VDatum and Strategies for National Coverage

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Abstract- **VDatum is a software tool being developed by the National Ocean Service that allows users to vertically transform geospatial data among a variety of ellipsoidal, orthometric and tidal datums. This is important to coastal applications that rely on vertical accuracy in bathymetric, topographic, and coastline data sets. The VDatum software can be applied to a single point location or to a batch data file. Applying VDatum to an entire data set can be particularly useful when merging multiple data sources together, where they must first all be referenced to a common vertical datum. Contemporary technologies, such as lidar and kinematic GPS data collection, can also benefit from VDatum in providing new approaches for efficiently processing shoreline and bathymetric data with accurate vertical referencing. VDatum is currently available for Tampa Bay, New York Bight, Delaware Bay, Louisiana's Calcasieu River and Lake Charles, central California, Puget Sound, Strait of Juan de Fuca, and north/central North Carolina. In addition, VDatum development is near completion for Chesapeake Bay, Mobile Bay to Cape San Blas, Southern California, Long Island Sound and New York Harbor, and projects are also commencing for an area from New Orleans to Mobile Bay, the Gulf of Maine and the Pacific Northwest. Given the numerous applications that can benefit from having a vertical datum transformation tool, the goal is to develop a seamless nationwide VDatum utility that would facilitate more effective sharing of vertical data and also complement a vision of linking such data through national elevation and shoreline databases.**

I. Introduction

The coastal land-water interface depends on how water levels and land move vertically in both space and time. To combine or compare coastal elevations (land heights and water depths) from diverse sources, they must be referenced to the same vertical datum in a common framework. Using inconsistent datums can cause artificial discontinuities that become acutely problematic when producing maps at the accuracy that is critically needed by federal, state, and local authorities to make informed decisions. The National Oceanic and Atmospheric Administration (NOAA) has developed a vertical datum transformation tool, VDatum, to address this inconsistent datum problem. VDatum is a software utility developed for the transformation of bathymetric/topographic data among approximately 30 different tidal, orthometric and ellipsoidal vertical datums. In this paper, we outline the procedures for developing VDatum, where the software currently is available, future development plans, and improvements needed for the software and associated metadata.

Standard operating procedures are being developed for creating VDatum applications such that similar procedures are applied regardless of the geographic region. The first stage of each project is to develop the tide model used to compute the tidal datums. For this, high-resolution coastline data and NOAA bathymetry in the area are processed in a quality-controlled manner. This information is used to construct a high-resolution unstructured grid for use by the tide model. The standard tide model used in VDatum applications is ADCIRC, and modeled tidal datums are compared with datums computed from observations obtained by NOAA's Center for Operational Oceanographic Products and Services (CO-OPS) for operating and historical tide stations. Model-data inconsistencies are adjusted using spatial interpolation techniques, and resultant tidal datums are provided to the VDatum software on a structured marine grid. NOAA's National Geodetic Survey (NGS) then uses these results to help compute the relationship between tidal datums and the North American Vertical Datum of 1988 (NAVD 88). NGS also provides the orthometric and ellipsoidal transformations used by the VDatum software.

The successful development and implementation of VDatum in a given geographic region is useful to numerous coastal applications. Existing bathymetric and topographic data can be integrated into a seamless digital elevation model (DEM) by first using VDatum to reference the data to a common vertical datum. Shorelines may be accurately computed by applying VDatum to LIDAR data. Applications dependent on a seamless land-water DEM also benefit, such as storm surge and tsunami modeling, habitat restoration, sea level rise effects, and ecosystem studies. All of the benefits of having VDatum available exemplify its utility in serving as a national backbone for linking and transforming vertically-referenced data from a multitude of sources.

II. Vertical Datum Transformations and Availability of VDatum

VDatum is a software tool developed by the National Ocean Service (NOS) for transforming bathymetric/topographic data among 28 tidal, orthometric and ellipsoidal vertical datums. The ability to properly reference data to multiple vertical datums is

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critical to a variety of applications in the coastal zone, and it also serves to extend the capabilities of emerging technologies in providing state-of-the art products. Figure 1 shows locations where VDatum is currently available as well as where it is anticipated to be completed by 2008. The goal is to develop a national VDatum database, starting with the contiguous U.S. and followed by Alaska, Hawaii, Puerto Rico and the U.S. Virgin Islands.

