Hydrographic Surveying Using the Ellipsoid as the Vertical Reference Surface

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SUMMARY

High-accuracy GPS positioning is being used in hydrography to resolve vertical movement of the survey vessel. Combining GPS heights with ellipsoid-to-chart datum separation models provides chart datum referenced depths for nautical chart production. Utilization of this technology to remove the tidal effect is a significant change from the traditional use of tide gauges, co-tidal charts and tide zoning. Standards and "best practices" used by the hydrographic community to create nautical charts are based on the traditional technology and methods. A thorough vetting of the new technology and methods is necessary for the development of new standards and best practices. This paper provides some background of the traditional and new technology and methods. It also outlines the issues and provides some recommendations.

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1 INTRODUCTION

Many groups involved in hydrographic surveying and ocean mapping are using High-accuracy GPS for three dimensional positioning. Of particular interest to hydrographers is the vertical component. The benefit of this form of vertical positioning is that objects in question (sea surface, water column, sea floor etc) are referenced directly to a mathematically derived reference ellipsoid.

Hydrographic surveying has traditionally been conducted solely for the purpose of creating nautical charts for safety of navigation. It now encompasses a multitude of methods and applications in the marine environment, and has a vital role in coastal zone management. The coastal zone encompasses a wide swath along the shoreline that includes both the land and sea, and properly merging information from the two is essential for the analysis of coastal processes and sound management decisions. In the past, vertical land (topography) and ocean (bathymetry) data were collected for different purposes, using different methods and related to different vertical reference surfaces. The need to merge the two data types has driven the need to resolve these differences.

One surface that is used for modern data collection on both land and sea is a reference ellipsoid. Traditionally, reference ellipsoids were used to define horizontal datums. With the emergence of high-accuracy GPS, reference ellipsoids are being used to define vertical datums. Data collected both on land and at sea can be related to the same satellite based vertical reference surface, making the merging of the two a trivial process. Although these reference ellipsoids are convenient, they are not physical surfaces, such as those defined by gravity (geodetic datum) or mean sea level (tidal datum); therefore, for analysis and map/chart production, GPS derived vertical information must be translated. Translations from the ellipsoid to geodetic or tidal datums are usually performed through transformation models. The ellipsoid can be used as the reference for all of the translation models.

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.

This paper is divided into four sections: 1) Introduction. 2) Background on high-accuracy GPS and the components of depth determination including: effect of vessel motion on height translation, vertical datums, tidal correctors and zoning, and water level modeling. 3) Summary of the issues surrounding the use of high-accuracy GPS and tide models for depth determination. 4) Recommendations for hydrographic community involvement and topics for further study.

2 BACKGROUND

In order to understand the issues surrounding surveying to the ellipsoid it is necessary to understand the various contributors to the process. The following sections briefly describe:

1. Vertical components
2. Ellipsoidal, geoidal and tidal vertical datums
3. Sea surface topography
4. Hydrodynamic models
5. Traditional tidal datums
6. High-accuracy GPS

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).

- Observed GPS height is the distance from the Ellipsoid to receiving antenna phase centre
- ΔZ (antenna) is the vertical offset between the antenna phase centre and the vessel reference point (RP).
- ΔZ (transducer) is the vertical offset between the RP and transducer.
- Observed depth is from transducer to bottom.
- 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).
- 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.

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Comment: Settlement is the vertical change due to movement through the water and squat is the change in trim due to that movement. If the transducer is at the pivot point for squat, there will be no squat but settlement will remain.

- Removal of heave, settlement and squat produces a water level (WL), which includes the tidal component.
- Removal of the tidal component from the WL produces the Chart Datum.
- Ellipsoid to Chart Datum is the separation model (SEP)

