Article




GPS-based Vertical Control, Unaided by a Shore Station

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Abstract

The United States Naval Oceanographic Office (NAVOCEANO) conducts worldwide hydrographic surveys in accordance with the International Hydrographic Organization (IHO) S-44 hydrographic survey standards. The current approach to meeting IHO standards requires the use of shore-based assets to establish and maintain vertical control via in-situ water level measurements. NAVOCEANO is upgrading its shipboard mission systems to support use of the vertical component of Global Positioning System (GPS) measurements for vertical control of hydrographic survey data. The technique of utilizing the GPS measured height for vertical control is referred to as Ellipsoidal Referenced Survey (ERS). The ERS approach simplifies hydrographic survey operations by reducing the need for shore-based infrastructure for water level measurements and by allowing for the production of data products in a tactical time frame. ERS offers the potential for a more seamless vertical datum from deep water through shallow water and up onto shore. However, this approach to vertical control presents new challenges in the need to define the separation between the ellipsoid and the required vertical datum. Precise point positioning (PPP) techniques make use of GPS satellite clock corrections and satellite orbit corrections which are freely available via the Internet. PPP processing is a post-time activity, lagging data acquisition by the 18 hours to 24 hours needed to gain access to the correction values. Positioning accuracies of better than 20 cm horizontal (95% confidence) and better than 30 cm vertical (95% confidence) have been demonstrated with PPP techniques using commercial off-the-shelf (COTS) software packages. An integrated survey system configured with current state-of-the-art equipment for the sonar, motion sensor, and profiling sensor can meet IHO order 1 survey requirements using a PPP-based GPS track-line when the separation uncertainty is suitably controlled.

Résumé

Le NAVOCEANO (Service océanographique naval des Etats-Unis) exécute des levés hydrographiques dans le monde entier, conformément aux normes pour les levés hydrographiques de la S-44 de l'Organisation hydrographique internationale (OHI). L'approche actuelle pour satisfaire aux normes de l'OHI nécessite l'utilisation de ressources à terre afin d'établir et de maintenir un contrôle vertical par le biais de mesurages du niveau de l'eau sur place. NAVOCEANO améliore actuellement ses systèmes embarqués à l'appui de l'utilisation de la composante verticale des mesurages à l'aide du GPS (système de détermination de la position global) pour le contrôle vertical des données relatives aux levés hydrographiques. La technique d'utilisation des hauteurs mesurées à l'aide du GPS pour le contrôle vertical est appelée ERS (Ellipsoidal Referenced Survey). L'approche ERS simplifie les opérations de levés hydrographiques en réduisant le besoin d'une infrastructure basée à terre pour les mesurages du niveau de l'eau et en permettant la production de données dans un délai de temps tactique. L'ERS offre le potentiel d'un système de référence verticale encore plus ininterrompu, allant des eaux profondes jusqu'à la côte, en passant par des eaux peu profondes. Toutefois, cette approche du contrôle vertical va de pair avec de nouveaux défis relatifs à la nécessité de définir la séparation entre l'ellipsoïde et le système de référence verticale requis. Les techniques de positionnement de points précis (PPP - Precise point positioning) utilisent les *corrections d'horloge et les corrections d'orbites par satellite GPS, disponibles à titre gracieux sur internet. Le traitement PPP est une activité « heure de départ », qui retarde l'acquisition des données des 18 aux 24 heures nécessaires pour obtenir l'accès aux valeurs de correction. Les exactitudes du positionnement supérieures à 20 cm à l'horizontale (95% de fiabilité) et supérieures à 30 cm à la verticale (95% de fiabilité) ont été démontrées à l'aide des techniques PPP utilisant des progiciels commerciaux standards (COTS - Commercial off-the-shelf). Un système de levés intégré, configuré à l'aide d'équipements modernes pour le sonar, les détecteurs de mouvement et les détecteurs de systèmes de sondage sur profils peut satisfaire aux prescriptions des levés de l'Ordre 1, à l'aide d'une trajectoire GPS basée sur les PPP, lorsque l'incertitude de la séparation est contrôlée de façon appropriée.*

Resumen

El Servicio Oceanográfico de la Marina de Estados Unidos (NAVOCEANO) lleva a cabo levantamientos hidrográficos en todo el mundo, conforme a la norma de levantamientos hidrográficos S-44 de la Organización Hidrográfica Internacional (OHI). El enfoque actual para cumplir las normas de la OHI requiere el uso de recursos basados en la costa, para establecer y mantener el control vertical mediante medidas del nivel del agua in-situ. NAVOCEANO está mejorando sus sistemas a bordo de los buques, para apoyar el uso de la componente vertical de las medidas del Sistema Global de Posicionamiento (GPS), para el control vertical de los datos de levantamientos hidrográficos. Se hace referencia a la técnica consistente en utilizar la altura medida gracias al GPS para el control vertical como al Estudio de Referencias Elipsoidales (ERS – Ellypsoidal Referenced Survey). El enfoque del ERS simplifica las operaciones de levantamientos hidrográficos reduciendo la necesidad de una infraestructura basada en la costa para las medidas del nivel del agua y permitiendo la producción de datos en un espacio de tiempo táctico. El ERS ofrece el potencial de un datum de nivelación más uniforme, procedente de aguas profundas, atravesando aguas poco profundas para llegar a la costa. Sin embargo, este enfoque del control vertical supone nuevos desafíos en la necesidad de definir la separación entre el elipsoide y el datum de nivelación requerido. Las técnicas de Posicionamiento de Puntos Precisos (PPP - Precise Point Positioning) utilizan las correcciones del reloj del satélite y las correcciones orbitales del satélite GPS, que están disponibles gratuitamente en Internet. El procesado del PPP es una actividad de la hora de envío, que retrasa la adquisición de datos de las 18 a las 24 horas requeridas para obtener el acceso a los valores de corrección. Se han demostrado las precisiones de posicionamiento que superan los 20 cm horizontalmente (95% de fiabilidad) y los 30 cm verticalmente (95% de fiabilidad) con técnicas de PPP que utilizan paquetes de programas comerciales genéricos (COTS - off-the-shelf). Un sistema hidrográfico integrado configurado con equipo moderno para el sonar, el sensor de movimiento y el sensor de sistemas de sondeo por perfilado puede satisfacer los requerimientos de los levantamientos de Categoría 1 de la OHI que utilicen una trayectoria del GPS basada en el PPP cuando la incertidumbre de la separación sea adecuadamente controlada.

I. Introduction

For NAVOCEANO, conventional vertical control techniques for hydrographic and bathymetric surveys in water shallower than several hundred meters are based on pressure sensor-derived water level measurements combined with a hydrodynamic model of the area to be surveyed. Establishment of a suitable vertical datum from the pressure sensor-based (tide gauge) data can take several months. Tide gauges must be operated concurrently with acquisition of the survey data. Establishment of a suitable hydrodynamic model and corresponding tidal zoning requires a high level of expertise and considerable effort. NAVOCEANO field operations require shore access to install, operate, and maintain the pressure sensor-based tide gauge(s). On a global scale, this requires host country access permission and necessitates asset security infrastructure.

The accuracy of the vertical component of Global Positioning System (GPS) positioning can reach better than 0.3 meters (95%) for GPS-Inferred Positioning SYstem (GIPSY) solutions, when the solid earth tide (SET) correction is employed. (van Norden 2005), (Hatch, 2002) Real-time GIPSY (RTG) positioning techniques can be accomplished without dependency on a user-managed shore-based reference station by using a dual-frequency GPS system and a paid subscription to an International Marine/Maritime Satellite (INMARSAT®)-based (International Mobile Satellite Organization) correction service. If raw GPS observables are acquired on the survey platform, precise point positioning (PPP) techniques can be used 24 hours post-time to produce a three-dimensional (3D) position track-line with a solution accuracy that is superior to the RTG solution and without dependency on the paid INMARSAT correction service. PPP techniques require availability of L1 and L2 raw GPS observables from the survey platform and access to the Internet to acquire the orbit and clock corrections for the GPS constellation that are freely available approximately 24 hours post-time. When clock and orbit corrections are applied with suitable precision and update rate, PPP results have been demonstrated to the centimeter level for static positioning and to the decimeter level for dynamic positioning. (Kouba, 2001). The accuracy of the vertical component of GPS-based positioning can reach 0.05 meters (95%) for post-processed kinematic (PPK) GPS solutions with reference-station-to-rover baseline distances of 10 kilometers or less. Kinematic positioning techniques require availability of one or more stationary reference stations and broadcast of corrections from the reference station to the survey platform if kinematic positioning must be done in real time.

