in both Saint John and Digby, the latter established specifically for this project).

UNB is collecting 12 months of continuous PPK and weather data on the ferry and at both terminals. Data from other continuously operating PPK reference stations (for example, the Canadian Active Control Stations in Fredericton, New Brunswick and Halifax, Nova Scotia operated by the Geodetic Survey Division of Natural Resources Canada) will also be collected. In addition to the long / short baseline comparisons, PPK height solution variations are being compared against predicted vertical positions based on tide gauge water levels, plus dynamic draft models for the ferry.

Successful operation of the GPS and meteorological equipment on board the *Princess of Acadia*, and at the Saint John and Digby base station began on 16 October 2003, and after a shake-down and testing period, systematic data collection began 28 November 2003, and will continue for one year from that date.

2. **Buoy data collection**. Data collected on a moored data buoy has the stability of a single set of PPK geometries, which can be assessed over the widely varying tropospheric conditions encountered during a long data series. The data buoy can be moored anywhere, and can be moved according to experimental priorities. The buoy can be equipped with auxiliary sensors to assist in partitioning the observed PPK signal into actual buoy motions and PPK measurement artifacts.

   Practical PPK buoy applications include ground truth and inter-calibration between satellite altimeters carried on different satellites (by placing the PPK buoy where the ground tracks from these satellites cross); determining Chart Datum offshore (improving and simplifying the process of tidal zoning); and real-time water level monitoring close to an area of operations (supplementing and or reducing the need for traditional shore-based tide gauges).

   The first PPK buoy experiment was carried out in 1994 at UNB (Deloach et al, 1994a, 1994b, 1995a, 1995b, 1995c). It produced excellent PPK data, but failed prematurely due to power management problems.

   One of the many groups experimenting with operational use of PPK buoys is a collaborative team led by NAVOCEANO, including Planning Systems Inc. (PSI), and USM. The buoy developed for NAVOCEANO has used PPK receivers supplied by USM, and USM has processed all the data collected by this buoy. Lessons learned from the first deployment in 2001 were that the buoy should initially be deployed near a reference tide gauge and continuous (weekly) PPK data quality assurance procedures are needed. The lesson learned from the second deployment (late 2002) was that a more sophisticated power management strategy is required (during short winter days especially). The buoy was deployed a third time (late 2003). Xx add xx

   Learning from this experience, we have acquired a PPK data buoy that is more robust, has greater power capacity, can be deployed with more sensors, and has a proven reliability. We have subcontracted with the Texas Automated Buoy System (TABS) team at Texas A&M University to construct and instrument this buoy for us. The TABS buoy (Guinasso et al., 2001) has a reputation for reliability such that the National Data Buoy Center is now including TABS buoy data as part of the National Weather Service buoy network.

This is a 3-meter discus buoy, capable of supporting the following PPK and auxiliary instruments:

- Dual-frequency, survey grade GPS receivers for buoy and base-station
- Meteorological sensors for measuring local weather parameters that have an effect on GPS signal propagation. The buoy will monitor air pressure, air temperature, humidity, and wind vectors.
- Motion and orientation sensors for the buoy to monitor how well GPS receivers can resolve high frequency oscillations caused by waves.
- Bottom mounted pressure sensor for monitoring squat of the buoy.
- Single point (2 m) current meter and ADCP for current profile (10 m to bottom) to monitor drag on complete mooring for understanding changes in squat. The wind vector data will also be used in this application.
- Communications links to shore: VHF radios for standard PPK link; Satellite phone system for providing data telemetry (for PPK and ancillary data) in both near shore and offshore deployments, respectively; Inmarsat equipment as a backup link for offshore deployment;
- Acoustic modems to telemeter bottom pressure data to buoy.

After near-shore deployments for checkout and calibration, this data buoy will first be deployed near N 29° 58.649', W 88° 36.297', the location of a Chevron gas platform 40 km off the Mississippi coast. USM has a collaborative agreement in place with Chevron to use this platform for scientific purposes. Locating the buoy within 5 km of this platform, and locating an PPK base station on the platform itself, will permit the long / short baseline strategy to be used in investigating the long distance tropospheric effect on PPK. The long baseline base stations will be located at various shore stations designed to be specific distances (between 30 and 200 km) from this location. The intention is to maintain the buoy at this location for at least 12 months.

We intend to moor this buoy for the first time in April 2004.

We will use the datasets collected on the ferry (temperate climate) and data buoy (sub-tropical climate) to test various tropospheric models, with various processing algorithms, under varying controlled data collection situations to determine what combination performs the best (most reliable PPK positioning over longest baselines) and to provide insight as to how best to improve the models and algorithms.

In time, it is envisaged that these mid-latitude ferry and Gulf of Mexico buoy datasets will be augmented with additional data such as tropical ferry or cruise ship-based data, which USM is engaged in the planning phase.

Improved Tropospheric Modeling

The differential troposphere experienced by combining GPS measurements from a coastal base station and a near-shore reference station baseline can differ significantly from land-based baselines. Weather fronts, temperature inversions, and other dynamic coastal weather phenomena degrade the effectiveness of present generic tropospheric delay models (Gregorious and Blewitt, 1998) to the extent that their inability to describe the behavior of the differential troposphere hampers and eventually prevents the successful ambiguity resolution process (which is required in order to obtain cm-level positions) as baselines are lengthened. As the primary limiting factor in successful long baseline PPK (between 20 and 200 km), we propose to improve upon existing tropospheric delay models, and integrate these enhancements in PPK software signal processing.

This work builds on experience in the tropospheric modeling that was performed for the Federal Aviation Administration's (FAA) Wide Area Augmentation System (WAAS) (Collins, 1999) and the evaluation of existing geodetic tropospheric delay models (Mendes, 1999). Also, expertise is available in the GPS modeling and signal software processing necessary for other Wide Area Differential GPS (WADGPS) systems similar to JPL's Real Time Gypsy (RTG) (Bisnath and Langley, 2003).

We plan a combination of strategies to tackle this problem. Improvements are expected through the following five research areas:

1. Reviewing the performance of **existing GPS tropospheric delay models** and determining the effectiveness of each for long-range coastal and marine PPK. By characterizing the limits of the best tropospheric delay models, all of which are designed to be passive and generic, the extents of the improvements required will be defined. This will be accomplished by a review of the scientific literature, and evaluation of models using our marine PPK database.

2. Determining the feasibility and potential of **estimating the residual tropospheric delay** after applying the best performing of these models. One option for improving the usefulness of passive tropospheric models is to utilize the GPS measurements to estimate the portion of the delay due to the troposphere for which the model could not compensate (Pattison, et al., 2002). The difficulty is to estimate the delay precisely without adversely affecting the positioning solution.

3. Evaluating the application of **in situ meteorological sensor measurements** to drive the tropospheric models more realistically. Another approach to potentially improve the utility of the tropospheric models is to collect temperature, pressure, and humidity readings at the GPS receivers and allow the models to be adapted to the current local surface conditions, as is being done in the collection of our marine PPK database.

4. Analyzing the level of benefit of employing **regional weather data** (in the form of interpolated terrestrial and satellite data, and numerical weather prediction models) in place of the tropospheric prediction models. Rather than relying on the weather-independent tropospheric models, the measurement strength of the GPS data, or the ability of surface meteorological measurements to characterize the neutral atmosphere, direct regional weather information can be ingested into the PPK processing (Jensen, 2002). This involves obtaining appropriate data, deriving the delay of the GPS signals due to the wet and hydrostatic components of the troposphere, and correctly applying these values in the software signal processing. We have negotiated an agreement with the **Atmospheric and Environmental Service of Canada** that provides us with access to their twice-daily NWP numerical weather data.

