Assessing 155 Years of Hydrographic Survey Data for High Resolution Bathymetry Grids

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Abstract **- Seafloor representation over vast areas requires the fusion of depth measurements from numerous data sets having variable spatial resolution and coverage. The most extensive coverage for U.S. coastal waters usually consists of data from hydrographic surveys conducted between 1850 and 2006. Intended for navigational charts, these survey projects have been planned, collected, and processed by the National Oceanic and Atmospheric Administration's National Ocean Service and its predecessor organizations over the past 155 years. Integrating the extremely dense and localized data from modern multibeam echo sounders with the much more significant area coverage of older survey data presents the fundamental challenge when creating high resolution coastal bathymetry grids.**

Data from nearly 7000 hydrographic surveys are being assessed to produce bathymetry grids for the coastal U.S. Every survey in the database is associated with metadata attributes summarized from the survey's descriptive report. Compiling high quality coastal bathymetry over extensive regions involves several hundred surveys whose range in age often spans over a century. Compared to survey measurements and the original hydrographic processing shortly after field collection, the greater uncertainties in representing the seafloor come from errors in the archive data retrieval processing that occurred years after field collection, as well as from the unknown depths between sparse soundings of historic surveys, whose interpolated values will constitute a substantial portion of gridded bathymetric coverage for the entire U.S. coast.

I. Introduction

Hydrographic surveys conducted by National Oceanic and Atmospheric Administration (NOAA)'s National Ocean Service (NOS) and its predecessor organizations constitute the primary, if not the sole, sources of depth information to reconstruct the coastal seafloor topography around U.S. waters, as well as for depicting depth on approximately 1000 navigational charts produced by NOAA. Current bathymetry grid development is focused on the quality of data processed from multibeam echo sounders (MBES) that collect voluminous measurements of depth (soundings) within a small locality. Nevertheless, the best available survey coverage for the majority of U.S. coastal waters consists of widely spaced soundings from NOS hydrographic surveys conducted between 1850 and 2006 (Fig. 1). Integrating the extremely dense MBES data, which cover a fractional area along the coast, with the much more significant coverage of interpolated older survey data, presents the fundamental challenge when creating high resolution bathymetry grids needed for hydrodynamic ocean models, coastal inundation models, nearshore geomorphologic change detection, estuarine ecosystem models, benthic habitat maps, satellite altimetry calibration, digital elevation models, and navigational charts.

Originally collected and processed for navigational charts, the NOS hydrographic surveys cover variable areas with different spatial resolutions. Every survey has a unique coverage that often overlaps, adjoins, or supersedes existing older bathymetry data (Fig. 2 and Fig. 3). As a result, the hydrographic data over extensive coastal regions are mostly comprised of widely spaced soundings from hundreds of surveys whose variable spatial resolutions challenge conventional mapping techniques when attempting to represent the most reliable depths.

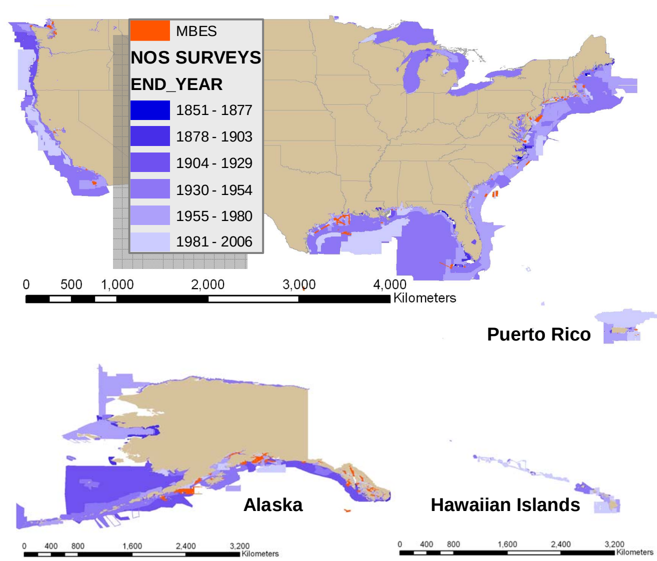

Figure 1. The most extensive coverage of U.S. coastal bathymetry comes from NOS surveys with widely spaced soundings (blue), in contrast to the local coverage of multibeam echo sounder (MBES) surveys (orange). Most surveys employed lead-line and single vertical beam echo sounders.

