Article

ELLIPSOIDALLY REFERENCED SURVEYS : ISSUES AND SOLUTIONS.

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Abstract

One of the most significant issues in hydrography today is the use of the ellipsoid as a vertical reference for surveying measurements. High-accuracy GPS is used to vertically position hydrographic data collection platforms, relating bathymetric observations directly to the ellipsoid. Models are used to translate those observations to another datum. The use of high-accuracy vertical GPS and translation models to replace traditional tidal correctors is relatively new to the hydrographic community and, as such, requires some discussion. Even though individual components of the process are well understood in their particular field, it is their amalgamation and application to hydrography that requires explanation, clarification and evaluation.

Many hydrographic organizations around the world are using Global Navigation Satellite Systems (GNSS) derived heights in their data collection and processing stream. The International Federation of Surveyors (FIG) has recognized the importance of these new developments and has established a new working group under Commission 4, tasked to developing best practices for Ellipsoidally Referenced Surveys (ERS). Over twenty groups from academia, industry and government who are engaged in some form of ERS have provided the working group with a summary of their practices and experiences. This paper outlines the issues related to ERS and summarizes the solutions being employed.

Résumé

Une des questions les plus importantes en hydrographie aujourd'hui est l'utilisation de l'ellipsoïde comme référence verticale pour le mesurage des levés. Le GPS à haute précision est utilisé pour positionner verticalement les plates formes de collecte des données hydrographiques, rapportant les observations bathymétriques directement à l'ellipsoïde. Les modèles sont utilisés pour convertir ces observations dans un autre système. L'utilisation du GPS vertical à haute précision et des modèles de conversion pour remplacer les correcteurs de marée traditionnels est relativement nouvelle pour la communauté hydrographique et, en tant que telle, nécessite une certaine discussion. Même si les composantes individuelles du processus sont bien comprises dans leur domaine spécifique, c'est leur fusion et leur application à l'hydrographie qui nécessite des explications, des éclaircissements et une évaluation.

De nombreux organismes hydrographiques dans le monde utilisent les hauteurs dérivées des systèmes globaux de navigation par satellite (GNSS) dans leur collecte et flux de traitement des données. La Fédération internationale des géomètres (FIG) a reconnu l'importance de ces nouveaux développements et a établi un nouveau groupe de travail dans le cadre de la Commission 4, chargé de développer de meilleures pratiques pour l'ERS (Ellipsoidally Referenced Survey). Plus de vingt groupes du milieu universitaire, de l'industrie et du gouvernement engagés dans une quelconque forme d'ERS ont fourni au groupe de travail un résumé de leurs pratiques et expériences. Cet article passe en revue les questions liées à l'ERS et résume les solutions mises en oeuvre.

Resumen

Uno de los temas más significativos en la hidrografía actual es el uso del elipsoide como referencia vertical para las medidas hidrográficas. El GPS de alta precisión se utiliza para posicionar verticalmente las plataformas para la recogida de datos hidrográficos, relacionando las observaciones batimétricas directamente al elipsoide. Se utilizan modelos para traducir esas observaciones a otro plano de referencia. El uso de un GPS vertical de alta precisión y de modelos de traducción para sustituir a los correctores de mareas tradicionales es relativamente nuevo para la comunidad hidrográfica y, como tal, requiere una cierta discusión. Aunque se entienden bien las componentes individuales del proceso en su campo particular, lo que requiere una explicación, una aclaración y una evaluación es su amalgama y su aplicación a la hidrografía.

Muchas organizaciones hidrográficas del mundo entero están utilizando en la recogida y el flujo de tratamiento de sus datos las alturas derivadas mediante los Sistemas Mundiales de Navegación por Satélite (GNSS). La Federación Internacional de Geodestas (FIG) ha reconocido la importancia de estos nuevos desarrollos y ha creado un nuevo grupo de trabajo en la Comisión 4, a la que se ha atribuido la tarea de desarrollar las mejores prácticas para los Levantamientos Referenciados Elipsoidalmente (ERS). Más de veinte grupos de la enseñanza, la industria y el gobierno, que están implicados en alguna forma de ERS, han proporcionado al grupo de trabajo un resumen de sus prácticas y experiencias. Este artículo destaca los temas relativos a los ERS y resume las soluciones que se están empleando.

1. Introduction

Many of the groups using ellipsoidally references surveying (ERS) techniques have developed their internal standard operating procedures (SOP) through in-house testing and experience (trial and error). It is this wealth of experience that is being drawn upon to help develop a set of "best practices" for the hydrographic industry. The development of ERS best practices is being conducted by an FIG working group under Commission 4.

