Measuring the Water Level Datum Relative to the Ellipsoid During Hydrographic Survey

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Abstract

Hydrographic surveys are referenced vertically to a local water level "chart" datum. Conducting a survey relative to the ellipsoid dictates a datum transformation take place before the survey is used for current navigational products. Models that combine estimates for the tide, sea surface topography, the geoid, and the ellipsoid are often used to transform an ellipsoid referenced survey to a local water level datum. Regions covered by these vertical datum transformation models are limited and so would appear to constrain the areas where ellipsoid referenced surveys can be conducted. Because areas not covered by a vertical datum transformation model still must have a tide model to conduct a hydrographic survey, survey-time measurements of the ellipsoid to water level datum can be conducted through the vessel reference point. This measured separation is largely a function of the vessel ellipsoid height and the standard survey tide model and thus introduces limited additional uncertainty than is typical in a water level referenced survey. This approach is useful for reducing ellipsoid reference surveys to the water level datum, examining a tide model, or for evaluating a vertical datum transformation model. Prototype tools and a comparison to typical vertical datum transformation models are discussed.

Introduction

An essential part of hydrography concerns the manner by which survey data are referenced to the vertical datum. A local, tide-based "chart datum" is vital to products intended for safety-of-navigation and to improve a mariner's overall ability to transit areas with a secure under keel clearance. Traditionally, the reduction of observed soundings to the tidal datum has been included as an integral part of hydrographic survey data processing. Sounding data acquired over the period of the survey is comparable for internal consistency when reduced to such a common datum reference.

In the traditional approach, echo sounder measurements observed relative to the vessel are referenced to a tidal datum via the in situ water level, and vary according to vessel hydrodynamic effects and the stage of (modeled) tide. The dynamic uncertainties associated with both the vessel waterline and the tide model are difficult to estimate in real time. Biases which exist in this datum-referencing procedure are evidenced in the mismatch of repeated estimates of reduced depth. Because the bias and uncertainty in the realization of the datum reference is not observable as a component separate from the processed bathymetry data, conventional editing procedures are unable to evaluate the true nature of the error and to minimize those clearly deleterious effects. Also, bathymetric surfacing algorithms have difficulty dealing with such variations attributed to parameters unrelated to those which truly govern the echo sounder measurements. Efforts to mitigate datum-related inconsistencies through adjustments to some bathymetry-based proxy comprise a highly ineffective and inefficient use of the hydrographer’s time.

Inconsistencies associated with the realization of a hydrographic tidal datum may be managed by surveying instead to a geodetic datum (e.g. NAD83 (CORS96)) based on a fixed reference ellipsoid (e.g. GRS80). Vessel position in the geodetic datum is achieved via Global Navigation Satellite System (GNSS) measurements, and often aided by inertial motion sensors. Ellipsoidal Referenced Survey (ERS) real-time uncertainties are adequate, with achievable kinematic height measurement accuracies in the sub-decimeter range. However, echo sounder magnitudes relative to an ellipsoid are devoid of physical meaning for the mariner; indeed, the geodetic height of the seafloor is predominately a negative quantity (“below” the reference ellipsoid) for the United States and the ellipsoid surface is parallel neither to a gravitational equipotential surface nor a tidal datum surface. A vertical separation model (SEP), amounting to the ellipsoid height of the water level datum, is required to transform ERS depths for nautical charting applications.

The standard approach to the creation of a SEP requires knowledge of the intervening surfaces which relate a reference ellipsoid to a tidal datum. The reference ellipsoid is a datum for geodetic heights, where the earth’s surface is approximated in size and shape by an artificial, geometric surface. The geoid is the datum for orthometric heights; gravity is an essential part of a physically-meaningful height, as water seeks an equipotential. The separation between a geoid and local mean sea level (MSL) is known as sea surface topography (SST). SST stems from ocean dynamics and is affected by meteorological events and other phenomena [Vaníček, 2009]. Geoid and SST models account for the differences between the reference ellipsoid and MSL at water level gauges. Several vertical datum transformation models exist worldwide, such as VDatum (USA) [Hess, 2003], VORF (UK), and AUSHYDROID (Australia), but the extent of coverage in each region is limited. Consequently, locations ready-made for ERS may appear also to be limited.