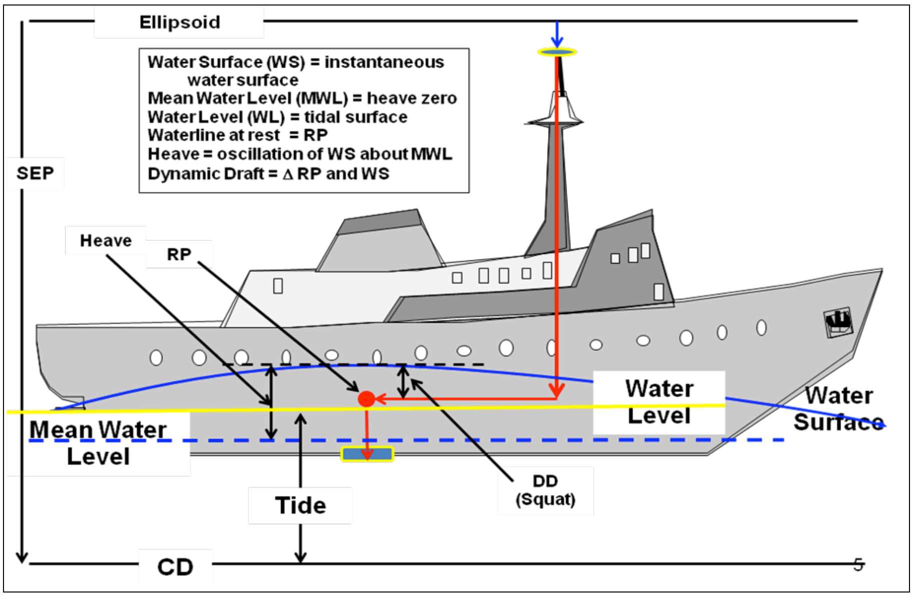

Figure 1: Vertical Components

2.2 Vertical Datums

Vertical reference surfaces can be categorized under three general headings; tidal, geodetic (both physical surfaces) and ellipsoidal (mathematical surface). Traditionally, bathymetric data has been collected and stored relative to a tidal datum and topographic data relative to a geodetic datum.

Bathymetric data displayed on charts are referenced to a low water tidally referenced vertical datum below which the water surface will not usually fall (e.g. Lowest Astronomical Tide [LAT], Mean Lower Low Water [MLLW]). Topographic data, on the other hand, are often referenced to a local geodetic datum, approximated by Mean Sea Level (MSL), which is above LAT and MLLW. A geodetic datum is a surface that varies with gravity (geoid). MSL is a surface that varies from the geoid due to sea surface topography (see section 2.3). The chart datum surface varies from MSL due to the effects of tides and ocean dynamics.

GPS derived heights must be transformed from the reference ellipsoid to the geoid or chart datum. In some cases, data sets can be adjusted by simply applying a constant offset. In other cases it is necessary to apply more complex algorithms taking into account sea surface topography and hydrodynamic ocean models.

2.2.1 Geodetic Vertical Datum

When the height of an object is expressed, it must be related to something. The height of a ceiling is relative to the floor. The height of a building is relative to the ground outside. The elevation of a mountain is relative to Mean Sea Level (MSL). The expression MSL, when applied to elevation, usually refers to the height above the local geodetic datum. The Canadian Geodetic Vertical Datum (CGVD28) and the USA North American Vertical Datum (NAVD88) are referenced to MSL at Rimouski, Quebec. The elevations of all reference marks (bench marks) within the two systems are related to MSL at Rimouski through precise levelling and gravity observations. These geodetic vertical reference datums do not coincide with observed MSL at any other location due to atmospheric and oceanographic effects. These reference surfaces do, however, coincide with the geoid.

The geoid is a surface of equal gravity potential and is used to approximate the shape of the earth. The geoid coincides approximately with MSL and is represented by a geodetic vertical reference datum, as discussed above. If there were no long term atmospheric or oceanographic effects (e.g. prevailing winds and currents), then MSL determined over a long period (~19 years) would coincide with geoid. In reality, determination of MSL at a location will vary from the geoid by up to ±1 metre. This variation is known as sea surface (or ocean) topography.

2.2.2 Chart Datum (CD)

Chart datums (CD) are used on nautical charts to reference water depths. Traditionally, bathymetric data has been collected relative to a survey (or sounding) datum, then translated to chart datum for storage and chart production. As a result, most legacy bathymetric data contains depths relative to some local chart datum.

The following is a listing of some chart datum definitions:

– MLW	Mean Low Water
– MLLWLT	Mean Lower Low Water Large Tide
– MLLW	Mean Lower Low Water
– LNT	Lowest Normal Tide
– LLWLT	Lower Low Water Large Tide
– LAT	Lowest Astronomic Tide (atmospheric and oceanographic effects removed)

Chart datums are only fully valid at the location where the tides are observed. Even if MSL is the same at two locations (relative to the geoid), the low water datum will likely be different. One of the most significant challenges in traditional hydrography is establishing the relationship between the instantaneous water surface and chart datum, away from tide gauge locations. Tidal correctors are measured at tide gauge locations and then translated to the survey site through co-tidal charts or tide zoning. Uncertainty in the relationship between the instantaneous water surface and CD at the survey site is a significant component of the overall depth uncertainty.