5. Customizing a **subset of these strategies**, depending on their utility, for the marine environment. Improvements will be based on model performance installed in improved versions of the PPK software we are using, obtained from the analysis of a variety of data from our marine PPK database.

Improved PPK GPS Algorithms

In order to validate tropospheric model improvements and to make them useful, they need to be implemented into PPK processing software. This process will involve development and implementation of a blend of deterministic and stochastic models in already-sophisticated PPK software and will represent novel advancements in GPS data processing. The improvements will involve the augmentation or possible replacement of existing processing algorithms.

We propose attacking this issue on two fronts:

1. Using well-proven, highly regarded **proprietary commercial software**. USM, UNB, and UNH already have licenses for and experience with one such package: the DynaPos processing software supplied by XYZ's of GPS, Inc. In recent years, the XYZs have spent considerable resources improving DynaPos performance and capability, and it is a proven PPK commercial package with a great deal of flexibility. It is a real-time and playback engine for computing low centimeter to low decimeter GPS positioning with carrier and code measurements. DynaPos has already been used by USM and UNB to evaluate code and carrier phase differential GPS data collected using (a) differential data from base stations up to 200 km from the user (Cove et al. 2003), and (b) differential data provided by commercial carrier phase-based Wide Area Differential GPS services (Bisnath et al., 2003a).

   XYZs has also supplied licenses to USM and UNB for their GRIM (GPS Receiver Independent Modem) software that interfaces with GPS receivers by direct connection or via telecom link. GRIM logs data in the standardized format RINEX and in the receiver's native formats for playback. GRIM is network capable (TCP/IP). For real time transfer of data using a very narrowband link (e.g., 50-100 bytes/s.) GRIM provides useful compression options. Typically GRIM supplies real-time or post-mission data to DynaPos, but DynaPos can also process RINEX data without GRIM.

   We propose to use DynaPos to study, analyze and implement some of the tropospheric modeling improvements designed at USM. XYZs proposes to maintain and improve GRIM and DynaPos and provide USM with updated versions of these. These improvements would come from

   (a) Covariance analysis: development and testing to anticipate what improvements in height determination might be expected when the GPS satellites broadcast three navigation signals; and quantitative and qualitative indications regarding the effect of GPS constellation design on height determination, and

   (b) Tropospheric analysis: compute numerical or analytic partials of tropospheric delay as a function of each of temperature, pressure, and humidity (holding the others fixed); demonstrate the effect that vertical tropospheric delay determination has on the current GPS geometry; and also possibly the effect of an improved (i.e., GPS III) geometry. The covariance and tropospheric delay investigations, particularly the latter, will be leveraged by taking a cooperative approach with the University of Southern Mississippi. USM and XYZs improvements in modeling and/or eliminating the tropospheric path delay is an important element of reducing the uncertainties in PPK vertical positioning.

2. Participate in the enhancement of **excellent academic software**. Based on the analysis of our marine PPK database using various new approaches to tropospheric modeling, we plan to implement these models as algorithms in new versions of the UNBRTK, PCPOS and USMOTF software packages. Of these, the UNBRTK software package is most advanced, and warrants further description:

   Over the past several years, UNB has developed PPK GPS processing software. The **first generation** UNBRTK software was initially developed under a grant to improve real-time kinematic GPS positioning over long distances in support of bathymetric surveys. The research and development carried out by UNB was mainly to improve the carrier-phase ambiguity resolution methods and associated algorithms to achieve more precise and reliable kinematic GPS positioning over distances up to, and even longer than, 75 km for the real-time positioning support for bathymetric surveys and other applications (Kim and Langley, 2001). However, this first generation software was not fully operational or automatic.

The **second generation** UNBRTK software was developed under a contract for an RTK-controlled container port gantry crane auto-steering system. This system is now installed and operating with excellent results, maintaining a vertical position uncertainty of 3 cm at near 100% confidence level, with high availability (more than 99.9%), and high rate navigation solution updates (10 Hz). This new ultrahigh-performance GPS RTK software is fully operational and automatic. However, practical applications using this software are limited to short-baseline situations.

Work on a **third generation** UNBRTK software is underway, based on tests of the software for deformation monitoring, carried out at an open pit mine with significant height differentials, causing differential tropospheric delay concerns. Technical and scientific aspects of the UNBRTK software, especially in handling residual tropospheric delay and multipath, have been investigated. The UNBRTK software is being upgraded to enable multi-epoch processing.

The UNBRTK software includes the UNB3 tropospheric prediction model and residual tropospheric delay estimation routines. Joint research and development between USM and UNB will be carried out to improve these forms of tropospheric modeling. Weather model-based delay estimates will be ingested into the processor, as another form of tropospheric delay modeling. Multi-epoch processing will be adopted to improve ambiguity search success rate over longer baselines. Investigations will be made into improvements in stochastic modeling similar to the high-pass filtering technique already implemented in the UNBRTK software.

The Princess of Acadia Project

On 16 October 2003 Novatel OEM4-G2 GPS receivers, and Campbell Scientific meteorological stations were installed on the Princess of Acadia (station BOAT), at a base station located on the roof of the Canadian Coast Guard base in Saint John, New Brunswick, about 1.8 km from the Saint John ferry terminal (station CGSJ), and at a base station located on the roof of Digby Regional High School (station DRHS), about 4.4 km from the Digby ferry terminal. Data are recorded on laptop computers at each location. After an initial period of testing and calibration, systematic data collection began on 28 November 2003. The DRHS data are recovered remotely by File Transfer Protocol (ftp), while the BOAT and CGSJ records are manually transferred to a portable hard drive about once every two weeks.

Two stations at Fredericton (station FRDN) and Halifax (station HLFX), part of the 42-station Active Control Network operated by the Geodetic Survey Division of Natural Resources Canada, record data at 1 Hz, making them suitable for our project. With cooperation from the Geodetic Survey Division, we will be using data from these base stations as well.

Figure 2 shows the geographical relationship among these stations. Figures 3 shows the Princess of Acadia. Figure 4 shows the equipment installation at BOAT, figures 5 and 6 at CGSJ and figures 7 and 8 at DRHS.

