Initial Results from a Long Baseline, Kinematic, Differential GPS Carrier Phase Experiment in a Marine Environment

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Abstract - **The University of Southern Mississippi (USM) and the University of New Brunswick (UNB) have collaborated to devise and carry out a long-term experiment in precise GPS positioning over long distances in a marine environment. A pair of GPS reference stations have been deployed on either side of the Bay of Fundy in Canada, at the terminals of an approximately 75 km ferry route. A geodetic receiver has been installed on the ferry. Surface meteorological equipment has also been collocated with the three receivers.**

The primary goal of the study, over the course of one year of data collection from the daily ferry runs, realizing that the differential troposphere is a major limiting factor in marine positioning, is to attempt to advance positioning results by means of improved differential tropospheric modeling.

The results presented in the paper include a full description of the experiment, and descriptions of the GPS and meteorological data collected, as well as the software used in the processing. Initial PPK data processing results are presented illustrating positioning accuracy versus baseline length. And results from tests using various tropospheric delay values are presented.

I. 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, 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 data processing, and not for survey track control, although under-keel clearance applications would require RTK.

The goal of our campaign is to advance the science of modeling microwave tropospheric delay over marine 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).

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, navigation, and amphibious and other operations at sea.

Our campaign consists of the collection of a marine PPK database from a moving platform (the Princess of Acadia ferry) located in a temperate climate (the Bay of Fundy) with significant seasonal tropospheric variations (e.g. temperatures between – 30°C and + 30°C). This ferry repeats the same routes between two and four times daily (depending upon the season). We refer to this data collection strategy as the Lagrangian approach (spatial sampling).

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 position solutions from longer PPK baselines over which the tropospheric models are being assessed. In this paper we concentrate on initial results from the Princess of Acadia ferry project.

II. 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 [1] [2] [3]. 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

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(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 Fig. 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.

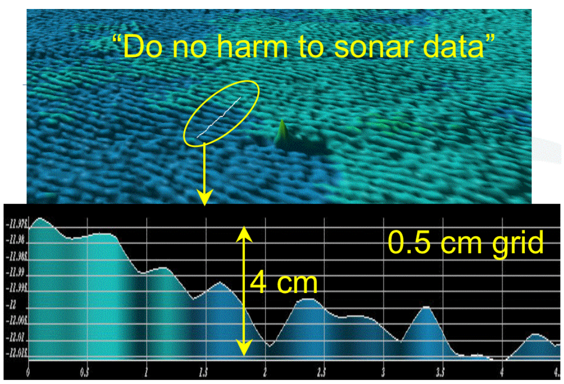

Fig. 1: Sub-centimeter sandwave heights measured by Reson 8125 multibeam sonar near Martha's Vineyard (IVS Fledermaus image courtesy of Larry Mayer, Center for Coastal and Ocean Mapping, University of New Hampshire). This image demonstrates that modern multibeam sonars are capable of delineating features 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.

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 [4] [5] [6]. 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 hydrodynamical 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 hydrodynamical 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 surveys using one LIDAR 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 [7]. 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. Ionospheric delay uncertainty is almost completely eliminated by two-frequency estimation. GPS satellite orbit errors can be eliminated by post-processing with precise ephemerides (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 [8]. 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 the marine climate differs 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.

III. APPROACH

A three-pronged approach is proposed to improve the range capability of PPK GPS:

1. The collection of a **database of PPK data** that can be used to test, evaluate, and improve tropospheric models and algorithms. This marine PPK dataset will be collected under varying tropospheric conditions with seasonal variations in different climates. Two efficient methods of accomplishing this goal are to collect data from scheduled vessels with repeat routes, such as ferries, and from stationary platforms, such as buoys. We are employing both methods.

2. The development of **better tropospheric models**. 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 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 and PCPOS developed at UNB, and USMOTF under development at UNB. These programs will be adapted and used to evaluate the effectiveness of new approaches to tropospheric models.

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* car ferry, all year on the 75-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).

Fig. 2: Local of ferry experiment: Base stations CGSJ and DRHS on either side of Bay of Fundy – ~75 km crossing.

UNB is collecting 12 months of continuous PPK and weather data on the ferry and at both terminals (see Fig. 2). Data from other continuously operating PPK reference stations (for example the U.S. Coast Guard CORS station at Eastport ME, 75 km from Saint John, and an International GPS Service station on the UNB campus, 100 km from Saint John) 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 28 November 2003, and will continue for one year from that date.

