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# GPS TIDES AND DATUMS

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## BIOGRAPHICAL SKETCH

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## ABSTRACT

The recent development of On-The-Fly (OTF) ambiguity resolution techniques with Global Positioning System observations has created a powerful tool for the study of dynamic time series, such as tidal analysis or the study of water level heights. Using OTF technology it should be possible to obtain a time series of water surface heights to an accuracy of 1 to 2 centimeters, at a 1 second sampling rate, many kilometers from the nearest land. Subsequent time series analysis will yield a water surface datum at the receiver location.

This paper describes the concept and preliminary design of a project to determine water surface datums with GPS observations made from a floating navigation buoy. A navigation buoy was selected because of the availability of this type of platform in areas of interest to those agencies with charting and navigation missions. It should be possible to work with the Coast Guards' Aids-to-Navigation function to install "GPS Tide Gauges" and minimize the effort, versus deployment of a specific purpose scientific buoy.

## AN EXPERIMENT FOR THE BAY OF FUNDY

The ultimate goal of this project is to develop a new system for the determination of tidal datums. A secondary benefit is the potential to describe the water surface as a sloping surface, with both spatial and temporal variations. The project is also intended to introduce the technique to the federal agencies in Canada and the U.S. responsible for tidal datum determination, in hopes that they will be able to exploit GPS technology as a viable tool for tidal, and other oceanographic studies.

To benefit engineers and scientists in a practical application this system should be designed to provide the data necessary to establish a datum and inversely to recover that datum at a future time. Therefore the Bay of Fundy experiment considers three primary objectives. First is the establishment of a datum at a location that impedes the use of conventional gauging techniques. Next the ability of GPS to provide a data series sufficient for established methods of datum determination will be examined. Finally, a datum recovery is necessary to complete the project (Martin, 1994).

Site Selection

The location chosen for this study is Saint John Harbor, New Brunswick. It is located at the mouth of the Saint John River, about midway along the north shore of the Bay of Fundy. The river widens into the Bay of Saint John where the bed gradually rises from a depth of 30 metres at the seaward edge to zero at the beach of Courtney Bay (Neu, 1960) over a distance of about 8 kilometres. The harbor area is protected from the open sea by Partridge island and two breakwaters. Although Saint John Bay is largely saline, during the freshet the river flow dominates and a fresh water wedge extends to the interface with the larger Bay of Fundy (Neu, 1960). On most years the freshet seems to peak in late April and early May, with more typical flows by June.

The Canadian Hydrographic Survey (CHS) has a primary tide station located in the harbor, adjacent to a Coast Guard facility, that has been in operation for many decades (O'Reilly, 1994). This station serves as a reference port for the prediction and publication of the Canadian tide tables. It is a mechanical float / counter weight design connected to a digital data recorder that logs heights every 15 minutes.

Project Overview

The project is scheduled to occur in two phases. The first phase is the planning and execution of the field data collection. This will be followed by data processing and reporting. Project planning began in September, 1993, with the commencement of the University of New Brunswick winter term. A preliminary meeting took place at the Bedford Institute, Dartmouth, Nova Scotia, on 29 October 1993, to discuss the project with those agencies that had an interest in the GPS technology and the GPS Tides concept. Those in attendance were the Canadian Hydrographic Service, Department of Public Works, Canada, the Canadian Coast Guard, and the University of New Brunswick. The project was also discussed during subsequent telephone calls with the U.S. Army Corps of Engineers and the National Oceanic and Atmospheric Administration (Martin, 1994). Each of these in turn agreed to participate in the project at various levels, according to their particular interest.

The data collection began on 9 June 1994, after two and a half weeks of buoy modifications and equipment installation. Data will be collected for two weeks in the river near the conventional gauges, adjacent to the Coast Guard property. In addition 30 days of data, the minimum length for a satisfactory development of the more important tidal constituents (Schureman, 1958), will be collected offshore in the Bay of Fundy.

The data collected in the river at the Coast Guard station will be used for two purposes. First the GPS will be set to the local CHS chart datum and the tide tracked for about two weeks to demonstrate a datum recovery. This data will also be directly compared to a Socomar TMS 1000 tide gauge established in the Coast Guards' boat slip for this project and the Saint John reference gauge. The Socomar gauge uses a pressure sensing device corrected for water density. This, along with a tide staff, will serve as a ground truth for accuracy computations.

The purpose of an offshore data series is to demonstrate the technology in a real world situation. The success, and failures, of this one month offshore will lead the way for future projects. A harmonic analysis will be performed to compute the amplitudes and Greenwich phase lags of the driving tidal constituents. These will be compared with the values from CHS cotidal models of the same geographic area (O'Reilly, 1994).

