COMPARISON OF HORIZONTAL AND VERTICAL RESOLVABLE RESOLUTION BETWEEN REPETITIVE MULTI-BEAM SURVEYS USING DIFFERENT KINEMATIC GNSS METHODS

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Abstract

Ellipsoid referenced surveying is quickly becoming the standard in hydrographic surveying. Traditionally tidal measurements were used to reduce soundings down to the survey datum. With Kinematic Global Navigation Satellite System (GNSS) techniques currently providing sub-decimeter level precision, in-situ tide measurements are no longer required for vertical referencing. This places a heavy dependence on GNSS techniques to consistently provide accurate positioning in the horizontal and vertical with low uncertainty. Hydrographers need to know which GNSS technique yields the best solution and if that method works in all conditions. The development of Real Time Networks (RTN) allow for a triangulated Virtual Reference Station (VRS) to be established anywhere in the survey area, eliminating the need for a physical base station set up over a benchmark. This project compares the differences in accuracy and uncertainty between RTN based VRS corrections, Post Processed Kinematic (PPK), Precise Point Positioning (PPP), and Real Time Kinematic (RTK) solutions. Repetitive overlapping multi-beam surveys were completed at one survey location on different days to assess the repeatability of ellipsoid referenced surveying.

Résumé

Les levés rapportés à l'ellipsoïde deviennent rapidement la norme en matière de levés hydrographiques. Traditionnellement, les observations de marée étaient utilisées pour réduire les sondes au zéro hydrographique. Grâce aux techniques cinématiques basées sur le système mondial de navigation par satellites (GNSS) qui fournissent actuellement une précision subdécimétrique, les observations de marée in situ ne sont désormais plus nécessaires aux fins d'établissement de la référence verticale. Il en résulte une forte dépendance envers les techniques GNSS pour fournir une localisation horizontale et verticale cohérente dans la durée avec un faible degré d'incertitude. Les hydrographes doivent savoir quelle technique GNSS fournit les meilleurs résultats et si cette méthode fonctionne dans toutes les conditions. Le développement de réseaux en temps réel (RTN) permet de positionner une station de référence virtuelle (VRS) à n'importe quel endroit de la zone de levé, en supprimant la nécessité d'établir une station de base physique au-dessus d'un repère. Ce projet compare les différences d'exactitude et d'incertitude entre les corrections VRS basées sur les RTN, des solutions de post-traitement cinématique (PPK), de positionnement précis (PPP), et de cinématique en temps réel (RTK). Des levés multifaisceaux répétitifs avec recouvrements ont été effectués à une position donnée sur plusieurs jours afin d'évaluer la répétabilité de levés rapportés à l'ellipsoïde.

Resumen

Los levantamientos referenciados a elipsoides se están convirtiendo rápidamente en la norma de los levantamientos hidrográficos. Las mediciones tradicionales de las mareas fueron utilizadas para reducir las sondas al datum hidrográfico. Con las técnicas cinemáticas del Sistema Global de Navegación por Satélite (GNSS) que proporcionan actualmente un nivel de precisión de sub-decímetros, ya no se requieren las mediciones de mareas *in situ* para las referencias verticales. Esto impone una fuerte dependencia en las técnicas GNSS para proporcionar de forma coherente un posicionamiento preciso en los planos horizontal y vertical con un bajo nivel de incertidumbre. Los hidrógrafos necesitan saber qué técnica GNSS genera la mejor solución y si ese método funciona en todas las condiciones. El desarrollo de Redes en Tiempo Real (RTN) permite establecer en cualquier lugar de la zona del levantamiento una Estación de Referencia Virtual (VRS) triangulada, eliminando la necesidad de crear una estación de base física por encima de una marca de referencia. Este proyecto compara las diferencias de exactitud e incertidumbre entre correcciones de VRS basadas en RTNs, soluciones de Posprocesado Cinemático (PPK), de Posicionamiento Preciso (PPP) y de Cinemática en Tiempo Real (RTK). Se completaron levantamientos multihaz con solapamientos repetitivos en un lugar del levantamiento durante diferentes días para evaluar la repetitividad de los levantamientos referidos a elipsoides.

1. Introduction

Since the development of satellite based positioning, scientists have been striving to increase their derived positional accuracy. There are several error sources that make this difficult: satellite and receiver clock biases; satellite orbital errors; atmospheric delays; multipath signals; bad satellite geometry (GDOP); and measurement noise (Zinas, 2011). The largest uncertainty comes from satellite clock drift, because that causes large uncertainty in phase and code signals. For example, a clock error of 1 µs translates to 300 m in range error (Teunissen and Kleusberg, 1998). This error can be accounted for by double differencing the phase ambiguities between two receivers (kinematic positioning) and can be done in real time (RTK) and post-collection (PPK).