IV. 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 [9] 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) [10] and the evaluation of existing geodetic tropospheric delay models [11]. Also, expertise is available in the GPS modeling and signal software processing necessary for other Wide Area Differential GPS (WADGPS) services [12].

We plan a novel combination of strategies, the breadth of which has not been attempted elsewhere, 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 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 [13]. 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 [14]. 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.

5. Customizing a **subset of the 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.

Initial results from the first and third research areas are now presented.

V. INITIAL RESULTS

The first step in the processing was a determination of the quality of the NovAtel OEM4 geodetic receivers performance at the two reference sites and on the ferry. Field tests of the equipment resulted in appropriately low levels of noise in the observed code and carrier observables. Quality control analysis of data from the installed receivers using the TEQC utility [14] showed that although the measurement noise was low at the three sites, the number of observations was also low. Fig. 3 illustrates the number of satellites tracked at the three sites on 10 January 2004 using a 0° elevation mask angle. Even though the daily average number of satellites tracked ranged from 8 to 9, there were short periods where as little as only 5 or even 4 satellites were tracked. This low number of satellites results in little or no redundancy in the data processing, causing poor solutions or processing filter re-initialization.

Such temporary "constellation deficiencies" at mid-latitudes (~45° in this case) illustrates the need for little or no elevation angle masking of GPS measurements for marine applications. Applications of a larger cutoff would result in the reduction of noisy elevation measurements, but would further reduce measurement strength, producing degraded position solutions or even worse – no solutions. This situation, to a certain extent, can be resolved by reducing or eliminating the elevation mask. The associated caveat though is that low elevation measurement noise arising mainly from atmospheric effects most be taken into account.

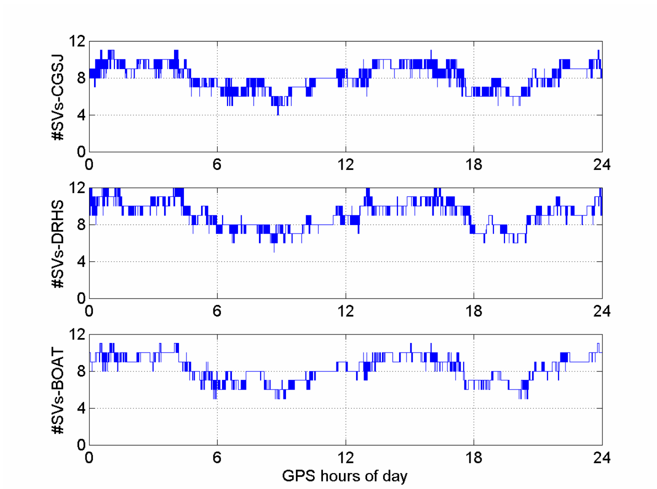

Fig. 3: Number of Satellite Vehicles (SVs) tracked at CGSJ reference station, DRHS reference station and BOAT rover station (all with 0° elevation mask angles) on 10 Jan. 2004.

One option for medium and long baseline processing is the use of the so-called ionosphere-free linear combination of code and carrier observables. The combination for the carrier phase observables is:

$$\Phi_{IF} = \rho + T + \alpha_2\lambda_1 N_1 - \alpha_1\lambda_2 N_2 + \alpha_2 m_1 - \alpha_1 m_2 + \alpha_2\varepsilon_1 - \alpha_1\varepsilon_2,$$

where ρ is the geometric range from receiver to the GPS satellite; T is the delay due to the troposphere; λ_i is the carrier wavelength; N_i is the number of cycles by which the initial phases are undetermined; $\alpha_1 \approx 1.546$ and $\alpha_2 \approx 2.546$; m_i represent the effect of multipath on the carrier phases; and ε_i represent the effects of receiver noise on the carrier phases. Satellite and receiver hardware delays and other small effects have been ignored as they have negligible effect on data preprocessing. The combination observable almost completely eliminates the ionospheric delay; leaves the tropospheric delay unchanged; transforms the ambiguities into the real number domain; and magnifies the phase multipath and receiver noise.

Use of the ionosphere-free observable allows for long baseline processing, since spatial decorrelation of the ionosphere is not a significant concern – as long as the differential troposphere is accounted for. Fixed (integer resolved) ambiguity solutions are not possible, as the phase ambiguities have been scaled by real numbers. However, appropriate error modeling combined with quality measurements allows for the real-valued, ionosphere-free phase ambiguity estimates to reach a steady state in the filtering process.