Spirit Level Ties. Four independent tide gauges are operating simultaneously in support of this project; the Saint John reference port gauge, an automatic gauge and a staff gauge located in the Coast Guard boat slip, and the GPS Tides buoy. All of these must be vertically referenced to a single datum to demonstrate and test, the GPS system. This was accomplished by running a spirit level network through the area and connecting each of the gauges. The spirit levels were run in accordance with CHS standards as set forth in the Canadian Tidal Manual (Forrester, 1983). Levelling equipment and personnel were provided by the CHS.

## MEASURING TIDES WITH GPS

The GPS carrier phase observables have been used to position boats or buoys by a number of investigators (Leick, et al, 1990, Hein, et al, 1991, Rocken and Kelacy, 1992, Frodge, et al, 1993, and Lachapelle, et al, 1993). While the ultimate accuracy is still controversial, each of the investigators have demonstrated results ranging from 1.5 to 10 centimeters, with the more recent results using the improved receivers all reporting 1 to 2 cm. Therefore our basic assumptions for using the GPS as a tool to collect a time series of water surface heights are: the measurement process will provide an ellipsoidal height difference between a reference station and a GPS receiver floating on the water surface; the data can be collected at a rate of one hertz; and, the GPS component of the height difference will have an accuracy of 2 cm.

By placing a GPS receiver on a buoy and anchoring it on station for a suitable time period a time series of tide heights can be generated for analysis. The analysis will result in the development of a tidal datum for that buoy station, relative to that reference station. If the buoy has no motion in the water, and the GPS antenna is always a constant height above the water surface, then the instantaneous elevation of the water surface at the buoy station, relative to a bench mark on shore is;

$$H^w(t) = H^b - \Delta h(t) - H^a \qquad (1)$$

where: $H^b$ is the height of the antenna mounted on the buoy above the water surface; $\Delta h(t)$ is the GPS determined ellipsoidal height difference at time, t; $H^a$ is the height of the antenna above the reference benchmark; and, $H^w(t)$ is an ellipsoidal based height describing a physical process, the tide.

Tidal analysis of a time series, $H^w(t)$, will provide datum values on the reference benchmark, such as mean lower low water (MLLW). This datum would be reestablished on site, at a single instant in time, by;

$$H_{MLLW} = H^a + \Delta h - H^b \qquad (2)$$

While simple in concept there are four considerations in the above model. First, the GPS determined height difference will be limited by the state of the art in GPS technology. Presently the accuracy is at the centimetre level, and the range between reference station and buoy is limited to 20 to 30 kilometres (Frodge et al., 1993). Second, the height of the reference station antenna above a reference benchmark is the same as measuring the height of a conventional tide gauge with respect to a set of benchmarks. The GPS antenna is not the permanent artifact. Each time the datum is used, a reference antenna must be established relative to the benchmarks by an appropriate form of levelling. Third, the height of the buoy mounted antenna above the plane of floatation of the buoy will be constantly changing, and some scheme must be developed to reconcile this situation. Finally, the simple model given is only valid if the reference station and buoy locations remain constant. In other words the differential slope between the ellipsoid and water surface will induce an error in the process if the geographic position of either the reference station, buoy, or both are changed. We can now rewrite the model in the form;

$$H^w(t) = H^b(t) - \Delta h(t) - \epsilon - H^a \qquad (3)$$

and the inverse, after tidal analysis;

$$H_{MLLW} = H^a + \Delta h(t) + \epsilon - H^b(t) \qquad (4)$$

where $\epsilon$ is the differential slope between the water surface and the ellipsoid at the two stations. If the decision is made to always place the reference GPS station in the same location, and the tidal datum generated at the buoy is sufficient for the project at hand, then $\epsilon$ is a constant that cancels out between the model and it's inverse. However, one of the most significant features of using GPS to establish tidal datums is the ability to model the differential slope, $\epsilon$, over a large geographic area (DeLoach et al., 1994). Once accomplished, a GPS reference station could be located anywhere within the modelled area, and a precise water surface could be determined, anywhere within the modelled area.

<u>Reduction to a Tidal Datum</u>
According to equation 4 there are four variables to contend with in the data processing, to arrive at a time series of heights for processing of the tidal datum(s).

The height of the GPS antenna mounted on the buoy above the water surface, $H^b(t)$, will be constantly changing. It must be corrected to provide a vertical height of the antenna corresponding in time to the GPS sample of the satellite signals. This can be accomplished by use of a roll, pitch and heave sensor. The device should have a data sampling rate at least equal to the rate of the GPS data. Further, the data stream must have a known latency to be correlated with a time tag generated by a GPS receiver.