Orbital errors are monitored by international agencies such as the International GNSS Service. Estimates can be provided in real time, but the accuracy is only as good as 5 cm (IGS, 2006). According to Teunissen and Kleusberg's (1998) simple orbital equation:

$$\left|\frac{db}{b}\right| = \left|\frac{dr}{r}\right|$$

satellite orbit errors (*dr*) are negligible for kinematic techniques as long as the baseline (*b*) between the receiver and base station is small when compared to the high altitude of the satellites (*r*). The propagated error (*db*) will be negligible as long as the baseline is less than 20 km. Even for a 300 km baseline, the largest orbital error would be ~2 cm.

Atmospheric delays are always changing, depending on the state of the Ionosphere and Troposphere (changes in water vapor content and pollution) (Adegoke and Onasanya, 2008). With the introduction of L1 and L2 carrier phase signals, most of the ionospheric delays are eliminated in real time. The two uncertainties that cannot be eliminated with the double difference technique are multi-path and measurement noise. However, multi-path can be limited by choosing good locations surrounded by non-reflective surfaces and by using receivers designed to limit multi-path. Measurement noise is any noise caused by previously unaccounted for uncertainties and electrical noise from the receiver.

Another factor that affects positional accuracy is the satellite geometries relative to the receivers, called Dilution of Precisions, or DOPs. Geometry Dilution of Precisions (GDOPs) will change with time, as satellites move relative to the receiver's zenith position on earth, and can be broken down into more specific DOPs such a Horizontal and Vertical DOPs (HDOP and VDOP). As satellites move below the horizon, or some set elevation mask, slips in carrier phase cycle can occur and seriously increase positional uncertainty. The introduction of GNSS capable receivers, which allow more satellites such as GLONASS, Galileo, and Compass to be seen, is one way of limiting these errors. Another method to minimize GDOP error is to plan surveys at times when there is good satellite coverage in the area.

To determine how uncertainties in position from RTK, PPK, and RTN methods affect ellipsoid referenced multibeam survey repeatability, bathymetric surveys were conducted on three different days with different GDOP and atmospheric conditions. Soundings from an Edgetech 4600 with different GNSS positional sources were compared to determine the uncertainty and repeatability of a survey with different GNSS techniques. Precise Point Positioning (PPP) GPS solutions were also examined to see how a non-kinematic, non-GNSS post processing technique compares.

There are two types of kinematic solutions, Fixed and Float. Float RTK is an initial estimate of the ambiguity integers. In this status, the rover is essentially creating a grid around itself and going through every single integer possibility until one meets a certain statistical criteria and locks or "fixes" on that solution. A fixed integer solution brings the uncertainty to a centimeter level, which differs from the decimeter level uncertainty of a float status. A minimum of five satellites are needed to do this (Trimble, 2003). Six or more are needed to have the best fixed solution, especially when you have moving baselines.

2. Background

I. PPK and RTK

This project used two GNSS Topcon GR3 receivers to collect PPK and RTK data. The base station receiver was setup on a nearby coordinated benchmark and used a UHF radio link to broadcast RTK corrections to the roving receiver. Post-processing of the GNSS data was conducted with a forward and reverse iteration to achieve the best ambiguity fix possible. This method could be used for any GNSS receiver as long as there is a reference station within a relatively short baseline from the receiver (such as a Continuous Operating Reference Station (CORS)).

II. Network RTK (RTN or NRTK)

Network RTK solutions are able to resolve and predict errors for a large area using a network of reference stations, reducing errors significantly more than a single reference station approach (Zinas, 2011). This widens the range of baselines to 50 -70 km while still remaining within 1-sigma RTK accuracy at the cm level and achieving decimetre level accuracy up to 200 km (Rizos and Han, 2003). Carrier phase ambiguities must be resolved between each of the reference stations in the network and stay resolved at all times through two way communications between stations, usually over the internet. All data is broadcast to a central server that a user can log into and, through one-way or two-way communication, receive the corrections for a Virtual Reference Station (VRS). Zinas (2011) explains, “The receiver sends a NMEA string to the central server and Algorithms at this server generate carrier phase and pseudorange observables for the approximate position using either atmospheric models or regional derived corrections. The virtual observations are then sent back to the user and a single baseline is established with the VRS” (***Figure 1***). Baselines from the VRS can be up to 70 km, but it is preferred to update your VRS position if you are traveling farther than 20 km.

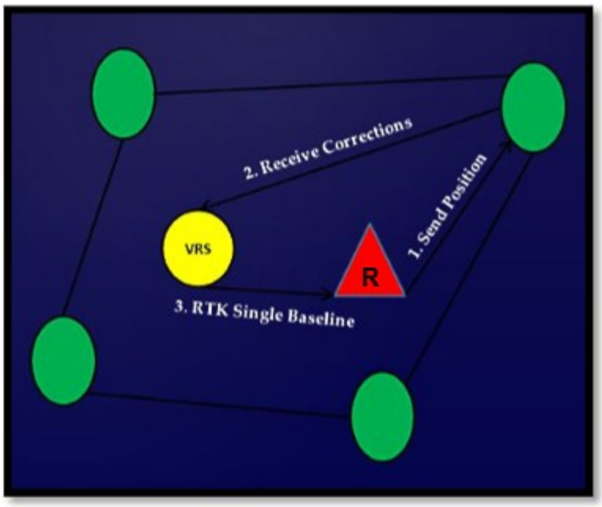

Figure 1. *A VRS (yellow circle) established inside a RTN network (green circles) with an established baseline to a roving receiver (R) (Zinas, 2011).*