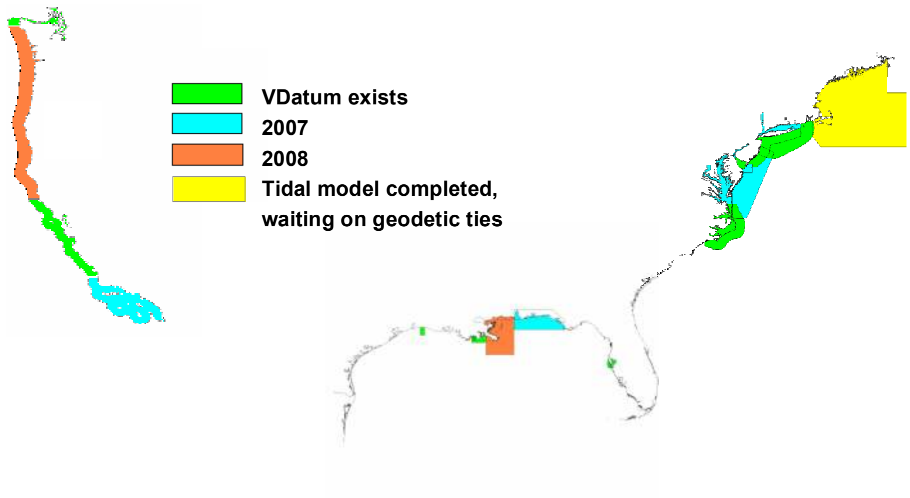

Figure 1. Current and projected VDatum coverage through 2008.

The VDatum software is currently available for Tampa Bay, the New York Bight, Delaware Bay, central California, central/northern North Carolina, Lake Calcasieu and Charles River, Port Fourchon, Puget Sound, and the Strait of Juan de Fuca. New VDatum regions are in the final stages of development for the Chesapeake and Delaware Bays, New York Harbor/Long Island Sound/Narragansett Bay, and Mobile Bay-to-Cape San Blas. VDatum for Southern California is expected to be available by the end of 2007, and the remainder of the contiguous west coast of the U.S. (northern California to Cape Flattery, Washington) should be completed by the end of 2008. In the Gulf of Mexico, VDatum from New Orleans to Mobile Bay is in development with a target completion date at the end of 2008. In addition, tidal datum relationships have already been completed for the Gulf of Maine (extending to Narragansett Bay). VDatum will be completed for the Gulf of Maine pending field work to obtain more geodetic ties in the region. Beyond this planned VDatum development, regional VDatum gaps will still exist for the west and east coasts of Florida, the southeast U.S. coast from Florida to southern North Carolina, the eastern Gulf of Mexico from New Orleans to the Texas/Mexico border, and Hawaii/Alaska/Puerto Rico/Virgin Islands.

A national VDatum will complement NOS work in developing a national bathymetric database, which can be combined with the topographic data in providing seamless data products across the land-water interface. Together, these products will also enable a consistent, accurate national shoreline to be defined relative to the tidal datums. Some other applications that benefit from VDatum include inundation modeling (storm surge, tsunami, sea level rise impacts), ecosystem modeling, and coastal zone management. VDatum also enhances the capabilities of technologies such as kinematic GPS (K-GPS) for vertical referencing of hydrographic survey depths, use of topographic and bathymetric LIDAR for determining mean lower low water (MLLW) and mean high water (MHW) shorelines, and development of digital elevation models (DEMs).

The vertical datums incorporated into VDatum were selected so as to accommodate the wide variety of bathymetric and topographic data sources that could potentially be used as input to the transformation software. Vertical datums can be classified as tidal datums (tidally-derived surface), orthometric datums, or 3D ellipsoidal datums. Examples of the types of data that are referenced to these categories of datums include bathymetric data that are usually referenced to a tidal datum, topographic data that are often acquired relative to an orthometric datum such as NAVD 88, and LIDAR data that are referenced to an ellipsoidal datum.

