NOS RTK TEAM FINAL REPORT
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Office of Coast Survey
Center for Operational Oceanographic Products and Services
Office of National Geodetic Survey

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PURPOSE

The RTK Team

Upon the recommendation of the National Ocean Service (NOS) Survey Team, a Real-Time Kinematic (RTK) Requirements Team was created (see ATTACHMENT 1). The RTK Requirements Team ("the RTK Team") was task to document requirements for the application of RTK global positioning system (GPS) technology in support of hydrography, tides, and related NOS navigation missions and programs[1]. The NOS Survey team helped develop a charter for the RTK Team (see ATTACHMENT 2). The charter specifies that the purpose of the RTK Team is to "investigate and report on applications of RTK GPS to support [chart-quality hydrographic surveying]"[2]. Here, chart-quality hydrographic surveying ("hydrography") means meeting, or exceeding, applicable NOS hydrographic survey specifications[3] and International Hydrographic Organization standards[4]. This is the final report of the RTK Team investigations into the use of kinematic GPS methods for NOS hydrography.

BACKGROUND

To avoid possible confusion that may result from colloquial terminology, a short discussion of GPS concepts is presented. A glossary of general GPS terms is found in APPENDIX A. Subsequent terms appearing in quotes or italics are contained in the glossary in one form or another. Some general knowledge of GPS theory and technology is assumed.

Differential GPS

The term "differential GPS" (DGPS) encompasses a family of GPS relative positioning techniques. DGPS uses two or more GPS receiver-antenna units to position an unknown point or set of points relative to a known point or set of points. DGPS improves upon the positioning accuracy otherwise attainable in *absolute point positioning methods*, which use a single GPS receiver-antenna unit.

For the purpose of our discussion, DGPS can be divided into two primary surveying categories: *meter level* and *centimeter level*. Meter-level DGPS surveys utilize GPS *code phase* measurements and are primarily based on the C/A code modulated on frequency L1; for example, a L1-only GPS receiver for the *rover* and (preferably) a L1/L2 *base station*. Centimeter-level DGPS surveys utilize GPS *carrier phase* measurements and are based on the carrier signal present on both L1 and L2. There are many variations employed in both meter- and centimeter-level DGPS (e.g., meter-level DGPS augmented with *carrier smoothing* and *carrier-aided tracking*, centimeter-level DGPS utilizing L1 only, etc.)[5].

Meter-level DGPS has been used as the primary source of *horizontal* control for all NOS hydrographic surveying operations in support of nautical charting since 1992[6]. The United States Coast Guard (USCG) meter-level DGPS reference station network has been in operation for almost as long[7]. Hydrographers and the general marine navigational community use the term

“DGPS” to refer to meter-level DGPS. Hereafter in our discussion, “DGPS” will refer to meter-level differential positioning based primarily on code phase measurements.

There are several forms of centimeter-level DGPS surveying and specific terms have been adopted by the GPS community-at-large to differentiate between those techniques.

Kinematic GPS

The term “kinematic GPS” refers to the form of centimeter-level differential positioning which (primarily) uses carrier phase observables. Intuitively, “kinematic” GPS implies that differential corrections are formulated in conjunction with a mobile GPS receiver (i.e., a rover in conjunction with at least one static base station). Although many “static GPS” techniques also exist which use both code- and carrier-phases and are used in hydrography, we will focus discussion on mobile, kinematic GPS-based methods.

Real-Time and Post-Processed Kinematic GPS

Operationally, the kinematic GPS solution can be determined either in *real-time* or after *post-processing*. “Real time” in the term “real-time kinematic GPS” (RTK GPS) simply refers to the fact that the carrier phase corrections are transmitted in real time via some (wireless) data link; e.g., via very-high frequency (VHF), HF, or ultra-HF (UHF) radio transmission–c.f., USCG real-time DGPS via HF radiobeacon. All post-processing techniques require the kinematic GPS carrier phase “observables” to be continuously recorded. Long, uninterrupted observation sessions could pose a data management problem. Post-processed kinematic GPS methods might not exist were it not for the complexity associated with real-time data links and the resolution of the carrier phase *ambiguity* in real time. Use of the GPS carrier phase permits resolution at the millimeter level, provided the ambiguity of the integer-number of carrier phase wavelengths can be determined and maintained. Incorrect ambiguity resolution translates to a degradation of positioning accuracy and, depending on user accuracy requirements, the percentage of system availability.

On-The-Fly Kinematic GPS

Kinematic GPS technology is not new to NOS. Starting in 1983, NOS has developed centimeter-level kinematic GPS techniques to support land, air, and marine applications[8]. At first these techniques relied on some form of *static initialization* procedure to resolve carrier phase ambiguity. During static initialization, the kinematic GPS receivers are required to be stationary for some period of time after loss of satellite signal lock (e.g., after receiver power-up or recovery from antenna signal interruption). In 1989 NOS extended kinematic GPS technology to circumvent the static initialization requirement. Subsequently, carrier phase ambiguity could be resolved in the presence of relative motion between two GPS receiver-antenna units “on-the-fly” (OTF)[9]. Not to be confused with the operational term “real time”, OTF refers to the mathematical technique that resolves GPS carrier phase integer ambiguities without requiring a GPS receiver to be stationary at any time. Indeed, OTF can be applied in real time during RTK GPS, or kinematic GPS data can be post-processed via OTF going either, or both, forward and reverse on the time line[8]. Because no GPS receiver can ever be completely immune to loss of satellite signal lock the application of OTF is vital to the practical use of kinematic GPS in hydrography and any other mobile application.

The utility of OTF is currently being applied in kinematic GPS for hydrographic calibration activities within NOS Coast Survey (CS). CS has been employing post-processed kinematic GPS methods using OTF since 1993 in support of hydrography[8,10]. Consequently, the term "OTF" has become so commonplace in this regard that NOS hydrographers typically use it to refer to the specific concept of *post-processed OTF kinematic GPS*. NOS hydrographers usually speak of "OTF" in referring to all kinematic GPS endeavors not computed in real time.