The separation between chart datum and the geodetic vertical datum can be divided into two parts; CD to MSL and MSL to geoid. CD to MSL is established through hydrodynamic modeling. MSL to geoid is established through Sea Surface Topography (SST) modeling.

2.2.3 Reference Ellipsoid

The shape of the geoid can be approximated by a three-dimensional ellipse (ellipsoid). Because the earth is symmetric about the poles, the ellipsoid can be defined with a bi-axial ellipse, with the semi-minor axis aligned with the earth's axis of rotation and the semi-major axis aligned with the equatorial plane. This mathematical representation of the earth allows for relatively simple geographic (latitude, longitude and height) position computations. The vertical relationship between the ellipsiod, geoid and terrain is:

$$h = H + N$$

Where:

h = ellipsoid height
H = orthometric height
N = geoid height, also known as the geoid/ellipsoid undulation

The reference ellipsoid does not define a datum, it simply defines the parameters of the ellipse. A combination of the ellipsoid and its location with respect to the earth, defines a datum. The GRS80 ellipsoid is used in the definition of both the NAD83 and WGS84 datums.

GPS heights are determined relative to the mathematically defined ellipsoid. These heights must be translated to the geoid, through a geoid height model, in order to give them a physical relationship to the earth. Geoid models are determined through co-located GPS and gravity observations. These geoid/ellipsoid separation models can be established using land based techniques including GPS observations, levelling and gravity observations. They can also be established using space based techniques with specifically designed and tasked gravimetric satellites. Some existing models are GEOID96, 99, 03, and 08, and EGM96 and 08.

As more information is being collected relative to a reference ellipsoid through GPS observations, that ellipsoid is becoming more popular as the reference surface for all information. This mathematical surface should not change. Translation to and from the geoid and chart datums can be accomplished through surface models. As the relationships between the different surfaces changes or becomes better established, the models can be updated without affecting the base data.

Figure 2 depicts the relationship between chart datum (CD), the geoid and the ellipsoid. The ellipsoid is depicted as the primary reference (horizontal line) and all other surfaces are shown with respect to it. "SEP" refers to the CD to ellipsoid separation at tide gauge locations, which are depicted as tide staffs in the figure. The geoid is shown as a straight sloping line; again, with respect to the ellipsoid. MSL and MLW are shown as undulating lines with similar but different trends. This is meant to indicate that they are closely related, but their separation will differ from place to place. This difference is represented by the hydrodynamic model. The separation between the geoid and MSL is shown as sea surface topography (SST).

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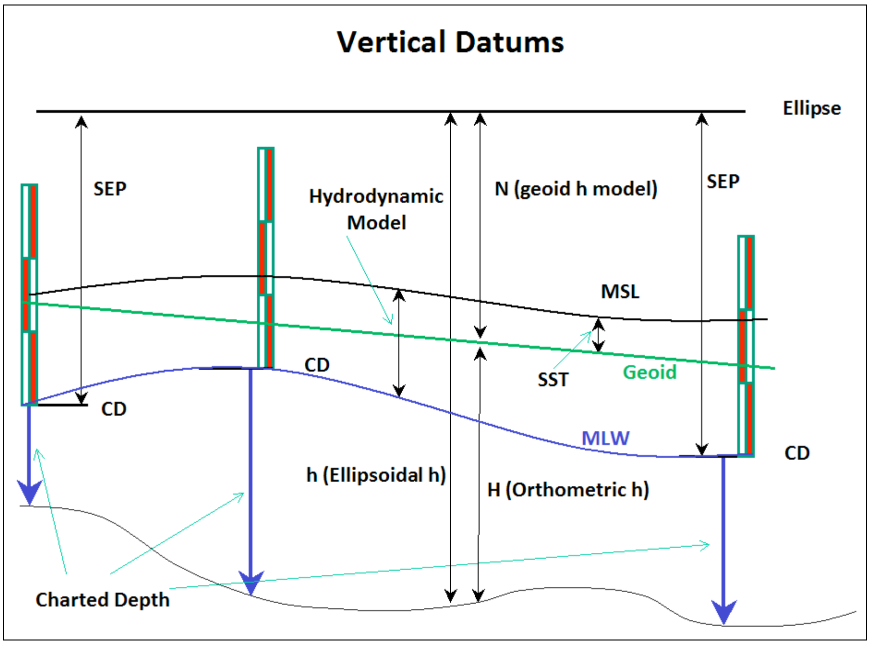