Table 1 shows the transformations that are needed to convert between these three main categories of vertical datums. This conversion relies on the use of a primary datum within each category. Thus, any other datums within a given category will need to first be converted to that category's primary datum before it can be converted to a datum in a different category. The primary datums used in VDatum are local mean sea level (LMSL) for the tidal datum, NAVD 88 for the orthometric datum and the North American Datum of 1983 (NAD 83) for the ellipsoidal datum. The VDatum software also transforms data that are georeferenced to the North American Datum of 1927 (NAD 27), a non-geocentric horizontal datum, to the NAD 83 primary ellipsoidal datum.

TABLE I
VERTICAL DATUMS AVAILABLE FOR TRANSFORMATIONS IN VDATUM

TIDAL DATUMS		**3D/ELLIPSOID DATUMS**	
MLLW	Mean Lower Low Water	NAD 83	North American Datum 1983
MLW	Mean Low Water	WGS 84 (G873)	World Geodetic System 1984 (G873)
LMSL	Local Mean Sea Level	WGS 84 (G730)	World Geodetic System 1984 (G730)
MTL	Mean Tide Level	WGS 84 (original)	World Geodetic System 1984 (original system)
DTL	Diurnal Tide Level	WGS72	World Geodetic System 1972
MHW	Mean High Water	ITRF00	International Terrestrial Reference Frame 2000
MHHW	Mean Higher High Water	ITRF97	International Terrestrial Reference Frame 1997
ORTHOMETRIC DATUMS		ITRF96	International Terrestrial Reference Frame 1996
NAVD 88	North American Vertical Datum of 1988	ITRF94	International Terrestrial Reference Frame 1994
NGVD29	National Geodetic Vertical Datum of 1929	ITRF93	International Terrestrial Reference Frame 1993
		ITRF92	International Terrestrial Reference Frame 1992
		ITRF91	International Terrestrial Reference Frame 1991
		ITRF90	International Terrestrial Reference Frame 1990
		ITRF89	International Terrestrial Reference Frame 1989
		ITRF88	International Terrestrial Reference Frame 1988
		SIO/MIT 92	Scripps Inst. of Oceanography / Mass. Inst. of Technology 1992
		NEOS 90	National Earth Orientation Service 1990
		PNEOS 90	Preliminary National Earth Orientation Service 1990

III. VDATUM DEVELOPMENT METHODOLOGY

The implementation of a national VDatum database that is both accurate and efficient requires a consistent methodology in the steps taken to develop each application. There are three primary steps that are taken to develop a VDatum application. First, bathymetric and shoreline data are gathered for the region of interest and are evaluated under quality control measures before they are used as input to the tide modeling. Hydrodynamic models are then developed to simulate tidal propagation, and the results are analyzed to compute spatially varying fields of the tidal datums. Finally, this information is provided to NGS for inclusion in the VDatum software with the ellipsoidal datum algorithms, the geoid model results, and the topography of the sea surface analysis. Within each of these steps, as described below, tools and approaches are chosen so as to best improve the accuracy and consistency of the VDatum applications as viewed from a national perspective.

A. Bathymetric and Coastline Data Used by VDatum

Digital vector shoreline is used to define the land-water boundary of the numerical tide models. The MHW coastline used for the finely resolved tidal models are compiled from the NOAA Office of Coast Survey's (OCS) Electronic Navigational Charts (ENCs), which are available at map scales up to 1:5000. Originally digitized from NOAA Raster Nautical Charts, ENCs comprise the official charting database provided in International Hydrographic Office (IHO) native S-57 vector format, a data standard used for the global exchange of digital hydrographic data. Vector shorelines are compiled in longitude-latitude pairs with precision up to 0.000001 decimal degrees referenced to the World Geodetic System of 1984 (original), a geospatial framework that is essentially equivalent to the NAD 83 reference system used in the U.S. If ENCs are unavailable for a particular area and the MHW shoreline cannot be hand-digitized from corresponding raster navigational charts, occasionally used are older vector shoreline data sets that have been manually extracted from raster nautical charts.

