# The Navigation Surface and Hydrographic System Uncertainty at NOAA's Office of Coast Survey

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**Abstract**

The immense volume of data collected by high-resolution multibeam sonar systems in support of the National Oceanic and Atmospheric Administration's (NOAA) nautical charting mission has overwhelmed manual bathymetric data processing and presentation methods. The integration of multibeam uncertainty modeling techniques developed by the Canadian Hydrographic Service (Hare R, 1995) and algorithms developed by NOAA and the Center for Coastal and Ocean Mapping & Joint Hydrographic Center (Smith, et al., 2002) into the hydrographic processing software package CARIS HIPS 5.4 is a solution that enables the efficient processing and accurate presentation of high-density bathymetry data. In order to fully take advantage of these techniques, knowledge of errors associated with the survey vessel and equipment are necessary. The accuracy of the individual estimates that compose the error model directly determines the usefulness of the new processing techniques. This paper will describe the effort underway to implement these new processing techniques on NOAA's Hydrographic platforms; including the evaluation of uncertainty for NOAA's hydrographic survey vessels, verification of new software, development of field procedures, documentation, archiving of data, and the affect on final charting products.

**Background**

Modern multibeam echosounders produce a huge amount of data. Historically, a final product of a hydrographic survey would be a shoal-biased sounding set, reduced so that individual shoal soundings do not overlap at a specific scale. "Cleaning" a multibeam data set such that it could be reduced to a valid shoal-biased sounding set is a tedious, time intensive and subjective process that can quickly overwhelm a survey team. The process also severely reduces the usefulness of the data beyond nautical charting.

In 2000, the Hydrographic Surveys Division (HSD) requested that the NOAA funded Center for Coastal and Ocean Mapping and Joint Hydrographic Center (CCOM/JHC) research ways to more efficiently process multibeam data. One result of the research conducted at CCOM/JHC was the development of the Navigation Surface concept. The distinguishing feature of the Navigation Surface is that the horizontal and vertical uncertainty for each sounding is used in a weighting scheme to create a digital terrain or elevation model of the seafloor. The Navigation Surface processing workflow offers a new approach to managing, archiving, and creating multiple products from hydrographic survey data. Lieutenant Shep Smith, NOAA, proposed the Navigation Surface concept at the Shallow Survey 2001 Conference (Smith, 2001). LT Smith further developed the concept in his Masters of Science Degree thesis in 2003 (Smith, 2003). NOAA is adopting the Navigation Surface concept into its hydrographic survey and nautical charting process. The algorithms have been made freely available for technology transfer and several vendors have commercialized the concept by incorporating it into their hydrographic and charting software.

In the Navigation Surface approach, survey data are archived as a certified digital terrain model rather than as a discreet set of verified or certified soundings. The archived elevation model is saved at the highest resolution supported by the sounding data. The highest resolution of the data is defined by the size of the beam footprint in a given water depth. For example, if the beam footprint on the seafloor of a full-coverage multibeam survey is 0.5 meter, the elevation model would be saved at a grid spacing of 0.5 meter. The intent of this process is to preserve the highest resolution data, even if such resolution will never appear on a navigational or charting product. Charting products such as paper charts are created from scale-appropriate generalizations of the elevation model (Armstrong, et al, 2003).

**Workflow Development**

The Navigation Surface concept was integrated into the hydrographic processing software program CARIS HIPS 5.4. The software development correlated to LT Smith completing his Master's Thesis at the University of New Hampshire and transferring to the NOAA Ship THOMAS JEFFERSON (TJ) to become the ship's Field Operations Officer. The Office of Coast Survey (OCS) made a commitment to continue the development of the Navigation Surface. Naturally, the TJ was the ideal platform to test and evaluate the new processing techniques. The TJ adopted a parallel processing approach by evaluating the data using both the beta version of HIPS 5.4 and traditional methods.

The seafloor model or Navigation Surface, known in CARIS as Bathymetry Associated with Statistical Error (BASE) surface, uses the computed total propagated error (TPE) associated along with the vertical and horizontal uncertainty of each sounding to generate a multi-attributed mean grid of the seafloor. Using the model, the hydrographer can analyze the data more efficiently by directing attention to only areas with high statistical inconsistencies.