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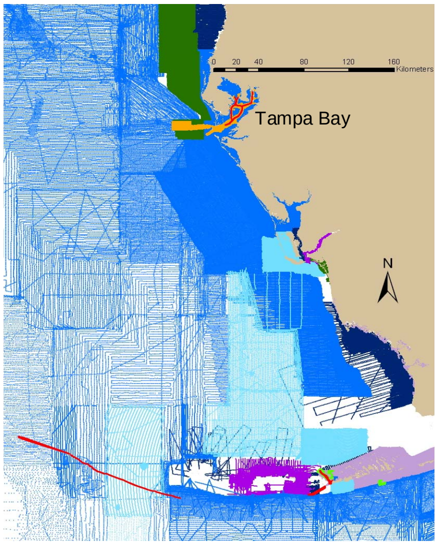

Figure 2. Location and collection year of NOS surveys for the eastern Gulf of Mexico. Regional bathymetry was compiled to develop the numerical model to forecast harmful algal blooms. The most recent soundings were selected from approximately 200 hydrographic surveys dating back to 1852.

Publicly available bathymetry compilations are usually generated from all of the available archive survey data [e.g., 1]. While acceptable at resolutions coarser than the largest estimated positional errors, compiling appropriate data for reliable coastal bathymetry at finer resolutions requires selective filtering and assessment of errors that propagate through the depth measurements, sounding positions, water level adjustments, datum transformations, original survey processing, and archive survey database processing. The most reliable source of high resolution bathymetry is interpolated from soundings selected by their quality, which is generally associated with the project, age (the end year of field collection), scale, and processing methodology of the hydrographic survey data.

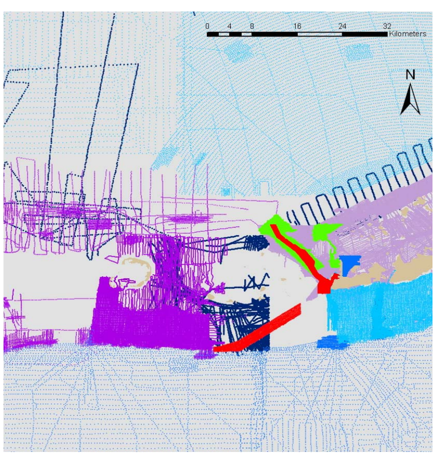

Figure 3. Detailed view of soundings from thirty-five NOS surveys in the Florida Keys of the eastern Gulf of Mexico. Dates range from 1852 to 2000.

II. Hydrographic Data Collection

NOAA NOS Office of Coast Survey (OCS) and NOAA's National Geophysical Data Center (NGDC) are assessing the bathymetry warehouse of digital data from nearly 7000 hydrographic surveys conducted between 1850 and 2006. Survey depth measurements were collected using different sounding methods, positioning systems, horizontal datums, and vertical (tidal) datums. The accuracy of multi-temporal survey data sources first depends on the standards used for sounding collection and position determination.

The surveys were conducted using different sounding methods. Lead-lines, sounding poles or wire-drag methods are typical for surveys from the late 1800's until the 1930's, while vertical (single) beam echo sounders (VBES) have been used in survey projects from the 1930's to present [2, 3]. The revised Hydrographic Manual of 1942 also gives instructions for radio acoustic ranging techniques [4]. Sounding record books and field sheets tracked daily depth measurements as they were collected, until after 1960 when soundings were acquired and recorded digitally by the survey vessels [5, 6]. Multibeam echo sounders (MBES), which were experimental in the 1980's, transitioned to operational use since the mid-1990's. The sonar systems employed a wide range of frequencies with varying beam widths.

From the late 1800's, nearshore soundings are commonly plotted at scales that range from 1:2,500 for harbors and channels to 1:80,000 for open ocean surveys, with 1:20,000 being the most commonly used scale. Soundings are adjusted for tides at the same intervals as the depth measurements. The hydrographic manuals recommend that many more soundings be processed than can be plotted to ensure plotting accuracy, especially with rapid changes in depth toward shoal areas.

Sounding locations were determined with different navigation methods. Visual navigation (three-point sextant fixes to objects on shore) was the most common method of survey positioning until the 1930's, and continued to be used for nearshore positioning until the 1980's. Radio waves were first used for offshore positioning in the 1930's. The electronic positioning systems became more accurate and reliable over the years, until they were operationally replaced by global positioning systems (GPS) in the mid 1990's.

III. A National Data Repository

The retrieval and transfer of hydrographic survey data to build a national repository occurred up to decades after their original processing for navigational products. The initial NOS data retrieval project, referred to as the Asheville Project, transferred data into electronic format by manually digitizing the smooth sheets of ~3200 selected surveys conducted in the 1930's through 1973. OCS later selected smooth sheets from an additional ~1100 historic surveys for two digitizing projects managed by NGDC between 1992 and 2005. Data from digitized smooth sheets, along with ~2500 NOS surveys originally processed and submitted in various electronic formats, were translated into a unified (HYD93) format in 1993, assimilated into NGDC's interactive GEOphysical DAta System (GEODAS), and made available for public distribution since 1996 [7].