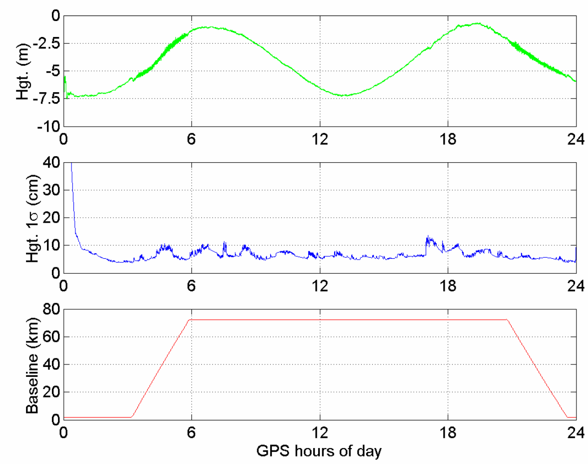

Fig. 4: Ionosphere-free linear combination height solution, height solution error estimates, and baseline length from CGSJ to BOAT on 13 Jan. 2004.

Fig. 4 shows the height solution from one kinematic baseline of processing (CGSJ to BOAT) for 13 January 2004 using the DynaPos commercial processing package in double-differenced, ionosphere-free mode [15]. The baseline length subplot describes the two crossings (slopes in time series) that the ferry made during the day. During this time the ionosphere-free solution provided sufficient resolution to observe vessel heave, as can been seen in the greater height profile noise. The middle subplot provides the 1σ height solution precision estimates from the DynaPos Kalman filter. As can been seen, the solution converged quiet slowly (> 1 hour) using the ionosphere-free combination.

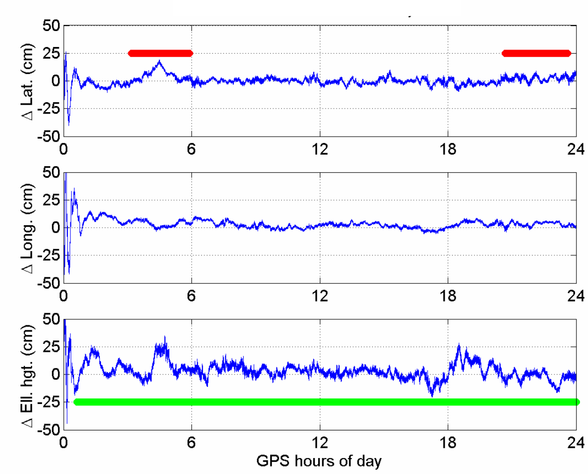

Fig. 5: Difference between ionosphere-free solutions CGSJ to BOAT and DRHS to BOAT on 13 Jan. 2004. (Red lines at top represent vessel motion. Green line at bottom represents solutions with 3D error estimates less than 25 cm.)

As discussed, one method to characterize long baseline positioning performance is to compare long / short baselines to the same rover. Fig. 5 contains this comparison with the results from the CGSJ to BOAT ionosphere-free solution for 13 January 2004 shown in Fig. 4 and the DRHS to BOAT ionosphere solution for the same time period. The horizontal red lines in the top subplot show the periods of vessel motion, and the horizontal green line in bottom subplot shows the period of "good" solutions – where good is defined as 3D filter error estimate less than 25 cm.

Fig. 5 illustrates that there is only few decimeter noise variations after filter convergence, regardless of the vessel's motion or distance from one of the reference stations. Table 1 summarizes the statistics in terms of vessel motion. Few centimeter mean differences are observed in each Cartesian component, and the comparison 1σ noise level is at the decimeter to few centimeter level. Further investigation is needed to determine why the docked statistics are worse than the sailing statistics.

Table 1: Summary statistics for difference between ionosphere-free solutions CGSJ to BOAT and DRHS to BOAT on 13 Jan. 2004.