Redundancy in the platform positioning systems is a fundamental requirement of the Naval Oceanographic Office's (NAVOCEANO's) shipboard mission systems. The NavCom Technology, Inc. (NavCom), SF2050 receiver provides the primary position solution. Deere & Company StarFire® correctors facilitate the RTG position solution, which is interfaced both to the Applanix Corporation's Applanix V4 Position and Orientation System for Marine Vessels (POS/MV) and to the Integrated Survey System (ISS-60), which is used for data acquisition and survey mission control onboard on the T-AGS 60 class ships. The POS/MV system provides position and orientation. The primary GPS in the POS/MV includes the dual frequency L1/L2 upgrade. In this configuration, the POS/MV position solution is based on the NavCom SF2050 RTG position solution. ISS-60 is configured to use the POS/MV position solution for real-time ship control, line following, and position merging with the bathymetry data. The Sperry Marine MK39 ring laser gyrocompass serves as a backup for heading, pitch, and roll. Having the two independent L1/L2 GPS receivers satisfies the positioning system redundancy requirement and provides a basis for performing consistency verification between the position solutions from the two units.

Migration to a vertical-controlled solution that is based on utilization of GPS measurements has several key advantages for NAVOCEANO survey platforms: (1) reducing the dependency on shore-based asset infrastructure for measuring water levels concurrent with the acquisition of the survey data; (2) production of preliminary data products in a tactical time frame; (3) reducing dependency on certain difficult-to-measure bathymetric correctors, such as loading draft and settlement and squat (S&S); and (4) the potential to achieve a seamless vertical datum that provides for better junctioning of bathymetric data from deep water to coastal and harbor areas and onto the shore.

Migration from conventional vertical control techniques to GPS-based vertical control techniques represents a paradigm change, operationally, that is being implemented as a phased integration. Initial operational capability will be a post-processing solution. With this first phase, the ISS-60v3.6 system is updated to capture the raw GPS observables from a NavCom SF2050 L1/L2 GPS receiver and to capture the raw GPS observables from the Trimble Navigation Limited BD950 (or BD960) primary GPS receiver contained within the POS/MV system.

ISS-60v3.6 merges the RTG latitude, longitude, and ellipsoidal height values with the bathymetry during acquisition. However, in this initial phase, real-time vertical control remains with conventional correctors for draft, S&S, heave, and predicted water levels. The GPS-based vertical control can be applied immediately in post-processing when the RTG position solution meets vertical control uncertainty requirements. When the RTG position solution does not meet uncertainty requirements, a PPP track-line can be generated and merged with the bathymetry data approximately 24 hours post-time. Application of the GPS height values for vertical control requires having a model of the ellipsoid-to-vertical datum separation (SEP) defined over the extents of the survey area. Definition of the SEP can occur asynchronously from the survey data acquisition, but must be available prior to application of the GPS height values for vertical control. It is envisioned that after successful deployment and operation of the post-processing solution, a subsequent phase will include application of the height solution for vertical control in real time.

Given the scope and nature of the system and software changes required to support a GPS-based solution for vertical control, the implementation is being pursued as an augmentation to existing capabilities. Conventional water-level prediction and measurement techniques will remain a requirement for some time. The approach to management of installation offsets on the survey platform remains largely unchanged. There is, however, a renewed need to define and achieve a suitable accuracy from the ship alignment survey and to quantify the uncertainty of the ship alignment survey results. For the ship alignment survey, a target uncertainty of 0.01 meters for lever arm offset measurements and 0.01 degrees for angular offset measurements is warranted to minimize the increase in uncertainty resulting from position translocation for lever arm offsets. Component uncertainty estimates for the lever arm offsets that are somewhat larger than 0.01 meters may be appropriate for the total propagated uncertainty (TPU) model in order to account for flexure on a platform the size of the T-AGS 60 class ship. Management of the angular alignment offsets required to bring the motion sensor frame of reference into alignment with the vessel frame of reference is necessary to preserve accuracy of the position during transfer from the GPS antenna phase center to the chosen master reference point (MRP) on the platform. Heading, roll, pitch, heave, draft, sonar transducer lever arms, and sound speed all continue to be required to convert the multibeam measurements into platform-relative X,Y,Z values. Operationally, each of these inputs is managed in a consistent fashion that is independent of the planned approach for final vertical control. A key point here is the importance of accounting for heave that is based on the input of real-time heave into the sonar system. This is essential to provide proper compensation for the motion of the transducers over the course of the sonar transmit and beam receive cycle. Application of the improved delayed heave available in post-processing offers a refinement, but as with application of real-time heave, this correction remains applied within the sonar processing to allow for proper compensation over the course of the sonar transmit and beam receive sequence. With this approach of leaving heave accounted for within the sonar processing, it is necessary to ensure that the heave applied at ping time is removed from the GPS ellipsoidal heights as part of computing the GPS-based vertical controlled correction value. The GPS position solution must then be sampled at a sufficiently high rate to allow removal of the ping-time heave value from the GPS height. For the dynamics encountered on the NAVOCEANO T-AGS ships a sampling rate of the GPS heights in the range of 5 Hz to 10 Hz is required.

This paper describes the workflow for and presents the results of processing a shallow-water Kongsberg Maritime EM710 multibeam sonar dataset using a PPP track-line for both horizontal and vertical control. The survey area, shown in *Figure 1*, was located on a coral reef on the western side of Saipan Island in the Pacific Ocean. This survey was completed as part of the operational evaluation of the EM710 system recently installed on the USNS *Bowditch*. The survey lines were spaced 80 meters apart, resulting in 50% overlap of swath coverage. All shipboard equipment required for this analysis was permanently installed, so no special setup or configuration was necessary.

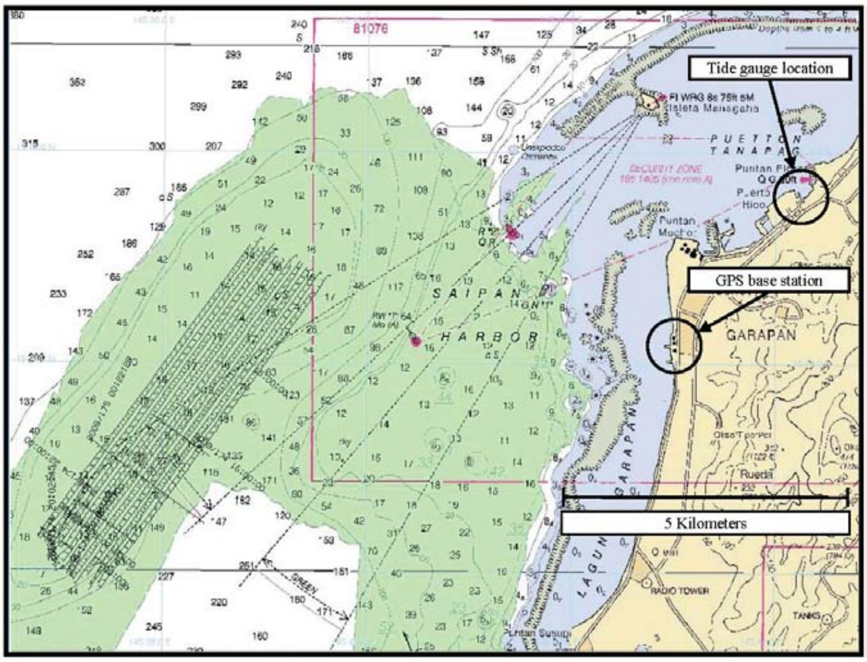

Figure 1 : Location of survey area, location of tide gauge, and location of Kinematic GPS (KGPS) base station