The Coast Survey Bathymetry Warehouse (CSBW) recently became the unified repository of the NOS hydrographic survey sounding records in order to support navigational chart production and public users of the data. The CSBW recently incorporated all the NOS survey data stored in GEODAS, combined with data from about 300 surveys conducted within the last decade. Every survey in the bathymetry warehouse is associated with metadata that include the unique survey identifier, parameters (soundings, features, or both), file creation date, file modification date, source institution, platform, start and end years of survey field collection, survey scale, general and specific geographic areas, position determination, original horizontal datum, calculated horizontal datum, original vertical (tidal) datum, calculated vertical datum, average tide range during the survey, original sounding units, sounding method, method of sound velocity correction applied to the acoustic depth measurements, data archival processing methodology, geographic coordinates of the survey area as a minimum bounding rectangle, the survey outline's geometry index, in addition to the universal resource locators of the original survey instructions, smooth sheet image, and descriptive report.

Soundings and features parameters relate to metadata fields by using the survey identification as the unique primary key. Depths were converted from the survey smooth sheet's sounding units (i.e., feet, fathoms and feet, fathoms and tenths, meters), and were stored as tenths of meters, thereby preserving the shoal bias of the original survey data. Descriptive Reports are normally available for NOS hydrographic surveys.

The archive soundings are originally referenced with different horizontal datums. Soundings retrieved from the survey smooth sheets are converted into a national standard geographic coordinate system that conforms to the geoid [9]. The original horizontal datum of each survey is transformed to North American Datum 1983 (NAD 83), which is equivalent to the World Geodetic System 1984 reference used by unaugmented global positioning systems. For surveys before 1927, horizontal coordinates are transformed using a single pair of datum latitude-longitude shift values for the entire survey to approximate the North American Datum 1927 (NAD 27), which is then transformed to NAD 83 using the North American Datum Conversion software utility (NADCON) developed at NOAA NOS [10].

IV. Archive Quality Control of Bathymetry

In contrast to the standards employed to assure the quality of the original NOS survey measurements (with their accepted shoal bias), uneven quality control occurred during the digitizing and archive data retrieval processes. Digital data originally processed by NOS OCS and surveys retrieved by NGDC undergo visual inspection to detect gross errors before assimilation into the bathymetry warehouse. Data digitized by the Asheville Project in the 1970's are least reliable due to the absence of integrated quality control procedures. At the time, NOS assumed that errors would be detected and removed when the data are accessed by scientific users. With at least 45 percent of the surveys in the bathymetry database lacking assured quality, a variety of archive data retrieval processing errors have been identified by users over the years. When these errors are reported and verified, corrections are applied to the survey records in the bathymetry database.

Particularly for surveys retrieved and processed from the Asheville Project, two types of data errors are being addressed for each survey: co-located soundings (multiple depths at coincident locations), and sounding outliers.