Figure 2: Chart datum, geoid, ellipsoid relationships

2.3 Sea Surface Topography

Sea Surface Topography (SST) is the average deviation of the surface of the ocean with respect to the geoid. This deviation is caused by atmospheric effects such as prevailing winds and weather patterns, as well as oceanographic effects, such as ocean currents. For example, the centre of the Gulf Steam is approximately 0.5 metres higher, relative to the geoid, than the east coast of North America. Figure 3 displays a colour shaded map of sea surface topography on the world's oceans.

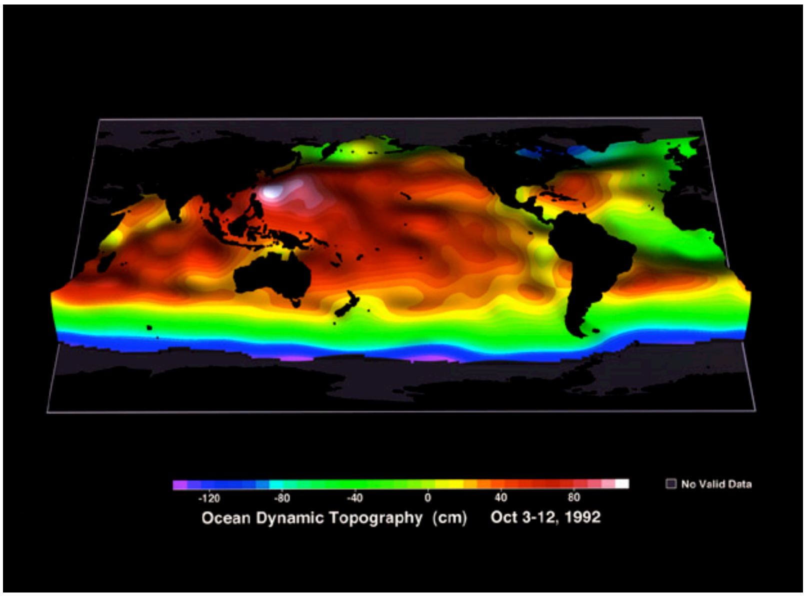

Figure 3: Map of Sea Surface Topography. [Taken from NASA, 2009]

Sea surface topography can be determined at tide gauges where the MSL has been observed, and the geodetic datum tied in through levelling. Alternatively, the geoid can be established relative to the reference ellipsoid through the geoid model, which requires establishment of the ellipsoid height at the tide gauge through GPS observations. Sea surface topography in the offshore is measured using satellite altimetry.

2.4 Hydrodynamic Models

Hydrodynamic models are derived from sophisticated applications used to estimate water level. Water level can be estimated for a given date and time for tidal predictions, or for a given mean tidal surface such as MLLW with respect to MSL. It is the latter that is used to translate data between MSL and CD.

Hydrodynamic models describe the reaction of a water body given certain boundary conditions and driving forces. The boundary conditions are coastlines and bathymetry. The driving forces are astronomic (sun/moon system) and oceanographic (currents etc.). Surfaces are derived by simulating the reaction of a body of water when it is forced over the given bathymetry and up against the coastline. The reaction of the water body is predicted using a set of algorithms based on fluid dynamics derived from Newton's laws of motion. In some models the solution is constrained by known tide station parameters.

2.5 Traditional Tidal Datums and Tidal Zoning

As mentioned in section 2.2.2, chart datums are used as the vertical reference for water depths on nautical charts and are chosen such that the water surface will not usually fall below it. The international standard for chart datums is Lowest Astronomic Tide (LAT) but different chart datums continue to be used by various nations (see listing in 2.2.2). Most of these tidal datums are computed over specific 19 year periods called tidal datum epochs

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In the coastal waters of the United States, Mean Lower Low Water (MLLW) is used as the chart datum. It is computed by averaging the height of the lower low water for each tidal day over a 19 year period. The Chart Datum for Canadian charts is Lower Low Water Large Tide which is the average of the lowest low waters, one from each of 19 years of observations. LAT, on the other hand, is based on the “predicted” lowest tide expected to occur in a 19 year period. This prediction is made by performing a harmonic analysis of the water level observations at a particular location, then using the resulting harmonic constituents to predict the elevation of the lowest tide that will occur over a 19 year period.