Areas not covered by a vertical datum transformation model must otherwise have a chart datum model to perform a hydrographic survey. Survey-time measurements of the ellipsoid to chart datum separation may be formulated through the vessel reference point during the ERS. Using the standard survey water level datum model in conjunction with vessel ellipsoid height to realize a SEP achieves a result that is entirely consistent with conventional hydrographic surveying data-reduction procedures. A key benefit ERS brings to hydrography is the improved precision afforded by the use of 3-D fixed geometric datum, with requisite-or-better accuracy per inertially-aided post-processed kinematic (IAPPK) GNSS positioning. During ERS, the vessel water level and tidal references customarily applied directly to soundings may be instead applied to the vessel ellipsoid height time series, creating a SEP estimate along the vessel track. These point estimates of the datum height cover the entire survey area, by definition. While the estimates incorporate the somewhat imprecise vessel dynamic waterline and zoned/interpolated water level reducer model, averaging over a large number of repeated measurements forms a relatively smooth SEP surface of reduced uncertainty.

Another benefit of ERS is the timeliness associated with the important process of datum accuracy confirmation. In ERS, ellipsoid height data is quality controlled and assured on the survey vessel. The creation of final ERS products can be dictated within the time frame appropriate to the survey, under the control of affiliated personnel in the field. Without ERS, water level gauge data and water level models are quality-controlled and -assured off location. These essential parts of the hydrographic survey workflow often arrive weeks to months after field work is complete, meaning all (preliminary) products created previously must be revised, thereby adding complexity and inefficiency in survey processing.

Measuring the water level height with GNSS is used in a variety of applications. Buoys [Chen 2004], ships [Wardwell, 2008; Bouin, 2009], aircraft, and satellites [Foster, 2009] may be used to measure water levels for tidal models as well as for fine-scale SST and geoid shape. Standard hydrographic methods provide a time-tested and simple approach for the estimate of the separation between the ellipsoid and the water level datum. The resulting separation estimates accurately model the datum height, including the important variations associated with the governing physics.

Because hydrographic water level modeling methods may be regarded as using some form of “zoning” (constant, discrete, or continuous) to define areas of similar water level regimes, the smoothed datum surface created from the process described here is called ellipsoidally referenced zoned tides, or ERZT.

Methods

Because the intended use of the SEP produced by this method is for hydrographic survey purposes, only the established hydrographic methods for making the datum estimates are used in this paper. There may be alternate ways of accomplishing the same outcome by modifying the steps described here. Furthermore, because the authors work primarily within the National Oceanic and Atmospheric Administration (NOAA) hydrographic process, some methods are very specific to the NOAA workflow.

The approach to creating an ERZT SEP begins with the vessel (vertical) position relative to the ellipsoid. First, the 3-D IAPPK solutions are extracted from a smoothed best estimate of trajectory (SBET). The SBET contains the time series of discrete ellipsoid referenced solutions for the vessel's position and attitude as well as ancillary information needed for the ERZT calculation.

Second, the vessel dynamic water level reference is recovered using the same methods typically used to reduce soundings in conventional hydrography; namely, heave and a dynamic settlement model are used to track changes. Accurate heave is extracted from the vessel's inertial navigation system data. Low frequency motion outside of the bandwidth of the heave sensor is estimated by displacing the vessel static water line according to a model wherein vessel settlement is expressed as a function of vessel speed. The speed used to look-up the settlement is also extracted from the SBET. All the static and dynamic offsets are combined with the vessel ellipsoid height to form a time series of the in situ water level geodetic height.

For the third step in this ERZT method, vessel position and time are used to compute the survey-time, in situ water level to water level datum height via a standard model. While this model could be formulated for a water body generally unaffected by tidal fluctuations, such as a river, this paper will generally refer to these models as "zoned tides". The important function of this model is that it relates the in situ water level to the desired water level datum, and not whether it is tidally affected. Both vessel position and time are extracted from the SBET file. The zoned tides for ERZT are computed by the NOAA software Pydro. The zoned tides calculation modifies the water level time series according to a phase offset and amplitude scaling according to the particular "controlling" gauge which, in general, changes as a function of the vessel position and time. Tidal Constituent and Residual Interpolation (TCARI) "continuous zoning" may also be applied to the ERZT calculation in Pydro. The resulting tide-datum corrector time series is combined with the in situ water level geodetic height time series from step two, to produce the geodetic SEP along all vessel survey tracks.