The operational evaluation of the EM710 was conducted using conventional techniques for measuring and correcting for water levels, draft, settlement and squat, and application of lever arm and angular alignment offsets. For this operational evaluation, a tide gauge was installed in Tanapag Harbor. The vertical datum for this gauge was established using the existing benchmark designated 163 3227 UH-5B on the National Ocean Service (NOS) tides and currents benchmark sheet. GPS observations of benchmark 163 3227 UH-5B and a neighboring benchmark named LIDAR were completed as part of the effort to establish the vertical datum. Benchmark 163 3227 UH-5B is located approximately 70 meters from where the tide gauge was installed. Benchmark LIDAR is located approximately 5 meters from where the tide gauge was installed. The tide gauge reference level was surveyed from benchmark 163 3227 UH-5B, and the tide gauge data was reduced to mean lower low water (MLLW). *Figure 2* shows a sample of data from the installed tide gauge for the time frame of the reef survey. Data from the tide gauge was used to define the water levels for a single tide-zone encompassing the entire Saipan Reef test area. The EM710 bathymetry data was then corrected using the water levels for this zone. The tide-corrected bathymetry data was then used to produce a reference bathymetry surface. A shore-based GPS base station was installed and operated during the reef survey.

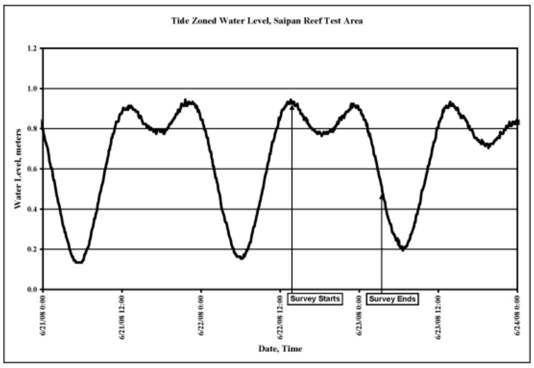

Figure 2. Water level heights relative to MLLW, showing variation over time frame of survey

While not exclusively motivated for testing of the GPS-based vertical controlled techniques, availability of both the GPS base station and the tide gauge for this survey provided the opportunity for a quantitative evaluation of the GPS PPP solution. The GPS base station was operated concurrently with acquisition of the survey data to support generation of a PPK solution as a means to help evaluate the overall uncertainty of the PPP track-line. Locations for both the installed tide gauge and the GPS base station are shown in *Figure 1*.

Although reduction of the dependency on shore-based assets and infrastructure is a fundamental overall objective, this has not yet been completely achieved. Definition of the SEP is a basic requirement when utilizing GPS-based vertical control techniques and demonstrations completed to date have utilized some minimal level of shore-based infrastructure to aid in definition of the SEP. NAVOCEANO is actively developing techniques to use GPS-equipped buoys as one potential technique to facilitate SEP definition without the need for shore-based assets. For IHO order 1 (IHO, 2008) and higher surveys, the envisioned operational concept utilizes RTG as the primary 3D survey platform positioning technique with utilization of PPP when the RTG uncertainty is not sufficient. A combination of geoid undulation models and GPS-equipped buoys are envisioned to provide the SEP.

Data Processing Overview

An overview of the data processing workflow is shown in *Figure 3*. The generic sensor format (GSF) data files produced by ISS-60v3.6 are processed for application of vertical correctors and removal of large outlier data points. In parallel with this, the GrafNav® software package from NovAtel, Inc., was used to produce the PPP navigation track-line. GrafNav provides the ability to download the precise clock and orbit corrections from the Internet. GrafNav has the ability to automatically select the service from which to obtain the clock and orbit corrections. For the June 22, 2008, PPP processing, the corrections were obtained from the International GNSS Service (IGS). For the June 23, 2008, PPP processing, the corrections were obtained from the Center for Orbit Determination in Europe (CODE). These corrections are available approximately 24 hours after acquisition. Corrections available within 24 hours post-time are typically referred to as the “rapid” version of the corrections. All PPP processing presented here was based on the rapid corrections. GrafNav uses these corrections along with the L1 and L2 observables to generate a 3D track-line solution. With this step, it is necessary to ensure that the raw observables are sampled at a sufficient rate to support generation of a track-line file that resolves the full frequency range of horizontal and vertical motion. For the data presented here, the SF2050 observables are recorded at a 5 Hz rate, and GrafNav computes a PPP solution on each epoch, resulting in a track-line file with a true solution rate of 5 Hz with no interpolation performed in GrafNav. GrafNav performs a forward pass and a backward pass and combines these for the final solution. With a PPP solution, a convergence time is typical on startup and is often seen near the end of the track-line time series. The output track-line file produced by GrafNav includes the horizontal and vertical standard deviation values for each position solution. The standard deviation values output from GrafNav provide the starting point for the horizontal position uncertainty and for the vertical position uncertainty with these values treated as being valid at the antenna phase center. The standard deviation values also facilitate quality control (QC) review of the 3D navigation time series.

GrafNav was also used to produce a PPK solution. For this, the SF2050 observables from the survey platform were combined with the raw observables from the GPS base station data, and GrafNav computed a post-processed kinematic solution. In *Figure 3*, the dotted blue steps are only required for processing the bathymetry data with conventional water levels to generate the reference bathymetry surface. The dotted blue steps are not required for production data processing using GPS-based vertical control. The navigation post-processing steps and application of GPS-based vertical control was executed twice, once for the PPP solution and once for the PPK solution. The PPK solution was used to produce an alternative reference surface to aid in evaluating the PPP solution. While PPK capability is an operational requirement, use of a PPK approach is envisioned only for engineering and IHO special-order mission requirements due to the additional burden of installing, maintaining, and providing security for the base station.

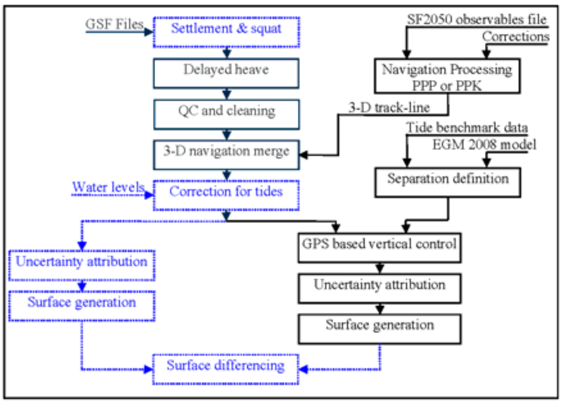

Figure 3: Data processing work flow

The PPP track-line produced by GrafNav is read into the SAIC Survey Analysis and Area Based Editor (SABER) version 4.3 software for updating the positions in the GSF files. The position merge updates the latitude, longitude, and ellipsoidal height for each ping. As part of the merge process, SABER performs the transformations necessary to translate the 3D position from the antenna phase center to the MRP. These transformations utilize the antenna lever arm offsets along with the roll, pitch, and heading time series. The position values saved with each ping represent the latitude, longitude, and ellipsoidal height of the vessel MRP at ping time. While SABERv4.3 does support smoothing of the GPS trajectories as a standard option, no smoothing has been applied to the trajectories presented here. Following this, the water level values from the tide gauge are applied. For the Saipan reef survey, a single tide zone encompassing the entire area was defined. For calculating the water levels at the survey area, a simplistic tide-zoning model consisting of a height multiplier of 1.0 and a phase offset of 0.0 was used. As the water level corrections are applied, each ping record is updated to reflect the type (observed, predicted, or verified) of gauge-based water level correction applied. At this point, copies of the GSF files were made. The first set of files was run through the total propagated uncertainty (TPU) model and then used to generate a combined uncertainty bathymetry estimator (CUBE) bathymetry surface. Here, TPU estimation includes components for draft, S&S, gauge-based water level measurement, and water level zoning. The resulting CUBE surface, with horizontal control from the GrafNav SF2050 PPP track-line and vertical control from the tide-gauge water level measurements, was considered the reference surface.