3. Methods

I. Collection

Hydrographic surveys were conducted on three different days: November 26th 2014, January 27th 2015, and February 10th 2015. Survey areas were located in the Mississippi Sound in close proximity to Ship Island, shown in ***Figure 2***. These areas were selected because of the known targets they contain and their proximity to Ship Island, where the RTK base station was established on a recently surveyed benchmark (***Figure 3***). For quality control, a 4+ hour static observation was done on the benchmark and was post-processed using OPUS (OPUS-RS, 2014) to verify benchmark coordinates.

Two sites were chosen for data collection (***Figure 2***). Site 1 contained a shipwreck with a 1.45 km baseline to the RTK base station. Two surveys were conducted at Site 1 on 11/26 and 01/27. This site was abandoned for Site 2, which contained larger and more defined targets. Site 2, which consists of an artificial reef made up of concrete culverts and other large rubble, was surveyed once on 01/27 and twice on 02/10. It had a baseline of 5.8 km.

Figure 2. *Surveys sites off Ship Island, MS. Located in the Mississippi Sound southeast of Gulfport Har-*

An EdgeTech 4600 bathymetric sonar was used for bathymetry collection, with an Applanix POS MV for real-time navigation and attitude data. The POS MV was supplemented by the GNSS RTN source. RTK and PPK data were collected with two GNSS enabled Topcon GR3's with UHF radio modems for RTK radio link connections. Data from a Trimble NetRS GPS receiver was also used for a PPP solution.

Figure 3. *From left to right. GNSS Topcon GR3 with radio link antenna over benchmark on Ship Island. Covered benchmark on Ship Island.*

Gulf Coast Geospatial Center (GCGC) RTN Network (Mississippi's networked reference stations) corrections were obtained through a cellular AT&T hotspot connection with open source software used to transport RTCM data over the internet (NTRIP) (Lefebure, 2015). HYPACK was used for navigation and line planning. EdgeTech data was collected in Discover, EdgeTech's proprietary collection software. The LeMoyne, the University of Southern Mississippi's 29 ft. survey vessel, was the data collection platform.

II. Processing

CARIS HIPS and SIPS 9.0.6 were used for bathymetric and navigation processing. Sound velocity and delayed heave were applied to the data, which was cleaned by the same technician for consistency. A GPS Tide was computed using the GNSS heights (GPS heights for PPP) and applied to reduce the soundings to the WGS84 ellipsoid. The data was then gridded to a 0.5 m surface. This process was done for each navigation source.

Finally, surfaces from two different GNSS kinematic techniques were differenced and compared statistically. MATLAB was used to compare vertical and horizontal differences from RTK, RTN, PPK, and PPP data for each survey. Waypoint's GravNav was used for PPK processing, plots, and statistics from PPK data.

4. Results/Discussion

I. GNSS

Three survey days were conducted to show the effects of varying GDOPs and how they might affect the data. ***Table 1*** shows how DOP's (Horizontal DOP (HDOP), Vertical DOP (VDOP), and Positional DOP (PDOP)) vary, throughout and between each survey day. Low DOP values (usually less than 2) are considered optimum (Langley, 2009). The effect of changing DOP values can be seen in a comparison between DOP's and the number of satellites tracked in Figure 4. An inverse relationship is observed between a drop in the number of satellites being tracked and the DOP increase. Linear regression analyses were run on all vertical GNSS/GPS data for each survey day and sigma values were computed, as well as best-fit residuals (***Table 2***). These statistics were used as the main determination on which solution had the least uncertainty. The PPK solution had the lowest average sigma value and goodness of fit value over all three days and was used as the navigation source for the control base surface for data comparison. Based on DOP values, February 10th was determined to be the day with least uncertainty in positional data and was used for comparisons of other GNSS data.

Table 1. *DOPs (PDOP, HDOP, and VDOP) statistics for each survey day at a 1 sigma level.*

Variation of DOPs from each Survey Day			
	November 26, 2014 (Site 1)	**January 27, 2015 (Site 2)**	**February 10, 2015 (Site 2)**
PDOP	RMS: 2.093 m Avg: 2.023 m Max: 3.820 m Min: 1.540 m	RMS: 2.238 m Avg: 2.103 m Max: 7.780 m Min: 1.450 m	RMS: 1.613 m Avg: 1.552 m Max: 2.130 m Min: 0.890 m
HDOP	RMS: 0.952 m Avg: 0.903 m Max: 1.920 Min: 0.650	RMS: 1.052 m Avg: 1.032 m Max: 2.990 Min: 0.710	RMS: 0.926 m Avg: 0.911 m Max: 1.170 Min: 0.660
VDOP	RMS: 1.864 Avg: 1.801 Max: 3.310 Min: 1.370	RMS: 1.970 Avg: 1.816 Max: 7.180 Min: 1.220	RMS: 1.320 Avg: 1.235 Max: 1.810 Min: 0.590