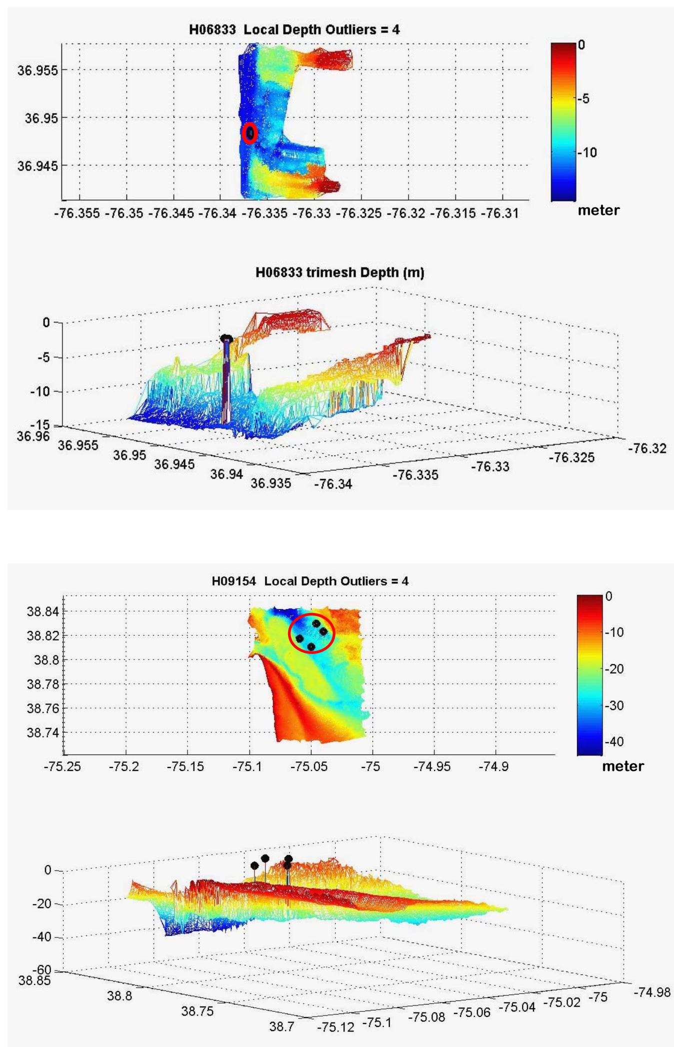

Figure 4. Outliers are identified on individual surveys before grid creation by using refined Delaunay triangulation and robust statistical criteria to detect unusual changes in depth with respect to distances around neighbor soundings.

To prevent poor interpolation of sparse soundings into grids, a unique depth must be selected for every point location of each survey. For co-located soundings that have identical depths, we use only a single point. For co-located soundings with depth differences that fall within the current NOS criteria for object detection [3], we select for the single shoalest sounding point from each set of identical geographic coordinates within a survey. If the depth differences of co-located soundings fall outside the NOS object detection criteria, a single depth value for each set of co-located points is manually selected by comparing the suspicious soundings against the survey's smooth sheet. For each survey, only a single depth value at every sounding point location is activated for grid generation.

Two general categories of anomalous soundings have been identified. Positional outliers are recognized by their extreme distance from the major survey area. Depth outliers in test areas have been flagged by using refined Delaunay triangulation and robust statistical criteria to detect unusual changes in depth with respect to distances around neighbor soundings (Fig. 4). Egregious depth outliers in the CSBW have also been found by identifying the historical surveys whose depths are significantly different from the depths of soundings on NOAA electronic navigational chart (ENC) cells. As with the co-located soundings, the statistically detected outliers are verified by visual comparison against the survey smooth sheet images. The anomalous soundings are then flagged, corrected or inactivated when producing bathymetry grids.

Anomalies in the bathymetry data warehouse are identified prior to grid creation for several reasons. First, quality controlled archive data optimizes the efficiency and accuracy of grid generation. Second, egregious systematic errors from the archive data transfer processes need to be identified and corrected in the CSBW. Third, minimizing the systematic and random errors in the survey sounding sets before grid compilation improves the uncertainty analysis of gridded bathymetry by eliminating error sources resulting from the archive data transfer processes. Finally, the CSBW supports public users who may prefer to apply their own grid generation schemes.

V. Merging Historical and Modern Data

As with the horizontal datums, soundings from surveys are originally referenced to different tidal datums and tidal epochs throughout more than fifteen decades. Data collected along the Atlantic coast before 1980 are usually referenced to Mean Low Water (MLW) tidal datum, whereas Mean Lower Low Water (MLLW) is the tidal datum for most NOS hydrographic surveys conducted since 1980. Prior to creating regional surface models, depths are converted to a standard vertical reference in areas where the VDatum transformation software is available [11, 12]. Software for datum conversions such as NADCON and VDatum are essential to ensure consistent merging of coastal geospatial data [13].

When compiling regional bathymetry for coastal ocean models and for testing the development of future navigational charts, vector or raster layers representing survey boundaries are generated to create the spatial coverage necessary to distinguish data from different projects, end year of field collection, and scale. Adjacent surveys from the same project or whose age difference falls within a few years are sometimes merged together. Often resembling a jagged multilayered jigsaw puzzle (e.g., Fig. 5), the attributed polygons or surface layers are used to select for the most reliable soundings, which generally correspond to the most recent survey projects. A simple example in the Chesapeake Bay illustrates where the soundings of recent surveys supersede those of older surveys (Fig. 6). This layering and clipping technique can be modified to select smaller areas within any survey.