GPS-based vertical control is applied to the second set of GSF files. Any previously applied tide correction is removed, and any previously applied settlement and squat correction is removed. The draft correction is removed and the transducer Z offset is applied so that the depth values are now relative to the MRP. The GPS tide corrector is computed by removing the SEP and the heave from the ellipsoidal height and inverting the sign to change the value from a height to a height corrector. The GPS height corrector is then applied to the depth values and the GSF file is updated with the resulting depths and supporting information. As the GPS height corrector is applied, each ping record is updated with a flag to reflect GPS vertical control. This ping flag is used as a switch to guide the TPU estimation. For vertical control based on GPS, TPU estimation starts with the track-line uncertainties valid at the antenna phase center, and these values are increased to accumulate the uncertainty associated with translocation of the position to the MRP before being combined with the uncertainties for each depth value. Uncertainty of the SEP is currently modeled as a single value over the entire survey area. A value of 0.1 meters for the component of SEP uncertainty is used in the results presented here. For GPS-based vertical control, the uncertainties associated with draft, S&S, tide measurement, and zoning are bypassed. With the depth values corrected and the uncertainties estimated, a CUBE surface is generated and evaluated in comparison to the reference surface.

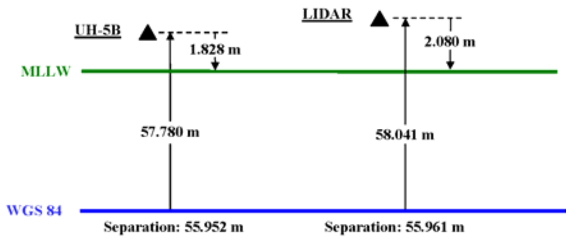

Figure 4. Separation definition at benchmarks in vicinity of installed tide gauge

In order to compare the GPS PPP vertical-controlled bathymetry data to the tide gauge vertical-controlled bathymetry data, the SEP value must be defined. GPS observations on benchmark UH-5B combined with the offset from the benchmark to the MLLW chart datum result in an ellipsoid to MLLW SEP determination of +55.952, indicating that the MLLW chart datum is 55.952 meters above the WGS-84 ellipsoid. This is shown graphically in *Figure 4* for the benchmarks named UH-5B and LIDAR. GPS observations completed on the LIDAR benchmark resulted in an ellipsoid to MLLW SEP determination of +55.961. The observed 0.009 meter difference between the SEP determinations from these two benchmarks is well within the expected uncertainty. The observation from the LIDAR benchmark was used just for establishing confidence, with SEP at the tide gauge based on the +55.952 meter observation from UH-5B. This single SEP value is valid only at the location where the measurements were made. For a sufficiently small survey area, a single SEP value might be adequate; however, in general, this simplification will not be sufficient. Height of the chart datum relative to the ellipsoid changes spatially, even over distances of a few kilometers. In the absence of additional measurements, a model of the spatial variability of the height of the chart datum relative to the ellipsoid is required. Height of the chart datum relative to the ellipsoid can be decomposed into two primary components. These are: 1) the height of mean sea level relative to the ellipsoid, and 2) the offset to the chart datum from mean sea level. Both of these components have spatial variability, but are driven by differing factors.

A model predicting the height of MLLW relative to the ellipsoid is not available for Saipan and would be prohibitively expensive to develop. However, a model of geoid height relative to the WGS-84 ellipsoid is available. The color-filled portion of the image in *Figure 5* shows the geoid undulation, or height of the geoid relative to the ellipsoid, as modeled by the U.S. National Geospatial-Intelligence Agency's (NGA's) earth gravity model (EGM) 2008 (NGA 2008). EGM 2008 is available as a one-minute-by-one-minute worldwide grid that provides a model of the geoid undulation referenced from the WGS-84 ellipsoid. *Figure 5* also shows the location of the tide gauge, location of the GPS base station, and the survey track-lines superimposed on the geoid undulation. The color scale bar shown in *Figure 5* defines the height of the geoid relative to the WGS-84 ellipsoid.

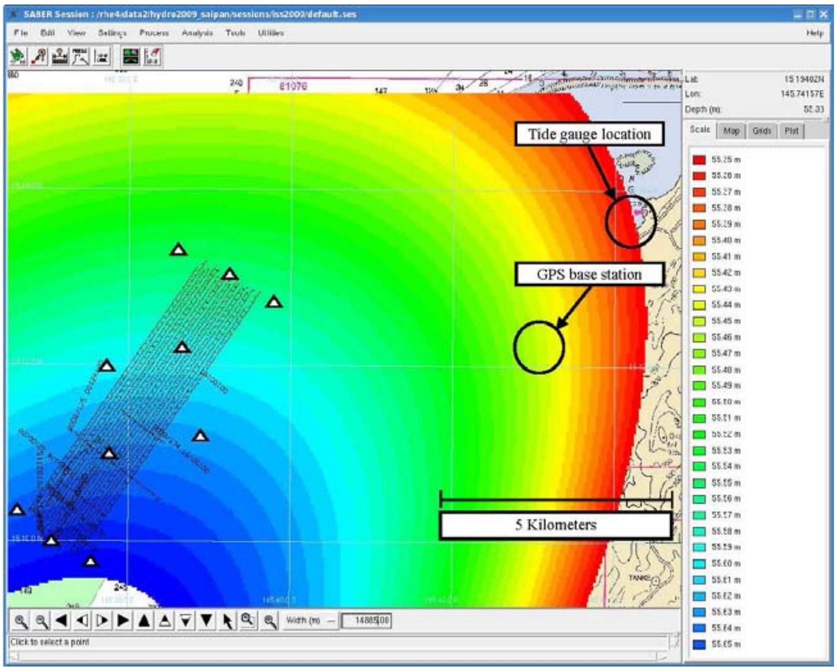

Figure 5: EGM 2008 model of geoid undulation over the survey area

Given the small size of the Saipan Reef survey area and its close proximity to the tide gauge, the spatial variability between MLLW and the geoid is assumed to be negligible. With this assumption, it is then possible to apply the slope predicted by EGM 2008 to transfer the SEP from UH-5B (55.952) out to various points in the survey area. Using this approach, a grid of irregularly spaced, discrete point observations that bracket the survey area was defined. The resulting grid is shown in *Figure 5,* and the locations of these points are identified in *Figure 5,* as the triangles bracketing the survey lines. The SEP values in the survey area were estimated by taking the difference between the SEP at the benchmark and the geoid undulation at the benchmark and adding this difference to the geoid undulation at each of the grid positions. These values were input into the post-processing software as the definition of the WGS-84 to MLLW SEP over the survey area. The post-processing software computes a SEP value for each ping, using an inverse distance interpolation, allowing for a unique SEP value to be used for each ping. The estimated SEP is observed to change from a minimum of 56.151 meters at the north end of the westernmost survey line to the a maximum value of 56.292 meters at the southern end of the easternmost line, resulting in 0.141 meters of variability over this relatively small survey area. Clearly, the SEP must be well defined over the entire extent of the survey area as a fundamental aspect of using GPS height measurements for vertical control. Additional background information and steps for calculating a separation model are well covered by FIG publication No. 37. (FIG 2006)

Latitude (Deg N)	Longitude (Deg E)	SEP (meters)
15.22572	145.63426	56.151
15.20908	145.61611	56.181
15.18928	145.59400	56.211
15.21957	145.65443	56.171
15.20491	145.64471	56.211
15.19025	145.63325	56.241
15.16807	145.61675	56.281
15.20878	145.66531	56.191
15.18552	145.65030	56.251
15.16559	145.62496	56.291