The TJ has been processing data using the new CARIS tools for over a year. They worked closely with CARIS, troubleshooting the software, suggesting improvements and ensuring the software's reliability. The TJ implementation concentrated on guiding the development of Navigation Surface tools in CARIS HIPS. Additional objectives included documenting procedures and best practices for these tools to be used by the NOAA hydrographic fleet.

Testing in the field showed that hydrographer manipulation of the data is reduced as a result of targeting just those areas where significant ambiguity is indicated in the Standard Deviation and Uncertainty attribute layers of the BASE surface. The standard deviation grid is derived from the depth differences of the soundings that contribute to each node. Anomalous patterns in the standard deviation surface are examined to identify systematic errors, burst failures, and seafloor features. Processing efficiencies are gained by addressing only burst failures that affect the Depth surface. Noise in the dataset that does not affect the BASE surface is ignored.

The working knowledge aboard the TJ was distributed throughout NOAA via exchange of personnel, development of written documentation and presentations given at internal meetings. The TJ stayed in close contact with CARIS during testing to provide feedback and suggestions on improvements.

**Validation of Algorithms**

CCOM/JHC researched and published papers on the reliability and efficiency gains achievable through Navigation Surface processing. Several papers are included in the References. Research was mainly conducted by Dr. Brian Calder and Shep Smith. Several surveys processed using the new processing tools were compared to the traditional shoal-bias smooth sheets. The final results compared well, however, the Navigation Surface depths were on average slightly deeper than the traditional smooth sheet depths. There were concerns that the Navigation Surface may be biased towards deeper depths.

In response to the concerns of deep biasing in the Navigation Surface, Dr. Brian Calder wrote,

> "There are essentially three reasons for the 'bias' observed in the comparison:
>
> 1. The CUBE/Navigation Surface method generates 'most probable' depths, with associated uncertainty values, and because they understand and accommodate the uncertainties in input data, the depths generated are typically below the shoalest soundings in the area (and above the deepest soundings). The traditional approach selects only the shoalest soundings everywhere, and therefore would be expected to return soundings shoaler than the CUBE/Navigation Surface methods. This does not make them true, however. The residual picking error of the MBES systems used in this survey (i.e., the consistency of depths from the same MBES in any one region) can be expected to vary from about 5-10cm to over 30cm in places, increasing with depth. Given the 'selected sounding' method's preference for outer-beam soundings, the practical effect could be significantly more. In shallow water, this can easily be 1-2% of depth, typical of many of the discrepancies observed...

2. The comparison was done between hydrographically rounded soundings on the smooth sheet and non-rounded depths from the Navigation Surface product. As observed above, this can lead to significant bias. If the Navigation Surface depths are rounded appropriately, many of the observed discrepancies are either significantly reduced or disappear. In the deeper water, soundings were taken with the Elac 1180 systems, which are also known to be significantly noisier in bottom detection than the Reson 8101s used in the remainder of the survey. Therefore, we should expect higher discrepancies in this region due to a combination of this effect and that of (1) above.

3. The Navigation Surface paradigm allows for the selection of 'Golden Soundings' to represent the hydrographically significant features of the survey. It is possible that some of the discrepancies observed should have been marked in this way, but in this processing no Golden Soundings were selected in order to make the point that in most cases the procedure is unnecessary. The recommended quality control procedure would be to double-check the measurements against the grid and designate soundings as 'golden' as necessary. With current generation tools, this is not particularly time consuming." (Calder, NOAA internal memo, 2004)

It is important to note that the hydrographer has the ability (and responsibility) to review the surface and ensure that it truly reflects the conditions in the survey area. No algorithm will ever perfectly model the seafloor. An experienced hydrographer must review the data and occasionally select "designated" soundings (CARIS's implementation of "Golden Soundings") which override the gridded surface and force the model to recognize the shoal sounding. Especially in the case of small diameter objects (pilings, small rocks, etc.), depending on the resolution of the gridded surface, it is unlikely that the surface will capture the absolute least depth.