Summary

In summary, the following GPS terminology is used in the NOS hydrographic community:

DGPS – Meter-level differential positioning based on code phase measurements

RTK GPS – Or simply "RTK"; centimeter-level (i.e., less-than-or-equal-to one decimeter) differential positioning based on GPS carrier phase measurements transmitted in real time; static initialization may be necessary, but "OTF RTK" usually implied

OTF RTK – RTK GPS technique where static initialization is not necessary

Post-Processed OTF – Sometimes simply "OTF"; centimeter-level differential positioning based on GPS carrier phase measurements computed off-line (i.e., not in real time); and, static initialization is not necessary. The ability to post-process forward and reverse on the time line provides a means of data quality assurance.

NOS HYDROGRAPHIC SURVEY SPECIFICATIONS

Concepts related to water level observations are discussed in this section. A glossary of some important tide terms is found in APPENDIX B. Subsequent water level terms appearing in quotes or italics are tabulated in the glossary. Some general knowledge in the theory of tides is assumed.

Basic Minimum Criteria

The Hydrographic Surveys Division of the Office of Coast Survey document NOS Hydrographic Surveys Specifications and Deliverables[3] contains the minimum criteria for shallow-water hydrographic surveys. These requirements are used by NOAA field units and by organizations under government contract to deliver data for application to the nautical charts produced by NOAA. The specifications detailed are based, in part, on the International Hydrographic Organization Standards for Hydrographic Surveys[4]. Additional details for specific project areas are provided in the "Letter Instructions" for NOAA field units and in a "Statement of Work" for contractors.

Horizontal and Vertical Accuracy Budget

NOAA hydrography references all horizontal positions to the North American Datum of 1983 (NAD83) which, by definition, uses the Geodetic Reference System 1980 (GRS80) ellipsoid. Bathymetry data and least depths on all wrecks, rocks, and obstructions (collectively, "soundings" hereafter) are referenced to a *chart datum*–usually implemented to *mean lower low water* (MLLW). All heights, such as bridges and overhead cables, are referenced to *mean high water* (MHW).

<u>MAXIMUM ALLOWABLE HORIZONTAL ERROR FOR A SOUNDING</u>

Total error in the measured position of a sounding, at the 95 percent confidence level, must not exceed:

5 meters + 5 percent of the depth

<u>MAXIMUM ALLOWABLE VERTICAL ERROR FOR A SOUNDING</u>

Total error in the measured depth of a sounding, at the 95 percent confidence level, must not exceed:

$$\left|\sqrt{[a^2 + (b \cdot d)^2]}\right|$$

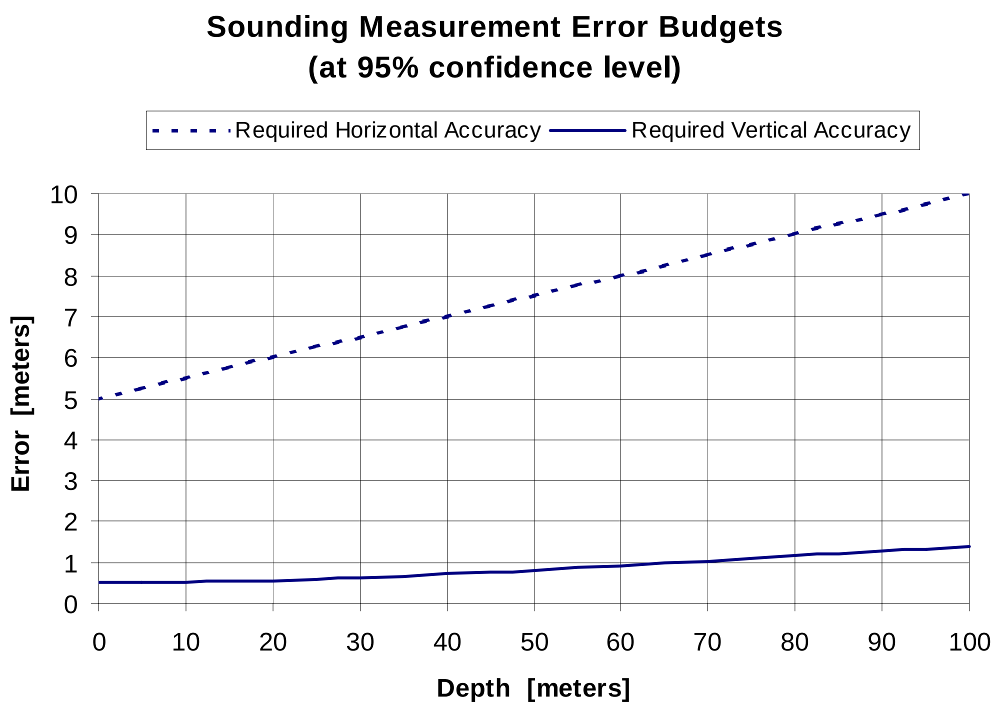

Figure 4

The constant $a = 0.5$ meters and represents the sum of all remaining non depth-dependent measurement errors. Parameter d is the measured depth of a sounding in meters and the term $(b \cdot d)$ represents the sum of all remaining depth-dependent measurement errors. A scale factor of $b = 0.013$ is used (i.e., 1.3 percent).

Note that the sounding measurement error budgets are independent of any scale-of-survey that might be in use during the hydrographic project. A summary of the sounding error budgets is shown in Figure 1.

The summation of all the error sources associated with a hydrographic sounding measurement must fit into this three-dimensional error budget. The maximum allowable error in the horizontal position of a sounding must be less than or equal to the combined positional errors arising from inaccuracies in vessel heading, roll, and pitch, as well as the contribution from the GPS positioning subsystem. The maximum allowable error in measured depth must be less than or equal to the combined depth errors arising from inaccuracies in slant-range timing, vessel heave, roll, pitch, and draft, water column sound velocity, and water level (*tide*), as well as any residual biases in the equipment. Only a portion of the three-dimensional error budget total can be allotted to kinematic GPS.