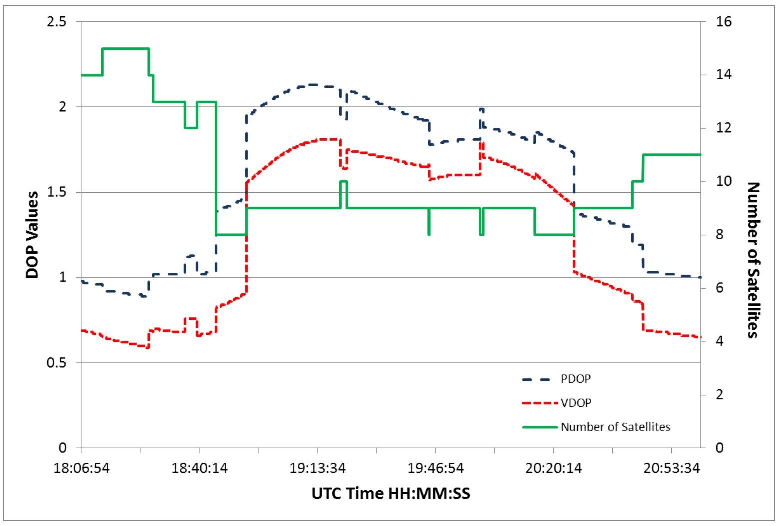

Figure 4. *Comparisons of PDOP, VDOP, and Number of Satellites tracked for PPK data on the 10th of February 2015.*

Table 2. Statistics from each survey day for each GNSS solution. Goodness of fit was determined from a linear fit to the data with the following equation: y = p1*z + p2 *z, where: z =(x-mu)/sigma (centered and scaled for calculations and to remove large outliers); p1=slope; p2= y-intercept.

Statistics of each Position Method for each Survey Day			
	November 26, 2014 (Site 1)	**January 27, 2015 (Site 2)**	**February 10, 2015 (Site2)**
PPK	sigma = 0.023 goodness of fit = 2.405	sigma = 0.037 goodness of fit = 11.235	sigma = 0.035 goodness of fit = 6.273
RTK	sigma = 0.026 goodness of fit = 2.205	sigma = 0.034 goodness of fit = 35.031	sigma = 0.035 goodness of fit = 15.892
RTN	sigma = 0.024 goodness of fit = 62.985	sigma = 0.037 goodness of fit = 223.070	sigma = 0.040 goodness of fit = 91.389
PPP	sigma = 0.023 goodness of fit = 3.317	sigma = 0.037 goodness of fit = 31.106	sigma = 0.035 goodness of fit = 6.502

Figures 5-7 show vertical positions from each GNSS source for each survey day. The RTN solution has large lapses in time and ellipsoid height, either from cycle slips or cellular internet drop-outs. It is also possible that these lapses occur because we are surveying outside of the RTN network. There are only three reference stations near the survey sites and none on the south side of the survey (***Figure 8***). The closest reference station is near Gulfport, MS, located 18 and 15 km away from the first and second survey areas, respectively. The other reference stations are 30-36 km away. This is well within the acceptable ranges for network RTK baselines for sub-decimeter accuracy. However, surveying outside the reference station network grid potentially causes triangulation issues in the algorithm and interpolation of the VRS (Wei et al., 2006). This could result in larger positional uncertainty. Horizontal ambiguities need only three reference stations in the area to be resolved, while vertical ambiguities may need up to five, which may result in large vertical uncertainty (Wei et al., 2006). Instances can be seen where the RTK loses its fixed ambiguities or misses a cycle, causing signal drop outs that result in short temporal vertical uncertainty lapses. Post processing RTK data to obtain a PPK solution eliminated these errors and others that were previously unaccounted for.