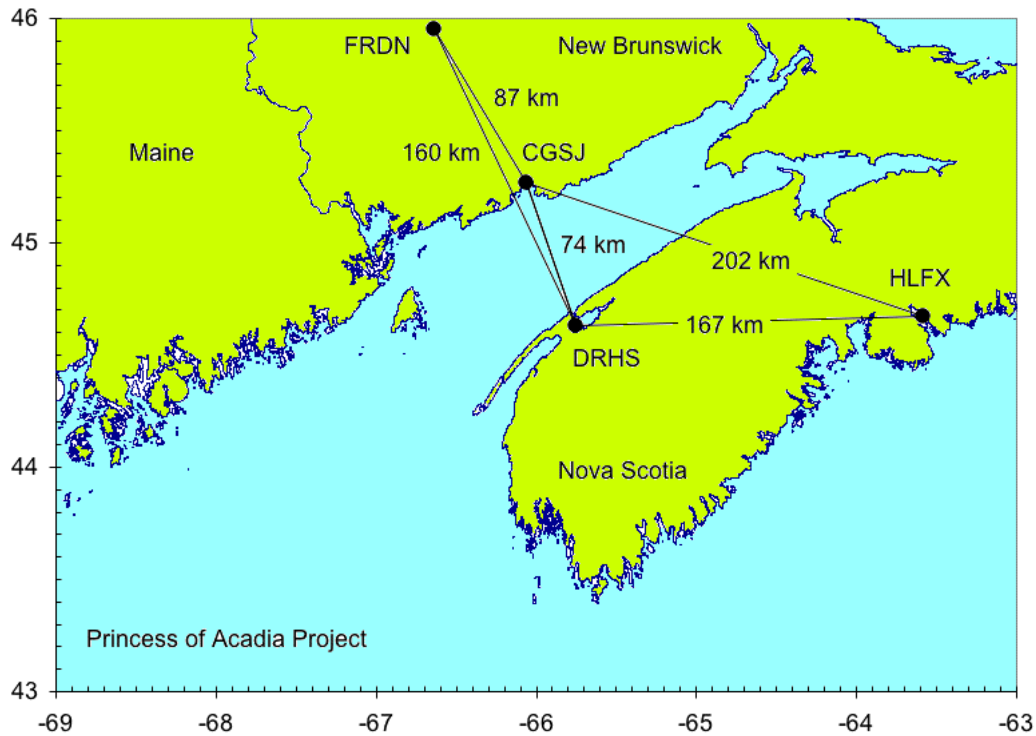


Figure 2. The Princess of Acadia ferry travels the 74 km between Saint John (CGSJ) and Digby (DRHS) two or four times per day, depending upon the season. Using four base stations, the base-station-to-ferry distances range from 1.5 km to 202 km.

Figure 3. The Princess of Acadia. This car-ferry accommodates up to 650 passengers, 155 automobiles and 33 tractor-trailers. The ship was built in 1971, has a length of 146 m, beam of 20.5 m, and draft of 4.6 m.

Figure 4. GPS and meteorological station locations on the Princess of Acadia. They are approximately 19 m above the vessel waterline.

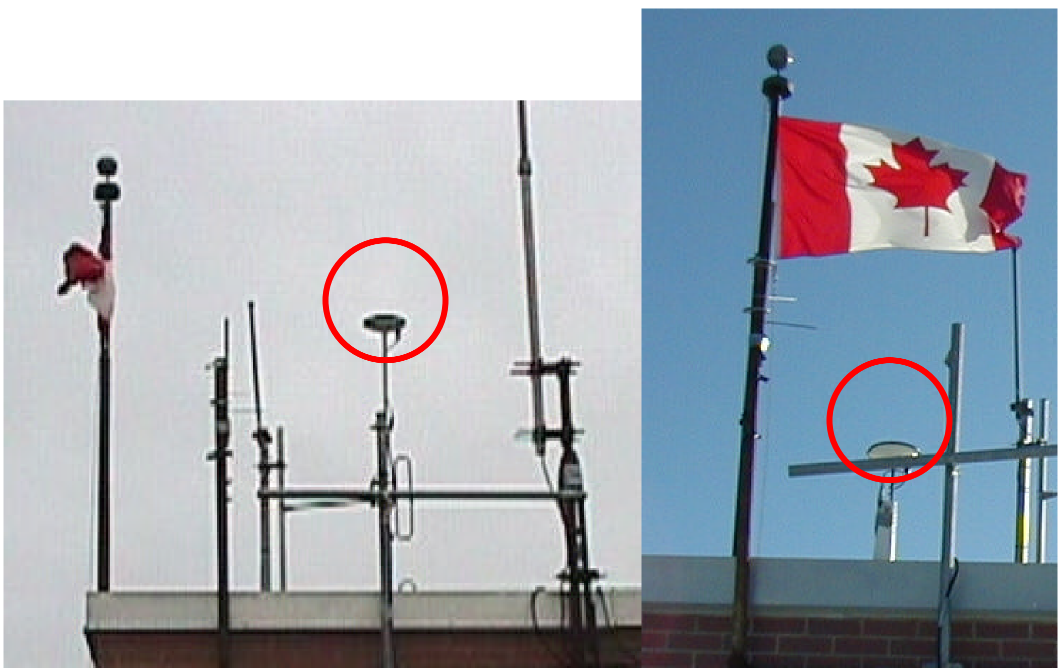
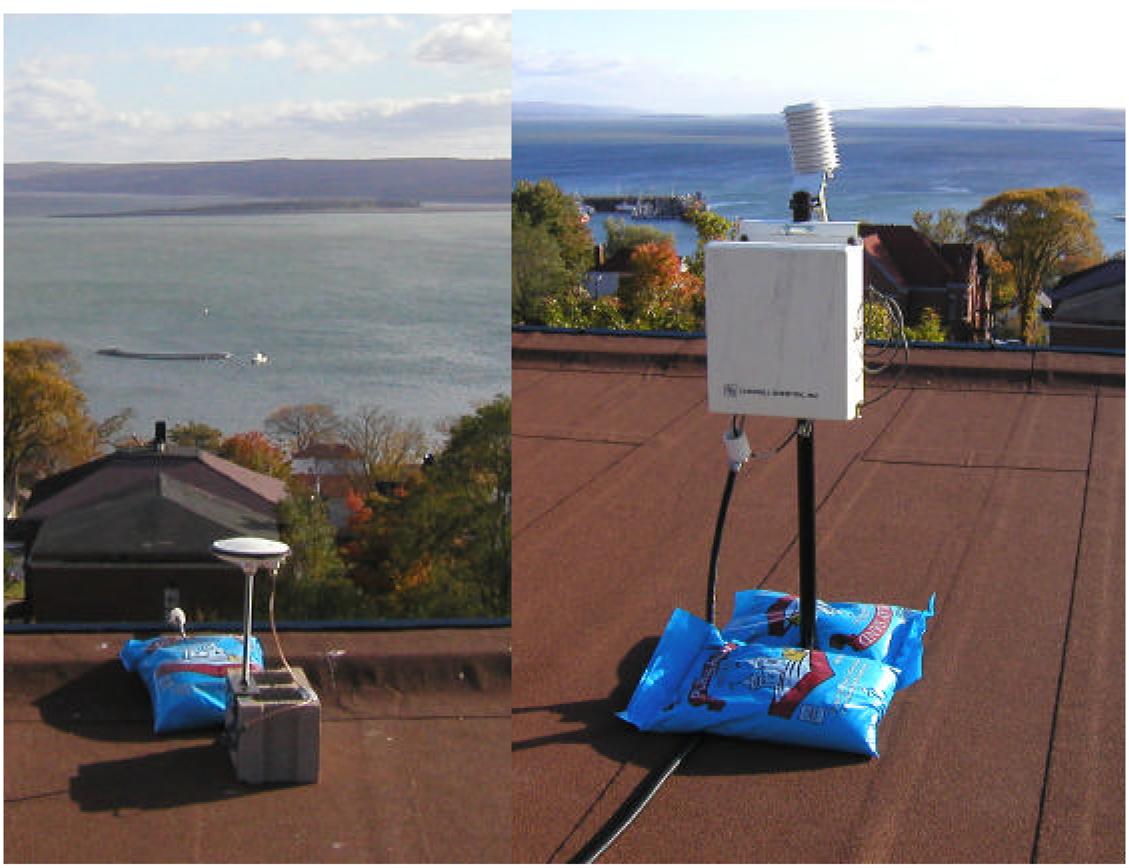


Figure 5. Locations of the GPS antenna at CGSJ. Data from the first mount indicated the antenna was unstable and moving. It was re-mounted lower. Data from the second location suffered a higher level of multipath than at the other two stations. After further analysis, the antenna may be repositioned again in April 2004.