After the time-dependent part of the vessel to datum reference has been applied, the resulting geodetic SEP may now be examined in the purely spatial domain. Examination of the orthometric and tidal components of VDatum (where coverage exists) reveals that the primary factors contributing to changes in the ellipsoid to water level datum separation are the geoid and SST. In comparison, the MSL - tidal datum component separation appears relatively "flat." All constituent grids are smooth over the spatial sampling scale of the survey vessel. For this paper, gridded ERZT surfaces are achieved by averaging over 1-km square bins. The 1-km binning process effectively low-pass filters the vessel point measurements of SEP, preserving the geoid and sea surface topography signal content and removing noise from the datum reference measurements.

The uncertainty associated with an estimate can be just as important as the estimate itself. A straightforward method to assess the total uncertainty in the ERZT estimate is to combine the individual uncertainty components, assuming statistical independence. The square root of the sum of the squares of the uncertainty associated with the tide model, the vessel waterline estimate, the heave measurement, and the vessel ellipsoid height computation comprising each 1-km bin is computed. With the possible exception of the tide model uncertainty, the estimated uncertainty components are expected to be somewhat independent of vessel position and time, in general. Current procedures for constructing tide model uncertainty treat the measured water-level uncertainty at the gauge as a constant, as well as assume a fixed, conservative zoning-error. The overall uncertainty associated with the SEP grid is, hence, a nearly constant value that may not accurately describe the true uncertainty variation in the computed datum reference. Since survey vessels acquire duplicate lines across the survey area (e.g., cross-line checks of main-scheme lines), and since many survey lines are generally collected within a single 1-km bin, a second method for estimating ERZT uncertainty is to compute the sample variance. Binned-sample variance may provide better insight into the uncertainty stemming from each estimate than the total propagated uncertainty (TPU) formed from the modeled contributions. Assuming that the redundant measurements are from an unbiased, zero-mean distribution, any systematic bias present in the cross-check ties could be removed and the SEP grid recalculated, with the resulting sample variance being lower. While this latter method described holds promise, it has not been implemented for the results presented in this paper; only the root sum square TPU calculation is examined.

For case studies, two surveys were used to produce an ERZT surface in areas also with VDatum coverage. The ERZT surface was compared to VDatum by differencing the estimates for the datum separation over the survey area.

Results

Two ERZT case studies based on data extracted from different NOAA surveys are presented. One ERS was conducted in Port Madison, Washington (Puget Sound) by NOAA ship *Fairweather*, designated as survey H12216; the other ERS was conducted in Chesapeake Bay by NOAA ship *Thomas Jefferson*, designated as survey H12180. In both cases, the tidal datum used was mean lower low water (MLLW). The root sum square uncertainty for both survey ERZT surfaces was less than 0.1 meters (ERZT $\sigma < 10$ centimeters).

An example of one vessel's survey day time series for the estimate of the ellipsoid to MLLW SEP is shown in Figure 1.

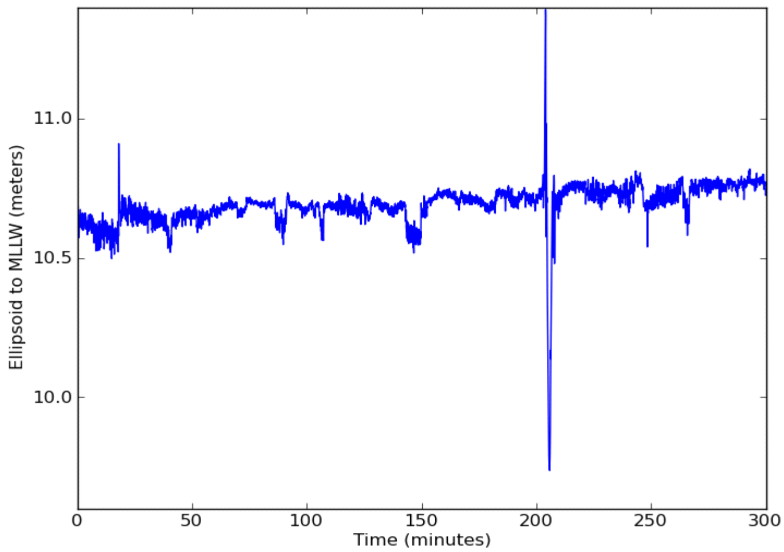


Figure 1 – Time series of ellipsoid to MLLW separation as estimated from one vessel with no filtering

The ellipsoid to MLLW difference from two different days with the same vessel in the same 0.5 square kilometer area is shown in figure 2.