Information was gathered for this project in two stages. The first stage, beginning in the summer of 2009 prior to the formation of the ERS working group, was sponsored by CARIS™. Their interest was in the development of tools and procedures to assist the CARIS HIPS™ user community in the editing, evaluation and application of ERS related information. In this initial stage, requests for information on ERS practices were sent to contacts of the author. Several groups, having experience in ERS practices since the early 2000's, provided extensive details of their procedures. The results of this information gathering stage was compiled in an unpublished discussion paper outlining the issues surrounding ERS in hydrography and detailing the procedures used by respondents (Dodd, 2009). A summary of the issues described in that discussion paper was presented at the 2010 FIG conference in Sydney Australia (Dodd, et al, 2010). A list of contributors can be found in the Stage 1 section of **Contributor References** at the end of this document.

The second stage of information gathering, beginning in the summer of 2010, was initiated under the auspices of the FIG Commission 4 ERS working group. Information was requested from a much wider audience through a questionnaire. The findings summarized in this paper were compiled from the results of both stages of information gathering. A list of contributors can be found in the Stage 2 section of **Contributor References** at the end of this document.

2. Background

The issues associated with ERS are summarized in the FIG proceedings paper Dodd et al (2010). A brief overview of these issues will be presented here along with a new section discussing airborne Lidar bathymetric (ALB) applications. Airborne and ship borne ERS have many issues in common, but also have several distinctions. Both require high accuracy GPS and translation of the antenna position to the vehicle reference point; however, the processing and data collection procedures differ somewhat. The primary difference is the establishment of the sea surface. In ship borne operations, the vessel itself measures the sea surface location, whereas with Lidar, the laser measures the location of the sea surface. The vessel measures a smoothed sea surface (with swell but no waves), whilst the lidar measures the instantaneous sea surface, including waves and swell. In both cases, a mean sea surface must be determined in order to apply observed tides, unless ERS techniques are being used.

2.1 GPS Terminology

For the purpose of this discussion, the following GPS terminology will be used:

- RTK: Real-Time Kinematic (fixed or float solution)
- PPK: Post-Processed Kinematic (fixed or float solution)
- RTG: Real-Time Gypsy, real-time precise point positioning
- PPP: Post-processed Precise Point Positioning.

2.2 Ship Borne Derived Ellipsoid Depth

Vertical surveying with respect to the ellipsoid in the marine environment includes:

1. GPS positioning of the receiving antenna
2. Translation of that height to the vessel reference
3. Relating of the GPS derived vessel reference height to the smoothed water surface (GPS Tide) or directly to the seafloor
4. Transformation of the seafloor height to a geodetic or tidal datum
5. Storage and manipulation of information, with respect to a common datum, for merging with other data (land or sea), analysis and creation of products.
6. Propagation of uncertainties through the entire process.

2.2.1 *Vertical Components*

The following list describes the terminology associated with the vertical components of hydrographic surveying with respect to the ellipsoid (see Figure 1).

1. Observed GPS height is the distance from the Ellipsoid to receiving antenna phase centre
2. DZ (antenna) is the vertical offset between the antenna phase centre and the vessel reference point (RP).
3. DZ (transducer) is the vertical offset between the RP and transducer.
4. Observed depth is from transducer to bottom.
5. Dynamic draft (DD), or settlement and squat, is the change in the vessel's vertical position in the water due to speed through the water (water surface to RP).
6. Heave is the short term vertical movement of the vessel with the water surface (WS), about a mean water level (MWL), measured at the RP.
7. Removal of heave, settlement and squat produces a water level (WL), which includes the tidal component.

8. Removal of the tidal component from the WL produces the Chart Datum.
9. Ellipsoid to Chart Datum is the separation model (SEP)

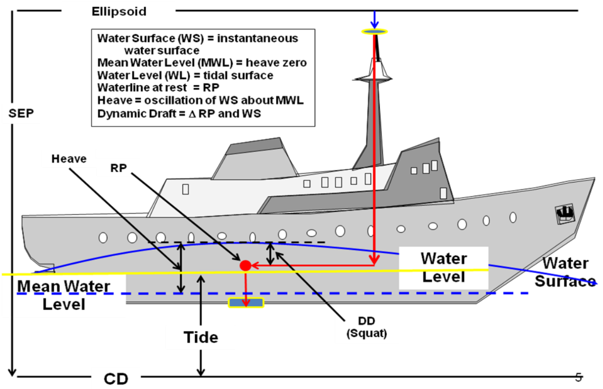

Figure 1: Vertical Components [Dodd et. al (2010)]

2.2.2 *Heave*

For ship borne applications the use of observed heave in combination with GPS heights can be confusing. There are essentially two methods of dealing with heave: One is to apply observed heave to depths and then remove the observed heave from the GPS height observations. The other is a direct observation from the ellipsoid to the seabed, ignoring heave altogether.