Kinematic GPS Horizontal and Vertical Accuracy Budget

The vertical accuracy requirement is nearly an order of magnitude smaller than the horizontal accuracy requirement (e.g., 0.5 meters versus 5 meters). Unfortunately, height measurement using GPS is inherently less accurate than the (corresponding) determination of horizontal position. A detailed analysis of the relevant dynamic parameters which affect the measurement of sounding depth is needed. Although such an analysis is beyond the scope of this document, a first order approximation to the GPS component of the vertical error budget total can be estimated. Some relevant parameters, along with their "practical" (c.f., NOS Hydrographic Surveys Specifications and Deliverables[3], Section 5.4.5, "Error Budget Analysis for Depths") expected contribution to depth error model are:

RELEVANT DYNAMIC PARAMETERS IN VERTICAL MEASUREMENT
(practical depth error model contributions shown at the 95% confidence level)

- Vessel heave, pitch, and roll: 0.30 meters
- Vessel dynamic draft: 0.15 meters
- Water column sound velocity: 0.25 meters
- Water level (*tide*): 0.35 meters

"Vessel dynamic draft" encompasses the notion of static draft as well as changes in *settlement*[10] as a vessel's hull moves through the water and as a vessel's load changes due to, say, fuel consumption. Change in vessel *squat* (or *trim*) is assumed to be measured by the pitch sensor. Some of these dynamic parameters can be replaced by high-accuracy height measurements obtained from kinematic GPS, provided the frequency of motion is sufficiently low. The measurable frequency is dictated by the available position update rate from the GPS receiver-antenna unit. Modern kinematic GPS receivers are nominally capable of one to ten position updates per second (1 to 10 Hz). In general, the potential exists to measure vessel draft (not heave) and water level using kinematic GPS for hydrography. There are numerous international technical papers which discuss the measurement of tides using kinematic GPS[11, 12, 13].

A more detailed error budget analysis is warranted to determine exactly which parameters can be effectively measured by GPS positioning, while assuring compliance with the total error budget requirements. The list of practical depth error contributions above is somewhat casual in the sense that the root-sum-square error is ≈ 0.54 meters, slightly larger than the required minimum vertical error of 0.50 meters. Nonetheless, order-of-magnitude requirements are presented below.

HYDROGRAPHIC ACCURACY REQUIREMENTS FOR THREE-DIMENSIONAL GPS
(at 95% confidence level)

GPS Horizontal Error: ≤ 2.5 meters (final solution), ≤ 5.0 meters (available in real time)
Position update rate ≥ 1 per second

GPS Vertical Error: ≤ 0.20 to 0.35 meters (depending on the vertical parameters measured)
Position update intervals:

– For dynamic draft measurement:	20 to 60 seconds
– For water level measurement:	≤ 6 minutes temporal, and ≤ 1 kilometer spatial

The NOS goal for the availability of the three-dimensional GPS solution for hydrography is 97% (or better), at the respective position update rates shown above. Here, "availability" refers to the existence of a positioning solution which meets the stated accuracy requirements, without regard to whether the calculations occur in real-time or offline (i.e., from RTK GPS or post-processed kinematic GPS, respectively).

CHART DATUM ISSUES

Traditional hydrographic surveying scenarios use tide and water level gauges and discrete *tidal zoning* to produce *tide reducers to MLLW*. The error budget is separated into: (i) component parts of water level measurement error, (ii) error in tidal datum computation using less than a 19-year tidal datum epoch, and (iii) error associated with extrapolation of the tide or water level using time and range correctors (tidal zoning).

For kinematic GPS surveying scenarios, the error associated with water level measurement relative to a tide staff leveled to permanent bench marks is replaced by the error in measuring water level height relative to the ellipsoid (NAD83/GRS80) using kinematic GPS. The error associated with traditional tidal zoning is replaced by the errors associated with determining the relationship between the ellipsoid and MLLW throughout the survey area.

The MLLW datum relative to GPS must be determined in all scenarios. Tide gauges must be installed at "critical locations" wherein ellipsoidal height relationships are established by occupying tidal benchmarks with GPS. This should be accomplished prior to actual hydrographic surveying operations. The error associated with tidal datum determination using short periods of observations (i.e., less than 19 years) will always exist as long as the chart datum is based on a tidal datum.

In summary, the kinematic GPS water level error budget would need to have estimates of:

- Errors of knowing OTF elevations of the water surface relative to the ellipsoid at the time and location of each sounding

- Errors of establishing or recovering MLLW/Ellipsoidal relationships at shore points using appropriate combinations of new tide gauge measurements and datum determinations; benchmark and tidal datum recoveries from historical locations; and occupations of tidal bench marks with GPS to establish the relationships

- Errors in interpolating and extrapolating the MLLW/Ellipsoidal relationship using various means such as interpolation, offshore GPS/tide gauge measurements, numerical estuarine models, and continuous zoning approaches such as "Tidal Constituent And Residual Interpolation" (TCARI)[14].

KINEMATIC GPS IN HYDROGRAPHY

Operational Requirements (RTK, OTF RTK, or Post-Processed techniques?)

Strictly speaking a *real-time*, highly accurate and precise, 3-D position is not necessary for hydrographic surveying operations. Real-time horizontal positions need only to be good enough to maintain survey line *navigation* (DGPS 5-meter horizontal accuracy sufficient for real time).

Vertical positioning is inherently an *off line* procedure in hydrography. Soundings are formed by reviewing and editing associated sensor data (i.e., vessel attitude and speed) as well as testing for potentially anomalous depths, managing sound velocity profile data and performing speed and refraction corrections, managing tide data and, finally, merging everything together into a vertical position solution. Nominal post-processing time required to "clean & merge" soundings might be, at best, 1:1 as compared with acquisition time (1 hour of time on-line data acquisition requires 1 hour of off-line data processing). Hence, both real-time and post-processed kinematic GPS scenarios are feasible.