Several sources of bathymetric data are evaluated and processed for the development of numerical tidal models. Sounding points are initially selected from the OCS hydrographic database maintained at the National Geophysical Data Center (NGDC). NGDC developed the interactive GEOphysical DAta System (GEODAS) to assimilate, store and manage geophysical data. The OCS bathymetric database contains soundings digitized from smooth sheets of hydrographic surveys completed between the years 1851 and 1965, as well as digital soundings acquired by survey ships since 1965. Lead line measurements are assumed to be the data collection method for surveys before 1940. Water depths are recorded by echo sounders from approximately 1940 onward. For some regions of the coastal United States, the OCS bathymetric database includes high-density multibeam measurements from hydrographic surveys since 1980.

Soundings from each survey are most often vertically referenced to either MLLW or MLW. Bathymetric soundings are filtered sequentially by date using a series of raster layers whose spatial resolutions are determined by sounding point density. In addition to the temporally filtered soundings from the OCS bathymetric database, the Coastal Relief Model (CRM) at NGDC is an alternative source of historical NOS bathymetry that is available in an interpolated, gridded format at a horizontal resolution of 3 arc-seconds, or approximately 90 m, with seafloor elevations vertically resolved to 0.1 m. CRM bathymetric grids are interpolated from all of the combined historic NOS soundings from the 1850s until about 1995. CRM bathymetry does not represent the high level of detail nor the accuracy that can be obtained from the original NOS soundings because they are coarsely interpolated from soundings merged from all dates. CRM depths are uncorrected from their horizontal datum and vertical datum.

Recent bathymetric data from inlets and channels, multibeam subsets of NOS hydrographic surveys, and soundings from many older surveys that are unavailable from NGDC are collected from the latest editions of NOAA ENCs, whose depth values have been processed and validated for publication by OCS. Depths within maintained inlets and channels that are published in the ENCs are provided by the U.S. Army Corps of Engineers (USACE). USACE surveys are usually georeferenced to NAD 83 and local MLW. Where applicable, USACE depth values blend with or supersede the historical NOS bathymetry.

The implementation of multi-purpose national bathymetric and shoreline databases complement the National VDatum philosophy. VDatum is critical to the implementation of a seamless bathymetric database as an operational national archive. The NOS bathymetric database will incorporate data from historical hydrographic surveys presently maintained by NGDC's GEODAS, multibeam surveys, local spot soundings, LIDAR measurements, USACE dredging areas, and other sources. VDatum will transform all depth values to a standard datum (MLLW) used in NOAA nautical charts and IHO S-57 vector products. The transformed data sources will be used to produce bathymetric surface models, such as the Navigation Surface [1], and national shorelines that are consistently defined by the tidal datums.

B. Modeling the Tidal Datums

A tidal datum is a base elevation from which relative heights and depths may be determined [2]. It can be measured by analyzing time series of water levels from observational data. Mean sea level (MSL) is an example of a tide datum, taken as the arithmetic mean of hourly water observations over the NTDE (presently the 1983-2001 NTDE). Other tidal datums are calculated based upon recorded high or low water values, including MHHW, MHW, MLW, MLLW, DTL and MTL. Since each of these datums depends upon the tide characteristics of a particular location, there is a spatial variation in the fields in between observation locations.

To resolve the spatially varying nature of the tidal datums in between observation locations, hydrodynamic models and spatial interpolation techniques are developed for each VDatum application that simulate the tidal propagation characteristics in the region of interest. Keeping in mind that all of the individual VDatum applications will ultimately merge together to form a continuous national VDatum product, a consistent methodology for computing the tidal datums is adopted here. The approach consists of first using the bathymetric and coastline data to generate a grid to be used by the model, then calibrating a hydrodynamic model to best simulate the observed tidal datum characteristics for the region, correcting the model-data errors using a spatial interpolation technique, and finally providing the corrected modeled datums on a structured grid of points to be used by the VDatum software.