In many cases heave is applied to depths in real-time, and must then be removed from the GPS height observations. In this case the heave corrected GPS heights can be used as pseudo-tide observations, and can be smoothed to remove noise from the vertical GPS position. The term pseudo-tide is used here because the smoothed water level will still include dynamic draft and other variations in the vertical offset (including heave artifacts). It should be noted that this method removes longer term heave artifacts while retaining the advantage of higher frequency heave for interpolation between GPS epochs. In order to view corrected data during acquisition, the application of heave is necessary; however, when using ERS, the heave component is no longer as essential (and problematic) a component as it once was.

In theory, heave is not necessary because vertical antenna movement is the same as the vertical transducer movement. A single observation of the antenna location combined with a depth observation at the same epoch (adding the pitch and roll corrected antenna/transducer offset) will produce a depth from the ellipsoid to the sea bed.

However, GPS and depth observations are rarely collected at the same rate, with GPS usually collected at a much lower rate and interpolation is required. Also, the GPS rate is usually not high enough to capture the entire heave signal (although that is changing). Inertial-aided GPS positioning (e.g. from PosPac^{TM}), which interpolates a position of the IMU reference for every motion epoch, provides a smoothed height with high enough resolution to allow for direct combination with the depths. In this case the heave observation is not necessary

Although heave and dynamic draft observations may not be necessary to determine a final depth value, they may be necessary to determine the location of the transducer within the water column for precise ray tracing calculations and to retrieve the actual water surface. One significant advantage of retrieving the water surface is that it allows for a comparison with traditional tidal techniques. The ellipsoid to water surface observations also provide validation for hydrodynamic models.

2.3 Airborne Lidar Derived Ellipsoid Depths

Surveying with respect to the ellipsoid is particularly advantageous in Airborne Lidar Bathymetry (ALB) (Guenther, 2001). Traditionally, depths are determined by differencing the water surface return from the sea bottom return and applying tide gauge observations to establish depths relative to the sounding or chart datum. The main difficulty in this process, other than the usual propagation of tidal datum to the survey site, is the establishment of the water surface. Algorithms must be used to determine and remove the wave height, as well as the longer period swell. A mean water surface must be established using surface returns from a period of time greater than a few wavelengths of the swell period. Vertical movement of the aircraft (heave) during this period must also be accounted for. When using GPS heights of the aircraft to reference the sea bottom surface, it is not necessary to establish the mean water surface for tidal reduction, and knowledge of the aircraft heave is no longer needed. Surveying to the ellipsoid has the added advantage of establishing bathymetric and topographic returns to the same reference when both are observed in a survey swath. (Guenther et al, 2000)

2.4 Ellipsoid to Chart Datum

The transformation of depths from the ellipsoid to chart datum is the most problematic part of the ERS process. Finding models for ellipsoid to geoid height difference is relatively straight forward. The main problem comes when translating from the geoid through to chart datum. The most straight forward method is to establish an ellipsoid height at a tidal benchmark. This will establish a directly observed separation (SEP) between chart datum and the ellipsoid. For small survey areas, this single value may suffice, as long as the geoid/ellipsoid (N) separation in the area does not change. If it does, then the SEP observation at one location can be used to anchor the local variations in N. This can be done by applying a single chart datum to geoid shift to a grid of N values. Essentially, what is needed is a method to determine the chart datum to geoid separation, then attaching that to the local N model. If several tide gauge locations are used, the chart datum to geoid values can be interpolated between stations and then attached to the N model.

As the area in question gets larger, and/or ocean dynamics become more complex, the chart datum to geoid models also become more complex. Separation models include chart datum to mean sea level, mean sea level to the geoid (sea surface topography) and geoid to ellipsoid (N). The United Kingdom Hydrographic Office (UKHO) has developed VORF (Vertical Offshore Reference Frame) separation models for their coastal waters (see Adams, 2006). The National Oceans and Atmospheric Administration (NOAA) had developed VDatum for much of the USA coastal waters (see Gesch and Wilson, 2001).

Of particular importance to the hydrographic community is total propagated uncertainty (TPU). TPU models have been developed for all aspect of the ERS process except for the SEP translation process. A discussion of TPU and VDatum can be found at the website: http://vdatum.noaa.gov/docs/est_uncertainties.html

3. Questionaire

The following is a list of questions sent to various organizations. The responses to these questions are summarized in the next section.