It is clear that installing and maintaining tide/water level gauges continuously for 19 years is difficult and expensive so the number of such primary gauges is limited in number. However, supplemental shorter term gauges can be installed to geographically densify the points of water level data acquisition. In most cases, not enough water level stations can be installed in a practical sense to provide direct control to all areas of a hydrographic survey. Hence, tide and water level zoning must be used to extrapolate or interpolate the tide and water level variations from those water level stations closest to the survey area. The more stations which can be established throughout a survey area, the less the zoning error. However, the desire for more stations must be balanced with higher cost and increased logistical complexity.

Any zoning scheme requires an oceanographic study of the water level variations in the survey area. For tidal areas, co-tidal maps of the time and range of tide are constructed based on historical data, hydrodynamic models and other information sources. Based on how fast the time and range of tide progress through a given survey area, the co-tidal lines are used to delineate discrete geospatial zones of equal time and range of tide. Once this is constructed, time and range correctors to appropriate operational stations or tide prediction stations can be calculated.

2.6 GPS Positioning

High-accuracy GPS for vertical positioning is relatively new to the hydrographic community. In the past, the vertical relationship between the GPS antenna and the transducer was important, but not vital. Now, with the use of GPS vertical positioning to establish bathymetry, it is essential that all aspects related to the measurement of that position be understood and dealt with appropriately. All measurement uncertainty will propagate directly into the final depth. Total uncertainty resulting from the use of GPS heigths includes; the uncertainty in the GPS vertical position of the antenna phase center, the measurement of the three dimensional offsets between the phase center and transducer, and the translation of the vertical position to the transducer (or reference point), taking into account the effects of pitch and roll.

High-accuracy GPS in hydrographic surveying has two basic applications; bathymetric data collection and chart datum development. For bathymetric data collection, GPS observations at the antenna are related directly to the depth observations through vessel offset measurements, thus providing a direct measurement from the ellipsoid to the sea floor. All vertical movement of the vessel, including tides, heave, static and dynamic draft are included in the GPS height observation. Chart datums can be established from GPS tide buoys to estimate the mean water surface, relative to the ellipsoid. This datum is used to translate the ellipsoid related bathymetric data to chart datum.

Figure 4 shows the relationship between the reference ellipsoid, a tide gauge buoy and vessel, and chart datum. The buoy height, combined with its draft observation, provides the water surface measurements for datum determination in relation to a shore-based tide gauge. The datum-to-ellipsoid relationship is represented by a separation (SEP) model. The vessel GPS height is connected to the depth observation through the "Z" offset. Although this offset is shown here as a single value, it actually varies with the pitch and roll of the vessel. The vessel air draft (antenna to waterline), taking into account all vessel motion, including heave, pitch, roll, long term draft and dynamic draft, can be used to validate water level observations and datum determinations.

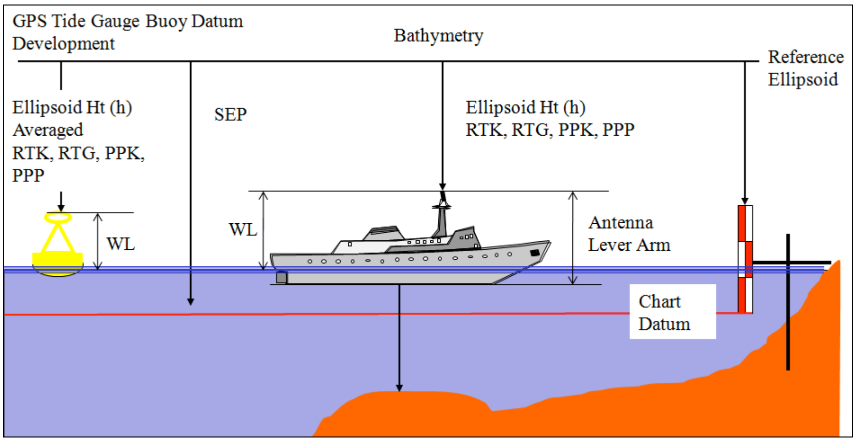

Figure 4: Relationship between reference ellipsoid, antenna, water line (WL) and chart datum.