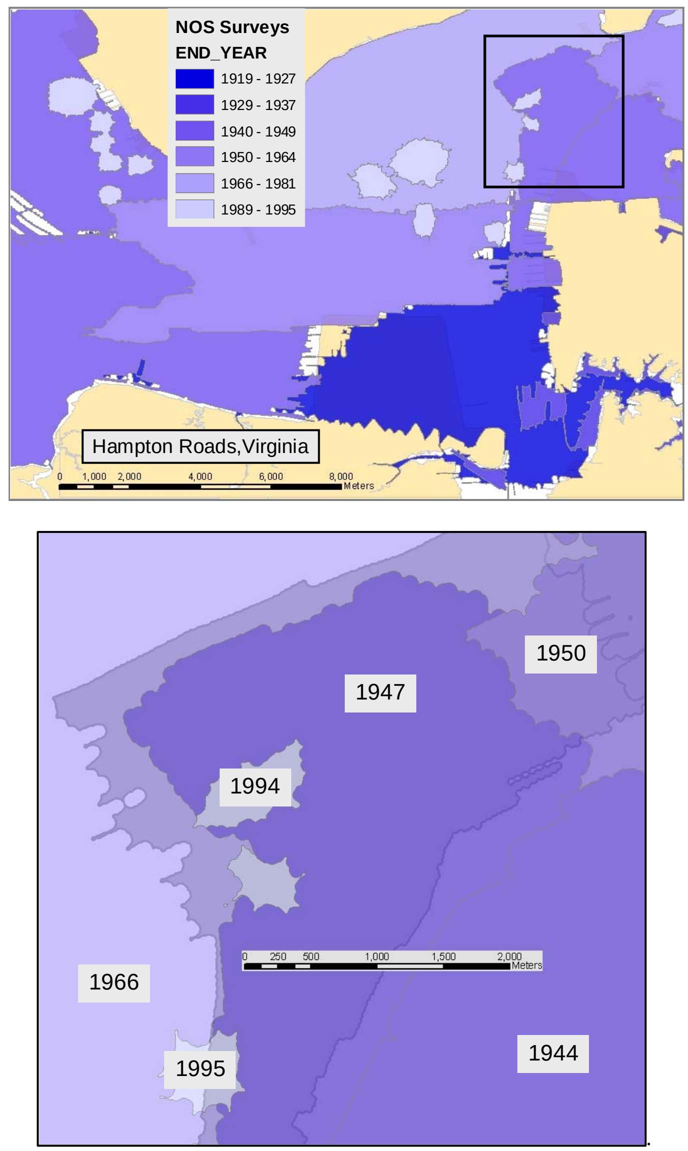

Figure 5. Attributed polygons are created to wrap closely around boundaries of individual NOS survey projects in the vicinity of Hampton Roads, Virginia. Dark blue areas in the inset box show overlapping years of survey coverage.