The first step is the generation of a grid to be used by the hydrodynamic model. Currently, tide modeling applications for VDatum are using the ADCIRC [3] hydrodynamic model. ADCIRC uses triangular unstructured grids in its solution of the hydrodynamic equations for time- and spatially-varying parameters such as water levels and velocities. The generation of unstructured grids for each VDatum region is presently being made with a software tool called SMS (Surfacewater Modeling System). SMS allows the user to control the distribution of triangular elements between the coastlines and the open ocean boundary in a facile manner. For example, since the wavelength of propagating tides is decreased in shallow water, more triangular elements are needed there to properly resolve the features of the waves. Higher resolution is also more ideal near the shorelines to better represent land-water interface geometry and its effect on tidal propagation. Examples of some triangular grids used in recent VDatum projects are displayed in Figure 2.

Once an unstructured triangular grid is constructed for a region, it may then be used in numerical simulations of the tides. ADCIRC is a finite element model that uses the generalized wave continuity equation to solve for water levels and the momentum equations to solve for velocities. Time steps used by the model vary according to the smallest size of triangles in a grid, and they are typically on the order of a few seconds or less. Simulations are normally carried out for 37 days, and the model must therefore process several million time steps for completion. On a single processor computer, this would normally take approximately one month to run. Development of tide models for all of the nations' coastal areas would be hindered by this time to complete the simulations, and therefore access to clustered computer systems at NOAA's Earth System Research Laboratory (ESRL) was granted for running our tide models using an MPI (Message Passing Interface) version of the ADCIRC model. The simulations are typically distributed in parallel among 48-72 processors, thus reducing the time to run the model down to approximately 12-24 hours.

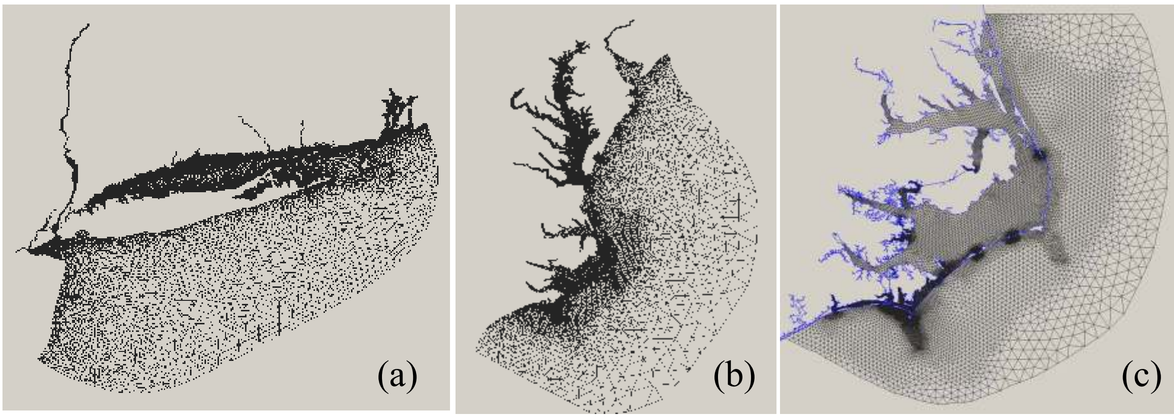

Figure 2. Examples of triangular unstructured grids used in (a) Long Island / New York Harbor, (b) Chesapeake Bay, and (c) coastal North Carolina.

The models are first calibrated to best reproduce observed datums by adjusting such model input parameters as bottom friction, viscosity, the connectivity and shapes of the triangular elements, and the representation of the bathymetry on the grid (each node has a depth assigned to it, and the depths vary linearly within each triangular element). The boundary of the grid along the open ocean is used to force the tides into the model through specification of amplitudes and phases for the M_2, S_2, N_2, K_2, K_1, O_1 and Q_1 tidal constituents. These tidal boundary conditions must be obtained from a larger model of the tides. Regional models for the Eastern North Pacific [4,5,6] and Western North Atlantic [7] are ideally suited for providing this information to the more localized VDatum modeling applications. The Eastcoast2001 [7] regional model grid for the western North Atlantic Ocean, Gulf of Mexico, and Caribbean Sea is displayed in Figure 3.