Survey Scenarios

Kinematic GPS requires an accurate horizontal and vertical reference frame in order to determine an accurate position on each sounding, relative to NAD83, and to determine an accurate depth of each sounding, relative to MLLW or other appropriate (local) chart datum (tide or water level;

e.g., Great Lakes).

The issue of determining separation between kinematic differential GPS vertical datum and the local chart datum is important to resolve for each survey area. These relationships may or may not be well know. The complexity of the geodesy of the area, the tidal characteristics of the area and the geographic complexity and size must be taken into account. Constant relationships may be adequate in small areas; simple interpolation may be adequate in others; or complex spacial interpolation may be required using numerical models and continuous zoning procedures (e.g., TCARI[14] and other tidal datum transformation models[15]).

Moored vessels or GPS buoys have been used by NOS, USACE, and organizations in Canada in several special projects for determining offshore tidal datums and their relationships to the ellipsoid. Simultaneous tide measurements from offshore GPS platforms, with onshore control tide stations, have been successfully used to determine tidal datums and separation between chart datum and the ellipsoid at offshore positions. This technique is operationally feasible for future survey operations[16].

There are a number of possible operational survey scenarios, depending on the availability of suitable horizontal and vertical control. The availability of control must be evaluated during survey planning. Establishment of the appropriate control prior to survey operations (soundings) must become an integral part of the survey process. Establishment of the proper control for some survey areas may not be trivial and consequently may not be accomplished without considerable effort and time.

The following is a list of some possible survey scenarios:

(1) MAXIMUM EXISTING WATER LEVEL AND GPS CONTROL

- The survey area contains NGS approved continuously-operating reference stations (CORS). For example, USCG, United States Army Corps of Engineers (USACE), Federal Aviation Administration (FAA), or International GPS Service for Geodynamics (IGS) CORS might be within a useable distance of the survey site.

- The survey area has a combination of operational NOS NWLON water level stations with known chart datum relationships to ellipsoidal heights and/or historical water level station locations with a minimum of three bench marks with known up-to-date chart datum elevations relative to the ellipsoid.

- The relationship between local chart datum and the ellipsoid is known throughout the survey area with confidence based on interpolation techniques between the known shore locations.

- Carrier phase corrections are broadcast or archived at a suitable epoch update for real-time or post-processed kinematic GPS.

(2) MID-LEVEL WATER LEVEL DATUM AND GPS CONTROL

- The survey area has high accuracy reference network (HARN) marks, but there is no suitable CORS station nearby. A GPS base station must be set up on one of the HARN marks to record and/or broadcast the required carrier phase corrections to the survey vessels.

- The survey area has a network of historical water level station locations with known up-to-date chart datum elevations on the bench marks. Some of the water level station benchmarks must be occupied temporarily with GPS to establish the chart-datum-to-ellipsoidal-height relationship.

- Some developmental (continuous or discrete zoning) work is required to determine the chart-datum-to-ellipsoidal-height relationship in offshore areas. Offshore GPS buoys may be deployed and TCARI may be used to establish these relationships

(3) MID-LEVEL GPS AND INADEQUATE WATER LEVEL DATUM CONTROL

- The survey area has HARN marks but no operational or historical water level stations with up-to-date chart datum elevations. A GPS base station must be set up on one of the HARN marks to record and/or broadcast the required carrier phase corrections to the survey vessels.

- Prior to collection of soundings, water level stations need to be established, chart datum elevation relative to the bench marks established and the bench marks occupied with GPS to establish the chart-datum-to-ellipsoidal-height relationships. Significant development work may have to be done to extend the chart datum/ellipsoid height relationship over the entire survey area (depending on the particular tide regime and the geographic area).

(4) INADEQUATE GPS AND MID-LEVEL WATER LEVEL DATUM CONTROL

- The survey area has no CORS or HARN marks established but has an adequate network of operating or historical water level stations with chart datum established. A GPS base station will have to be established to record and/or broadcast carrier phase observables during survey operations.

- The water level station bench marks need to be occupied with GPS to establish the chart-datum-to-ellipsoid-height relationships and significant developmental work may have to be done to determine the relationship throughout the survey area.

(5) INADEQUATE GPS AND INADEQUATE WATER LEVEL DATUM CONTROL

- Significant pre-operational survey field work must be done to establish the horizontal and vertical control necessary for the survey to be accomplished using kinematic GPS.

Obviously, there are numerous combinations of these situation elements that may exist in a given hydrographic survey project area. The important point to note is that the complete situation must be identified early on in the project planning stages so that a ample time and resources can be organized and mobilized to establish the vertical control necessary (prior to beginning survey operations). As noted in the above scenarios, this may entail conducting static GPS observations to establish a control point for a base station or installing a water level measurement system to establish a chart datum.

Although real-time solutions might appear to be the preferred operational scenario, it has been demonstrated that NOS kinematic GPS hydrographic operations should not be limited to RTK alone. Scenarios based on post-processed kinematic GPS positioning may be the best approach in many instances.

Issues: Benefits & Costs

When GPS control and chart datum are established prior to survey operations, the survey vessels can accomplish their survey without the need to establish and monitor traditional tide and water level gauges. The survey personnel may only need to construct a GPS base station if a CORS station is not nearby. Pre-survey activities dealing with tide gauge and GPS control are traditionally accomplished right at the beginning of surveys, but they could be scheduled and accomplished much earlier in the project cycle. The potential benefit to be gained from accomplishing this earlier in the project cycle stems from the reduction in the time it takes to produce “final” sounding data for a nautical chart product. That time would be reduced because the post-processing and application of tide data, tidal datums, and tidal zoning process would become streamlined. Soundings would be automatically referenced to chart datum in the course of field data acquisition and processed on-board or during shore-based processing operations.

Both horizontal and vertical accuracy (vis-a-vis more accurate tide and dynamic draft measurements) could be increased in hydrographic surveying. Increased accuracy means hydrographic surveying is organized for change as future, more-demanding charting requirements arise. Hydrographic data accessible via electronic navigation charts will be commensurate with the best capabilities of GPS marine navigation.