1) What vertical positioning methods are used?
   a. Real-time or Post Processed
   b. PPP, PPK, RTG, RTK
   c. Are GPS heights smoothed to extract the tidal signal or used directly?
   d. Are heave and/or dynamic draft and/or waterline O/S applied to the GPS heights?
2) How do you determine the vertical offset between the GPS phase center and depth reference point? Are any calibration/validation procedures used?
3) Do you have any vertical position QC procedures?
4) How do you estimate and apply vertical positioning uncertainty?
5) Do you use observed water levels (traditional tides during data collection?
6) How do you deal with the Ellipsoid to Chart datum separation (SEP)?
   a. Single value
   b. Separation surface; if so, do you include:
      i. Hydrodynamic modeling
      ii. Sea Surface Topography
      iii. Water Level Stations
      iv. Geoid Modeling
      v. Direct GPS/Water Level observations at shore stations
      vi. GPS buoy observations
7) How do you validate your SEP and deal with uncertainty associated with it?
8) What processing methods do you use and in what sequence do you perform the various operations (e.g. where do you translate from the ellipsoid to chart datum)?
9) Data archive (format, vertical datum, as soundings or as surfaces…)

3.1 Vertical Positioning Method

Most of the respondents are using a combination of post-processed kinematic (PPK) and real-time kinematic (RTK). Several groups are experimenting with precise point positioning (PPP) in post-processing. Very few are using real-time PPP (RTG).

Most groups indicated that they observe heave and process to establish a mean waterline similar to a tidal surface. Many use an inertial-aided solution (from PosPac™) to generate high frequency positions of the vessel RP. Some also include dynamic draft to get a mean water surface, which will allow for a direct comparison with tide gauge observations. Others apply heave, but not dynamic draft, in which case the mean water surface will include dynamic draft. NOAA applies static draft, dynamic draft and heave to determine the location of the transducer in the water column for ray tracing. These observation are subsequently removed from the GPS height observations (Riley, 2010)

<u>Recommendations</u>

1. Use RTK and/or PPK as the primary positioning method
2. Use PPP as a back-up and as primary if necessary
3. Until RTG reaches lower uncertainty, it should be used for real-time data collection, but replaced by PPP in post-processing.
4. Always record and archive raw GPS and motion observations
5. If using a base station, adhere to strict installation and data recording protocols, especially when recording antenna heights.
6. Continue to record real-time heave for data validation, even if it is not used in the final solution.

3.2 Vertical Offsets and Validation

All respondents determined the antenna to vessel reference point (RP) either through total station observations or tape measure. Most perform some form of offset check at a tide gauge location where GPS heights, translated to the waterline (with the vessel at rest), are compared to the tide gauge observations. This evaluates offsets as well as the separation model, at that location. No specific time durations were quoted. Some respondents use the above methods, as well as surveying over a well established section of seafloor, such as the concrete lock in a waterway (Bartlett, 2010).

Establishment of the antenna phase center with respect to the antenna reference point can be problematic. Some use manufacturer's values while others use US National Geodetic Survey (NGS) published values, either absolute or relative. Although the phase center is usually referenced to a single point (mean phase center), there is a variation in that mean that is relative to the elevation (and to a lesser extent azimuth) angle of the incoming signal.

The relative calibration refers to the phase center as determined with another "base" antenna. The absolute phase center refers to the phase center without a reference antenna. NGS relative and absolute phase center values can be obtained from "http://www.ngs.noaa.gov/ANTCAL/". (Bilich and Mader, 2010)

Recommendations

1. Perform side-by-side validation at an established tide gauge at the beginning and end of each project. Comparisons should take place over an entire tide cycle, or at a minimum three hours.
2. Use the NGS average values from the absolute calibration sheets for antenna phase center offset values.

3.3 Vertical Positioning Quality Control

Vertical position quality control refers to the methods used to determine the confidence in the vertical GPS solution. Most respondents use traditional validation methods such as cross-check lines and comparison to other surveys. Some determine GPS tides and compare them to observed tides from nearby tide gauge observations. Heave is also used to validate GPS movement. The statistics and solution types (float or fixed) from GPS processing software are also used. In ***Figure 2***, a problem with the GPS solution is indicated by the solution and vertical uncertainty, whereas the heave value remains consistent. Viewing a standard deviation surface will also show areas where GPS "outages" occur (see ***Figure 3***). Some respondents also compare results determined using PPK to those determined using PPP. This method helps to validate base station coordinates, antenna height and vertical ellipsoid reference.