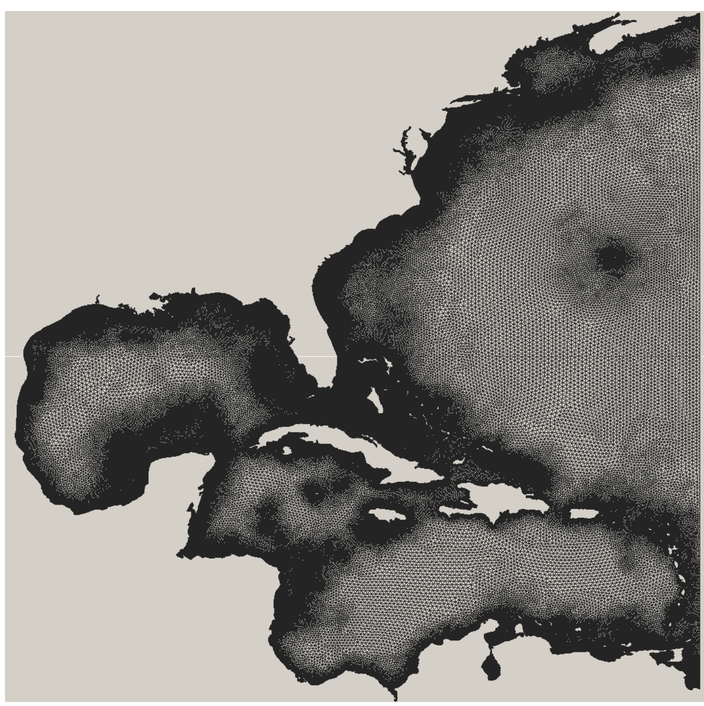

Figure 3. Eastcoast2001 regional grid.

After the model parameters have been calibrated, simulations are made to adjust the bathymetry to be vertically referenced to MSL. As most bathymetry is referenced to MLLW, an initial guess of the MSL to MLLW difference is made to correct the bathymetry for a tide simulation. After that initial simulation is complete, the model output is used to compute new MLLW-MSL differences that are then used as a new correction to the bathymetry. The process is repeated until the computed corrections do not change from one simulation to the next.

A final hydrodynamic model simulation with the calibrated parameters and corrected bathymetry is then made, and the results are used to compute tidal datum fields. These modeled tidal datums are compared with observed datums, and the model-data differences are spatially interpolated using TCARI [8,9]. TCARI (Tidal Constituent and Residual Interpolation) solves the Laplace equation using internal boundary conditions where observations are available. In this case, the observations used in TCARI are the model-data differences. Once TCARI has spatially interpolated these differences, the resulting fields may be used as corrections to the modeled datums. The corrected modeled datums will now match exactly at locations where observations are available.

VDatum incorporates the corrected version of the modeled tidal datums through the use of a marine grid. This is a regularly spaced set of data points, onto which the corrected model results are interpolated. Using the high resolution shoreline data, each marine grid point is evaluated as to whether it falls inside (water) or outside (land) this shoreline. A small buffer is also taken into account, such that marine grid points that fall just slightly on the land (within 0.1 nautical miles) may still be assigned a tidal datum value. There may also be areas for which the hydrodynamic model grid does not fully extend through the entire water domain as defined by the shoreline data, and interpolation techniques are used to extend the tidal datums in these regions. The final marine grid of tidal datum fields is provided as input to the VDatum software. A user-supplied longitude/latitude pair to VDatum will thus interpolate from the marine grid the desired tidal datum.