As in any satellite-based differential GPS positioning technique, the availability of kinematic GPS solutions (i.e. "fix" data) depends on four key issues[17]:

- Time to first fix
- Recovery of data after an interruption
- Proximity of reference station(s) for computational purposes
- Proximity of reference station(s) for purposes of radio data link coverage

The first three issues are intimately tied to the technical problem of acquiring and maintaining phase-lock in the carrier tracking loop of the kinematic GPS solution.

In the case of post-processed OTF, where forward and reverse kinematic GPS computations can be compared, "NOS has found that GPS vertical positions of suitable accuracy are typically available only 85% of the time."[13]. However, recent investigations by NOS have shown that hydrographic requirements for kinematic GPS availability are within reach, using a combination of "carrier triple differences", "code double differences", and Kalman filtering[13].

Inspiring Field Work

<u>GPS Expedition to Tangier Island, Chesapeake Bay</u>

A week-long experiment was conducted in Chesapeake Bay in the vicinity of Tangier Island. The experiment utilized the BAY HYDROGRAPHER, on which had been installed two additional dual frequency GPS receivers. The BAY HYDROGRAPHER was operated in close proximity to several NOS tide gauges varying in location from Annapolis MD to Windmill Point VA and the data from the tide gauges were used to determine the accuracy and precision of the GPS-based estimate of the ellipsoidal height of the free water surface. This experiment was a cooperative effort with The XYZ's of GPS, Inc. Shore-based reference sites were setup and operated at ranges from 40 to 140 Km to Tangier Island. The results indicated the ability of kinematic GPS (in a post-processing mode) to estimate the water levels with accuracy on the order of 10 cm at distances greater than 100 km between the BAY HYDROGRAPGER and the reference site. The test successfully demonstrated the ability to utilize multiple reference sites in the kinematic GPS solution. The tests also provided the first characterization of a newly developed (by The XYZ's of GPS, Inc.) double code difference, triple phase difference GPS algorithm. This work was reported on at the ION 2000 Annual Meeting in Anaheim CA, January 2000.

RECOMMENDATIONS

This report represents preliminary efforts and findings based on considerable discussion and research by the RTK team. This report represents only the first phase of NOS moving towards conducting hydrographic surveys using kinematic GPS. The Team has developed several specific recommendations based on what was learned in the process of preparing this report.

The Team recommends that:

1. A new crosscutting team of appropriate technical personnel should be established that will continue this effort in a formal manner. The new NOS RTK team should also have a "home" within a line office, possibly NGS, such that the line office is responsible for keeping the momentum of the team going and takes ownership for its' success. Through NGS, the team could gain access to GPS hardware and expertise, as well as have a home base that would be capable of providing R&D funding.

2. Starting immediately, all new GPS equipment (receivers and antennas) purchased for NOS hydrographic surveying should be dual frequency and either equipped for RTK operations, or have an optional upgrade path to full RTK operations.

3. Greater use should be made of the BAY HYDROGRAPHER to field test operational scenarios so that standard kinematic GPS operating procedures can be developed for hydrographic surveying.

4. Project instructions for NOS hydrographic surveys should be modified to include a requirement for the acquisition of GPS phase observables at one-second intervals on the survey platform and at one or more suitable shore sites. The observed data would be provided to NGS or another designated group within NOS that would be tasked and funded to process the data, to determine the time history of latitude, longitude, and Height of the shipboard GPS antenna at one-second intervals, estimate the performance and investigate any problems encountered in the data processing.

5. Future Hydrographic Survey Contracts should be modified to require the acquisition of GPS phase observables at one-second intervals on the survey platform and at one or more suitable shore sites. An initial strategy may be to specify that both traditional surveying procedures and kinematic GPS procedures be employed as the contractor conducts patch tests. The phase observables would be processed, by the contractor in a post-mission mode, to determine the time history of Lat, Lon, and Height of the shipboard GPS antenna at one-second intervals. The observed data and the processed results would become deliverables under the contract. The observed data would be provided to NGS or another designated group within NOS that would be tasked and funded to process the data, to determine the time history of Lat, Lon, Height of the shipboard GPS antenna at one-second intervals, estimate the performance and investigate any problems encountered

in the data processing.

6. NOS should establish and/or nurture existing operational partnerships with the private GPS industry. One possible means to accomplish this would be to continue to work cooperatively with the several developers and suppliers of GPS processing software to assess the reliability/ availability of solutions at different levels of accuracy and precision. The sets of GPS phase observables from shipboard antennas and relevant shore based antennas, are available from the BAY HYDROGRAPHER, NOS hydrographic survey platforms, and Hydrographic Survey Contracts, could be used for algorithm testing.

7. The Joint Hydrographic Center partnership of NOAA with UNH should be encouraged to explore GPS technology through applied research and operational testing for purposes of implementing kinematic GPS for NOS hydrographic surveying.

8. NOS should move quickly to determine ellipsoidal heights of MLLW for the US coastal waters and to update MLLW to the current epoch. NOS should also continue to improve the accuracy and spatial resolution of the geoid in the coastal waters of the US because uncertainties in the local geoid height and the ellipsoidal height of MLLW translate directly into uncertainties in elevations and depths relative to local MLLW.

9. NOS should plan for and provide adequate R&D funds to rapidly address new issues of RTK-GPS as they are brought to light by the increased exposure associated with additional field data and the attempts to establish practical field operating procedures.

10. The future RTK team or others in NOS should further investigate the issues of post-mission processing of RTK data as compared to true real-time operations. Issues to be investigated include: (i) cost and complexity of real-time communication of GPS phase observables from the reference station to the moving platform, and (ii) impact of post-mission vs. real-time knowledge of the Lat, Lon, Height of a shipboard antenna on the time required for the hydrographic field unit to process, review and forward a hydrographic survey data set.

11. NOS should anticipate that upon the decision to convert NOS hydrographic surveying to RTK-GPS, it may be necessary to purchase of a significant amount of RTG-GPS equipment in addition to that which was acquired by the ongoing slow purchase of such equipment, as stated in recommendation (2), above.