Table 1: SEP grid definition

Analysis

A fundamental objective of this work was to demonstrate the use of a PPP track-line for both horizontal and vertical control of a shallow water multibeam survey to IHO order 1 standards. Evaluation of the PPP vertical solution was facilitated by having access to both the gauge-measured water levels and a PPK track-line, while evaluation of the PPP horizontal solution was facilitated by the PPK solution alone. The three methods of determining depth correctors (PPP, tide gauge measurements, and PPK) were compared by creating CUBE surfaces for each type of vertical control where each uses the same PPP solution for horizontal control. This makes the comparison of vertical control more uniform. As shown on the chart in *Figure 1*, a steep slope exists on the southeast edge of the reef. This creates the opportunity for large differences between CUBE surfaces; therefore, only the top of the reef was used in the comparisons. *Figure 6* shows the CUBE standard deviation for a portion of the top of the reef where horizontal control is from PPP and vertical control is from PPK. The color scale bar in this image has a step size of 0.04 meters, with dark blue having a value of 0.0 meters and green having a value of 0.5 meters. The CUBE standard deviation values are generally 0.2 meters or less, except along the slopes where the values reach 0.5 meters. The band that parallels each track-line results from the nearly 50% overlap in swath coverage, where we have a slight reduction in CUBE standard deviation from single swath coverage in the area immediately below each track-line. *Figure 7* shows the difference grid produced when the PPK vertical controlled depth surface is subtracted from the tide gauge vertical-controlled depth surface. The color scale bar in this image has a step size of 0.02 meters, with red having a value of -0.25 meters and dark blue having a value of +0.25 meters. The CUBE standard deviation image provides a sense of internal consistency or repeatability where the warmer colors indicate a larger standard deviation. The difference grid provides an indication of overall uncertainty – at least to the extent of our confidence in the tide gauge-controlled reference surface. Increased standard deviation around the areas of steeper slope is expected. *Figure 6* and *Figure 7* provide a favorable indication of both repeatability and agreement between the PPK vertical-controlled solution and the tide gauge vertical-controlled solution.

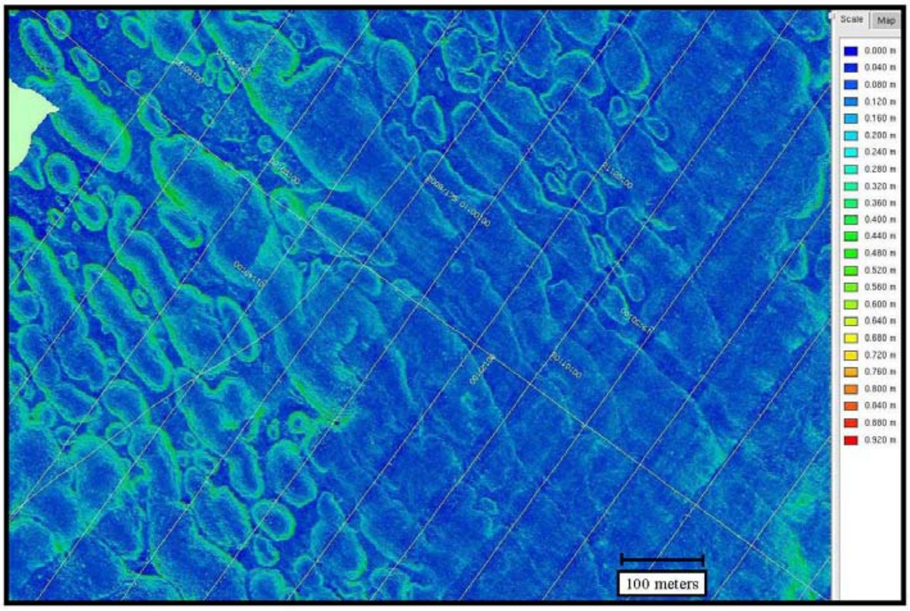

Figure 6: CUBE standard deviation for PPK vertical-controlled depth

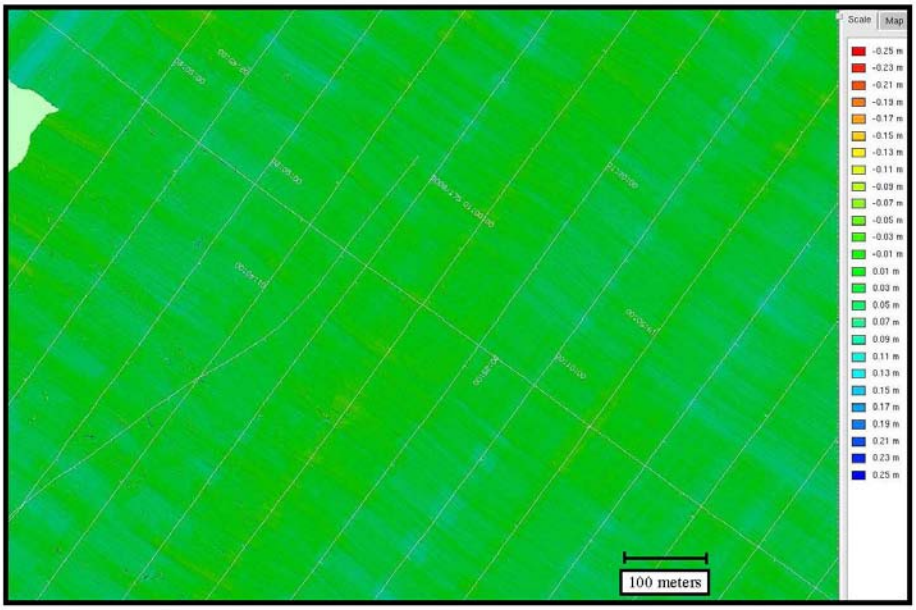

Figure 7: Difference grid produced by subtracting PPK vertical-controlled CUBE surface from tide-gauge-controlled CUBE surface

Table 2 shows comparisons for tide-gauge-controlled depths minus PPK vertical-controlled depths over the full length of the survey. The skew to positive differences in Table 2 indicates that the tide-gauge-controlled depths are slightly deeper than the PPK GPS vertical-controlled depths. *Table 2* shows that for the comparison of the tide gauge vertical control to the PPK vertical control, greater than 98% of the comparisons agree to within 0.1 meters.

Difference Range Cm		All Comparisons		Positive		Negative		Zero	
		Count	Percent	Count	Percent	Count	Percent	Count	Percent
0	5	6292583	79.45	4474365	75.33	1122629	87.34	695589	
5	10	1496511	98.34	1359284	98.22	137227	98.02		
10	15	104110	99.66	92777	99.78	11333	98.9		
15	20	11806	99.81	8776	99.93	3030	99.14		
20	25	4341	99.86	1284	99.95	3057	99.38		
25	30	4802	99.92	1307	99.97	3495	99.65		
30	35	2774	99.96	1348	100	1426	99.76		
35	40	1695	99.98	156	100	1539	99.88		
40	45	1099	99.99	0	100	1099	99.96		
45	50	470	100	0	100	470	100		
50	60	1	100	0	100	1	100		
Totals ->		7,920,192	100.00%	5,939,297	74.99%	1,285,306	16.23%	695,589	8.78%

Table 2: Tide gauge vertical-controlled depths minus PPK vertical controlled depths over top of reef

Figure 8 shows the CUBE standard deviation for the same area portrayed in *Figure 6* but based on the bathymetry data where both horizontal control and vertical control are from PPP. The color scale bar in this image has a step size of 0.04 meters, with dark blue having a value of 0.0 meters and green having a value of 0.5 meters. The CUBE standard deviation values are generally 0.3 meters or less, except along the slopes where the values reach 0.5 meters and higher in a few places. *Figure 9* shows the difference grid produced when the PPP vertical-controlled depth surface is subtracted from the tide gauge vertical-controlled depth surface. The color scale bar in this image has a step size of 0.02 meters, with red having a value of -0.25 meters and dark blue having a value of +0.25 meters. The CUBE standard deviation surface presented in *Figure 8* provides an indication of repeatability, where the warmer colors indicate a larger standard deviation. The grid difference provides an indication of overall uncertainty and may call our attention to a potential nonzero bias value. The areas of generally higher standard deviation around steeper slopes are expected. Some issues with the PPP vertical solution are clearly evident in both the CUBE standard deviation and the difference grid indicating greater uncertainties with the PPP vertical solution than are evident in the PPK vertical solution.