Figure 6. Location of the meteorological station at CGSJ, with downtown Saint John in the background.

Figure 7. Location of GPS and meteorological sensors at DRHS (on the roof of Digby Regional High School).



There have been a number of equipment failures over the past four months, none of them permanent. A few days of GPS data have been lost on a few occasions, most often due to computer logging failures, usually solved by simply rebooting the computer. The pressure sensor in the DRHS meteorological station developed a temperature-related failure mode on December 6, 2003, most likely due to a small amount of moisture in its sensor tube. This fault plagued this sensor for the next 3 months.

A permanent tide gauge has been operating in Saint John for over 100 years. With cooperation from Dalhousie University Department of Oceanography, and the Canadian Hydrographic Service, a second tide gauge was installed in Digby on October 3, 2003, adjacent to the ferry berth. Unfortunately, a severe storm on November 6, 2003 destroyed the stilling well on this gauge. Winter weather has prevented its repair, which is now scheduled for early April.

Numerical Weather Parameters (NWP) supplied by the Canadian Meteorological Service are downloaded from their website daily. Initially all available parameters were downloaded, amounting to about 1.5 Gb / day. Starting in late March 2004, only those parameters directly related to the estimation of Precipitable Water Vapor (PWV) were downloaded, cutting this volume considerably.

Initial meteorological data

Three days, January 12-14 2004, were selected for detailed analysis. On January 12, the Princess of Acadia remained in Saint John all day, so that a comparison between the short-baseline PPK heights and the Saint John tide gauge readings could be examined in detail. On January 13 the ferry made two crossings. During January 14 the temperature dropped from about 0 C to minus 25 C.

The meteorological conditions are summarized in Figures 8 to 13, for both the month of January 2004, and for the three days examined in detail. In all these figures, our mnemonically-chosen color-coding is **B**lue = **B**oat, **G**reen = c**G**sj, and **R**ed = d**R**hs.

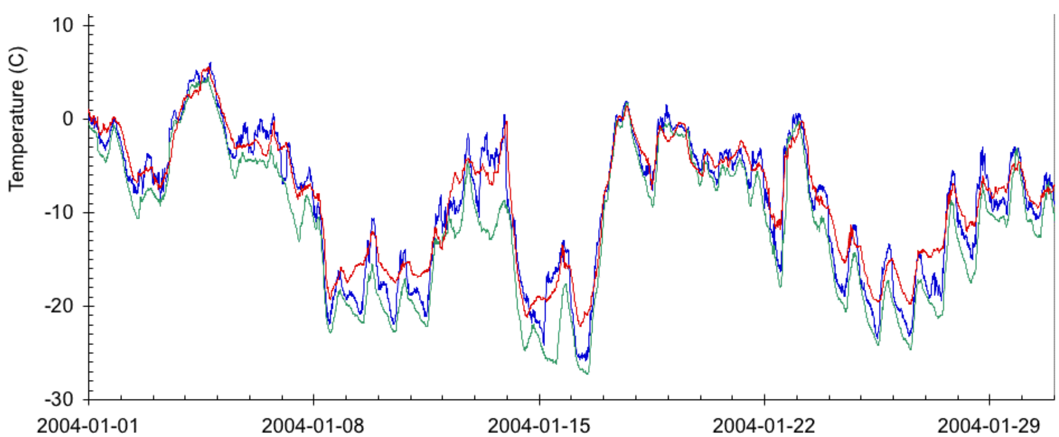


Figure 8. Surficial temperature measurements for January 2004. The week centered on January 16 was the coldest in 80 years.

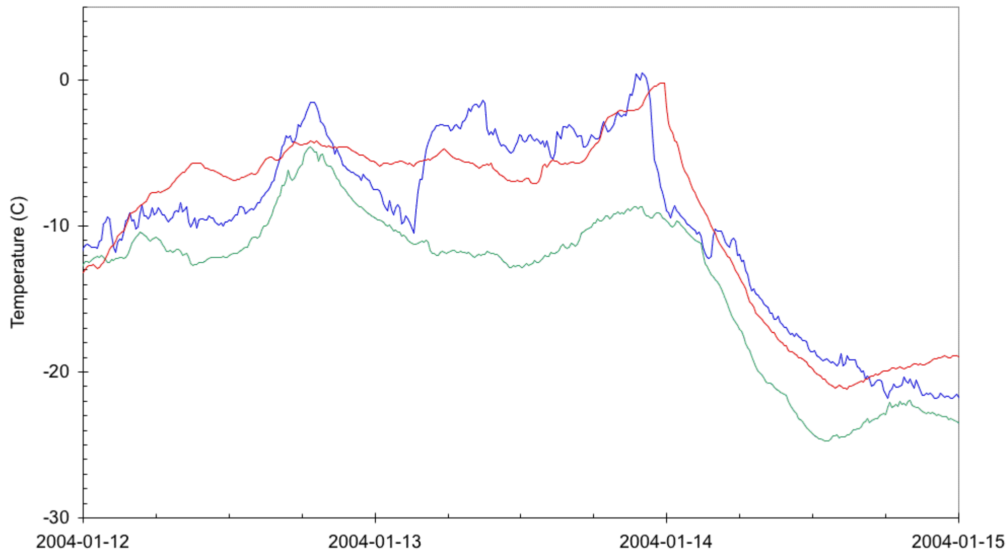


Figure 9. Surficial temperature measurements for the test period (January 12 – 14). The temperature dropped by about 25 C on January 14.

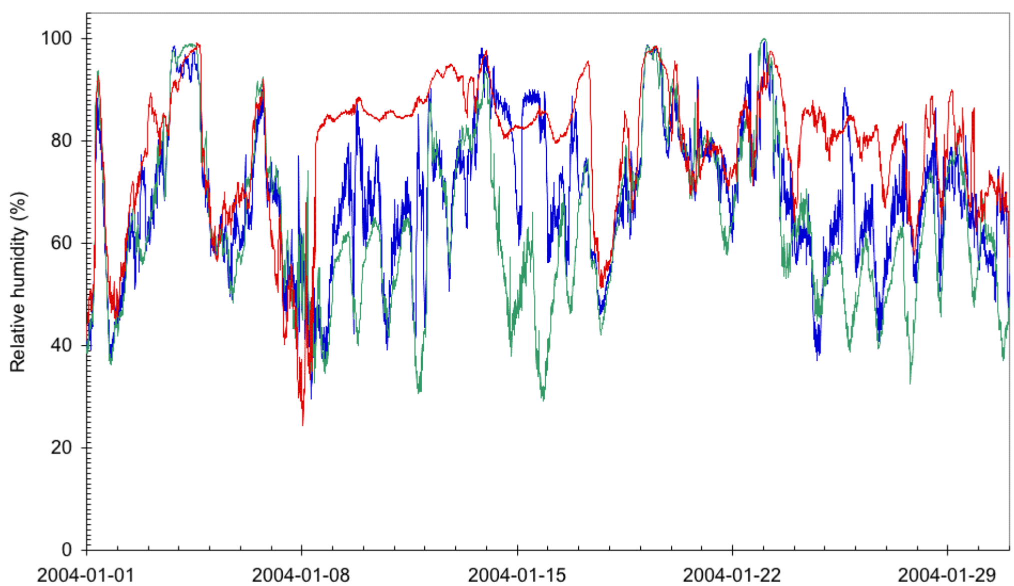


Figure 10. Surficial relative humidity measurements for January 2004.