Tide gauge buoys can be used to establish a chart datum in the area of the survey. Ideally, a water level transfer from a tide gauge in the area, with an established datum, is used to determine the datum at the buoy. Only long period buoy movement caused by the tides is required; therefore, the short term movement, such as heave, can be filtered out through averaging. A critical component for the establishment of a datum using a GPS tide buoy, is the waterline determination (distance from antenna to water line). Any error in the measurement of this offset will translate directly into the datum.

Tide gauge buoys can also be used to validate and strengthen hydrodynamic models by providing water level observations away from the shore. Carefully calibrated and positioned (with respect to the ellipsoid) bottom mounted gauges can be used in lieu of the GPS buoy.

Ship borne bathymetric data collection systems measure depths relative to a transducer. These depths are then translated to the vessel reference point. The GPS height, determined at the antenna, is also translated to the vessel reference point. Combining the GPS height and water depth provides a direct measurement from the ellipsoid to the sea floor. The change in vertical separation between the antenna and vessel reference point will vary depending on the horizontal and vertical offsets (as measured in the vessel frame), and the degree of vessel pitch and roll. Figure 5 shows an example of the effect of pitch on the vertical offset between the antenna and vessel reference point (RP), given a horizontal offset of "*y*". The "at-rest" vertical separation, with no pitch, is represented by "*z*", the vertical separation with a pitch value is represented as the red dashed line (*z'*). Without a horizontal offset, the change in vertical separation is minimal and the "*z*" lever arm is always shorter.

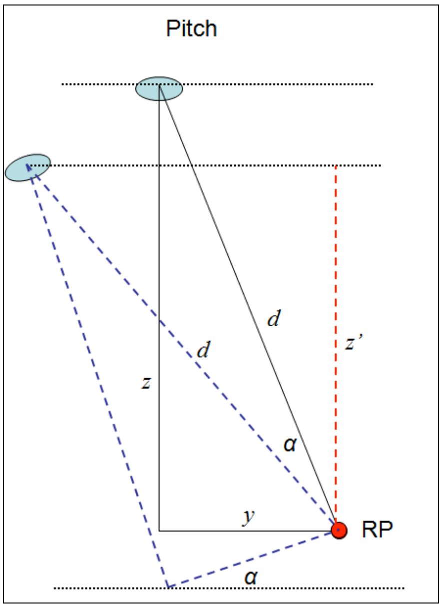

Figure 5: Effect of vessel pitch on height translation to the vessel reference point

3 ISSUES

Several issues must be addressed when attempting to conduct hydrographic surveys relating the vertical componenet to the ellipsoid. Theses issues include:

1. Type of GPS positioing
2. Necessity of tide gauge observations
3. Heave observations
4. Vertical offset calibration
5. Translation to chart datum
6. Uncertainty propagation

3.1 Type of High-Accuracy GPS Positioning:

High-accuracy GPS positioning techniques include; Precise Point Positioning, Real-Time Precise Point Positioing, Post-Processed Kinematic and Real-time Kinematic. When using GPS for tide gauge buoy datum development (averaging observations), all four methods provide comparable results [Dodd et. al., 2009]. For bathymetry, where epoch-to-epoch solutions are used, the type of positioning should be identified to allow for the assignment of uncertainty. The vertical uncertainty associated with the GPS heights will propagate directly into the uncertainty in the depth estimates. Regardless of the processing technique, it is suggested that raw GPS observaitons be recorded at all times. If using real-time methods, post-processing of all or a portion of the data can be used for quality control. Post-processing can also be used in case of an interuption in real-time computations.

3.2 Necessity of Tide Gauge Observations

When using GPS heights to remove the vertical vessel movement, traditional tide gauges are no longer necessary for the reduction of observed depths. Ellipsoid to chart datum separation models are used to transform the depths. However, tide gauge observations during surveys are still necessary to validate the models and for quality control of the GPS heights. Tide gauges are also used to establish chart datum through water level transfer from a primary tide gauge to a GPS tide gauge buoy at the survey site. Tide Gauge buoys can also be used to validate and enhance separation models.

3.3 Heave Observations

Heave of the vessel is included in the GPS antenna height movement, negating the need for a heave sensor. However, heave observations can be used to help with quality control of the GPS heights. Any vertical shifts in the GPS due to processing irregularities can be identified through heave comparisons. Also, because heave observations are usually measured at a much higher frequency than GPS, they are useful for the interpolation of vertical movement between GPS height records.