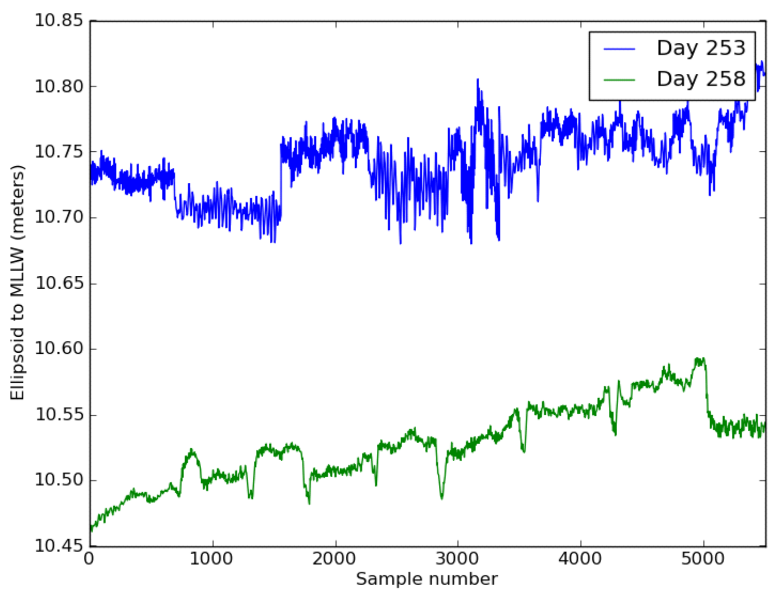


Figure 2 – Ellipsoid to MLLW separation estimates from the same survey vessel on two different days.

Figure 3 shows (a) the ERZT MLLW SEP, (b) the VDatum MLLW SEP, and (c) the difference between (a) & (b) for H12216. VDatum Puget Sound SEP MLLW modeled uncertainty [VDatum Report, 2010] is in Table 1, and Table 2 shows the statistics associated with the difference surface.

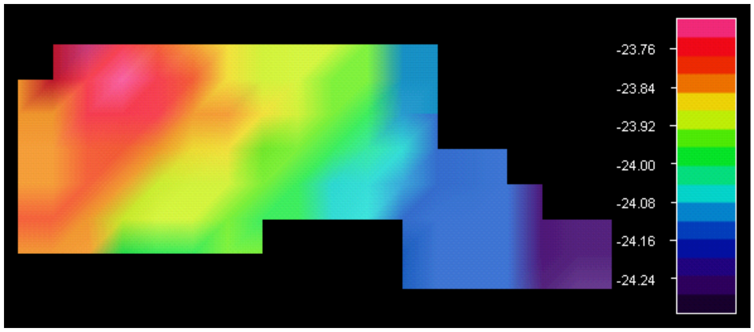


Figure 3a –ERZT MLLW SEP surface for NOAA H12216 [height in meters]

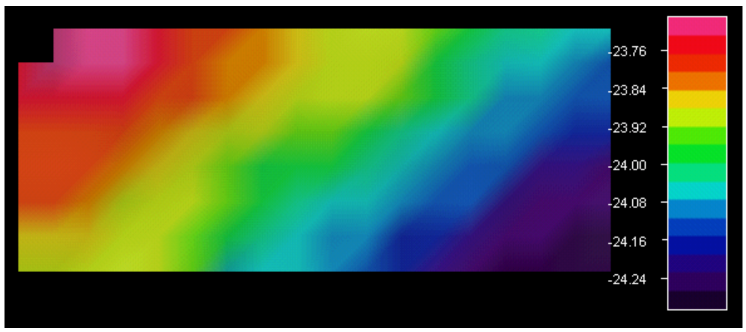


Figure 3b – VDatum MLLW SEP surface for NOAA H12216 [height in meters]

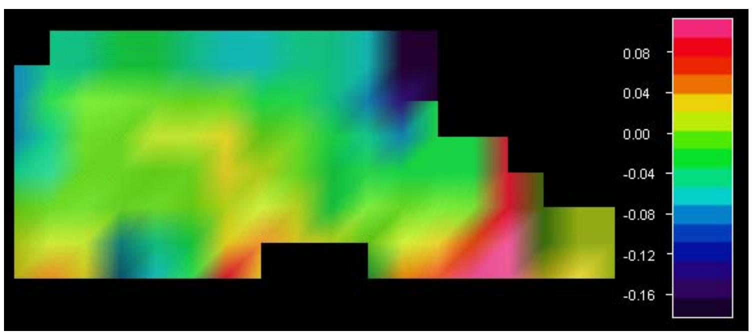


Figure 3c – Difference surface between ERZT and VDatum for NOAA H12216 [height in meters]