CCOM/JHC research proved that the Navigation Surface concept can provide an accurate statistical representation of the seafloor. Additional tests were conducted to ensure CARIS's implementation of Navigation Surface met NOAA's standards.

Validation of the BASE surface processing workflow was accomplished, in part, by comparing the results of a traditionally processed survey to the results of the survey processed with BASE surface. This was done to ensure that BASE surface resolution standards properly depict navigationally significant least depths without intensive manual selection of Designated Soundings by a hydrographer. The NOAA ship WHITING surveyed Woods Hole, MA, in 2001 with a RESON 8101. The survey was initially processed with an older version of CARIS HIPS, where the data was processed line by line, noise in the data ("fliers") was rejected, then a shoal-biased smooth sheet was created. The same data set was then reprocessed in 2004 using CARIS HIPS 5.4 BASE surfaces. The procedures and conclusions were presented by Crescent Moegling at the CARIS 2004 conference in Hamburg Germany (Moegling, 2004). The majority of sounding comparisons agreed well within the International Hydrographic Organization (IHO) standards for an Order One survey. The more significant discrepancies were on slopes where correlation of nodes was difficult due to steep bottom change. The BASE surface did not depict small features (small isolated rocks) at courser grid resolutions (Figure 1).

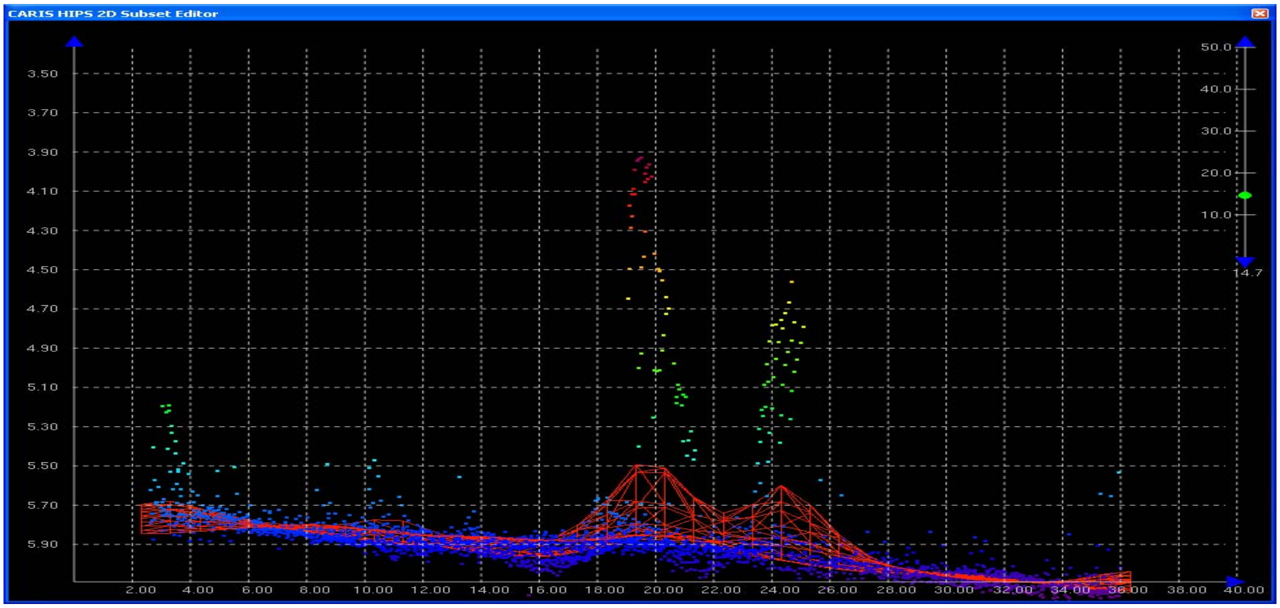


Figure 1. *BASE Depth Surface (1.0 M resolution) in approximately 5 meter water depth*

The BASE Surface resolution greatly affects the ability of the model to determine accurate least depths over small objects. The hydrographer must pick a resolution that is appropriate to the area being surveyed (Figure 2). If the grid resolution is too fine, the computer processing load increases exponentially and data files become unmanageably large. If the grid resolution is too coarse, then the model cannot accurately depict smaller objects. Necessitating manual selection of Designated Soundings by the hydrographer to ensure proper least depths are charted (Figure 3). Currently, the hydrographer must balance the two extremes and chose grid sizes and resolutions that are appropriate for the project area.