3.4 Vertical offset calibration.

A significant source of accidental error in GPS surveying (on land and at sea) can be attributed to incorrectly measured antenna heights, both at a base station and on a vessel. Regardless of how the vertical offsets are determined (tape measure or total station) validation of this measurement should be carried out.

Vertical offsets for both GPS buoys and vessels can be calibrated by situating the vessel next to a tide gauge. This allows for an evaluation of the positioning method and a calibration of the antenna to waterline vertical offsets. Some groups recommend at least 25 hours, covering a complete tidal cycle.

If the tide from the gauge are considered as true, any differences between GPS tide and the gauge tide are one or more of the following:

1. Error in base station height
2. Error in vessel antenna Z-offset
3. Error in draft
4. Error in the separation model

[Olsson, 2009]

3.5 Translation to chart datum

The transformation from the ellipsoid to chart datum can take place during data collection, or data processing, or at final product creation. If real-time GPS heights are being computed, the transformation can take place during data collection; however, quality control may be an issue. In this case the separation models must be built into the data collection process. Translation during post-processing allows for the use of tide and heave observations for quality control and data editing. Translation prior to or during data processing allows the user to see the depths relative to chart datum.

Archiving the depths (or resulting surfaces) relative to the ellipsoid allows for comparison with other data sets, such as topographic data. Translation to chart datum can take place immediately before the creation of final product objects such as contours and depth areas. If the data is stored relative to the ellipsoid, and all separation models are also stored relative to the same reference ellipsoid, translation to any datum becomes a trivial process. It should be noted that regardless of how the data is archived, the metadata must include a very explicit description of the vertical reference, including epoch.

3.6 Total Propagated Uncertainty

The uncertainty associated with final depths reflects the effect of all equipment, translations and processes. The existing Total Propagated Uncertainty (TPU) computation methods must be modified to accommodate the surveying with respect to the ellipsoid. The uncertainty of the vertical GPS position must be included, as well as the effect of the translation of the position from the antenna to the vessel reference point. The uncertainty associated with this translation also includes the effect of pitch and roll and uncertainties associated with those measurements. If heave is to be used, then there will be uncertainty associated with it. If it is not to be used, then there will be uncertainty associated with the interpolation of vessel height between GPS observations. In some cases, the vertical position may be smoothed, adding another factor to the uncertainty determination. The final, and most problematic, effect is from the uncertainty associated with the separation model. There will be uncertainty associated with the model itself and uncertainty with its application.

4 RECOMMENDATIONS

GPS has been used for horizontal positioning in hydrography for many years. Although vitally important in hydrography, understanding the technology and position computation process has not been necessary to use GPS effectively. This is not the case for vertical positioning. In order to use the vertical component effectively, high-accuracy GPS processing techniques must be used. It is essential that the user understand the uncertainties associated with the results, and be able to determine when and why a vertical position is unusable. The vertical uncertainty requirements in hydrography are far more stringent than in the horizontal, and the uncertainty associated with the vertical component of GPS tends to be higher than that achievable in the horizontal.

The use of the vertical component of GPS should not completely replace tide gauges and heave sensors. Tide gauges should be installed and monitored as before to verify GPS observations and to validate separation models. Heave sensors should continue to be used to validate and augment the GPS height observations.

Raw GPS data should be collected on the vessel at all times, even if real-time processes are being used. If raw data is not recorded, any inconsistencies in the real-time solution will not be recoverable, resulting in lost data. GPS data should be collected whenever possible, even if the vessel is in port. Constant monitoring of the water level will help with offset calibration and separation model validation. At the very least, high-accuracy GPS observations should be available for the entire survey day, including transit to and from the survey site, and not only during survey lines.

Height offsets should be calibrated prior to and after the completion of a project.

It is essential that any depth products resulting from translation through a separation model be accompanied by appropriate metadata. This metadata must include the vertical datum of the dataset and how that datum was achieved. It must also include the vertical reference used for the GPS computations, including epoch.

The hydrographic community should work collaboratively to establish “best practices” for the use of GPS in vertical positioning. These guidelines would provide guidance for operationalizing this new technology and for uncertainty limits regarding vertical positioning, position translation and separation models.

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