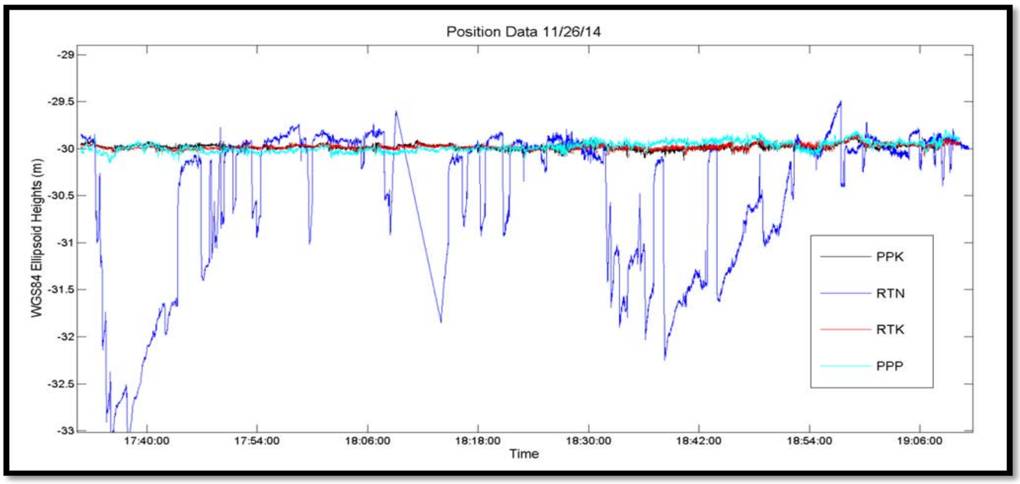

Figure 5. *GNSS survey Time verse Ellipsoid heights for 11/26/14 at Site 1. Dark Blue: RTN, Cyan: PPP, Black: PPK, Red: RTK.*

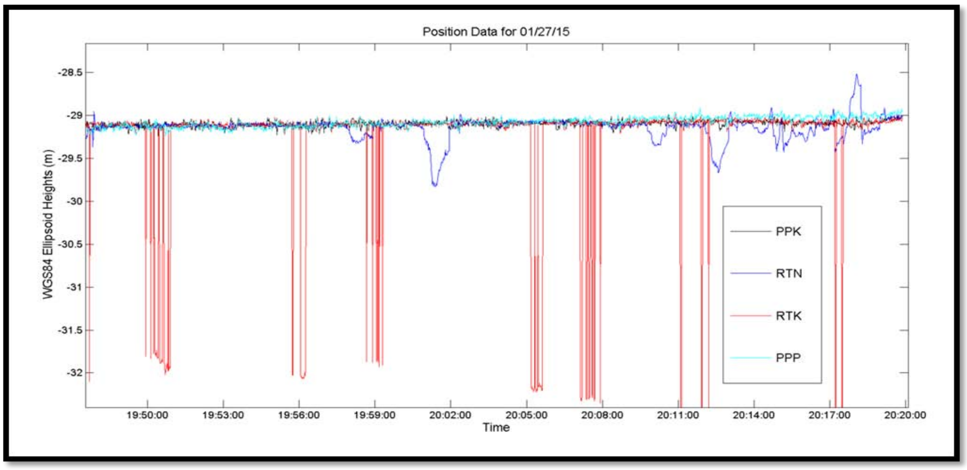

Figure 6. *GNSS survey Time verse Ellipsoid heights for 01/27/15 at Site 2. Dark Blue: RTN, Cyan: PPP, Black: PPK, Red: RTK.*

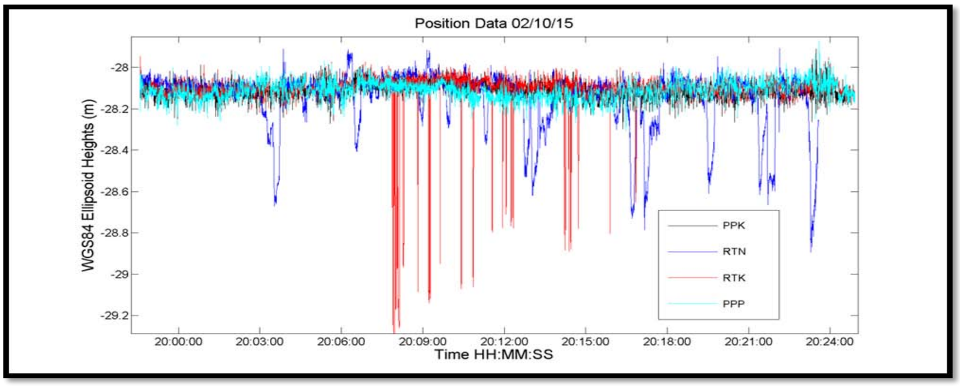

Figure 7. *GNSS survey Time verse Ellipsoid heights for 02/10/15 at Site 2. Dark Blue: RTN, Cyan: PPP, Black: PPK, Red: RTK.*

Figure 8. *Locations of the reference stations in the GCGC RTN network. The red rectangle is Site 1 and the blue rectangle is Site 2.*

II. Bathymetry

Bathymetric data was processed with data from each GNSS method and gridded to a 0.5 m surface. These were then differenced against the PPK 0.5m surface (Figure 9). Difference surfaces show minimum propagated GNSS uncertainty between methods on a flat sea bed, but a range of differences can be seen around targets on the sea floor. This might be attributed to the EdgeTech 4600's bottom detection algorithm picking different target points.