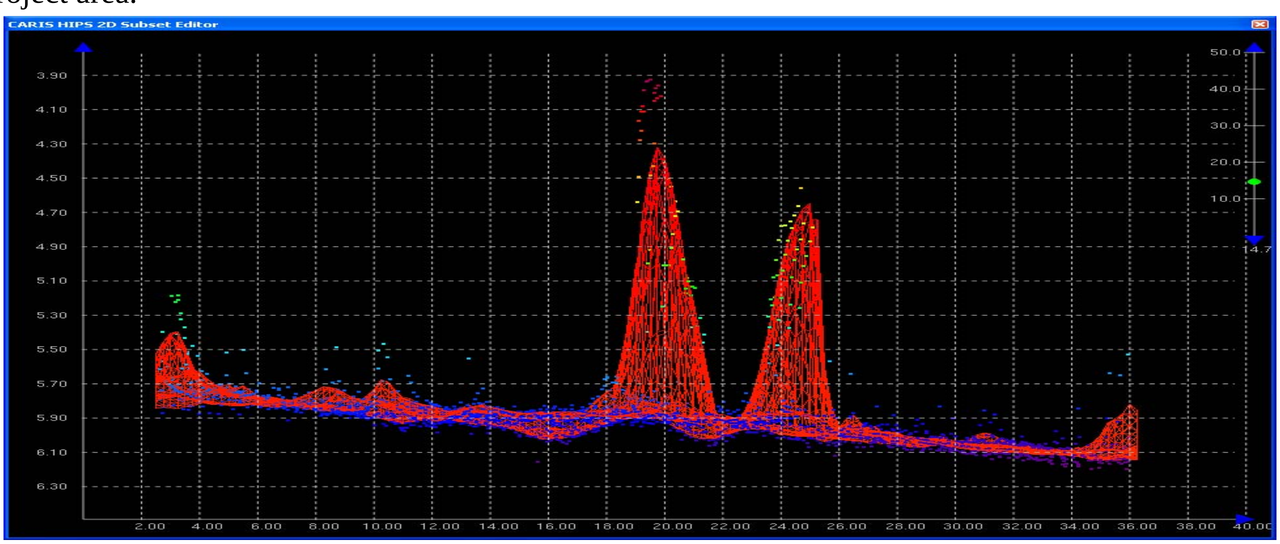


Figure 2. *BASE Depth Surface (0.25 M resolution)*

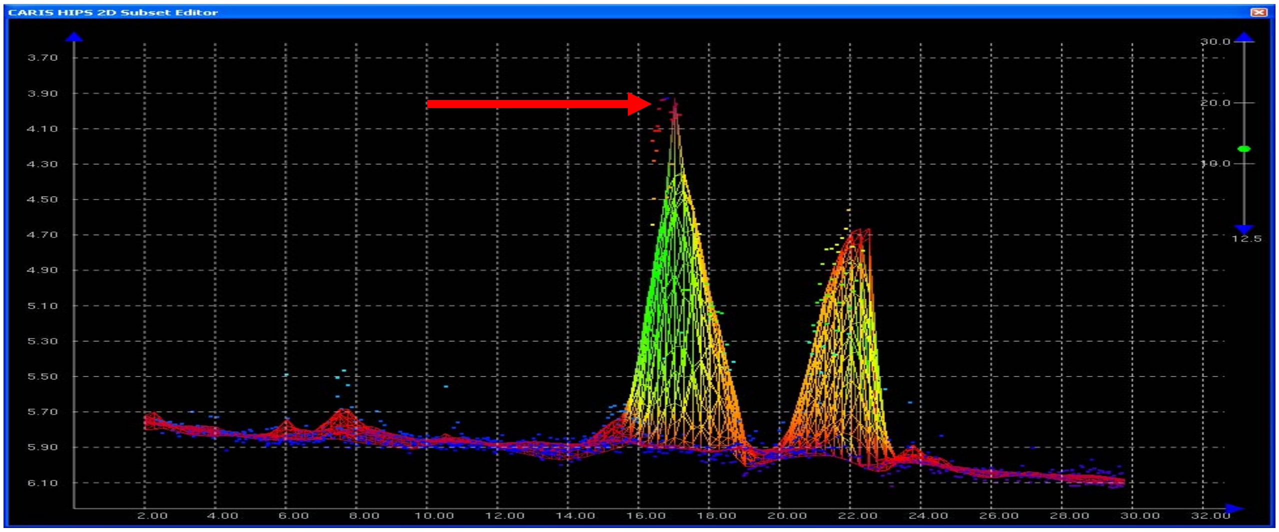


Figure 3. *BASE Depth Surface (0.25 M resolution) with Designated Sounding*

The CARIS 5.4 workflow model and the uncertainty estimates used to compute the TPE were further tested on a survey conducted in Sitkalidak Strait, Alaska. The survey area is characterized by dramatic, irregular bathymetry. The depth range for the survey area varies from over a hundred meters to less than five meters.

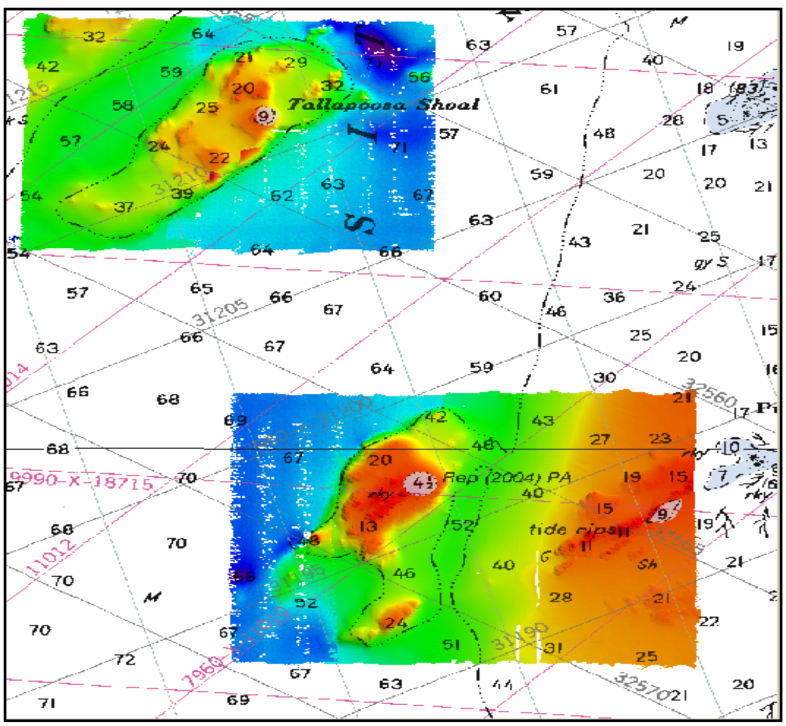


Figure 4. - *Sitkalidak Strait Survey Area overlaid on NOAA Chart 16592 (Charted depths shown in fathoms)*

Similar to the Wood Hole survey, Sitkalidak Strait was parallel processed using the BASE surface features in CARIS 5.4 and traditional line processes. Depths generated from the BASE surface grid nodes were compared to depths generated by the traditional shoal biasing method. The datasets were compared by both visual inspection and by differencing grids made from both datasets.

In order to difference the grids the data was first exported from CARIS to MapInfo. Vertical Mapper®, in MapInfo Professional® GIS software was used to create TIN grids. The Vertical Mapper® grids were created using the interpolation "Triangulation-with-Smoothing" method. The maximum triangle side limit was set to 250 meters and minimum coincident point aggregation was selected. The cell size was set to 15 meters, which was the resolution of the two datasets. The grid generated from the line bathymetry was subtracted from the grid created with the BASE surface depths using Vertical Mapper® Grid Manager. The absolute difference (at a 95 % confidence interval) for this survey was found to be 2.11 meters (table 1).