Motion	Comp.	Max. (cm)	Mean (cm)	Std. (cm)	95% (cm)
Docked	Lat.	10	-1	3	6
	Long.	21	3	4	10
	Hgt.	29	4	6	16
Sailing	Lat.	19	4	4	13
	Long.	9	4	2	7
	Hgt.	35	2	9	22

The solutions presented so far rely heavily on the quality and quantity of the GPS measurements (low receiver noise and multipath), and on the accuracy of the tropospheric modeling used. DynaPos, like most GPS processing software, uses a static, standard set of surface meteorological values to drive a tropospheric delay model, such as Hopfield's. The standard values used for the above processing were: 20 °C temperature, 1013 mb pressure, and 50 % relative humidity. Fig. 6 illustrates the meteorological parameters for 13 January 2004. As can be seen, the parameters vary over the day. The peak-to-peak variations are: 13 °C, 15 mb (note that the DRHS (red dash) pressure sensor appears to be malfunctioning), and 35 %, for temperature, pressure and relative humidity, respectively. And the mean values are -7 °C, 1007 mb, and 85 %, for temperature, pressure and relative humidity, respectively. These mean observed values are significantly different from the standard values used in the processing. The question then becomes: Will the use of the mean observed meteorological values improve the comparison over the use of the standard meteorological values? This question is kept in the context that the wet tropospheric delay is more difficult to model than the dry component, and the data processed does not contain very large amounts of wet delay.

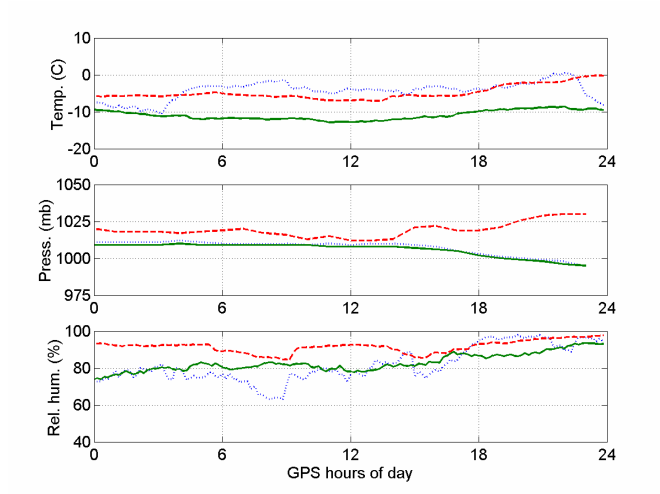

Fig. 6: Meteorological measurements at BOAT (blue dotted), CGSJ (green solid), and DRHS (red dashed) on 13 Jan. 2004. Note that standard values used in processing are: 20 °C temperature, 1013 mb pressure, and 50 % relative humidity.

As a very initial test of the utility of surface meteorological values, mean values were used to reprocess the 13 January dataset, and the 36 hour data arc (a ferry crossing) was compared. Mean rather than actual meteorological values were used since the processing software allows for the input of only a static set of meteorological values. Even though this averaging reduces the utility of meteorological values, perhaps some improvement in position differencing can be observed. The comparison results are given in Table 2. The significant improvements in the latitude and height 95% statistic (~5 cm) appear to be due to reductions in the maximum differences in those components. This improvement may be attributable to the use of accurate surface meteorological values.

Table. 2: Summary statistics for difference between ionosphere-free solutions CGSJ to BOAT and DRHS to BOAT on 13 Jan. 2004, using different meteorological values.

Mets.	Comp.	Max. (cm)	Mean (cm)	Std. (cm)	95% (cm)
Standard	Lat.	19	5	5	15
values	Long.	9	4	3	8
	Hgt.	35	7	9	24
Mean	Lat.	4	4	4	10
surface	Long.	7	3	3	6
values	Hgt.	19	10	10	17
Improvement	***Lat.***	***15***	***1***	***1***	***5***
	Long.	***2***	***1***	***0***	***2***
	Hgt.	***16***	***-3***	***-1***	***7***

VI. CONCLUSIONS AND FUTURE WORK

A comprehensive long baseline, kinematic, differential GPS carrier phase experiment has been described. The end goal of the work is to obtain few centimeter positioning over 10s to 100s of kilometer baselines by improving the tropospheric modeling over marine environments. The approach being taken to achieve this goal involves collecting a database of PPK data, developing better tropospheric delay models, and implementing these models in PPK software algorithms.

Results presented show the operation of the long / short baseline GPS and surface meteorological data collection. Initial GPS processing using the ionosphere-free linear observable combination produced sub-decimeter solution differences between the long and short baseline position estimates. Meteorological data analysis showed some sizeable differences between standard meteorological values and observed ones. The effect of these surface value differences on tropospheric modeling, hence GPS positioning could be seen at the few centimeter level.

A great deal of future work is planned focusing on the continual processing and analysis of GPS data from the growing database, and application of tropospheric delay estimates from surface meteorological and weather model data to the GPS data processing.

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