The ellipsoidal height difference measured by the GPS, $\Delta h(t)$, cannot be mathematically transformed to the geoid or a tidal surface. Essentially this system will be using an ellipsoidal "ruler" to measure a physical phenomenon, the tide.

The elevation of the reference GPS antenna above a benchmark, $H^a$, is actually the height of the antenna above a series of previously installed tidal benchmarks. The installation of a tide gauge and subsequent data analysis is an intensive endeavor, generally in support of a long term project or scientific study. Therefore the datum values are physically referenced to a series of stable and secure benchmarks in the vicinity of the tide gauge. The respective heights of the benchmarks and GPS antenna are determined by conventional levelling techniques as prescribed by the national tidal authorities (Hicks et al., 1987).

The differential slope between the water surface and the ellipsoid, $\epsilon$, requires the GPS data be collected at several offshore sites. While this is a valuable aspect of the technique being developed, it will require data collection outside the scope of this project. This project is concentrating on the design of a new tool that hopefully will be implemented in many different ways.

## EQUIPMENT

This project is primarily directed towards the development of a new method of observing the tide height for subsequent reduction to a datum. It is hoped some new ideas on data processing and the use of a "sloping" datum will be set out for future use. The nature of this project requires the description of some key components of the hardware.

<u>The GPS</u>

It is possible to use many differential GPS processing techniques for this project, however, only the OTF GPS positioning is considered to be feasible, in a practical sense. All techniques, except OTF, require a period of static initialization (Wells, 1992), making them impractical for a GPS Tides system. OTF techniques have been demonstrated by several groups (Hein, et al, 1991, Rocken and Kelacy, 1992, Frodge, et al, 1993, and Lachapelle, et al, 1993). The system used for this project is owned by the U.S. Army Topographic Engineering Center to support their activities in the Corps of Engineers Surveying and Mapping Research Program.

It is possible to perform OTF positioning with C/A code L1 frequency GPS receivers (Remondi, 1993). During their studies and design process TEC determined what they considered to be the best solution for a practical system operating in support of dredging and hydrographic surveying. This required a newer vintage receiver with C/A code noise of 0.2 to 0.3 m, and full wavelength L1 and L2 carrier frequencies, even under P code encryption (Remondi, 1993). Today there are several receivers on the market that meet these requirements, the manufacturers include Allen Osborne, Ashtech and Trimble. For their system TEC chose the Trimble Model 4000SSE (Frodge et al., 1993). Therefore that is the hardware being used on this project.

As with the hardware, there are several options for the software to be used for a GPS Tides project. Several institutions have an OTF capability, however only the Corps software has been designed for hydrographic operations. The major distinction in software is the ability to process in real time by use of a radio link, and proven field performance. Real time processing is desired for a tidal project to eliminate the need to store enormous amounts of data on board a buoy, or to visit the buoy daily, to download the data. Proven field performance is of course the precursor to transitioning from a GPS research project to a tides research project. The GPS software was also donated by TEC.

The system produces three types of output files; differential code positions, differential carrier positions, and the raw receiver files (Barker, 1994).

**Table I** Data storage requirement

| <u>Source</u> | <u>bytes/sec</u> | <u>bytes/day</u> |
|---|---|---|
| positions file | 80 | 6.9 Mb |
| raw data file | 500 | 43.2 Mb |
| TSS 335B | 26 | 2.3 Mb |

1 computer will log positions and TSS data
3 receivers will generate raw data for storage

Total storage per day = 6.9 + 2.3 + (3 * 43.2) = 138.8 Mb
Total storage per project = 138.8 * 45 days = 6,246 Mb

The latter two are of interest to this project. If everything works well, only the differential carrier positions are necessary. However the raw receiver data is also being stored to aid in examination of the overall GPS performance. The differential carrier positions that are computed in real time are output in an ASCII string. This includes latitude, longitude, height and time. The raw receiver data and the carrier positions are each logged to their own directories on a magneto-optical disk drive. These drives have the capability to store 1 Gbyte on a single disk, producing a relatively inexpensive medium for data archiving.

## Roll, Pitch and Heave Sensor

Correction of the antenna height above the water surface requires measurement of the pitch and roll of the buoy. Furthermore this data must be time correlated to the GPS data. The device chosen for these measurements is the TSS 335B Roll, Pitch and Heave sensor. This unit uses 5 accelerometers to sense motion and is designed to operate on small marine vessels. It measures pitch and roll with an accuracy of about 0.1° and heave to about 5 cm (TSS, 1993). The accuracy of the pitch and roll measurements will allow the height difference between the GPS antenna and the water surface to be calculated to an accuracy of 5 mm up to a roll angle of 40°.