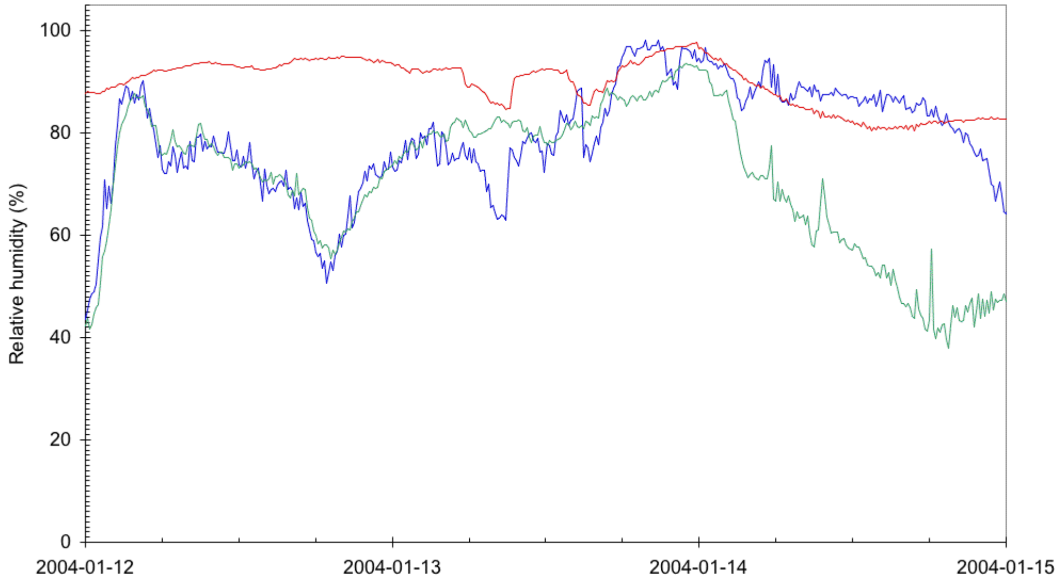


Figure 11. Surficial relative humidity measurements for the test period (January 12 – 14). The significantly higher humidity at DRHS for the first day and a half shown was confirmed by humidity trends computed by the Canadian Meteorological Service.

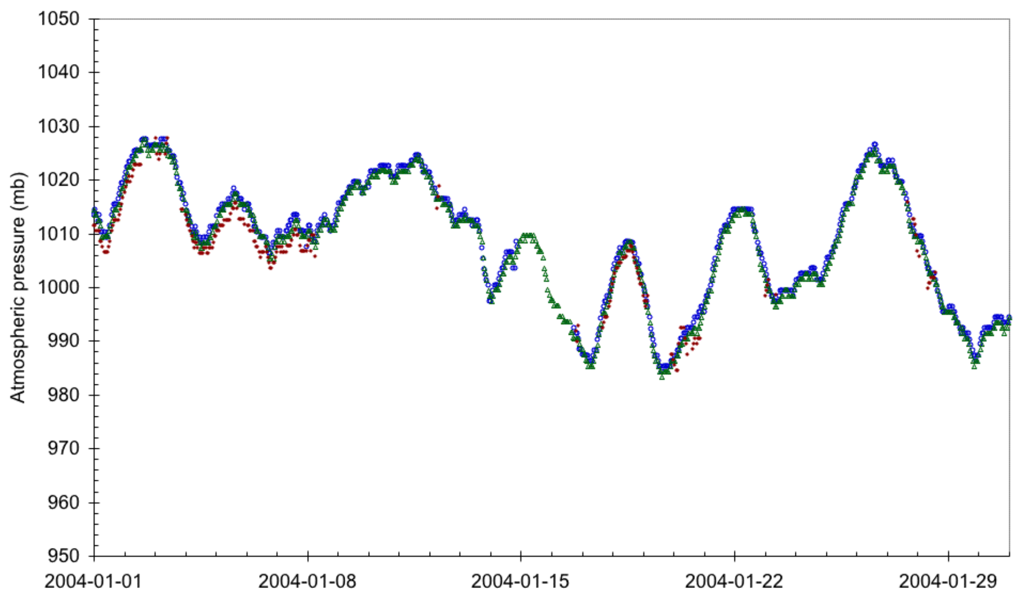


Figure 12. Sea level pressure for January 2004 estimated from surficial barometric pressure measurements at the heights of the three GPS / Weather station installations. Measured pressures at height h were projected down to their sea-level equivalents using the Smihsonian (1971) formula: P(sea level) = P(h) * exp(h/c), where c = 29.2897*(T-h/400), and P in mb, T is in K, and h in m.

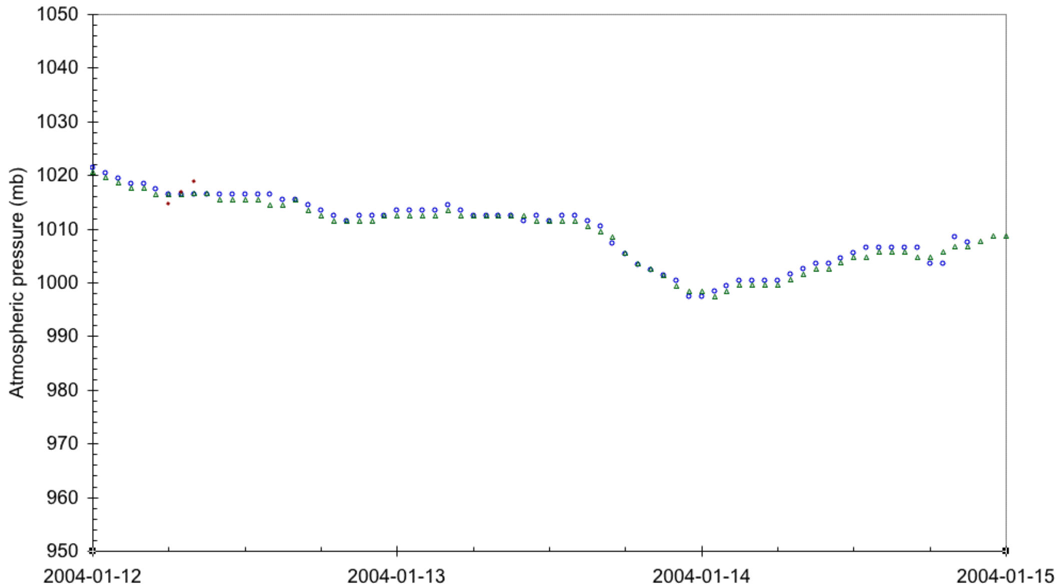


Figure 13. Sea level pressure for the test period (January 12 – 14).