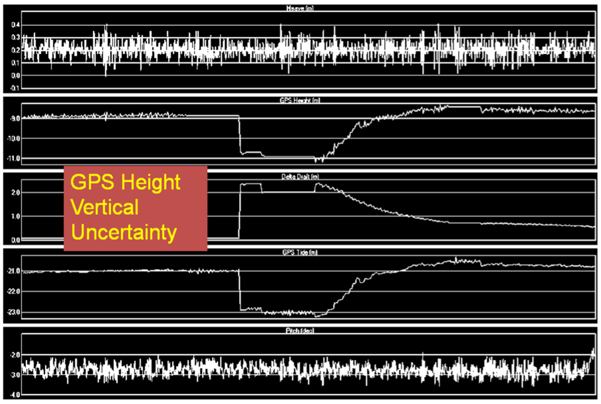

Figure 2: GPS Vertical Uncertainty

Recommendations

It is necessary to monitor the GPS solution to detect any precise positioning outages. Having a tool set that can display heave, GPS height, height uncertainty and observed tide can facilitate the editing of suspect areas. Automatic filtering tools could also be used to detect times where the GPS height uncertainty exceeded some criteria. Viewing a standard deviation surface early in the data processing/evaluation stream could also be used to identify potential problem areas. It would be advantageous to have a tool that will allow for the use of standard tides during GPS position dropouts.

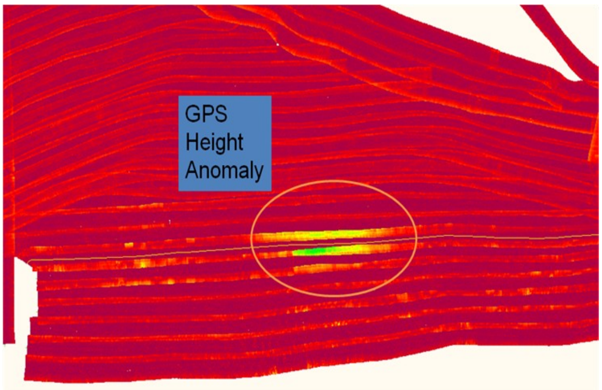

Figure 3: GPS height anomaly as seen in a standard deviation surface

3.4 Vertical Positioning Uncertainty

The most favored approach to handling vertical positioning uncertainty is to use the values derived in the GPS processing software. One example is the use of PosPac™ to derive a Smoothed Best Estimated Trajectory (SBET) of the positions, including the uncertainty values, and import them into CARIS HIPS™, where they are used in the overall uncertainty calculations. One improvement would be to have the ability to graphically view the uncertainty values in conjunction with the GPS heights.

Recommendations

The vertical uncertainty from the GPS observation and computation process must be included in the final depth uncertainty determination. Translation of that position to the RP must also be taken into account. Care must be taken to insure that heave and dynamic draft uncertainties are not included in the overall uncertainty determination.

3.5 Use of Observed Water Level

The response to this question was mixed. Some do not use tide gauges at all, while others use the gauges as a back-up and for QC. Several respondents still use gauges as the primary reference while the use of ERS is being evaluated. In general, in areas where the separation model is well established, tide gauges are either not used, or used only for back-up and QC. In areas where the separation model is not well established, tide gauges are used to help establish the model.

Recommendations

It is recommended that a tide gauge be used during a survey. This will provide a back-up in case of GPS outages and provide QC for GPS height validation. The gauge data can also be used to validate or even enhance the separation model.

3.6 Separation Model Development

Separation model development is the most difficult, and uncertain, portion of the entire ERS process. The most advanced groups in this area are NOAA with VDatum and the UKHO with VORF. Many respondents use a combination of methods. An actual separation value is observed at tide gauge locations and these values are then extrapolated/interpolated to cover the areas of the survey. In small areas, many simply use a single value derived at a gauge. Most use some variation of SEP determination at gauge locations and interpolation between gauges in combination with a geoid model. Most are experimenting with the inclusion of hydrodynamic models.

Naval Oceanographic Office Lidar operations use SEP observations at tide gauges and adjust (translate - one gauge, slope - two gauges, or rubber sheet - more than two gauges) the EGM08 geoid model to fit chart datum at each gauge location (Elenbaas, 2010). GPS buoys are used to enhance the model at survey location through water level transfer from a primary gauge.

NOAA uses VDatum in areas where there is coverage, and traditional tides elsewhere. In areas outside of VDatum coverage, they are exploring the use of observed tides and tide zoning in combination with GPS tides to derive an in-situ separation model (Riley 2010, Rice 2011).

Recommendations

It is recommended that any interpolation of SEP values between gauges include a geoid model. This is a reasonably simple method for developing a first estimate of an SEP model. Sea surface topography and hydrodynamic modeling should be incorporated into the model as that information becomes available.

3.7 Separation Model Validation and Uncertainty

Some respondents validate the separation model by comparing GPS tides to traditional observed tides at the survey location, or comparing the seafloor surfaces generated by the two methods. For groups just beginning to use ERS, this process is conducted for all data in all surveys. For those further along in ERS usage, this comparison is only conducted for a subsection of the data. Models can be validated by observing an SEP at a location that was not used in the model generation. GPS buoys will be very effective tools for this type of validation, and model enhancement.