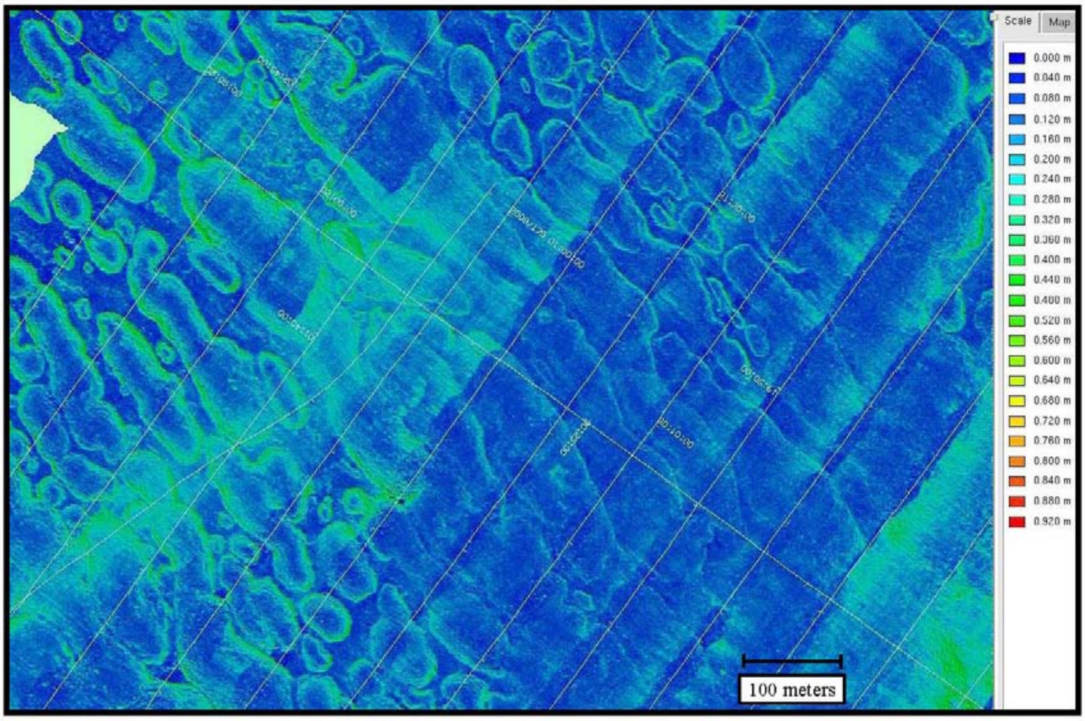

Figure 8: CUBE standard deviation for PPP vertical-controlled depth

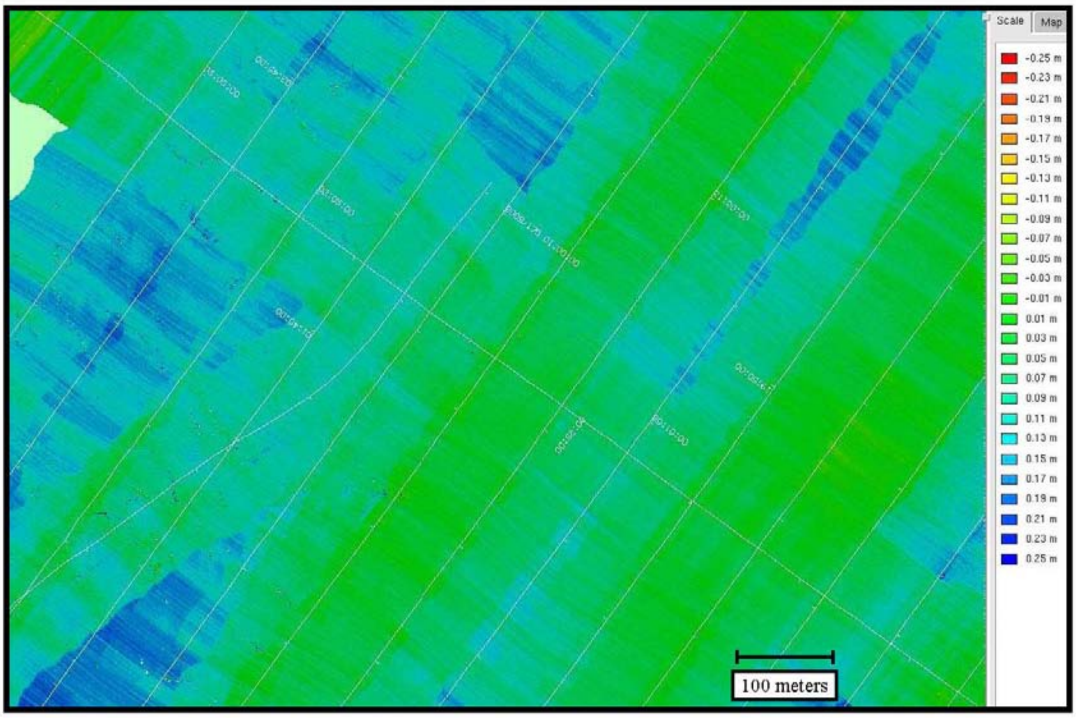

Figure 9: Difference grid produced by subtracting PPP vertical-controlled CUBE surface from tide-gauge-controlled CUBE surface

Table 3 shows the comparisons for tide gauge vertical-controlled depths minus PPP vertical-controlled depths over the entire length of the survey. The skew to positive differences in Table 3 indicates that the tide-gauge-controlled depths are deeper than the PPP GPS vertical-controlled depths. Table 3 shows that for the comparison of the tide gauge vertical control to the PPK vertical control, greater than 96% of the comparisons agree to within 0.2 meters.

Difference Range Cm		All Comparisons		Positive		Negative		Zero	
		Count	Percent	Count	Percent	Count	Percent	Count	Percent
0	5	1136805	14.87	792427	11.11	235827	57.91	108551	
5	10	2223021	43.93	2098861	40.54	124160	88.41		
10	15	3141139	85.01	3102929	84.05	38210	97.79		
15	20	874578	96.44	870338	96.25	4240	98.83		
20	25	236665	99.54	235190	99.55	1475	99.19		
25	30	28206	99.91	26025	99.92	2181	99.73		
30	35	4315	99.96	3505	99.97	810	99.93		
35	40	1239	99.98	944	99.98	295	100		
40	45	1310	100	1309	100	1	100		
45	50	241	100	241	100	0	100		
50	60	1	100	1	100	0	100		
Totals ->		7,647,520	100.00%	7,131,770	93.26%	407,199	5.32%	108,551	1.42%

Table 3: Tide gauge vertical-controlled depths minus PPP vertical-controlled depths over top of reef

Figure 10 shows the difference surface obtained when the entire extent of the PPP vertical-controlled CUBE depth surface is subtracted from the tide gauge vertical-controlled depth surface. The color scale bar in this image has a step size of 0.02 meters, with red having a value of -0.25 meters and dark blue having a value of +0.25 meters. The survey starts on the northern end of the easternmost survey line and the survey completes on the northern end of the westernmost survey line. Some anomalous differences are apparent near both the start and the end of the survey. In Figure 10, the areas with a difference larger than about 0.1 m in magnitude appear to result from variability in the GPS PPP height solution.