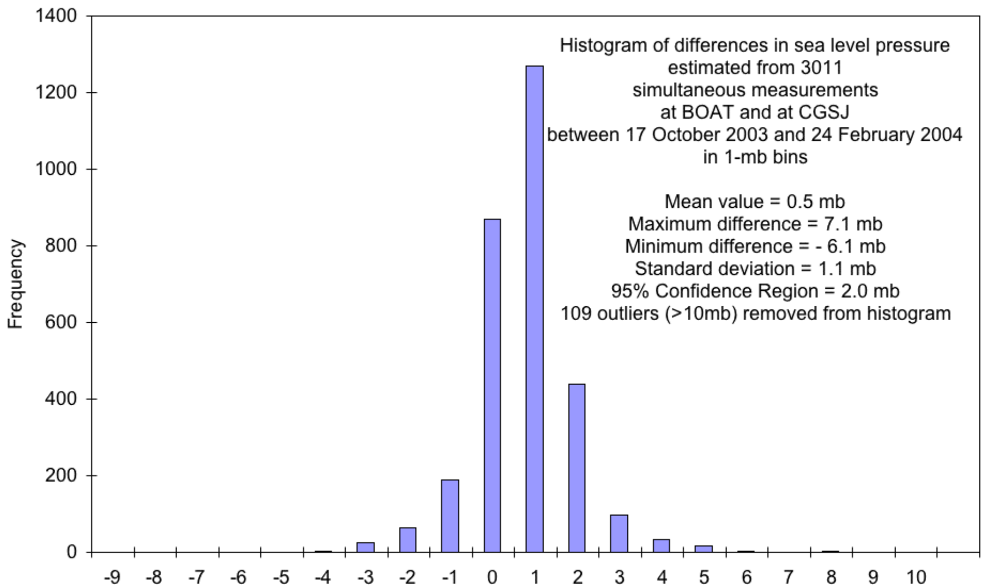


Figure 14. Comparison of the two working pressure sensors. The standard deviation is equal to the measurement resolution of 1 mb. BOAT measured pressures in Saint John and in Digby, as well as in transit between the two.

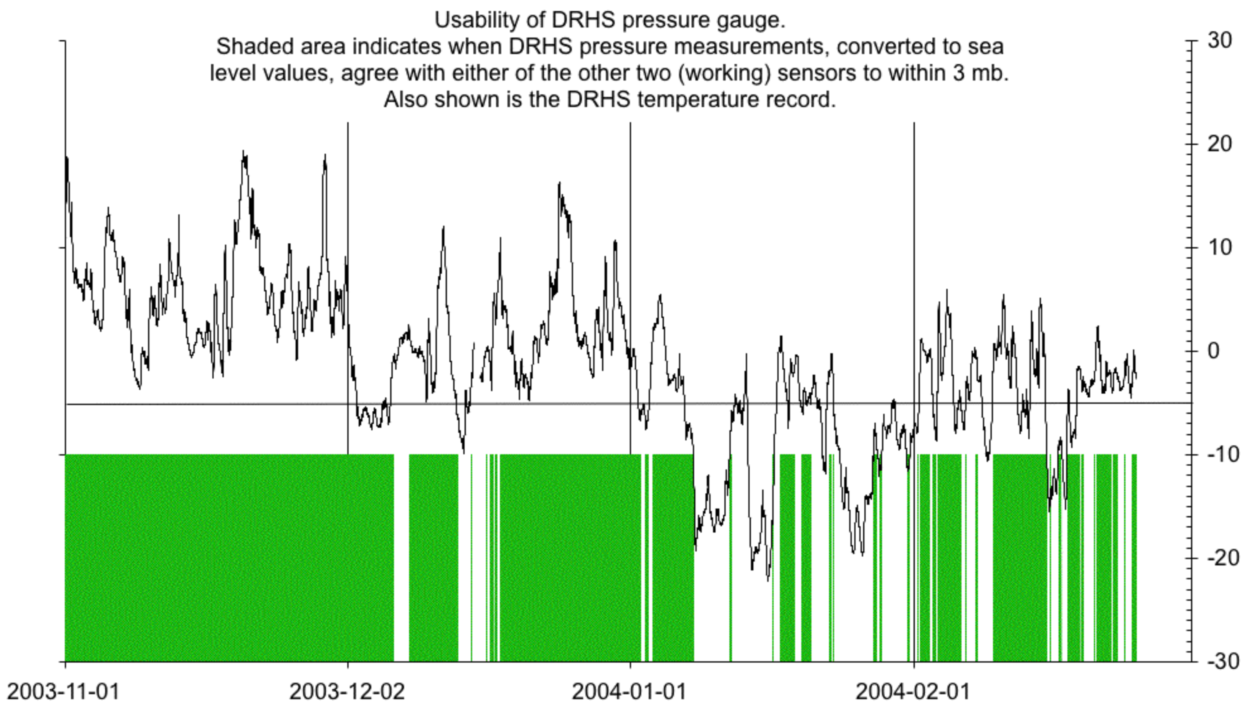


Figure 15. Temperature-dependent failure mode of pressure sensor at DRHS. There is a high correlation between periods when the temperature was below 5 C, and failure of the DRHS pressure sensor.

Except for the DRHS pressure sensor, all other meteorological sensors are operating within their specifications. The DRHS pressure sensor has a temperature-related failure mode, probably related to moisture in the sensor freezing at temperatures below minus 5 C. This has affected at least 30% of the data collected to the end of February 2004, or nearly 50% of the data collected since the failure first occurred on 6 December 2003.

It appears that the sea level pressure calculated from the measured values at each of the three sensors agree with each other to within the sensor specifications (except when the DRHS sensor is in failure mode).

Hence, for the Princess of Acadia project, it may well be that the sea level pressure from any of the sensors could be used as the surficial pressure input into a GPS tropospheric correction algorithm, applied to any of the receivers. This possibility will be more thoroughly assessed after longer time series of meteorological measurements are available. It may be a practical guideline for other coastal applications of GPS. It most certainly would not be applicable over much longer base-rover distances.

There is a bias of about 2 mb between the DRHS and other sea level pressure estimates. This may well derive from the following assumptions, made in calculating the height of the DRHS and other sensors above sea level:

(a) The heights of the pressure sensors are the same as the heights of the GPS antennas.

(b) The ellipsoid is 25.71 m above Chart Datum in Saint John, and 26.31 m above Chart Datum in Digby.

(c) Mean sea level is 4 m above Chart Datum in both Saint John and Digby.

(e) The BOAT GPS antenna is 19 m above the waterline.

(d) The CGSJ GPS antenna is 5.71 m above the ellipsoid, and the DRHS GPS antenna is 38.63 m above the ellipsoid.

We will be carefully verifying each of these assumptions as our processing proceeds.

The surficial meteorological measurements we are collecting are consistent and high quality (except for the DRHS pressure sensor). They should provide an excellent dataset with which to evaluate the impact on our PPK results of incorporating them in various ways into the processing algorithms.

Initial tide – PPK comparison

The tidal range at both Saint John and Digby approaches 10 m (see Figure 16).