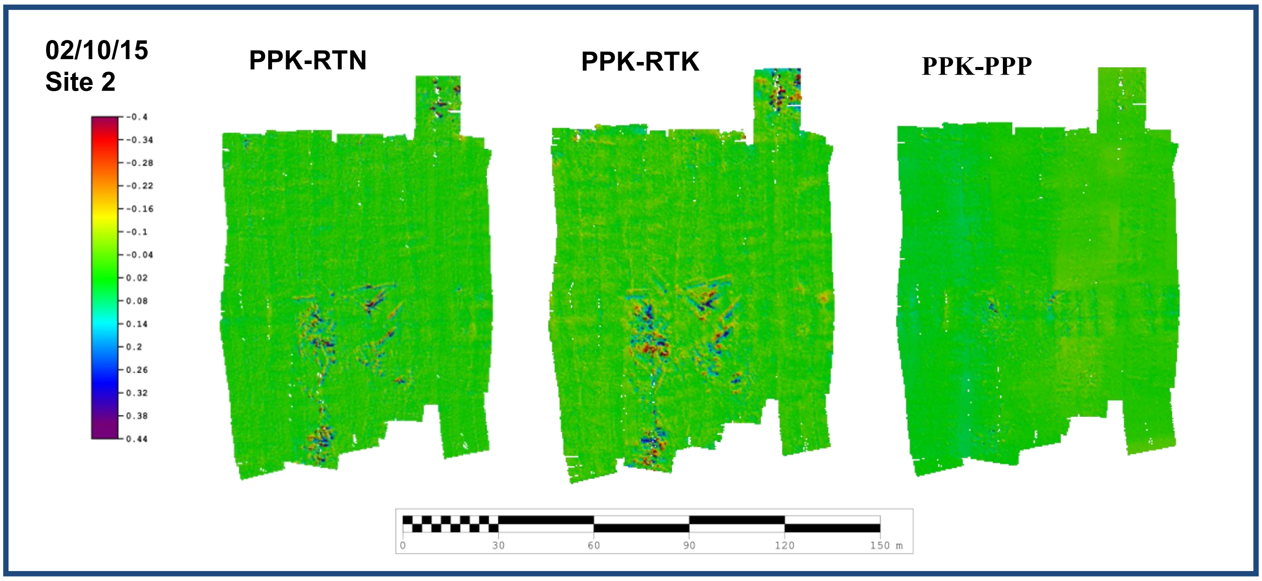

Figure 9. *Bathymetric difference surfaces generated to show the difference in positions between each GNSS method and PPK for survey day 02/10/2015 at Site 2.*

Large uncertainties in GNSS data from February 10th do not propagate enough to significantly affect bathymetric measurements. Table 3 shows the significant depth differences calculated from the difference surfaces. To determine the significance of the difference surfaces, the International Hydrographic Organization (IHO) S-44 specifications (IHO, 2008) were used. For Site 2, having an average depth of 5 meters, the maximum allowable THU is 2 meters for a Special Order Survey and 5.25 meters for an Order 1A survey. The maximum allowable TVU for this site was 0.253 meter for Special Order and 0.504 meter for Order 1A (Table 4). Survey data from February 10th had minimal uncertainty and met all IHO specifications for TVU and THU.

Table 3. Statistics of Difference surfaces taken from CARIS for 02/10/2015 (black) and 01/27/2015 (blue) at Site 2.

2/10/2015	**PPK vs RTN**	**PPK vs RTK**	**PPK vs PPP**
Average Difference	0.016 m	0.006 m	0.014 m
2 x Sigma (95% CI)	0.094 m	0.112 m	0.064 m
RMS	0.050 m	0.056 m	0.035 m
1/27/2015	**PPK vs RTN**	**PPK vs RTK**	**PPK vs PPP**
Average Difference	0.065 m	0.053 m	-0.006 m
2 x Sigma (95% CI)	0.254 m	1.150 m	0.116 m
RMS	0.143 m	0.578 m	0.059 m

Differences for Jan 27th show large uncertainties in vertical position due to GNSS propagated uncertainty. IHO Special Order TVU accuracies are not met for RTN or RTK positions. This is attributed to the high DOP's on this day. PDOP's and VDOP's spiked to over 4.5 multiple times during the survey as satellites traveled below the set 7 degree elevation mask. Post processing (PPK and PPP) techniques were able to account for the lost ambiguities fixes to meet Special Order requirements.

To test the repeatability of these surveys, 0.5m gridded difference surfaces were made for the second survey site comparing the same GNSS methods from Jan 27th and Feb 10th (Figure 10). Due to previously discussed uncertainties in RTN and RTK data (mainly on the 01/27/15), large differences can be seen when comparing the two survey days. Neither of these methods met IHO Special Order requirements for all soundings on Jan 27th, making them unreliable methods for survey repeatability. The RTK surface has some areas which also didn't meet IHO Order 1A. However, post processing fixed ambiguities allowing PPK and PPP solutions to meet Special Order criteria for 95% of the Jan 27th survey (Figure 11).