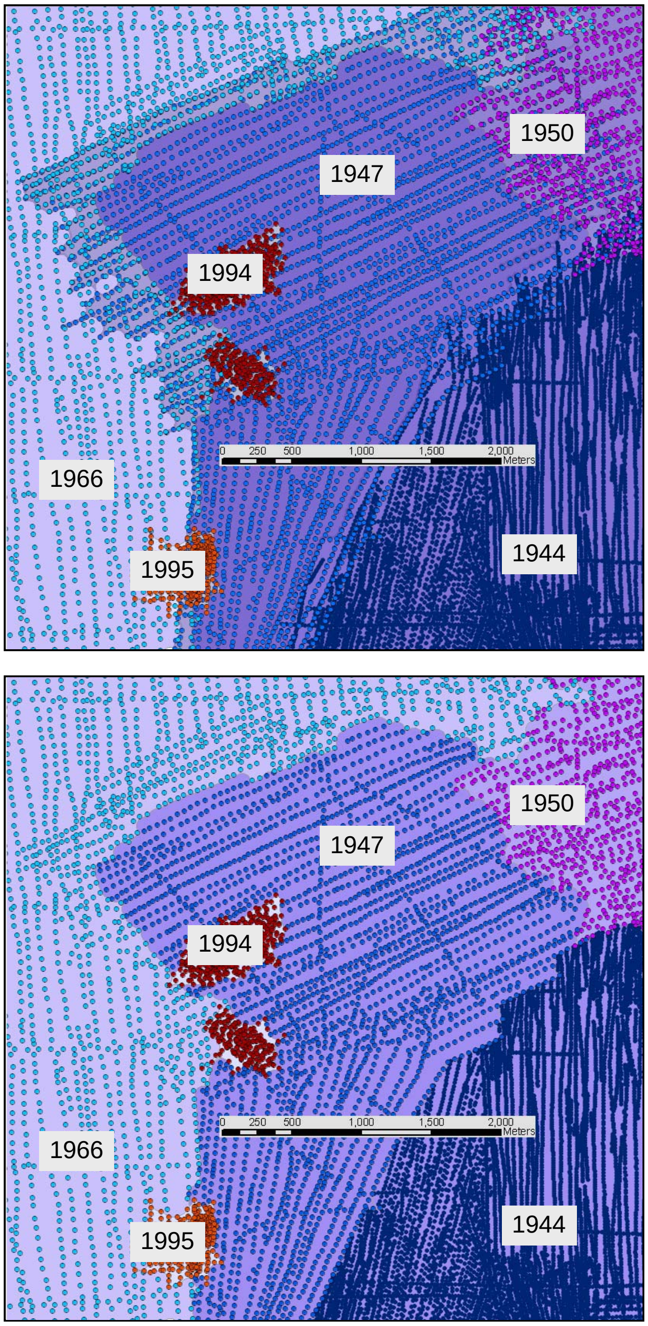

Figure 6. A simple example of soundings from recent surveys superseding those of older surveys. Bounding polygons are used to select for the most reliable soundings, which generally correspond to the most recent surveys.

In the development of coastal ocean circulation models for central North Carolina [14], the eastern Gulf of Mexico [15], and the Delaware Bay [Fig. 7], consistently georeferenced soundings were temporally filtered and merged into extensive data sets consisting of several hundred surveys whose range in age spans over a century and at scales from 1:2,500 (harbors and inlets) to 1:120,000 (towards the continental shelf). The regional compilations of selectively filtered bathymetric soundings were directly interpolated onto

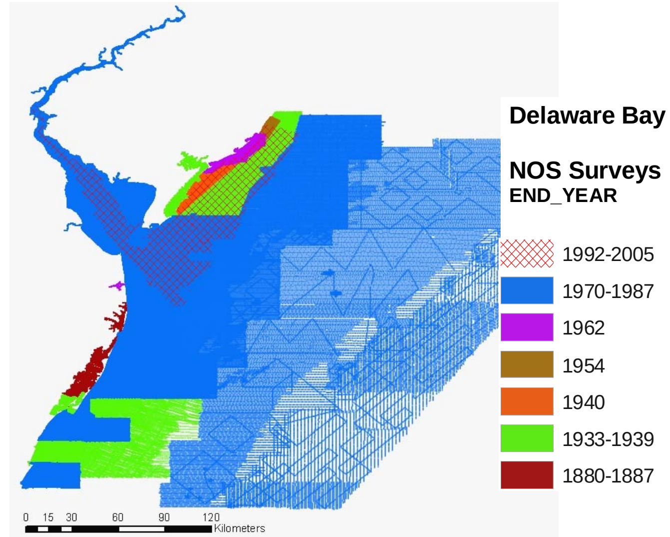

Figure 7. Temporally consistent soundings merged from approximately 150 NOS hydrographic surveys in the Delaware Bay. Several MBES surveys conducted in the last decade will supersede survey data from 1880 – 1987.

structured or unstructured triangular grids of circulation models such as the Regional Ocean Modeling System (ROMS, [16]) and the ADvanced CIRCulation Model (ADCIRC, [17]). Good bathymetry data are essential for numerically stable runs and reliable output from different types of hydrodynamic ocean models at multiple resolutions.

Technologies and processing systems are being developed to merge NOS hydrographic survey data to produce bathymetry for navigational charts. Nautical cartographers are currently faced with drawing continuous contours between the dense soundings of processed MBES surveys and the charted legacy soundings that have been significantly downsampled from the original historic surveys. Unlike the smoothed bathymetry created for numerical ocean models, chart bathymetry requires that the sounding points be honored exactly when they coincide with the grid node being interpolated (Fig. 8). Bathymetry grids created by inverse distance weighting and natural neighbor interpolation techniques are being analyzed by comparing their depth values against charted soundings and depth curves.

VI. Accuracy of Bathymetry Grids

The accuracy of high resolution bathymetry grids depends on the uncertainty of: 1) field measurements and positioning, 2) shoal-biased hydrographic data processing shortly after field collection to produce the original archive soundings, 3) archive data digitization or translation errors that occurred years after field collection and original data processing, 4) method of interpolating depths from sources having variable age and spatial consistency, and 5) estimates of the unknown depths between the sparse soundings which have variable spatial consistency in the vast majority of survey coverage.