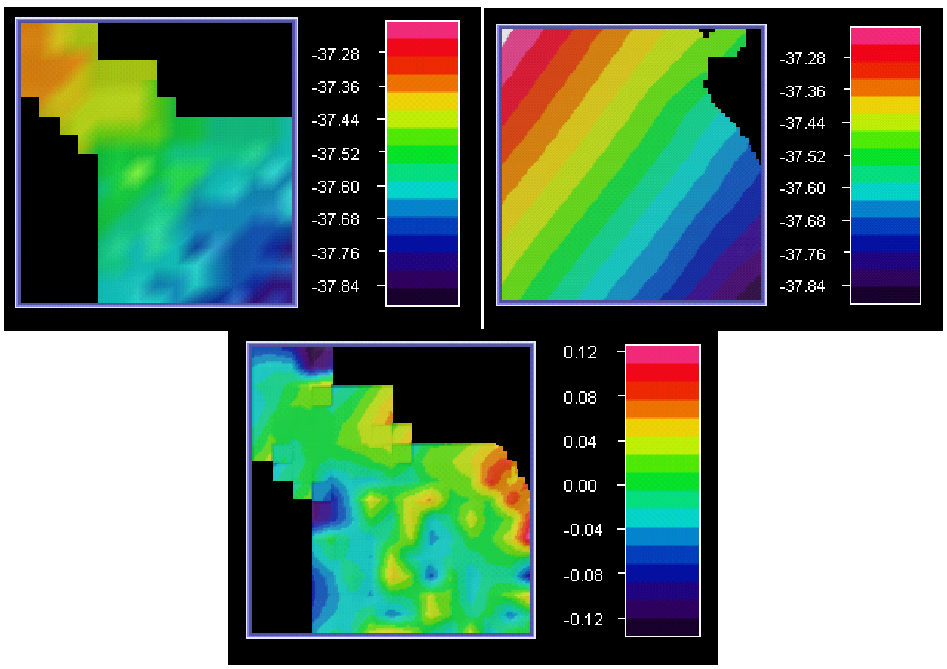
Table 1 describes the uncertainty associated with VDatum in the area of Puget Sound

ITRFxx to NAD83 transformation σ	2.0 cm
NAD83 to NAVD88 transformation σ	5.0 cm
NAVD88 datum realization accuracy	5.0 cm
NAVD88 to LMSL transformation σ	2.1 cm
LMSL datum realization accuracy	1.5 cm
LMSL to MLLW transformation accuracy	5.2 cm
MLLW datum realization accuracy	1.5 cm
Total VDatum σ (root sum square)	9.5 cm

Table 2 – Statistics for the difference surface between ERZT MLLW SEP and VDatum MLLW SEP for NOAA H12216

Mean Difference	-0.01 m
Standard Deviation Difference	0.05 m
Difference Range	-0.18 to +0.11 m
Combined Difference Uncertainty ($\sqrt{VDatum\ \sigma^2 + ERZT\ \sigma^2}$)	0.14 cm

Figure 4 shows (a) the ERZT MLLW SEP, (b) the VDatum MLLW SEP, and (c) the difference between (a) & (b) for H12180. VDatum Chesapeake Bay SEP MLLW modeled uncertainty is in Table 3. Table 4 shows the statistics associated with (c).



(a) top left (c) middle bottom (b) top right

Figure 4 Depicts the area from NOAA survey H12180 with a vertical scale in meters. 3a is ERZT surface, 3b is the VDatum derived ellipsoid to MLLW surface, 3c is the ERZT and VDatum difference.