ATTACHMENT 1

UNITED STATES DEPARTMENT OF COMMERCE
National Oceanic and Atmospheric Administration
NATIONAL OCEAN SERVICE
Silver Spring, Maryland 20910

MAR 25 1999

MEMORANDUM FOR: Captain David MacFarland
Charles Challstrom
Richard Barazotto

FROM: Captain Ted I. Lillestolen
Deputy Assistant Administrator

SUBJECT: Creation of a Real-Time Kinematic GPS Requirements Development Team

Upon the recommendation of the National Ocean Service (NOS) Survey Team, I am appointing the individuals named below to the "RTK Requirements Team." This will be a technical team. Its primary mission will be to develop a Requirements Document for the use of RTK technology to support hydrography, tides, and related NOS navigation missions and programs.

The Survey Team has developed a charter detailing the ~~responsibilities of the RTK Requirements Team. I am requesting~~ regular reports on the Teams progress.

Development of these requirements is a fundamental step in developing the near real-time navigation services of the future. Please provide your full support to the members of your staff that are on this team.

The team members are:

Lloyd Huff and Doug Martin, Coast Survey Development Laboratory
Jack Riley, Hydrographic Services Branch
Ed Carlson, Rick Fotte, Lucy Hall, National Geodetic Survey
Steve Gill, Cary Wong, Oceanographic Products & Services Division

cc: Nancy Foster
Mike Szabados
Dave Zilkowski

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ATTACHMENT 2

Charter for the Real-Time Kinematic GPS Team

Purpose:

The purpose of the RTK Team is investigate and report on applications of Real-Time Kinematic GPS to support hydrographic surveys and tide requirements (including tidal zoning applications) for chart-quality surveys.

Scope of Work:

The Team will limit its investigations to RTK applications in support of chart-quality hydrographic surveying. It will evaluate the state of the technology and review professional articles on the subject. It may consult experts. The Team will issue a report on the potential applications of RTK and make recommendations for research and demonstrations. The Team will not investigate other marine navigation applications of RTK technology, such as determining vessel squat and underkeel clearance for commercial vessels

Factors Investigated and Considered:

The team will consider the following factors:

- What literature is available on this subject matter? What does it say?
- What kind of accuracy levels can be obtained through the use of RTK?
- Is RTK reliable? What kind of quality assurance practices would be required to ensure data accuracy?
- What are the implications if there are no Continually Operating Reference Stations (CORS) or NWLON stations in the area being surveyed?
- Will use of RTK increase or reduce costs? Provide some cost/benefit analysis.
- Would RTK be more useful in some areas over others? For example, should RTK be utilized only in areas where accuracy requirements are very high, such as busy ports prone to shoaling?
- Would RTK be impractical under certain oceanographic conditions? Explain.
- Is research and development required? How much? Can the Team recommend some suitable demonstrations; perhaps project areas that could include working with contractors?

Reporting and Duration of the Team:

The RTK Team will provide interim reports to the Survey Team, the directors of the Coast Survey, National Geodetic Survey, and water level program. The Team will issue a final report to the NOS DAA and the organizations named above no later than September 1, 1999.

APPENDIX A

A. Glossary of GPS terms (adapted from http://www.navtechgps.com/glossary.asp and http://www.analog.com/techsupt/prod_briefs/glossary.html)

1. **absolute positioning** - mode in which a position is identified with respect to a well-defined coordinate system, commonly a geocentric system (i.e., a system whose point of origin coincides with the center of mass of the earth).
2. **ambiguity** - The initial bias in a carrier-phase observation of an arbitrary number of cycles. The initial phase measurement made when a GPS receiver first locks onto a satellite signal is ambiguous by an integer number of cycles since the receiver has no way of knowing when the carrier wave left the satellite. This ambiguity remains constant as long as the receiver remains locked onto the satellite signal and is resolved when the carrier-phase data are processed.
3. **availability** - The percentage of time that the services of a navigation system can be used within a particular coverage area. Signal availability is the percentage of time that navigational signals transmitted from external sources are available for use. Availability is a function of both the physical characteristics of the operational environment and the technical capabilities of the transmitter facilities.
4. **baseline** - A baseline consists of a pair of stations for which simultaneous GPS data has been collected.
5. **base Station** - Also called a reference station. A receiver that is set up on a known location specifically to collect data for differentially correcting rover files. The base station calculates the error for each satellite and, through differential correction, improves the accuracy of GPS positions collected at unknown locations by a roving GPS receiver.
6. **C/A code** - The Coarse/Acquisition or Clear/Acquisition code modulated into the GPS L1 signal. This pseudo random noise (PRN) code is a sequence of 1023 pseudo random binary biphase modulations on the GPS carrier at a chipping rate of 1.023 MHz, thus having a code repetition period of 1 millisecond. The code was selected to provide good acquisition properties. Also known as the "civilian code." C/A codes are transmitted only on the L1 frequency.
7. **carrier** - A radio wave having at least one characteristic (e.g. frequency, amplitude, phase) that can be varied from a known reference value by modulation.
8. **carrier-aided tracking** - A signal processing strategy that uses the GPS carrier signal to achieve an exact lock on the pseudo random code.
9. **carrier phase measurements** - GPS measurements based on the L1 or L2 carrier signal.
10. **code phase GPS** - GPS measurements based on the C/A code.