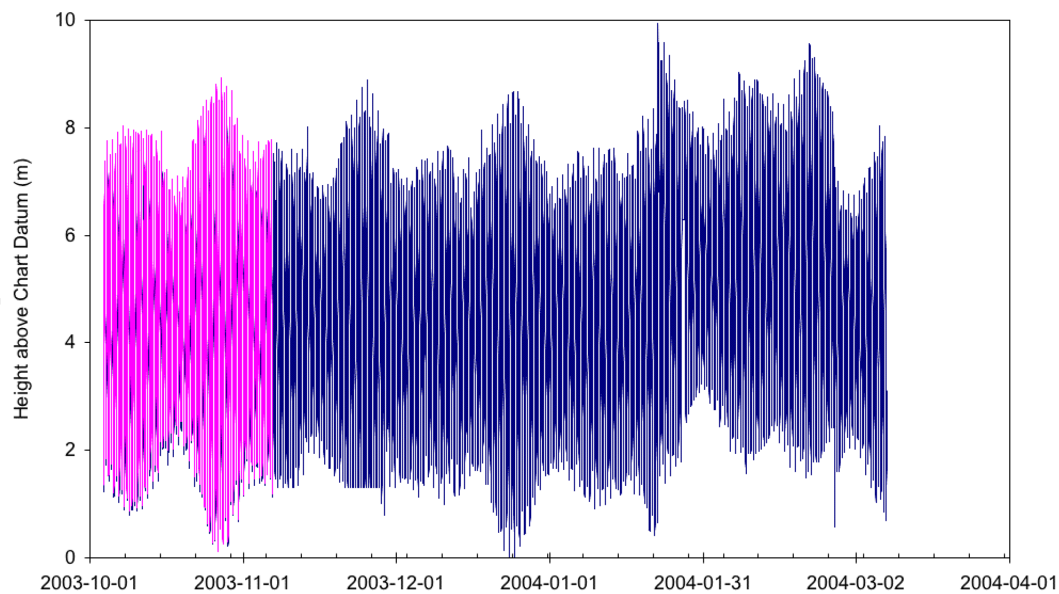


Figure 16. Complete tidal data set up to 8 March 2004. The Purple curve indicates the data recorded by the Digby tide gauge before it's stilling well was destroyed on 6 November 2003. Almost 150,000 readings (at 15 minute intervals) are included in the Saint John tide data plot shown here.

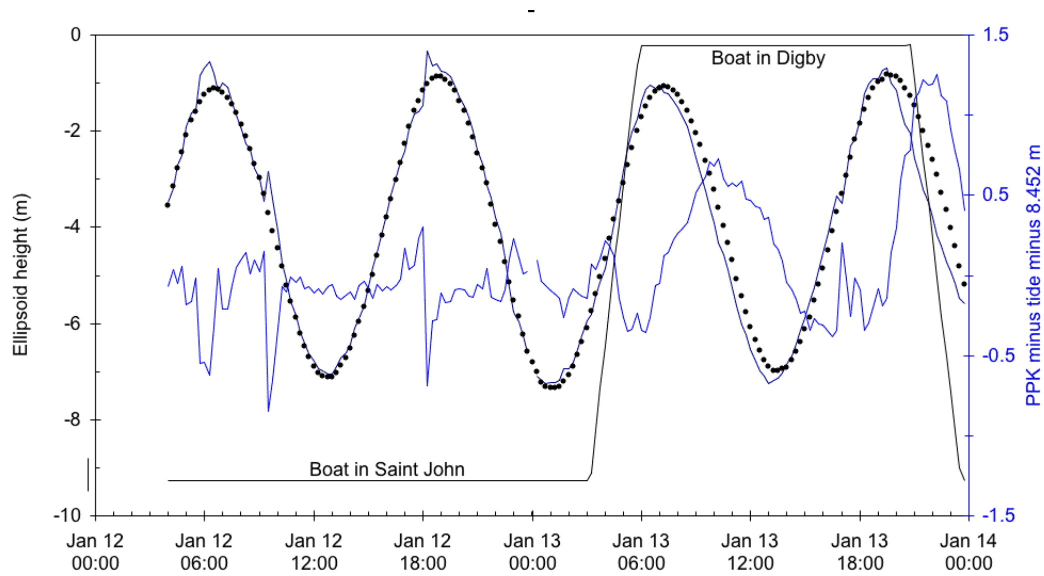


Figure 17. PPK heights from the CGSJ – BOAT baseline solution, compared to the Saint John tide gauge readings, for January 12 and 13. Also shown is the BOAT location (in Saint John, in Digby, and in transit between them). The right hand scale refers to the discrepancies between PPK and the tide gauge. [Figure computed by Christian Solomon].

The Saint John tide gauge water level heights, when suitably transformed, agree with the PPK heights at the few decimeter level, when the Princess of Acadia is in Saint John. Once the Digby tide gauge has been restored, we will perform a similar comparison against that gauge. The existing model for the change in vessel draft of the Princess of Acadia, as a function of vessel loading, has not yet been applied to this comparison.

When the comparison is restricted to those periods for which the PPK formal estimate of height uncertainty is less than 0.03 m (the usual case when narrow lane solutions are converged and successfully maintained), the comparison between the tide and PPK results is at the decimeter level.

Initial long baseline vs. short baseline comparisons

We adopted a strategy of computing short baselines using narrow-lane fixed-ambiguity solutions (out to 12 km from the base station), and computing long baselines using the ionosphere-free linear combination of L1 and L2 observations, estimating ambiguities as floating point numbers in a Kalman filter. Dynapos was used for both computations.

Figure 18 shows the results obtained for 13 January 2004. At the start and end of the day, the boat was in Saint John, so the green curves show the difference in ellipsoidal heights using a narrow lane solution for the CGSJ-BOAT baseline (a distance of 1.5 km), and an ionosphere-free solution for the DRHS-BOAT baseline (a distance of 74 km). During the main part of the day, the boat was in Digby, so for that period (shown in blue on the plot) the roles were reversed: heights from short narrow-lane DRHS-BOAT solutions, and long ionosphere-free CGSJ-BOAT solutions are compared. The periods when the boat was in transit are ignored in this comparison, since neither baseline fell within our present definition of “short” (less than 12 km). One way of restating the main goal of our research is that we intend to find ways in which it is possible to extend this definition of “short” out to much longer distances.

Also shown as red lines in Figure 18 are the formal estimates of the uncertainties in these comparisons (at the one-sigma confidence level). Note that the initial convergence at the beginning of the day takes about two hours. This convergence period has been consistent over all of our analyses so far. After convergence this formal estimate of uncertainty hovers around the 0.1 m level.

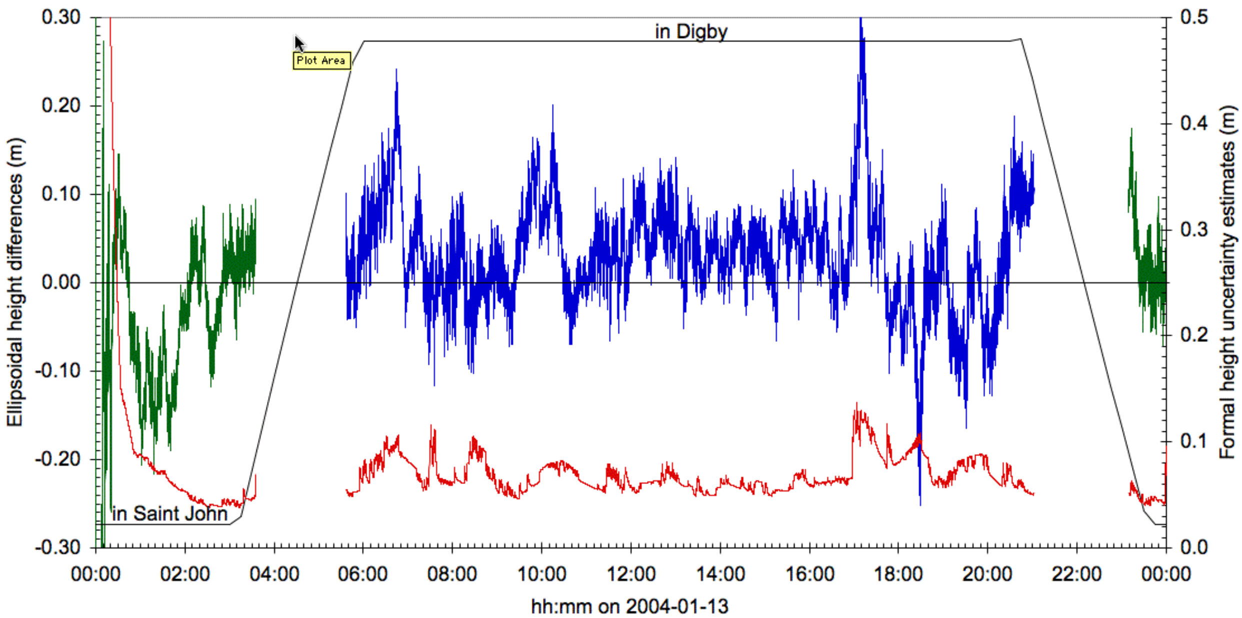


Figure 18. Comparisons between long baseline and short baseline PPK height solutions for 13 January 2004.