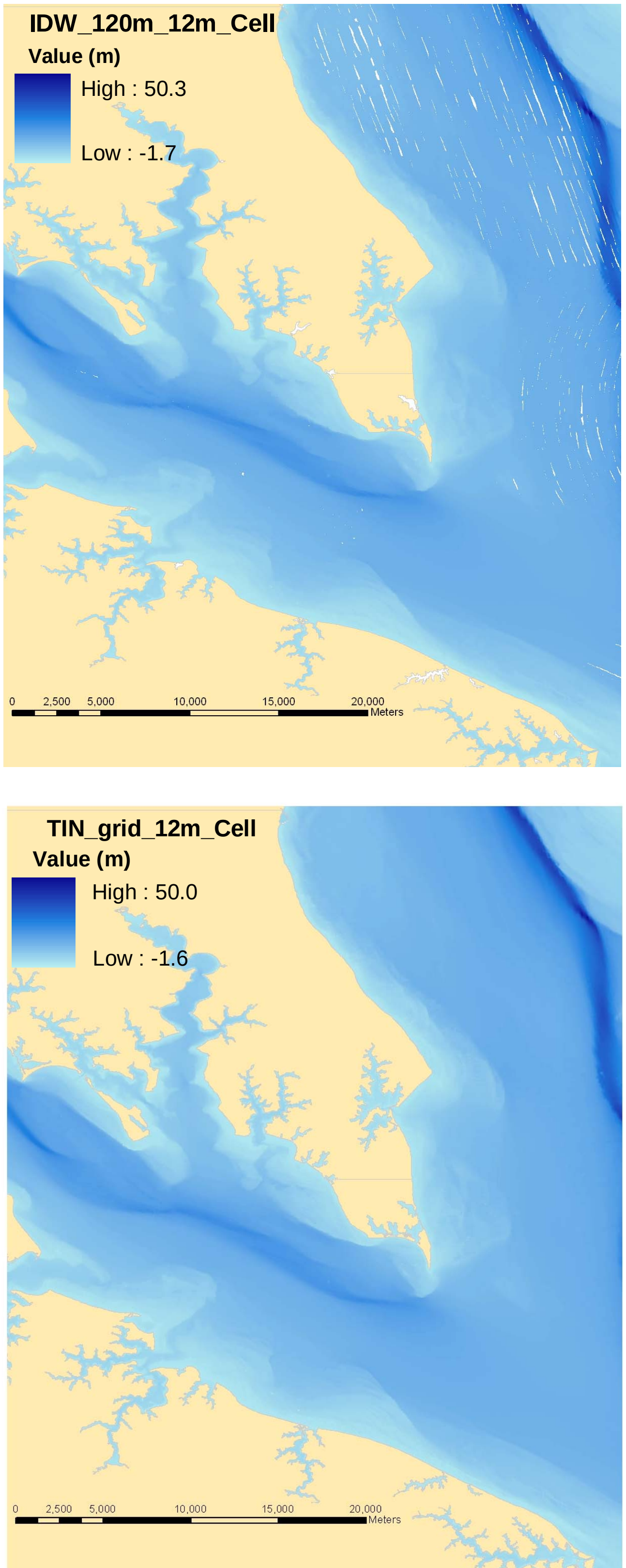

Figure 8. Interpolation techniques are applied to create bathymetry grids of 12 m cell size in the Chesapeake Bay: Inverse distance weighted (IDW, top) and natural neighbor interpolation with slight smoothing (TIN_grid, bottom). Depths are positive meters.

Sounding and navigation techniques have changed over the many years of hydrographic data collection. Along with improved instrument platforms and sounding methods are increasingly rigorous horizontal and vertical accuracy standards for surveys over time. The nominal accuracy of the survey measurements is usually much better than the minimum standards specified by the NOAA Coast (and Geodetic) Survey hydrographic manuals and the International Hydrographic Organization. The accuracy of original depth measurements depends on seafloor rugosity, field conditions (e.g., weather, winds and currents), and water level variability. Differential GPS improved the level of positioning accuracy considerably for the most recent surveys.

Processed as sources for navigational products, the NOS soundings are shoal biased to exclude the deeper depths. For each survey, sounding depths are initially cleaned to eliminate invalid measurements of objects that are not part of the seafloor (e.g., fish, kelp). Other invalid soundings result from measurement angle effects, interference, or instrument effects. Until 2006, when the Combined Uncertainty Bathymetry Estimator algorithm (CUBE; [18]) became the standard method to process modern MBES data, soundings that exceed the desired measurement error tend to be over-cleaned as hydrographers typically rejected soundings in deeper areas while selecting sounding data in shallower areas.

Traditionally, the depth measurements were downsampled into shoal-biased five meter bins to generate the archive data sources for navigational products, until the Navigation Surface processing method [19] became operational after 2005. The binned shoal-biased depths were downsampled further (with additional shoal bias) as they were selectively plotted at prescribed scales to create the survey smooth sheet. Even with Navigation Surface processing, shoal bias is inevitable because the original depths are truncated for navigational charts using prescribed NOAA rounding rules [20].