11. **control point** - Also called a control station. A monumented point to which coordinates have been, or are being assigned by the use of surveying observations. The National Geodetic Survey maintains a nation-wide set of control points.
12. **cycle slip** - A discontinuity of an interger number of cycles in the measured carrier beat phase resulting from a temporary loss-of-lock in the carrier tracking loop of a GPS receiver.
13. **differential positioning** - Precise measurement of the relative positions of two or more receivers tracking the same GPS signals.
14. **differential GPS (DGPS)** - A technique used to improve positioning or navigation accuracy by determining the positioning error at a known location and subsequently incorporating a corrective factor (by real-time transmission of correction or by post-processing) into the position calculations of another receiver operating in the same area and simultaneously tracking the same satellites.
15. **dilution of precision (DOP)** - an indicator of satellite geometry for a unique constellation of satellites used to determine a position. Positions tagged with a higher DOP value generally constitute poorer measurement results than those tagged with lower DOP.
16. **distance root mean square (DRMS)** - It is the root-mean-square value of the horizontal distance error. The root-mean-square value of the distances from the true location point of the position fixes in a collection of measurements. As typically used in GPS positioning, 2 drms is twice the root mean square of error ellipse. This implies that the probability of finding the true horizontal position is within 95%.
17. **elevation mask angle** - That angle below which satellites should not be tracked to avoid interference problems caused by buildings and trees and multipath errors.
18. **ellipsoid height** - The measure of vertical distance above the ellipsoid. Not the same as elevation above sea level (or MLLW). A roving DGPS receiver output position fix height in the same datum as the base DGPS receiver.
19. **epoch** - Measurement interval or data frequency, as in making observations every one second (1 Hz).
20. **geoid** - The particular equipotential surface that coincides with mean sea level and that may be imagined to extend through the continents. This surface is everywhere perpendicular to the force of gravity.
21. **geoid height** - The height above the geoid, often called elevation above mean sea level.
22. **ionosphere** - The band of charged particles 80 to 120 miles above the

earth's surface, which represents a nonhomogeneous and dispersive medium for radio signals.

23. **ionospheric delay** - A wave propagating through the ionosphere experiences delay. Phase delay depends on electron content and affects carrier signals. Group delay depends on dispersion in the ionosphere as well, and affects signal modulation (codes). The phase and group delay are of the same magnitude but opposite sign.

24. **ionospheric refraction** - The change in the propagation speed of a signal as it passes through the ionosphere.

25. **L-band** - The group of radio frequencies extending from 390 MHz to 1550 MHz. The GPS carrier frequencies L1 (15735 MHz) and L2 (1227.6 MHz) are in the L-band.

26. **local area DGPS (LADGPS)** - A form of DGPS in which the user's GPS system receives real-time pseudorange and, possibly, carrier-phase corrections from a reference receiver located within line of sight

27. **multipath** - Interference caused by reflected GPS signals arriving at the receiver, typically as a result of nearby structures or other reflective surfaces. Signals travelling longer paths produce higher (erroneous) pseudorange estimates and, consequently, positioning errors.

28. **on-the-fly (OTF)** - The term used to identify a technique that resolves differential carrier phase integer ambiguities without requiring a GPS receiver to be stationary at any time.

29. **P-code** - The precise or precision code of the GPS signal, typically used alone by US and allied military receivers. A very long sequence of pseudo-random binary biphase modulations on the GPS carrier at a chip rate of 10.23 MHz which repeats about every 267 days. Each one-week segment of this code is unique to one GPS satellite and is reset each week.

30. **positional dilution of precision (PDOP)** - Measure of the geometrical strength of the GPS satellite configuration and translates into position error. For example, a 3 m error in the pseudoranges will translate into a 6 m position error if the PDOP is 2.

31. **phase lock** - The technique whereby the phase of an oscillator signal is made to follow exactly the phase of a reference signal. The receiver first compares the phases of the two signals, then uses the resulting phase difference signal to adjust the reference oscillator frequency. This eliminates phase difference when the two signals are next compared.

32. **post-processed differential GPS** - In post-processed differential GPS the base and roving recievers have no active data link between them. Instead, each records the satellite observations that will allow differential correction at a later time. Differential correction software is used to

combine and process the data collected from these receivers.

33. **pseudo-range -** A distance measurement based on the correlation of a satellite transmitted code and the local receiver's reference code, that has not been corrected for errors in synchronization between the transmitter's clock and the receiver's clock.

34. **range rate -** The rate of change between the satellite and receiver. The range to a satellite changes due to satellite and observer motions. Range rate is determined by measuring the Doppler shift of the satellite beacon carrier.

35. **real time kinematic (RTK) -** The DGPS procedure whereby carrier phase corrections are transmitted in real time from a reference station to the user's roving receiver.

36. **real-time differential GPS -** A base station which computes, formats, and transmits corrections usually through some sort of data link (e.g. VHF radio or cellular telephone) with each new GPS observation. The roving unit requires some sort of data link receiving equipment to receive the transmitted GPS corrections and get them into the GPS receiver so they can be applied to its current observations.

37. **relative positioning -** The process of determining the relative difference in position between two locations; in the case of GPS, by placing a receiver over each site and making simultaneous measurements observing the same set of satellites at the same time. This technique allows the receiver to cancel errors that are common to both receivers, such as satellite clock and ephemeris errors, propagation delays and so forth.

38. **receiver independent exchange format (RINEX) -** A set of standard definitions and formats that permits interchangeable use of GPS data from dissimilar GPS receiver models or post processing software. The format includes definitions for time, phase and range.

39. **RTCM SC-104 -** The special committee of the Radio Technical Commission for Maritime Services that develops recommended standards for DGPS.

40. **rover -** Any mobile GPS receiver collecting data during a field session. The receiver's position can be computed relative to another, stationary GPS receiver.

APPENDIX B

B. Glossary of tide terms (adapted from the NOS Tide and Current Glossary on the CO-OPS web site: http://www.co-ops.nos.noaa.gov/tideglos.html)

1. **accepted values** - Tidal datums and Greenwich high and low water intervals obtained through primary determination or simultaneous observational comparisons made with a primary control tide station in order to derive the equivalent of a 19-year value.

2. **chart datum** - The datum to which soundings on a chart are referred. It is usually taken to correspond to a low-water elevation, and its depression below mean sea level is represented by the symbol Z . Since 1989, chart datum has been implemented to mean lower low water for all marine waters of the United States, its territories, Commonwealth of Puerto Rico, and Trust Territory of the Pacific Islands. See datum and National Tidal Datum Convention of 1980.