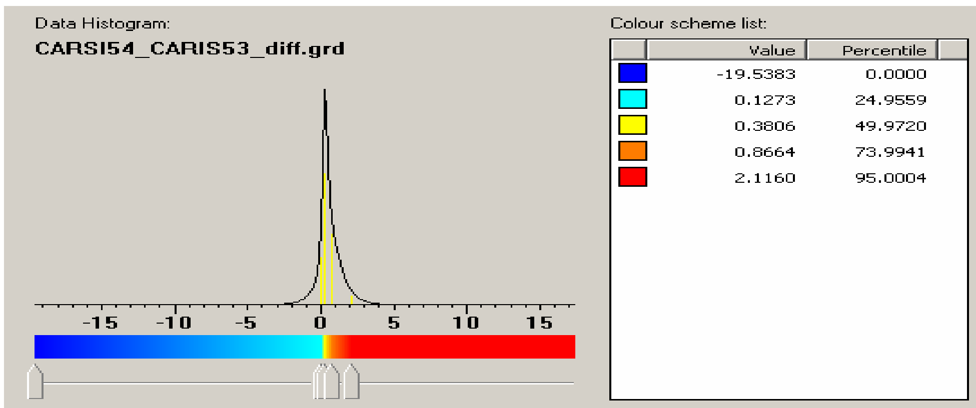


Table 1. *Data Histogram of the differences between the BASE surface-processed depths and line-by-line shoal biased-processed depths*

The discrepancy between the BASE surface and shoal biased processing is expected. Dr. Calder described, some of the variation between the grids is due to the difference in data representation between the shoal biased line data and the BASE surface.

Similar to the Woods Hole parallel processing results, the bulk of the differences between the BASE surface generated sounding set and the traditional shoal biased sounding set is a result of horizontal nodes displacements between the grids. This was confirmed by evaluating the differences between the two datasets on a slope aspect grid. Areas of high slope (as indicated by the red color in Figure 5) correlated with the greatest differences between the two datasets.

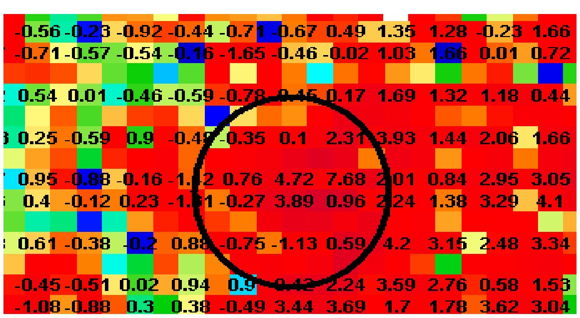

Figure 5.-*Grid difference overlaid on a slope aspect grid*

Manual comparison between the two dataset revealed average differences of a meter or less. These discrepancies are within the International Hydrographic Organization's allowable error tolerances for an Order 1 survey at the selected water depths. The least depths selected as Dangers to Navigation agreed exactly with the BASE surface, as they were previously flagged as Designated Soundings. Grid coarseness may have also affected the results of this comparison, especially in areas of greater slope. Since there are no tools for differencing surfaces in HIPS, the overall resolution (15M) was directly related to the number of data points that can be imported in MapInfo.

**Uncertainty Estimates**

Precise measurements are fundamental to the field of hydrography. Synchronization of multiple sensors with the sonar system is essential for meaningful spatial analysis of the data. All measurements, however careful and scientific, are subject to some uncertainties. Error analysis is the study and evaluation of these uncertainties with the purpose of estimating the extent of the uncertainties and when possible, reducing them.

Uncertainty-based processing has fundamentally altered bathymetric data processing and product creation. The validity and usefulness of the products are directly correlated to the accuracy of the individual estimates that compose the error model. The error model incorporated into CARIS is contained in the HIPS Vessel File (HVF). The HVF has entries for the uncertainties associated with the sensor and sonar, physical offsets, latency, draft, loading, tide and tidal zoning.