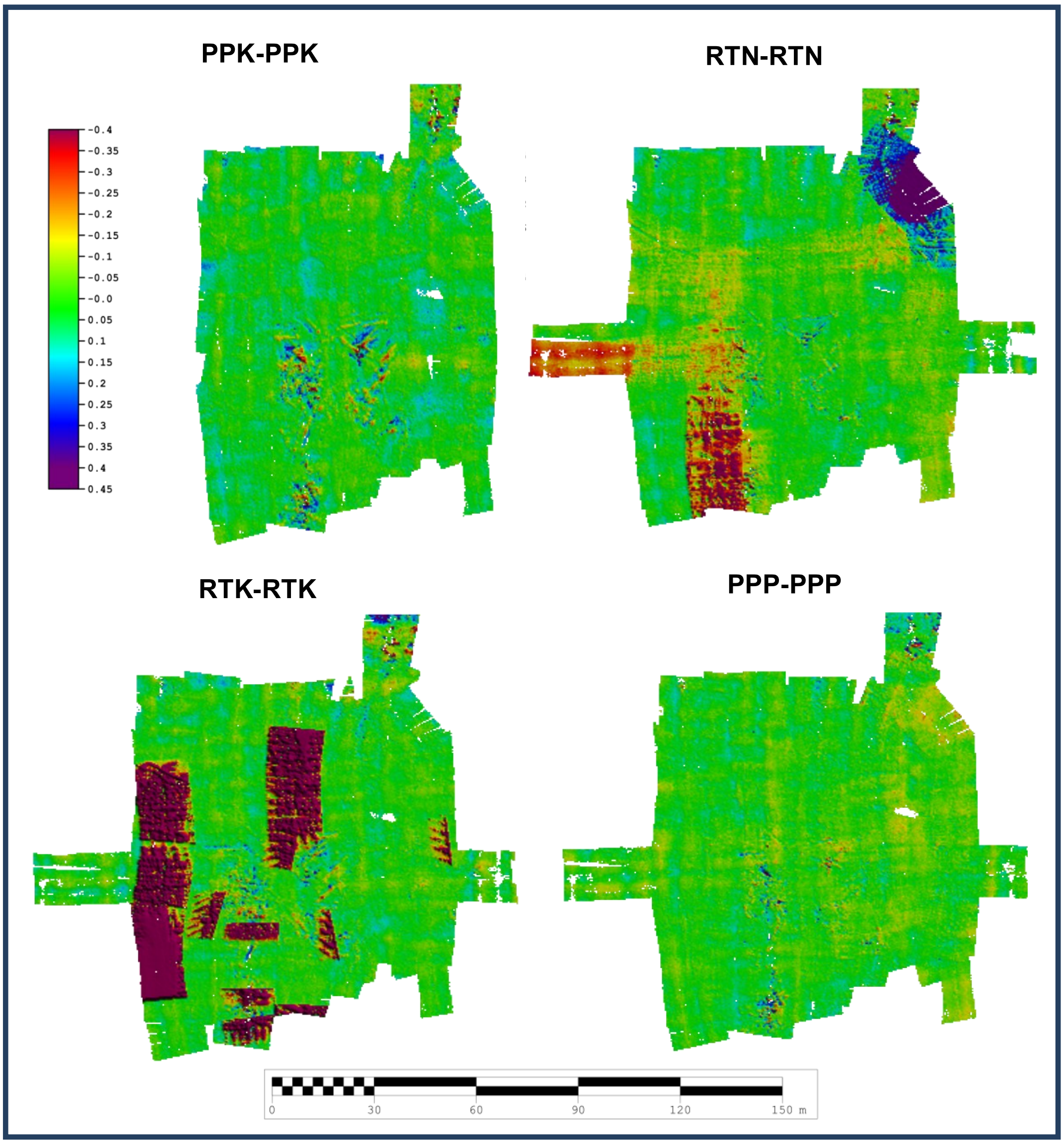

Figure 10. *Difference surfaces of the same GNSS technique for two different days (01/27/15 and 02/10/15) at Site 2.*

Table 4. IHO Standards for Hydrographic Survey (S- 44) (van Norden, et al, 1998). The 95% Confidence Levels are calculated by: $\pm\sqrt{a^2} + (b\ x\ d)^2$ where a and b are given for each order and d is depth (see IHO S-44 for further information).

Order	**Special**	**1A**	**1B**	**2**
Description of areas.	Areas where under-keel clearance is critical	Areas shallower than 100 meters where under-keel clearance is less critical but features of concern to surface shipping may exist.	Areas shallower than 100 meters where under-keel clearance is not considered to be an issue for the type of surface shipping expected to transit the area	Areas generally deeper than 100 meters where a general description of the sea floor is considered adequate.
Maximum allowable THU 95% Confidence level	2 meters	5 meters + 5% of depth	5 meters + 5% of depth	20 meters + 10% of depth
Maximum allowable TVU 95% Confidence level	a = 0.25 m b = 0.0075 m	a = 0.5 m b = 0.013 m	a = 0.5 m b = 0.013 m	a = 1.0 m b = 0.023 m
Maximum allowable TVU for Site 2	**0.253 m**	**0.504 m**	**0.504 m**	**0.513 m**