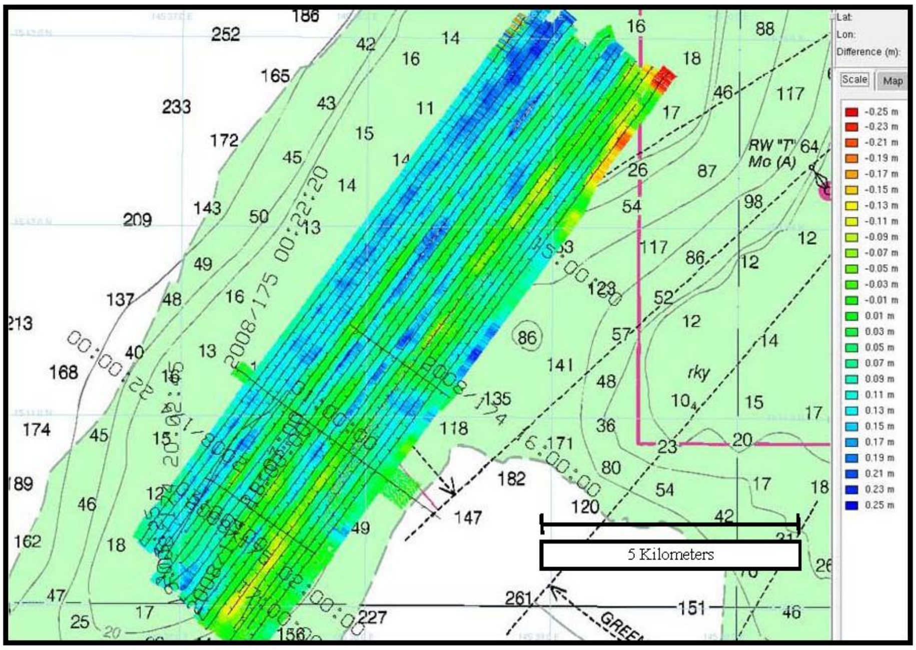

Figure 10: Difference surface produced when PPP vertical-controlled depth is subtracted from tide gauge vertical-controlled depth

Figure 11 and Figure 12 show the PPK- and PPP-derived water level height values plotted with the tide-gauge water level measurements. The PPK heights and the PPP heights have been corrected to the water surface by transferring the position to the MRP, removing the SEP, removing the heave, removing the settlement and squat, and adjusting for the MRP to water surface offset. This is done just for the purpose of plotting the GPS-based water level measurement against the tide gauge data for quality control. Data values are plotted only for the on-line time frames from the two consecutive days. As a result, the time frames during which the ship turned at the end of one transect line onto the next transect line are shown as the short-duration gaps in Figure 11, and in Figure 12. These are not representative of gaps in GPS coverage, rather these short-duration gaps result from the processing approach of eliminating the turn data from the gridded bathymetry product. The longer-duration gap spanning the day change from June 22 to June 23 results from an outage where the NavCom SF2050 RTG position solution was not reliable. With a gap in availability of the primary real-time horizontal control system, data acquisition was suspended for a little over one hour. Figure 11 and Figure 12 show the same level of agreement observed from analysis of the bathymetry data. The PPK solution is considerably tighter than the PPP solution, as expected. These plots illustrate the convergence problems that can occur on startup and/or on the end of a data segment. The level of agreement between the PPK-based water level heights and the gauge-based water level heights is reasonable given the simplistic tide-zoning model used to transfer the measured water levels from the gauge out to the survey area, and the uncertainties associated with translocation of the GPS ellipsoidal height measurement from the antenna phase center down to the MLLW relative water surface height. The observed range of the post-processed GPS height solutions is consistent with expectations for both the PPK solution and the PPP solution.

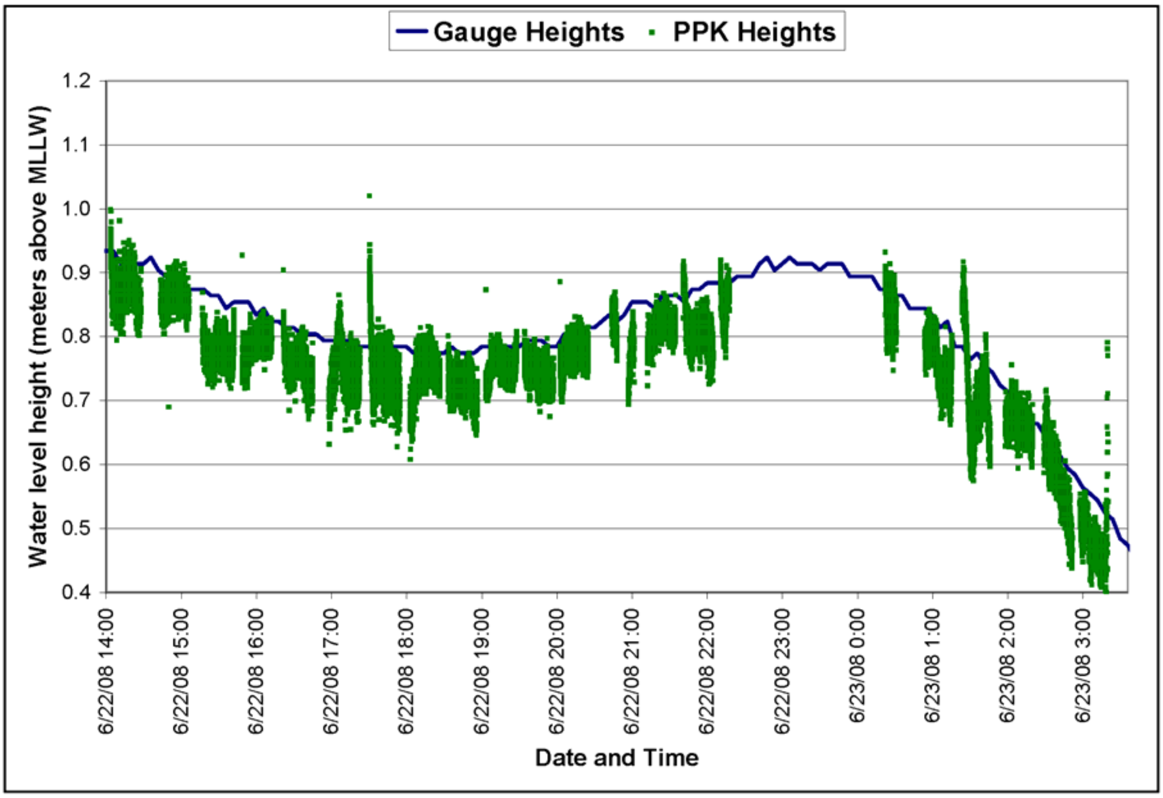

Figure 11: PPK water level height versus tide gauge water-level height

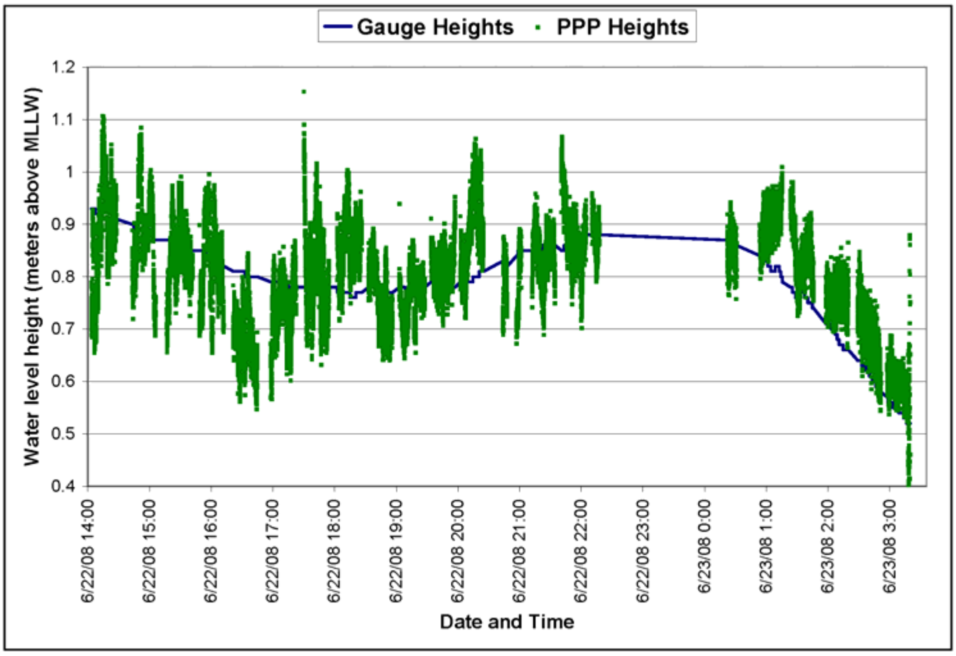

Figure 12: PPP water level height versus tide gauge water-level height

Figure 13 shows a comparison of the GrafNav SF2050 PPP height solution against the GrafNav SF2050 PPK height solution. The comparison is made directly on the ellipsoidal height values output from GrafNav. The red and green lines are the PPP ellipsoidal height and the PPK ellipsoidal height, respectively, both of which are plotted against the right-hand axis. The blue line is the difference that results when the PPP ellipsoidal height is subtracted from the PPK ellipsoidal height. No smoothing or averaging has been applied to these observations. The time span plotted is approximately 14 hours. For the displayed time span, the average of the differences is -0.4 centimeters; the average of the absolute values of the differences is 9 centimeters; the standard deviation is 9.6 centimeters; the minimum is -45.4 centimeters; the maximum is 46.5 centimeters; and 95% of the differences agree to within 19 centimeters or less.