In order to develop an accurate error model, the sources of uncertainty were evaluated and quantified on the NOAA Ship RAINIER. RAINIER has eight survey platforms, most of which are configured with multiple sonar systems. In the process of completing a comprehensive error analysis the following challenges were confronted; limited knowledge of uncertainty associated with certain error sources, manufacturers not documenting the errors associated with their equipment and the inclusion of non-vessel specific error sources in the CARIS HIPS Vessel File.

The uncertainty estimates for the auxiliary sensors (i.e. inertial navigation system) were derived mainly from manufactures specifications with the exception of sound velocity and positional uncertainty. Documenting the uncertainty of the sonar equipment, however, proved to be more challenging. This was a direct result of some of the manufacturers not releasing error estimates for their sonar equipment. These uncertainty estimates are complex and associated with proprietary algorithms. These unavailable error estimates resulted in rough approximations for significant error sources.
The authors highly recommend that NOAA explicitly insists on the release of sonar error estimates and methods of the error deduction from the manufactures prior to any future equipment purchases.

The uncertainty associated with static draft, loading and alignment of the sensors and sonar to the ship's reference frame were only loosely understood on RANIER since it had not been routinely measured prior to implementation of the uncertainty processing paradigm. Despite these inadequacies (which will be addressed as resources are allotted) the sum of these errors is relatively minor when compared to the most significant source of uncertainty in the error budget.

Water level correction is often the largest source of error for shallow water multibeam surveys. Water levels are recorded at tide gauges but the spatial-temporal variation of tides across a survey is not well understood or modeled. Currently, NOAA's Center for Operational Products and Services (CO-OPS) computes the uncertainty associated with the primary tide gauge for each discrete six minute water level sample and the total uncertainty for discreet tidal zoning is estimated by bounding the survey area post acquisition. The uncertainty of tidal zoning is affected by topographical and bathymetric geomorphology, the number of gauges in a given region, tidal range, degree of historic water level observations and confidence in the hydrodynamic modeling of the region.

In order to better quantify the error associated with water levels and tidal zoning, CO-OPS is developing and testing the use of GPS-tracked buoys**,** Tidal Constituent and Residual Interpolation (TCARI), Kinematic Global Positioning System (KGPS), and the Vertical datum (VDatum) (Imahori, et al., 2003). TCARI separates the tide prediction constituents from the residuals caused by local atmospheric and other effects and extrapolates the residuals. The result is a weighted mean between those effects seen at several stations (Hess, 2002). To benefit from of Real Time Kinematics water level measurements and high resolution tidal zoning models, the application of these uncertainty estimates must be survey or project level specific.

## Non-Vessel Related Uncertainty Estimates

The integration of water level, tidal zoning, and sound velocity uncertainty estimates in the HVF greatly diminished the value of the error model. Similar to the other uncertainty estimates contained in the HVF, the accuracy of the sound velocity probe and tide gauge are derived from the precision of the equipment. However, unlike the other uncertainty estimates, water level and sound velocity corrections are not strictly related to a vessel. It is, for example, feasible that two different types of sound velocity probes could be used on a single vessel. This could be adequately depicted by creating separate HVFs that are unique to the equipment or by adding a timestamp to differentiate the equipment and associated error. It is much more difficult to track and compute spatially and temporally variable error sources such as tidal zoning or sound velocity. In order to accurately depict the tidal zoning variability throughout a project each survey would necessitate a separate HVF. Ultimately this would lead to an unwieldy combination of HVF's created for each vessel, for each survey, and potentially for each different type of sound velocity or tide gauge equipment used. An alternative method of error application needs to be developed so that non-vessel specific uncertainty estimates are not contained in the HVF.

## Documentation and Training

One major component of implementing any new technology is creating detailed documentation and providing proper training to personnel. New software versions rarely have proper documentation or training materials and CARIS HIPS 5.4 was no exception. As a means of compensating for this lack of documentation a major effort is underway within NOAA to complete a new Field Procedures Manual (FPM). The effort began with the TJ's development of field procedures and documenting their processes in a Standard Operating Procedures (SOP) document. The FPM will take into account the TJ's SOPs and techniques as further developed and documented in the SOPs of other NOAA platforms.