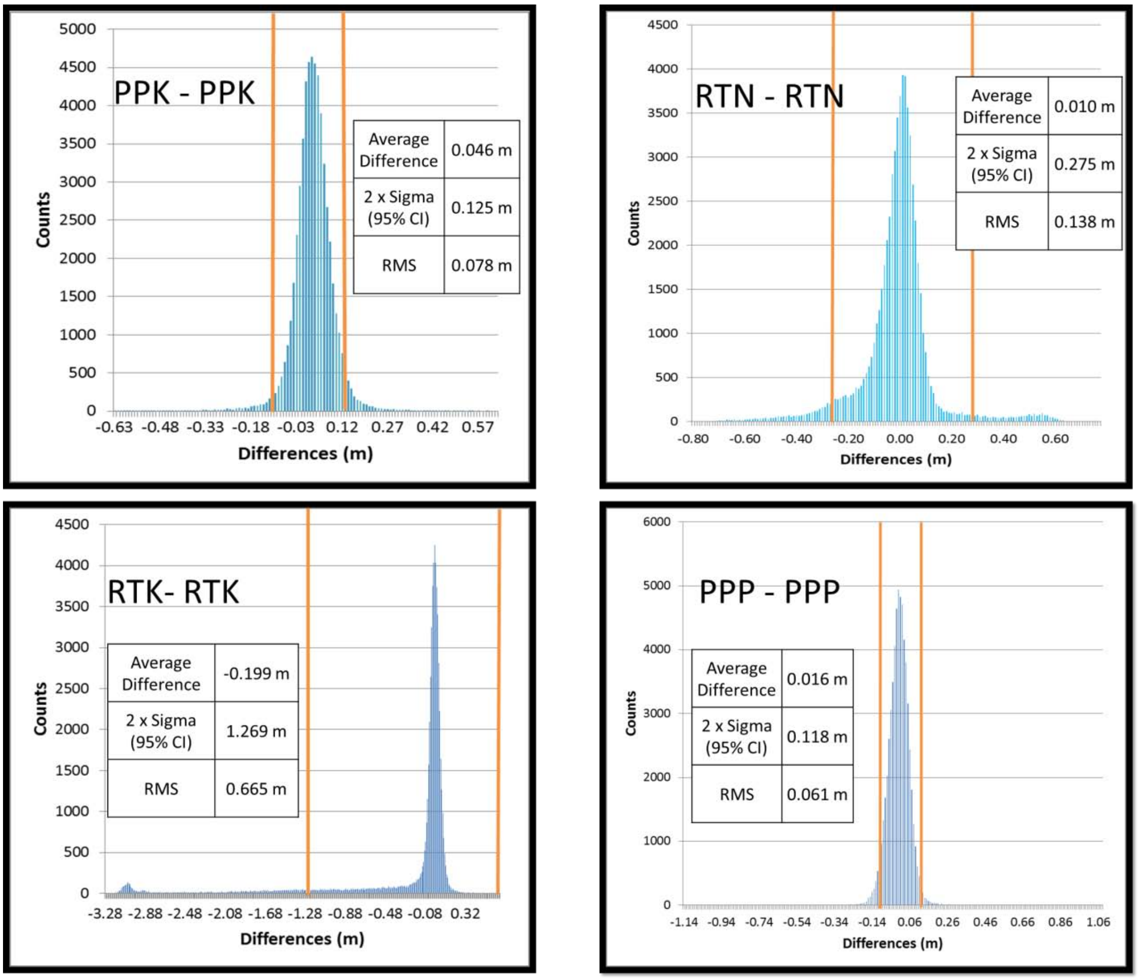

Figure 11. *Statistics from Difference surfaces of the same GNSS technique for two different days (01/27/15 and 02/10/15) at Site 2.*

Conclusion:

Hydrographic surveying is quickly adopting the technique of surveying to the ellipsoid to remove the need for accurate tidal benchmarks in the survey area. This places a heavy dependence on GNSS accuracies. Do current GNSS techniques provide solutions that make this possible and reliable in all conditions? Of the GNSS methods tested in this study, the two post-processed methods (PPK and PPP) are the only reliable methods when faced with varying DOP's, increasing baselines, and internet outages (for RTN) for the Mississippi Sound area. RTK performed well for days where DOP's were good and having greater than 8 satellites for the majority of the survey. However, it could not keep from losing ambiguity fixes due to a change in DOP with baselines larger than 3 km. RTN uncertainty propagation was better than expected. Being outside of the GCGC RTN network geometry was predicted to be a larger source of uncertainty, but it is believed that internet service through the AT&T hotspot was the main reason for high uncertainty in the RTN solution. However, this theory has not been tested and would require further study.

Ellipsoid referenced surveys in this area are recommended to use post-processed data. This ensures repeatable surveys with low uncertainties. For the Mississippi area, real time kinematic GNSS methods are not efficient enough to provide high accuracy repeatable swath bathymetric surveys with baselines larger than 3 km. This could also be the case in other coastal areas similar to the Gulf Coast. To achieve real time kinematic efficiency, networked RTK reference stations and additional cell towers should be set up on barrier island systems. This would ensure good internet coverage as well as good signal geometry for RTN corrections. These factors would allow hydrographers to reliably achieve GNSS sub-decimeter uncertainty in real time anywhere in the Sound, eliminating the need for post-processing.

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