C. Ellipsoidal, Orthometric and TSS Transformations

The VDatum software [10] encodes a four-step traversal path along a minimal spanning tree whose nodes represent the vertical datums grouped into 3D ellipsoidal datums, orthometric datums, and tidal datums: (1) transformations from the 3D ellipsoidal datums to the NAD 83 primary datum; (2) transformation between the NAD 83 primary ellipsoidal datum and the NAVD 88 primary orthometric datum; (3) transformations between NAVD 88 and the MSL primary tidal datum; and (4) transformations between MSL and the tidal datums. Conversions between the 3D ellipsoidal datums apply the 7-parameter Helmert transformations which ascribe the three-dimensional distance, rotation, and scale changes. Data that are referenced to the NAD 27 horizontal datum are transformed to NAD 83. The topography of the sea surface (TSS) for each region relates NAVD 88 and MSL. TSS is calibrated from measurements of tidal values, NAVD 88 orthometric datum values, and regional tide model predictions. The NAD 83 and NAVD 88 primary datums are related directly by the GEOID99 geoid height model [11]. A newer version of the VDatum software also includes the option of using the GEOID03 [12] to make this transformation, and the GEOID06 geoid height model will similarly be incorporated when it is available.

The geoid models developed by NGS are based in part on the National Geospatial-Intelligence Agency's Earth Gravity Model 1996 in which geopotential heights are expressed as spherical harmonic coefficients complete to 360 degrees. GEOID03 reflects ellipsoidal heights that are constantly being updated to new reference frames. GEOID03 is supported by densified benchmarks from GPS networks and additional data from remote regions and Canada. With an increase from 6169 data points used in GEOID99 to 14,185 available points for GEOID03, the newer geoid model is more finely resolved both analytically and spatially. Revised modeling techniques capture the elevational short wavelength features. Whereas a single filter was used for GEOID99 to resolve features at about 800 km wavelength, two filters are used for GEOID03 at about 1300 km and 120 km to capture the longer and shorter wavelengths, respectively, which better resolve the actual signal. As a result, in contrast to GEOID99 which has about 2.5 cm national error over a 20-40 km wavelength, the GEOID03 model has a national error of only 1 cm over a 5-10 km wavelength. For VDatum, GEOID03 will be used to convert between the NAD 83 and NAVD 88 datums reliably up to the several centimeter level within the conterminous U.S.

VDatum requires a gridded topography of the sea surface (TSS), which is the difference between the elevation of NAVD 88 and MSL. A regional TSS field can be generated by spatially interpolating the observed NAVD 88-MSL differences from NOAA tide stations and through a value calibrating approach of fitting tide model results to tidal benchmarks leveled in NAVD 88. In the future, TSS may be replaced by an improved Mean Dynamic Topography derived from LIDAR altimetry measurements in conjunction with gravity field observations.

IV. FUTURE DIRECTION OF VDATUM

While VDatum is developed for regional applications, the goal is for each of these applications to seamlessly blend into a national software utility program. Many of these applications already overlap, and quality control programs are used to ensure smooth transitions in the datum transformations across regions. After the current ongoing projects in the Gulf of Maine, Pacific Northwest and New Orleans areas are complete, the remaining gaps in achieving a national VDatum for the contiguous U.S. will include the following: Texas to New Orleans, the Gulf coast of Florida to the northern limit of Cape San Blas, and the Southeast coast from southern North Carolina to the Florida Keys. VDatum is also intended to be developed for Alaska, Hawaii, and Puerto Rico/Virgin Islands, though issues relating to the geoid will need to be addressed in these areas.

As national coverage is approached for the contiguous U.S., the regional tide modeling applications used to compute the tidal datums may also be merged to become larger-scale regional models for the Western North Atlantic Ocean and the Eastern North Pacific Ocean. These larger-scale models would still maintain the same high grid resolution in the coastal areas and would allow tidal datums to be recomputed in a truly seamless manner using simulation results from the merged-grid models. Such modeling applications would be made available to other agencies and for multiple purposes.

The ability to update previous VDatum applications is also being evaluated. Vertical datum transformation fields may need to be updated for a variety of reasons, including changes in tidal datum epochs, updates to the geoid models, and availability of new data. One approach being considered to update previous applications is the use of TCARI to spatially interpolate differences introduced by such changes. Once VDatum is created for an area, it is important for it to be capable of dynamically changing over time to reflect the best available information.