Figure 19 is a histogram of the comparison between the DRHS-BOAT narrow-lane short baseline heights, and the CGSJ-BOAT ionosphere-free long baseline heights (the blue curve in Figure 18). A total of 55,556 heights were compared. There is a 3 cm bias between the two solutions. 95% of the height differences are within 0,1 m of this mean bias. If we include the bias as part of the uncertainty, then 95% of the height differences are within 0.13 m of zero.

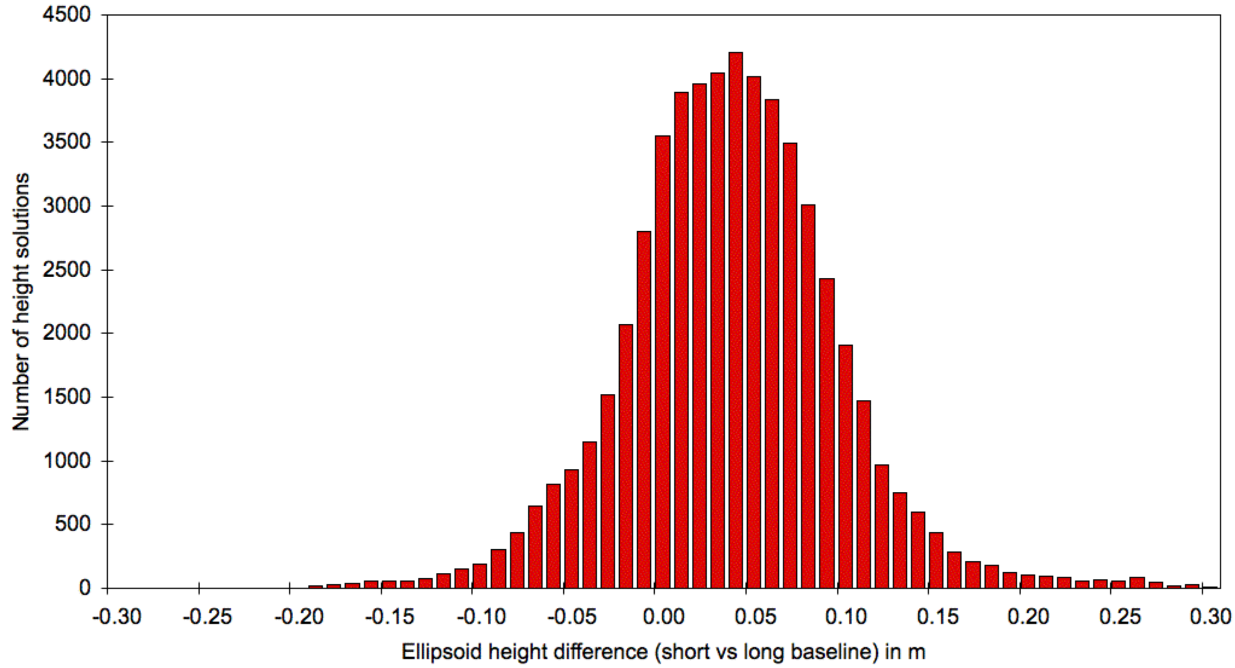


Figure 19. Histogram of the height differences plotted in blue in Figure 18.

These initial results indicate that, for long baseline distances of about 75 km, ionosphere-free solutions agree with narrow-lane short-baseline solutions to within about a decimeter at 95% confidence. There are many other comparisons between different linear combinations of the GPS carrier phase observables that we are currently undertaking. For these results, no extensive use of sophisticated tropospheric modeling has yet been attempted. We have made runs using a standard atmosphere with no meteorological input whatever, and using the daily average of the surficial meteorological measurements. We cannot draw firm conclusions about the improvements, if any, produced by this simple use of observed meteorological data.

We will be performing similar comparisons over the longer baselines to the CACS stations in Fredericton and Halifax.

Conclusions

We have described an ambitious program to collect an extensive dataset of GPS and meteorological information, in order to test new methods and algorithms for applying improved differential tropospheric corrections to long baseline carrier phase differential GPS positioning, with particular applications to improved height results at sea.

This paper has described the assessment of the initial meteorological, tide and GPS sensor data. We have experienced a number of operational problems, but so far they have had only a minor effect on the quality of the data we are collecting. The most serious issue has been the loss of our second tide gauge in early November, which is scheduled for replacement in early April.

The results presented here indicate that the meteorological data, with the exception of one pressure sensor, meets the equipment specifications, and is of high quality. Comparisons between tide and PPK heights indicate sub-decimeter agreement under optimal conditions. It is one of the goals of this project to more precisely quantify the statistics of this particular comparison, under a wide range of operating, weather, and computational scenarios.

Acknowledgements

This project is dependent upon support and collaboration from many individuals and organizations. The U.S. Office of Naval Research is funding this work. The U.S. Naval Oceanographic Office has and is funding related studies. The Natural Sciences and Engineering Research Council of Canada is funding many of the UNB activities in the Princess of Acadia project. Captains Oral Hamilton and Ken Smith Thorpe of the Princess of Acadia, and Donald Cormier, owner of Bay Ferries Limited have generously provided space on board their ship for our equipment. David Edmons and his team at Canadian Coast Guard Saint John Headquarters have generously provided space for base station CGSJ. Principal Ben Elms and science teacher Greg Turner of Digby Regional High School have generously provided not only space for our DRHS base station, but are also managing data acquisition using our equipment installed there. Mark Caissy and Marc Veronneau of the Geodetic Survey Division of Natural Resources Canada is providing access to data from their CACS stations FRDN and HLFX. André Methot and William Richards of the Meteorological Service of Canada arranged for our access to their Numerical Weather Parameter data. Seth Gutman of the U.S. National Oceanic and Atmospheric Administration is providing access to his Precipitable Water Vapor data product (based on NWP). Charlie O'Reilly of the Canadian Hydrographic Service and Dr. Keith Thompson of Dalhousie University Department of Oceanography provided access to the Saint John tide gauge data, and installation of the new Digby tide gauge. The original idea for the Princess of Acadia ferry project arose from a discussion with Lloyd Huff of the University of New Hampshire Coastal and Ocean Mapping Center. Ben Remondi and Kendall Ferguson of XYZs of GPS Inc. have provided invaluable help in refining the focus of our PPK measurement and processing strategies. At UNB, Dr. Don Kim is revising and providing a new version of his UNBRTK software for this project, and Julie Baglole, Mohamed Al-Shari, Mazhar Rafiq, and Christian Solomon have assisted with data acquisition, processing and interpretation. At USM, Jamie Davis is responsible for managing the several 100 Gb of data we are collecting.

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