Because sounding anomalies are compounded by geometric errors introduced by spatial interpolation when generating bathymetry surface models (Fig. 9), errors in archival survey processing are best identified and addressed for all the historic surveys before surface creation and supersession by recent MBES data (Fig. 10). The uncertainty of bathymetry grids compiled from archive data may be approximated using survey metadata and statistical surface models that estimate the combined errors associated with measurement, positioning, and interpolation [21, 22]. A complete bathymetry confidence model needs to factor in the potential error in estimating the unknown depths between sparse soundings as they are usually spaced tens of meters to several hundreds of kilometers apart.

VII. Conclusions

Because interpolated depths will constitute a substantial portion of gridded bathymetric coverage for the entire U.S. coast, the production of high quality bathymetry grids for the coastal U.S. primarily requires quality assured soundings data

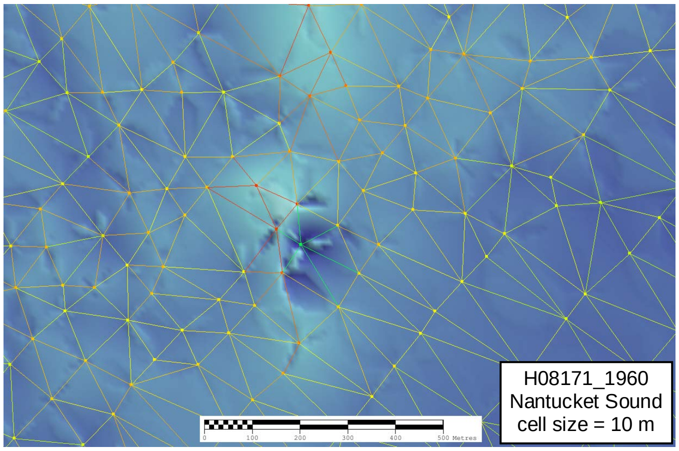

Figure 9. Depth anomalies in sparse surveys are compounded by grid artifacts and geometric errors introduced by natural neighbor interpolation. Nodes of the triangulated mesh represent exact sounding locations.

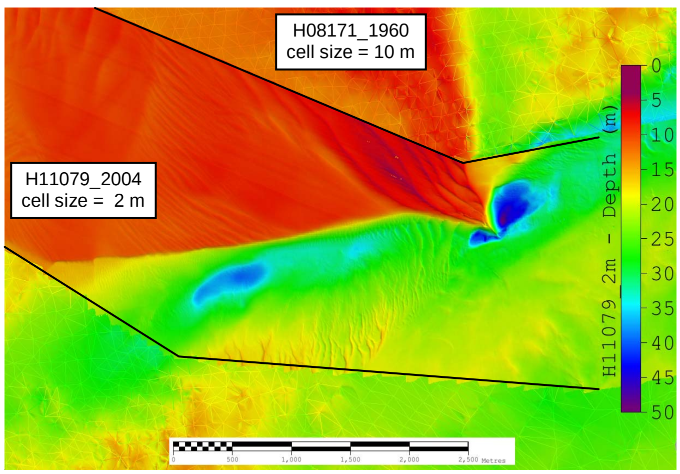

Figure 10. The recent MBES survey of H11079 at 2 m resolution will supersede portions of the older survey H08171, whose sparse soundings are interpolated to generate a bathymetry surface model at 10 m resolution.

processed from 155 years of NOS hydrographic surveys. Metadata and soundings records for 7000 archive surveys are being examined and corrected for inconsistencies that will adversely affect the efficiency and accuracy of fusion with modern MBES data. For the development of regional ocean circulation models, consistently georeferenced soundings were temporally filtered and merged into regional data sets consisting of several hundred surveys at various scales.

Whereas regional compilations of selectively filtered soundings can be directly interpolated and smoothed onto numerical model grids, bathymetry grids for navigational charts require exact interpolation of soundings where they coincide with the grid node being interpolated. Bathymetry grids created by exact interpolation techniques are being analyzed by comparing the modeled depths against charted soundings and depth curves. The measurement and positioning errors of historic soundings may be estimated by incorporating survey metadata information into statistical surface models. Most difficult to quantify in bathymetry grids are the potential errors of the unknown depths that have been interpolated from sparse soundings.

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Gerald Mills of NOS OCS Hydrographic Surveys Division contributed to the history of sounding methods, position determination, and information on the accuracy standards of NOS hydrographic surveys. Thomas Gross, formerly of the Coast Survey Development Laboratory, assisted with the development of outlier detection in survey sounding sets.

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