Uncertainty in the models includes a combination of uncertainties in all surfaces used to generate the model (ellipsoid, geoid, hydrodynamic, sea surface topography) as well as the translation between these surfaces.

Recommendations

It is recommended that those starting to use ERS continue to conduct surveys using traditional means and compare the GPS derived results. It is not necessary to go as far as developing seafloor surfaces from both methods. Simply comparing tides for each line determined using both methods (GPS tides and traditional) will suffice.

Determining uncertainty in SEP modeling is a topic of discussion in the industry and all those using, or planning to use, ERS are encouraged to participate.

3.8 Processing Stream

The responses to this question were mixed. Some apply SEP model translation in real-time (if using RTK) during data collection (e.g. in QINSy™ or Hypack™) and subsequently directly to the depth observations. Others perform translation in the early stages of data processing (e.g. in CARIS HIPS™). Others do all cleaning, evaluation and editing relative to the ellipsoid and move to chart datum at the final step (common in Lidar operations).

Recommendations

It is not relevant where the translation takes place, as long as it is documented. Separation models must have associated metadata to indicate what they translate between, including epochs. Resulting surfaces should also contain this information. Regardless of where the translations take place, it is essential that it be possible to translate back to the original ellipsoid surface if necessary. If separation models are applied in real-time, all data related to that translation must be recorded (including the RTK observations).

3.8 Data Archive

No clear consensus on how to archive data could be gleaned from the responses. Most are continuing with the traditional approach of storing soundings to chart datum. NOAA is archiving in BAG format that includes the storage of "corrector" surfaces such as the SEP model (Riley, 2010).

Recommendations

When data is archived it is essential that it be accompanied with metadata that clearly defines exactly what translations have been applied. Separation models also need metadata attached that will identify epochs and reference datums. Ideally, data should be archived relative to the most stable surface (e.g. reference ellipsoid) and all separation and translation surfaces should be related to it. If this is the case, the original data and reference would not change, only the separation models to get them to another datum (geoid, chart, ...) would change. However, this may take time because most historic data holdings are related to chart datum. The key is proper metadata management.

4. CHS Quebec Case Study

Reference: Godin et al 2009

CHS Quebec is responsible for the Quebec portion of the Saint Lawrence Seaway out into the Gulf of Saint Lawrence (see *Figure 4*). The Quebec region is divided into two sections; channel and offshore. The channel group is responsible for surveying critical channel areas that are dredged to maintain minimum depth. Their area of responsibility stretches from just west of Montreal to just east of Quebec City. The offshore group is responsible for all other navigable waters. The Quebec region started looking into the use of high-accuracy GPS heights for surveying in 1995 and the technology is now an integral part of their operations. The following subsections give an overview of their application of ERS.

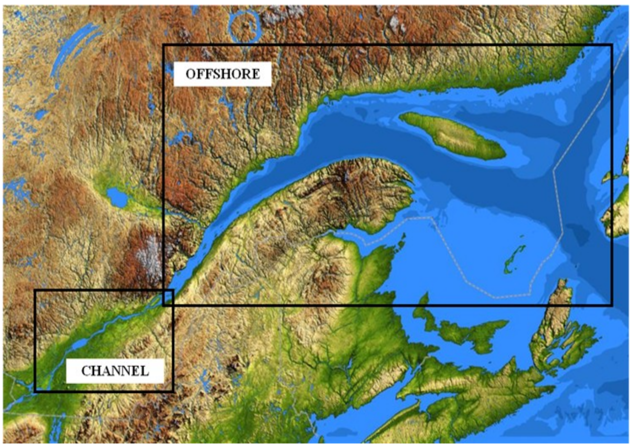

Figure 4: CHS Quebec Region

4.1 Data Collection

A series of permanent GPS base stations have been established along the shores of the Saint Lawrence River to enable the use of Real-Time Kinematic (RTK) positioning in all areas monitored by the channel group. The system in use is Thales™ LRK (Long Range Kinematic). Hypack™ is used for real-time navigation and tidal estimation using the RTK solutions. An ellipsoid to chart datum separation (SEP) model is used by Hypack™ to reduce the GPS heights to chart datum. Heave and dynamic draft (if available) are also removed to produce an instantaneous tidal estimate, with respect to chart datum. This GPS derived tidal estimate is compared to a predicted estimate derived from hydrodynamic modeling for real-time tide validation. The development of the SEP and prediction models will be discussed later.

The offshore group does not normally use RTK. Instead, they use Post-Processing Kinematic (PPK) software to determine high-accuracy 3D GPS solutions for the antenna.

