# The Integration of Bathymetry, Topography and Shoreline and the Vertical Datum Transformations behind It

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The integration of bathymetry, topography, and shoreline is beneficial for a number of coastal applications. This geospatial integration begins with the blending of bathymetric and topographic data into a digital elevation model (DEM) after all data sets have been transformed to a common vertical datum. A vertical datum transformation tool, VDatum, has been developed which allows transformation among 27 different orthometric, 3-D/ellipsoid, and tidal datums. The geographic distribution of the tidal datums in VDatum are produced with a calibrated hydrodynamic tidal model. An initial demonstration project was carried out in the Tampa Bay region where the bathymetric data from NOAA (US National Oceanic and Atmospheric Administration) was blended with the topographic data from USGS (US Geological Survey). One objective was to solve the problem of inconsistencies between NOAA's nautical charts and USGS's mapping products, especially with respect to shoreline. A method was demonstrated for determining a consistently defined mean high water (MHW) shoreline from high-resolution Lidar elevation data covering the intertidal zone after transformation of these data to the MHW datum (with the zero contour being the MHW shoreline). VDatum will also play a key role in: (1) the implementation of a seamless high-resolution National Bathymetric Database, which will support both the production of ENCs (Electronic Navigational Charts) and the GIS-based activities of coastal zone managers; (2) the ability to use quality 3rd-party bathymetric data, which in the past was a problem due to the many different datums in use; (3) marine boundary determination; and (4) the on-the-fly measurement of bathymetric data relative to chart datum (Mean Lower Low Water) in future hydrographic surveys, using VDatum to transform the RTK-GPS-referenced data to MLLW.

## Introduction

Recently more attention has been paid to the use of hydrographic data for applications beyond the production of navigation products aimed primarily at supporting safe navigation of commercial shipping. Many of these applications support the Coastal Zone Management (CZM) community, which uses bathymetric, shoreline, and other marine data sets. For a number of these applications maximum benefit results when land-side and marine-side data are combined, not simply in a database, but truly integrated in the geospatial sense. This begins with the integration of bathymetric and topographic data into a Digital Elevation Model (DEM), namely, a continuous seamless elevation surface from the bottom of the sea to

***Orthometric Datums***

| | |
|---|---|
| NAVD 88 | North American Vertical Datum 1988 |
| NGVD 29 | North American Geodetic Vertical Datum 1929 |

***Tidal Datums***

| | |
|---|---|
| MLLW | Mean Lower Low Water |
| MLW | Mean Low Water |
| LMSL | Local Mean Sea Level |
| MTL | Mean Tide Level |
| DTL | Diurnal Tide Level |
| MHW | Mean High Water |
| MHHW | Mean Higher High Water |

***3-D/Ellipsoid Datums***

| | |
|---|---|
| NAD 83 (86) | North American Datum 1983 (1986) |
| WGS 84(G873) | World Geodetic System 1984 (G873) |
| WGS 84(G730) | World Geodetic System 1984 (G730) |
| WGS 84(orig) | World Geodetic System 1984 (original . system – 1984) |
| WGS 72 | World Geodetic System 1972 |

***3-D/Ellipsoid Datums (continued)***

| | |
|---|---|
| ITRF00 | International Terrestrial Reference Frame 2000 |
| ITRF97 | International Terrestrial Reference Frame 1997 |
| ITRF96 | International Terrestrial Reference Frame 1996 |
| ITRF94 | International Terrestrial Reference Frame 1994 |
| 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 Institution of Oceanography/Massachusetts Inst. of Tech. 1992 |
| NEOS 90 | National Earth Orientation Service 1990 |
| PNEOS 90 | Preliminary National Earth Orientation Service 1990 |

*Figure 1: 27 different vertical datums included in NOS' vertical datum transformation tool, Vdatum*

the heights on land. A DEM provides the geospatial framework for all other types of coastal data.