Another key component of future VDatum development will be the creation of metadata describing how the vertical datum transformations were created, what the accuracies are, points of contact, and other pertinent information. One of the most critical portions of this metadata record will be the accuracies of the various datum transformations. The VDatum team is currently working on approaches for identifying uncertainties in the computed tidal datum fields, the topography of the sea surface, the geoid, and the ellipsoid transformations. Where it is difficult to quantify uncertainties, appropriate descriptions of the issues influencing the errors will be provided in the metadata.

Finally, improvements to the VDatum software are in progress to allow more user-friendly options. These will include more options for selection of the geoid model, the horizontal coordinate system for input/output, and batch file formats. Figure 4 shows the interface of a new version of the software being developed by the National Geodetic Survey. The VDatum team also would like to investigate innovative methods for accessing the datum transformations, possibly utilizing web feature and mapping services for this.

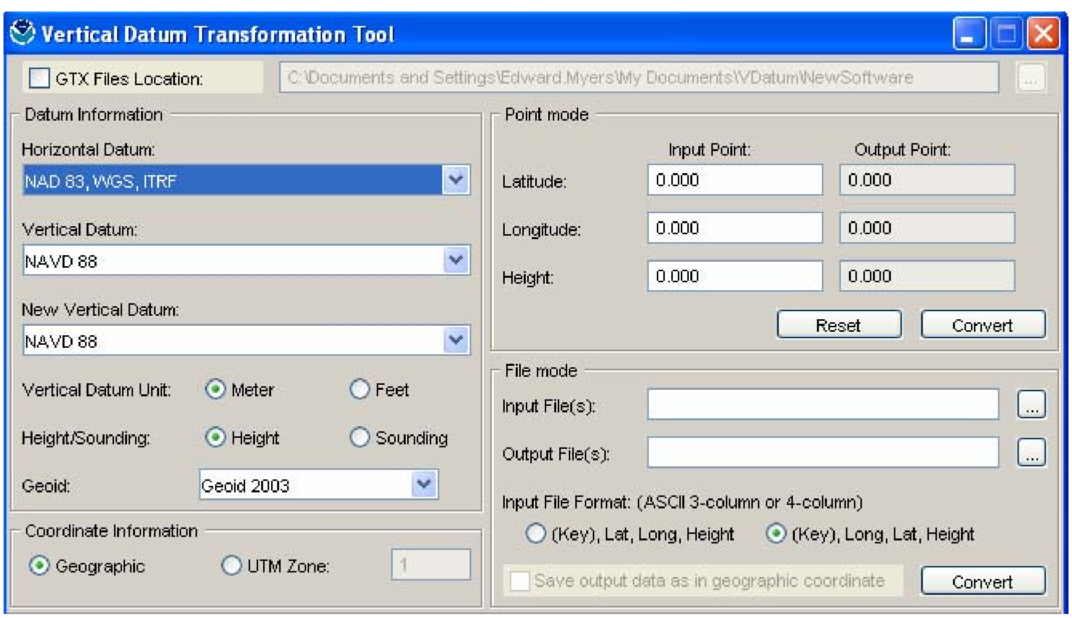

Figure 4. The new VDatum software interface being developed by NOAA's National Geodetic Survey.

V. ACKNOWLEDGMENT

Development of VDatum has been a team effort that is the culmination of collaborative efforts of many personnel from the Coast Survey Development Laboratory (CSDL), National Geodetic Survey (NGS), and the Center for Operational Oceanographic Products and Services (CO-OPS), all part of NOAA's National Ocean Service. The vision for a national VDatum was led by Bruce Parker (CSDL), Dennis Milbert (NGS), Kurt Hess (CSDL) and Stephen Gill (CO-OPS). VDatum applications have been funded from a variety of sources, including NOS' National Centers for Coastal Ocean Science, NOAA's National Marine Sanctuary Program, the United States Geological Survey, and the Army Corps of Engineers. The authors thank NOAA's Earth System Research Laboratory for use of their high performance computing system in running parallel tide simulations in support of VDatum.

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