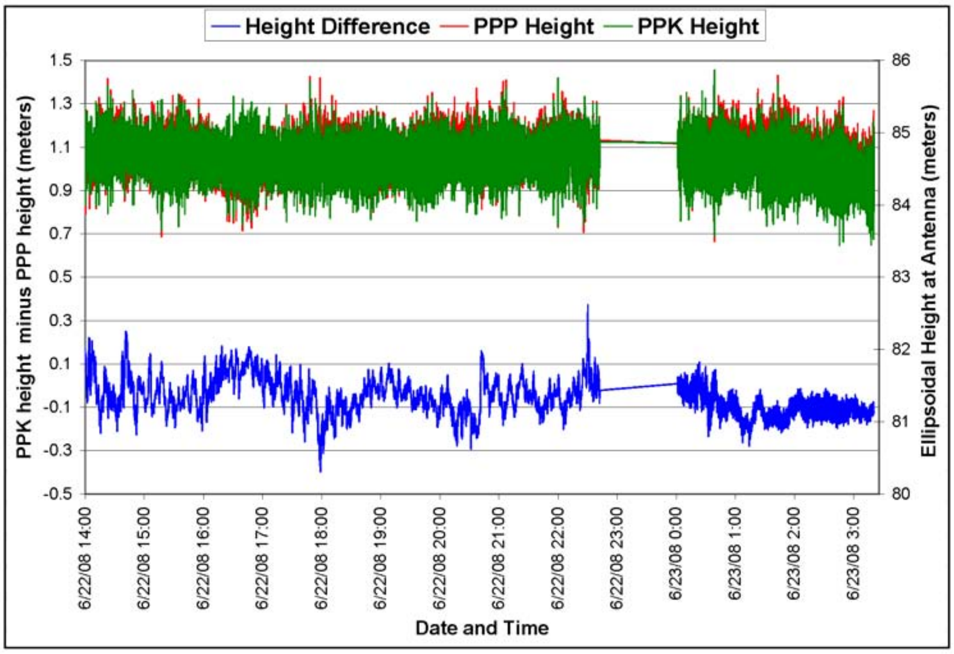

Figure 13: Comparison of PPP height solution against PPK height solution

GrafNav provides horizontal and vertical standard deviation values and a quality factor for each solution epoch. Review of the standard deviation values needs to be part of a standard operating procedure to isolate time frames when the solution does not meet requirements and to identify corrective action. The range of time around the occurrences of the larger, observed differences are generally identified by an elevated standard deviation value and occasionally are accompanied with a GrafNav quality value of 3, indicating that PPP solution has lost convergence. This provides sufficient information to support an automated mechanism for identification of potentially problematic areas to be given critical review.

While the uncertainty of the PPK solution is not quantified here, experience suggests that, for the short baseline distance, the PPK height solution should have an uncertainty of 0.05 meters or less. Given that 95% of the observed PPK-to-PPP height differences agree to 19 centimeters, the PPP height solution for this dataset should have an overall uncertainty of 0.20 meters at 95% confidence. This level of uncertainty is in agreement with the separate comparison of the PPP vertical-controlled bathymetry data to both the tide gauge vertically controlled bathymetry data and the PPK vertically controlled bathymetry data. The analysis indicates that for this particular dataset, the overall vertical uncertainty of the PPP bathymetry surface is largely dominated by the uncertainties associated with vertical control.

Conclusion

Two reference bathymetry surfaces, one controlled using tide gauge-measured water levels and the second controlled using GPS PPK heights, were produced and used to evaluate the PPP vertical-controlled bathymetry surface. The two reference surfaces agreed with each other to better than 10 centimeters at 95% confidence. The GPS PPP vertical-controlled bathymetry surface agreed with the tide-gauge vertically controlled bathymetry surface to better than 20 centimeters at 95% confidence. Given the sufficiently frequent profiling of sound speed employed for this survey, the majority of the observed differences likely result from a combination of uncertainties in the tide gauge-based measurement, the tidal zoning, the GPS height measurement, the SEP modeling, the settlement and the squat correction. Given the 10-centimeter agreement between the tide gauge vertical-controlled bathymetry and the GPS PPK vertical-controlled bathymetry, it is reasonable to infer that the SEP uncertainty has been managed to 10 centimeters or better for this particular area.

Comparisons of the PPP height solution with the PPK height solution suggest an overall uncertainty of the PPP height solution of 20 centimeters at 95% confidence. The observed differences for the PPP solution are well within allowable uncertainty for IHO order 1 surveys in these depths. Adequate definition of the SEP requires in-situ measurements and may include integration of measurements with existing models. It is essential to understand the SEP and its variability over the survey area in order to meet survey requirements.

The analysis presented here indicates that the GrafNav SF2050 PPP solution can be used to apply Ellipsoidal Referenced Survey (ERS) techniques to achieve IHO order 1 uncertainty when all factors are closely controlled. Use of ERS techniques can help overcome the numerous challenges with a zone-based approach to water-level correction. ERS techniques are expected to provide the additional benefit gained from use of a common approach for vertical control between shipboard multibeam sonar bathymetry surveys and airborne light detection and ranging (LIDAR) surveys. If the SEP is known in advance of the survey data acquisition, the ERS techniques will allow for data products to be produced in a tactical time frame. Use of a PPP solution as a standard part of applying ERS techniques to order 1 surveys provides partial autonomy from the need for shore-based infrastructure for measuring and modeling water levels, while some level of dependence on shore-based infrastructure remains needed to facilitate SEP definition. Use of GPS buoys is expected to aid in achieving additional independence from shore-based assets. Use of multiple GPS buoys is envisioned to manage the spatial variability of the SEP and to provide redundancy and SEP uncertainty estimation.

While all of the GPS post-processing presented here results from processing the raw GPS observables from the NavCom SF2050, which only tracks the US GPS constellation, receivers such as Trimble's BD960 are currently capable of tracking the satellites from the Global Navigation Satellite System (GLONASS) constellation. GPS receiver technology will continue to improve, making use of the GLONASS constellation and the Galileo constellation. Additional signals with higher strength, improved noise immunity, and with international interoperability are expected from the GPS block III satellites, when these come online. Initial results of a combined GPS and GLONASS PPP solution are covered in the literature (Cai, 2007).

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Gail Smith is the supervisor of the Tides and Geodesy section at the Naval Oceanographic Office and has 22 years of experience in hydrographic surveying and data processing. She holds a BS degree from Mississippi State University.

Walter S. Simmons is lead hydrographer at SAIC since 1994. During this time he has conducted multibeam and side scan sonar surveys, tested hydrographic systems and software, and written documentation and procedures. Prior to joining SAIC Mr. Simmons held the Blucher Chair for Surveying Excellence at Texas A&M, Corpus Christi. As a officer in the NOAA Commisioned Corps Captian Simmons conducted hydrographic surveys in Alaska, Hawaii, the U.S. Great Lakes, and the Atlantic and Pacific Oceans. He also directed the shoreline mapping, photogrammetric bathymetry, airport obstruction charting, and marine charting programs for the United States. Mr. Simmons is an ACSM/THSOA Certified Hydrographer.

Billy Mehaffey is employed at the Naval Oceanographic Office, where he works primarily with GPS and water levels. He received a BSc degree from Northern Arizona University.

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