## The Radio Link

Transmitting the GPS (and roll and pitch) data from the buoy to the reference station requires a data link capable of transmitting at 4800 baud (Frodge et al., 1993). This is a much higher data rate than is typically used for real time differential GPS positioning systems in marine applications. Most systems used for marine positioning have relied on the C/A code pseudoranges and differential corrections where the required data rate is 50 baud. Standard message structures for the differential code data have existed for some time allowing the users to maintain some independence in GPS receiver selection and to use broadcast corrections from another source. This standardized message structure has recently been expanded to include the carrier phase based OTF techniques (RTCM, 1993).

A significant complication in the use of a real time differential GPS system is the authorization process to broadcast the differential data. The administrative process for each country is different and the proper authorities must be contacted. Simply determining who these authorities are can be cumbersome. This subject is also within the domain of frequency allocations that may already be authorized to a federal agency and these agencies must confer within their own chain of command for such issues. This project received approval from Spectrum Management, Industry Canada, located in Saint John, New Brunswick.

## Buoy Considerations

Following a series of discussions with the Coast Guard, a 2.9 meter whistle buoy was selected as the platform for the GPS equipment. A prime consideration for this project was the use of a buoy that is already in service along a channel or fairway. If this is possible, then the cost of the platform will be minimized. Further, if the Coast Guard can place, and or service, the buoy as a part of their normal maintenance process then another major cost can be minimized.

Consideration has already been given to the determination, or computation, of the height of the GPS antenna above the water surface with respect to roll and pitch of the vessel. However the draft, or plane of floatation, of the buoy is also subject to change. Three things must ultimately be determined to successfully resolve any changes in the draft. First, the initial height of the antenna above the water surface must be measured. There are generally design drawings available for the buoys detailing the dimensions, often including the approximate plane of floatation. These can be used for initial estimates of the height of antenna above the water surface, and for design of equipment mounting systems. Final measurements must be made, however, with the buoy out of the water, referring the measurements to some easily recoverable reference system. The final draft, or plane of floatation, must be determined by placing the buoy in the water, and making measurements without disturbing or inducing motion on the buoy. Next, nonlinear changes in the draft may be caused by changing water density, and perhaps by strong currents or large seas. The water density will fluctuate with changes in temperature or salinity, and these must be considered in the design of the data collection. The buoyant force can be described as (Streeter, 1975);

$$F_b = \gamma \int_v dv \qquad (5)$$

where the density, $\gamma$, of the water varies with temperature and salinity, and v is the volume of displacement. Assuming a constant water temperature, the buoy selected for this project will exhibit a change in draft of about 6 cm from fresh to common salt (35 ppt) water.

Strong currents or large seas may partially submerge the buoy if the scope of the anchor chain is drawn to its limit. This factor may define the field season available for observations. For instance, conditions become severe enough to invert the buoys during winter ice buildup in the northern climates. Linear changes in draft would be a result of gradual sinking (or rising) due to changes in the buoyancy. Therefore no material can be added to, or taken from, the buoy once on station. Further, the draft must be checked before and after each observation period.

The buoy chosen for this project is a standard design of the Canadian Coast Guard and required minimum modifications. The modifications include mounting an equipment housing at the base of the whistle structure, fabricating and installing a 12V and

24V "bus bar" for the electronics, and painting 4 "staffs" along the draft line.

Estimates of the power demand show a total requirement of 7.7 amps per hour. This is provided by a series of 12 volt batteries placed in the battery pockets of the buoy. The batteries are those typically used by the Coast Guard, and require no modifications. A system was installed, however, to provide the 12V and 24V required for the various components on board.

GPS Reference Station

The reference station consist of a GPS receiver, a radio, computer, optical disk drive, and associated cables and modems. The Coast Guard offered the use of their rooftop for the antenna to be installed and an office space for installation of the remainder of the equipment. This has proven a valuable asset to the project. Everything is close at hand, making trouble shooting as pleasant as possible.

Data Reduction

At present, the most significant unknown component of this project is the optimum method of reduction to transform from the 1 Hertz GPS time series to the 1 hour time series for tidal analysis. One thought is to filter the high frequency noise of the wave induced buoy motion and then curve fit the data series to compute the hourly values, and daily highs and lows. An alternative, is to average the one second sampled series over a six minute period to match the data series typically collected by the NOAA (Martin, 1994). This would allow the NOAA to directly use the GPS data in their analysis process.

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