Table 3 describes the uncertainty associated with VDatum in the area of Chesapeake Bay

ITRFxx to NAD83 transformation σ	2.0 cm
NAD83 to NAVD88 transformation σ	5.0 cm
NAVD88 datum realization accuracy	5.0 cm
NAVD88 to LMSL transformation σ	5.6 cm
LMSL datum realization accuracy	1.6 cm
LMSL to MLLW transformation accuracy	3.1 cm
MLLW datum realization accuracy	1.6 cm
Total VDatum σ (root sum square)	10.0 cm

Table 4 – Statistics for the difference surface between ERZT MLLW SEP and VDatum MLLW SEP for NOAA H12180

Mean Difference	<0.01 m
Standard Deviation Difference	0.03 m
Difference Range	-0.14 to +0.13 m
Combined Difference Uncertainty ($\sqrt{VDatum\ \sigma^2 + ERZT\ \sigma^2}$)	0.14 m

Discussion

ERZT SEP surfaces have been computed using data from two NOAA surveys and compared to that published in NOAA VDatum. There is general agreement between the MLLW SEP produced by the ERZT method as described here and with the VDatum product for both survey areas. The standard deviation of the difference surface for each survey is significantly lower than the corresponding combined modeled-uncertainty value (TPU), but comparable to the magnitude of the difference range.

The vessel to ellipsoid reference component of ERZT usually has higher frequency noise, associated with short-period variations in the GNSS solution and the inertial motion filter. The vessel waterline reference exhibits an error that is on the medium- to low-frequency range of the motion spectrum. Tide datum models based on observed water levels cannot account for those sea surface topography events in the survey area not experienced or sampled at the water level gauge(s), regardless of frequency.

The time series depicted in Figure 1 contains examples of the high frequency noise from the IAPPK ellipsoid heights as well as the vessel dynamic waterline reference (errors). The ellipsoid reference generally fluctuates with centimeter-level variation, but infrequently there are large spikes, as in the time series presented in Figure 1 just after time 200 minutes. Both of these effects are easily filtered by simple interpolation or averaging as they are of high frequency and generally of a symmetric distribution (zero mean). The medium frequency effects, like the offset at time 145 minutes in Figure 1, result from abrupt changes in the vessel speed, an effect not represented by the smooth dynamic draft calibration table. Because these changes are of finite extent, both in time and magnitude, they also are effectively filtered by computing averages.

Relatively low frequency errors, generally with a period on the order of days, are likely a result of inconsistencies in the zoned tide model. Weather events or other transient forcing conditions such as storm surge or warm water eddies can make water level dynamics in the survey area significantly different than those of the water level gauge. Since the water level gauge drives the model, inaccuracies arise such as those demonstrated in Figure 2. The differences between the estimated ellipsoid to water level separation between two different days, within a half-kilometer area by the same vessel, indicates there was an offset in the water level in the survey area relative to the water level gauge model. Usually these inconstancies percolate to the bathymetric surface as discontinuities and are not properly accounted for in the depth uncertainty model. In an ERS these discontinuities are not contained in the bathymetric surface, or in the final water level referenced product because the datum transformation is justifiably averaged over large areas in the ERZT datum transformation surface (or the vertical datum transformation employed is inherently smooth; e.g., VDatum). Of course any real uncertainty should be properly incorporated into the vertical datum transformation error model for application into the uncertainty of the final depth estimate. Since the source of the uncertainty is the water level estimate, the datum uncertainty component is the best place to contain this effect.

The general agreement between the ERZT method and VDatum is illustrated in Figures 3 and 4, and Tables 2 and 4. The 1-km averaging process produces local fluctuations in the ERZT SEP as compared to corresponding regions in the VDatum surface, but it is not clear whether this represents noise or a physically-meaningful signal.

Another challenge for conducting ERS is the approval of the separation model. NOAA ERS projects (currently) conducted with VDatum must undergo a field-based verification process. ERZT could be used to verify SEP models, like that available in VDatum, in a more streamlined fashion than brute-force comparisons of bathymetric surfaces.

Because ERZT can be conducted anywhere a hydrographic survey is conducted with a water level model, ERZT could be useful for applications similar to those of other separation models. For instance, in a remote area where no separation model exists, the ERZT surface could potentially be used along the shore to support inundation models. This is important because GNSS technology is increasingly used in land survey but vertical heights need to be related back to a gravity-related datum, and available gravity data is often of poor quality just offshore.

Conclusion

ERZT can produce a useful datum separation estimate based on currently approved hydrographic methods. This datum separation estimate is produced using data already synthesized and is largely an automated process. The resulting surface is useful for transforming ERS surfaces to chart datum in areas where an approved separation model does not already exist. In addition, the ERZT can be used to verify other separation models.

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