3. **datum (vertical) -** For marine applications, a base elevation used as a reference from which to reckon heights or depths. It is called a tidal datum when defined in terms of a certain phase of the tide. Tidal datums are local datums and should not be extended into areas which have differing hydrographic characteristics without substantiating measurements. In order that they may be recovered when needed, such datums are referenced to fixed points known as bench marks. See chart datum.

4. **mean high water (MHW)** - A tidal datum. The average of all the high water heights observed over the National Tidal Datum Epoch. For stations with shorter series, simultaneous observational comparisons are made with a control tide station in order to derive the equivalent datum of the National Tidal Datum Epoch.

5. **mean lower low water (MLLW)** - A tidal datum. The average of the lower low water height of each tidal day observed over the National Tidal Datum Epoch. For stations with shorter series, simultaneous observational comparisons are made with a control tide station in order to derive the equivalent datum of the National Tidal Datum Epoch.

6. **mean sea level (MSL)** - A tidal datum. The arithmetic mean of hourly heights observed over the National Tidal Datum Epoch. Shorter series are specified in the name; e.g., monthly mean sea level and yearly mean sea level.

7. **national tidal datum epoch** - The specific l9-year period adopted by the National Ocean Service as the official time segment over which tide observations are taken and reduced to obtain mean values (e.g., mean lower low water, etc.) for tidal datums. It is necessary for standardization

because of periodic and apparent secular trends in sea level. The present National Tidal Datum Epoch is 1960 through 1978. It is reviewed annually for possible revision and must be actively considered for revision every 25 years.

8. **national water level observation network (NWLON)** - The network of tide and water level stations operated by the National Ocean Service along the marine and Great Lakes coasts and islands of the United States. The NWLON is composed of the primary and secondary control tide stations of the National Ocean Service. Distributed along the coasts of the United States, this Network provides the basic tidal datums for coastal and marine boundaries and for chart datum of the United States. Tide observations at a secondary control tide station or tertiary tide station are reduced to equivalent l9-year tidal datums through the comparison of simultaneous observations with a primary control tide station. In addition to hydrography and nautical charting, and to coastal and marine boundaries, the Network is used for coastal processes and tectonic studies, tsunami and storm surge warnings, and climate monitoring. The National Water Level Observation Network also includes stations operated throughout the Great Lakes Basin. The primary network is composed of 54 sites with 139 seasonal gauge sites selectively operated 4 months annually for the maintenance of IGLD. The network supports regulation, navigation and charting, river and harbor improvement, power generation, various scientific activities, and the adjustment for vertical movement of the Earth's crust in the Great Lakes Basin.

9. **primary control tide station** - A tide station at which continuous observations have been made over a minimum of 19 years. Its purpose is to provide data for computing accepted values of the harmonic and non harmonic constants essential to tide predictions and to the determination of tidal datums for charting and for coastal and marine boundaries. The data series from this station serves as a primary control for the reduction of relatively short series from subordinate tide stations through the method of comparison of simultaneous observations and for monitoring long-period sea level trends and variations. See tide station, secondary control tide station, tertiary tide station, and subordinate tide station.

10. **tertiary tide station** - A tide station at which continuous observations have been made over a minimum period of 30 days but less than 1 year. The series is reduced by comparison with simultaneous observations from a secondary control tide station. This station provides for a 29-day harmonic analysis. See tide station, primary control tide station, secondary control tide station, and subordinate tide station.

11. **tidal zoning** - The practice of dividing a hydrographic survey area into discrete zones or sections, each one possessing similar tidal characteristics.

One set of tide reducers is assigned to each zone. Tide reducers are used to adjust the soundings in that zone to chart datum (MLLW). Tidal zoning is necessary in order to correct for differing water level heights occurring throughout the survey area at any given time. Each zone of the survey area is geographically delineated such that the differences in time and range do not exceed certain limits, generally 0.2 hours and 0.2 feet respectively; however, these limits are subject to change depending upon type of survey, location, and tidal characteristics. The tide reducers are derived from the water levels recorded at an appropriate tide station, usually nearby. Tide reducers are used to correct the soundings throughout the hydrographic survey area to a common, uniform, uninterrupted chart datum. See tide reducers.

12. **tide** - The periodic rise and fall of the water resulting from gravitational interactions between Sun, Moon, and Earth. The vertical component of the particulate motion of a tidal wave. Although the accompanying horizontal movement of the water is part of the same phenomenon, it is preferable to designate this motion as tidal current. See tidal wave.

13. **tide (water level) gauge** - An instrument for measuring the rise and fall of the tide (water level). See ADR gauge, automatic tide gauge, Next Generation Water Level Measurement System, gas purged pressure gauge, electric tape gauge, pressure gauge, and tide staff.

14. **tide reducers** - Height corrections for reducing soundings to chart datum (MLLW). A tide reducer represents the height of the water level at a given place and time relative to chart datum. Tide reducers are obtained from one or more tide stations within or nearby the survey area. Often, due to differing tidal characteristics over the survey area, the tide reducers obtained directly from a tide station must be corrected to adjust for time and range of tide differences in the various zones of the hydrographic survey area. See tidal zoning.

15. **tide (water level) station** - The geographic location at which tidal observations are conducted. Also, the facilities used to make tidal observations. These may include a tide house, tide gauge, tide staff, and tidal bench marks. See primary control tide station, secondary control tide station, tertiary tide station, and subordinate tide station.

16. **type of tide** - A classification based on characteristic forms of a tide curve. Qualitatively, when the two high waters and two low waters of each tidal day are approximately equal in height, the tide is said to be semidiurnal; when there is a relatively large diurnal inequality in the high or low waters or both, it is said to be mixed; and when there is only one high water and one low water in each tidal day, it is said to be diurnal. Quantitatively (after Dietrich), where the ratio of K1 + O1 to M2 + S2 is less than 0.25, the tide is classified as semidiurnal; where the ratio is from 0.25 to 1.5, the

tide is mixed, mainly semidiurnal; where the ratio is from 1.5 to 3.0, the tide is mixed, mainly diurnal; and where greater than 3.0, diurnal.

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