Both the channel and offshore groups use relative positioning in that the solutions are determined using a base station. As such, the resulting position datum, both vertical and horizontal, is defined by the coordinates used for the base station. The channel chart datums were established relative to NAD83 using the Canadian Spatial Reference System CSRS'96 (version 1) adjustment. As a result, the base stations and resulting vessel positions remain in this coordinate system. The offshore group has been using NAD83 based on CSRS'98 (version 2). Therefore, the two vertical datums are slightly different – as defined by the base station coordinates.

4.2 CARIS HIPS™ Data Processing

The channel group ingests vessel motion, depths and 3D positions into CARIS HIPS™ through the Hypack™ converter. The offshore group ingests depths and motion through the Simrad converter and the 3D positions through the HIPS Generic Data Parser™.

The channel and offshore groups use the same post-processing methods in regard to GPS tides. Once in HIPS™, GPS tides are computed from the GPS heights. GPS tides in HIPS are used to replace the traditional tide gauge observations. To compute the GPS tide, the software removes the effect of heave, pitch, roll and draft (static and dynamic) and transfers the GPS antenna height to the waterline. This waterline height is transformed from the ellipsoid to chart datum through the separation model. The resulting GPS tide observations are time and height above datum, for each GPS epoch, which is applied during the Merge process. static and dynamic), and heave are applied as usual during the merge process.

Once the GPS tide has been computed, it is validated and smoothed in the attitude editor. Here it can be viewed with the GPS height, heave, pitch, roll, and traditional tide (if available). A smoothing algorithm can be applied to the GPS tide to remove any residual noise. The result is an actual tidal record that is applied to the soundings during the merge process; applying draft, heave, pitch and roll as usual.

4.3 Ellipsoid/Chart Datum Separation Models

Two separation models were used; one for the channel area and the other for the offshore area. The channel model was based on the separation relative to the NAD83, CSRS96 (V1) ellipsoid, as per the GPS reference stations. The separation between chart datum and the ellipsoid was determined through GPS observations at each of the primary tide gauges and at intermediate tide staffs. Chart datum of the primary gauges was determined through long observations. Chart datum at each of the intermediate tide staffs was determined through linear interpolation, with respect to the Canadian Geodetic Vertical Datum (CGVD28), between primary tide gauges. The channel separation model was created using Kriging, where the separation at the tide gauges and tide staff locations were considered to be correct; therefore fixed in the interpolation. No attempt was made to incorporate hydrodynamic modeling into the separation model. Extensive validation procedures were carried out to ensure the compatibility of GPS derived tides and tradition observed tides, including static tests where vessels sat near to gauges and dynamic tests where vessels transited between, and by, primary tide gauges.

Both the offshore and channel SEP models were binary grid maps known as "BIN" files. The format was developed by the US National Geodetic Survey for the geoid/ ellipsoid undulation models. The first channel version had a 6 arc-second grid and the current version has a 30 arc-second grid.

The software used to create the SEP maps was developed specifically for the channel area. It only accepted data with horizontal grid coordinates referenced to UTM Z18. Once the Kriging process was completed, the resulting SEP grid was transformed to geographic coordinates and then converted to the "BIN" format. The offshore area SEP maps, covered by UTM Z19 and Z20, had distortions resulting from the incompatible UTM zones. The software was no longer supported; therefore, updates or modifications were not possible. As a result, new SEP models are being developed. The new procedure still uses Kriging, but all processes can be performed on geographic coordinates.

Currently, the offshore model uses Kriging to interpolate between shore stations where the datum to ellipsoid is known. Consideration is being given to the incorporation of hydrodynamic models to help densify the network away from the shore stations. In-situ GPS tide gauges are also being considered to connect the hydrodynamic model to the ellipse.

4.4 Channel Validation Model (SPINE)

While conducting hydrographic surveys in the channel region, operators can validate their GPS tidal estimates in real-time. The GPS tides are estimated by Hypack^{TM} using the RTK heights and the SEP model. The SPINE hydrodynamic model is used for a comparison. This model is based on water level predictions from a hydrodynamic model combined with real-time tide gauge observations. The model produces water level estimates at discrete locations (nodes) along the centerline of the river between Montreal and Quebec City. At each location, the model predicts water level for a given time. The CHS hydrographers retrieve one day's worth of predictions for each node, at 7.5 minute increments. These estimates are adjusted by real-time tide gauge observations, which are then interpolated for the location of the vessel. The resulting water level height is compared to the GPS derived height, in real-time, for validation.

5. Conclusions and Recommendations

Given the complexity and diversity of ERS applications and methods, it is suggested that a document of case studies be developed. The CHS Quebec case study included here could serve as an example. Other examples that could be developed include projects from CHS Central and Arctic, CHS Atlantic (lidar), Brazil, Sweden, and NOAA. These studies would cover the complete ERS process from data collection through processing and evaluation to SEP development.