Official training was difficult since CARIS HIPS 5.4 was released after the beginning of the field season. In 2004, training typically occurred "on the job", or by rotating personnel that had experience with HIPS 5.4 to other vessels that lacked the experience. In 2005, all field units will have CARIS HIPS 5.4 training available before the start of the field season.

Based on the completion of several studies and the positive results found in the field, a Hydrographic Surveys Technical Directive (HSTD) was issued allowing NOAA field units to officially begin processing multibeam data using BASE surfaces. The HSTD stresses that, "The new processing techniques do not remove the requirement for hydrographers in the field (or personnel in the QA Branch) to review full resolution data. All critical soundings and dangers to navigation must be thoroughly reviewed to ensure that the appropriate depth will be forwarded for chart compilation." The new techniques provide a new tool that allows the hydrographer to focus on the important areas of the survey instead of needing to review each and every ping.

There is an attempt to stay updated with documentation as new versions of the software are released and as new more efficient procedures are developed in the field. This effort, however, is complicated by the ships that work in remote areas and therefore have limited communication.

**Hydrographic Office Quality Assurance**

The processing procedures and field deliverables discussed in this paper have altered the quality assurance techniques used by NOAA's Hydrographic Branches. The validity of the uncertainty estimates contained in the HVFs and the computation of the Total Propagated Error are initially assessed and reviewed as necessary (such as in the case of equipment change). This promises significant time saving for quality assessment since the computed TPE value is a stand alone assessment of survey data quality.

An additional gain in efficiency is achieved with BASE workflow by automating some cartographic processes that were once manually intensive. Contour generation and smoothing can be done directly from the surface in CARIS FieldSheet Editor. The output of CARIS FieldSheet Editor is a .hob file that can be used for S-57 ENC creation. These efficiency gains will be ideally utilized to reduce the throughput time necessary for survey data to be applied to a chart.

## Future Developments

CARIS HIPS 6.0 is due for release in the first quarter of 2005. It will include the Combined Uncertainty and Bathymetric Estimator (CUBE) algorithm developed by Dr. Brian Calder at CCOM/JHC. The current BASE Surface in CARIS uses all soundings to compute a statistical depth for each node of the grid. “Noise” in the data will affect the depth value at the node. If the affect is great enough, the hydrographer will need to ‘reject’ the bad data, to ensure the grid properly models the seafloor. CUBE is designed to accommodate areas where the data may conflict. Areas with multiple statistically valid depths are represented as different “hypotheses”. A hypothesis is defined as a depth estimate, which corresponds to a group of soundings that are internally self-consistent. For example, a school of fish might trigger its own depth hypothesis along with that of the seafloor. The hydrographer can then review these secondary hypotheses and determine their validity. (Brennan, 2004) If the CUBE algorithm chooses the correct hypothesis, no action is required by the hydrographer.

CCOM/JHC has conducted numerous studies showing the time savings and validity of the CUBE algorithms. Once CARIS HIPS 6.0 is released, NOAA will conduct studies to ensure that the CARIS implementation of the CUBE algorithms is valid. New field procedures will need to be developed and documented and personnel will need to be trained.

One benefit of moving to the Navigation Surface concept is archiving high resolution data that can be used by non-navigation communities. The final Navigation Surface of a survey provides details of sand waves, rock outcrops and other bottom features that can be useful for marine geologists, bethnic habitat researchers, and others. NOAA plans to archive the Navigation Surfaces for each survey at the National Geophysical Data Center (NGDC), where the general public will have access to the data.

## Summary and Conclusion

After several years of development, testing and evaluation, NOAA is in the final stages of the Navigation Surface implementation. As with any new technology, the process was not as straight forward as desired or expected. Much work was required to develop the new algorithms, test the implementation, develop and document field procedures, and formally authorize the use of the new techniques.

The effort took the combined skills of researchers at CCOM/JHC, field expertise of the NOAA Ships THOMAS JEFFERSON, RAINIER and FAIRWEATHER, numerous dedicated individuals at the Hydrographic Surveys Division Quality Assurance Branches in Norfolk and Seattle, the commitment of resources at headquarters and the help of our private sector partners.

The end result of this effort will allow NOAA to provide navigation products in a more timely and reliable manner and to potentially expand the significance of the product to a greater number of users.

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