Evaluation of GPS observations used for vertical positioning in hydrography is extremely important for bathymetric quality control. Any vertical fluctuations in the positions due to GPS processing will migrate directly into the representation of the bottom. Having the tools and information to help in this evaluation will greatly enhance the hydrographer's confidence in the results. Information needed for this evaluation includes heave and tidal observations as well as uncertainty estimates from the GPS processing software. Tools to help in this evaluation include graphical representation of heave, tide, GPS height, GPS vertical uncertainty and GPS Tide. Filters to help identify changes in uncertainty or deviations from heave and/or tide observation would also be of assistance.

The most critical outstanding issues associated with ERS are the development of separation (SEP) models and uncertainty estimates associated with those models. It is recommended that various methods for the development and validation of SEP models be created and distributed to the user community for comment and enhancement. A series of case studies dealing with this subject should also be compiled

The following is a summary of the recommendations put forward in the main body of this discussion.

1) Use RTK and/or PPK as the primary positioning method
2) Use PPP as a back-up and as primary if necessary
3) Until RTG reaches lower uncertainty, it should be used for real-time data collection, but replaced by PPP in post-processing.
4) Always record and archive raw GPS and motion observations
5) If using a base station, adhere to strict installation and data recording protocols, especially when recording antenna heights.
6) Continue to record real-time heave for data validation, even if it is not used in the final solution.
7) Perform side-by-side validation at an established tide gauge at the beginning and end of each project. Comparisons should take place over an entire tide cycle, or at a minimum three hours.
8) Use the NGS average values from the absolute calibration sheets for antenna phase center offset values.
9) It is necessary to monitor the GPS solution to detect any precise positioning outages. Having a tool set that can display heave, GPS height, height uncertainty and observed tide can facilitate the editing of suspect areas. Automatic filtering tools could also be used to detect times where the GPS height uncertainty exceeded some criteria. Viewing a standard deviation surface early in the data processing/ evaluation stream could also be used to identify potential problem areas.
10) The vertical uncertainty from the GPS observation and computation process must be included in the final depth uncertainty determination.

Translation of that position to the RP must also be taken into account. Care must be taken to insure that heave and dynamic draft uncertainties are not included in the overall uncertainty determination.

11) It is recommended that a tide gauge be used during a survey. This will provide a back-up in case of GPS outages and provide QC for GPS height validation. The gauge data can also be used to validate or even enhance the separation model.
12) It is recommended that any interpolation of SEP values between gauges include a geoid model. This is a reasonably simple method for developing a first estimate of an SEP model. Sea surface topography and hydrodynamic modeling should be incorporated into the model as that information becomes available.
13) It is recommended that those starting to use ERS continue to conduct surveys using traditional means and compare the GPS derived results. It is not necessary to go as far as developing seafloor surfaces from both methods. Simply comparing tides for each line determined using both methods (GPS tides and traditional) will suffice.
14) Determining uncertainty in SEP modeling is a topic of discussion in the industry and all those using, or planning to use, ERS are encouraged to participate.
15) It is not really relevant where the translation from ellipsoid to chart datum takes place, as long as it is documented. Separation models must have associated metadata to indicate what they translate between, including epochs. Resulting surfaces should also contain this information. Regardless of where the translations take place, it is essential that it be possible to translate back to the original ellipsoid surface if necessary. If separation models are applied in real-time, all data related to that translation must be recorded (including the RTK observations)
16) When data is archived it is essential that it be accompanied with metadata that clearly defines exactly what translations have been applied. Separation models also need metadata attached that will identify epochs and reference datums. Ideally, data should be archived relative to the most stable surface (e.g. reference ellipsoid) and all separation and translation surfaces should be related to it. If this is the case, the original data and reference would not change, only the separation models to get it to another datum (geoid, chart ...) would change. However, this may take time because most historic data holdings are related to chart datum. The key is proper metadata management.

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Jerry Mills is a Technical Assistant on the staff of the Hydrographic Surveys Division under NOAA's Office of Coast Survey and has been involved in hydrographic surveying for over 40 years. After graduating with a degree in mathematics from Washington State University, he was commissioned as a NOAA Corps officer in 1969. His 22-year career included assignments aboard three hydrographic surveying vessels, mainly in Alaska, before serving as the Deputy Chief of the Nautical Charting Research and Development Laboratory and the Chief of the Ocean Mapping Section which produced bathymetric maps from both multibeam and single beam sonar data. While on active duty, Jerry received a master's degree in Oceanography (Hydrography) from the Naval Postgraduate School where he subsequently taught for 3 years.

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