Shoreline data have been of special concern to the CZM community. Shoreline has been so difficult to measure in a truly consistent manner that the shorelines measured by different government agencies or institutions almost never match each other, leading to inconvenience and even confusion among various state, county, and city coastal zone managers. Shoreline, being the boundary where bathymetry meets topography (where the land meets sea), can be much more consistently defined and measured in the context of a bathymetric-topographic DEM.

The coastal applications for a bathymetric-topographic DEM include: storm surge modelling, hurricane evacuation planning, coastal construction and development, permitting, shoreline change analysis, marine boundary determination, determination of setback lines, habitat restoration, erosion studies, and renourishment projects, to name a few. The CZM community tends to rely on Geographic Information Systems (GISs) for its data analysis and interpretation activities. The progress over the last decade of the hydrographic and charting community toward digital vector products (e.g., ENCs, ECDIS, etc.) produced from maintained digital databases of attributed xyz-referenced data points directly supports the GIS needs of the CZM community. The building of these databases, whether bathymetric only, or bathymetric and topographic, requires the blending of a great many different data sets obtained over the years.

Of special concern are the many different vertical datums to which the various bathymetric or topographic elevation data sets were referenced, for in order to blend these data sets together, they must all be referenced to the same vertical datum. Thus, some type of a vertical datum transformation tool is required, a tool that can transform elevation data easily from one vertical datum to another. Such a vertical datum transformation tool not only allows us to blend bathymetric and topographic data and to build the databases that support the production of ENCs and the population of GISs, it also has a number of other important applications, including the measurement of a consistently defined shoreline and the improved efficiency of hydrographic surveys. One could say that in the digital world charting and mapping are finally coming together, and that vertical datum transformation plays a key role in that unification.

## The Tampa Bay Bathymetric Topographic Demonstration Project

In addition to the coastal applications that would benefit from the blending of bathymetry and topography into a DEM, there was a special motivation in the United States for this activity – the inconsistencies between the products of its two primary domestic mapping agencies. U.S. coastal waters are charted by the National Oceanic and Atmospheric Administration (NOAA) and U.S. land is mapped by the U.S. Geological Survey (USGS), the two agencies meeting at the shoreline. However, the shorelines on the topographic products of USGS often do not match the shorelines on the nautical charts of NOAA. Although part of this inconsistency can be traced back to data that may have been obtained at different times (with shoreline changes having occurred in between), most of the problem was due either to the use of different vertical datums or the inherent difficulties in measuring shorelines referenced to a specific vertical datum (which will be discussed later in this paper). The problem was serious enough that representatives from the CZM users community participating in a Users' Needs Workshop in St. Petersburg, Florida, in December 1999, expressed the view that data consistency was often more important than data accuracy for many of their applications. It has also been extremely difficult for state and local agencies to blend their own data with each other and with data of NOAA and/or USGS. Given the severe shortage in resources needed to map the more than 95,000 miles of coastline in the U.S., federal mapping agencies must be able to begin using quality data obtained by a state and local agencies and universities. For NOAA this is especially true in the shallower waters outside the navigation channels. (With limited resources NOAA has had to give top priority to hydrographic surveys around navigation channels, so that in many bays and estuaries the shallower waters important to the CZM community often have bathymetry on nautical charts based on data that is 50 years old.) However, to be able to use quality '3rd-party' bathymetric or topographic data, all these various data sets must all be transformable to a common datum, and they must fit into an accepted national geospatial framework. As a first step toward solving the above problems, NOAA's National Ocean Service (NOS) and the USGS's National Mapping Division (NMD) began a joint demonstration project in which they blended their bathymetric and topographic data sets into a bathymetric-topographic Digital Elevation Model (DEM) for the Tampa Bay region of Florida. Such blending was possible after all data sets were transformed to a common vertical datum (initially NAD 83) using a newly developed vertical datum transformation tool.

## Vertical Datum Transformation Tool

A vertical datum transformation tool, VDatum, was developed by NOS (Milbert, 2002), which allows the easy transformation of elevation data between any two vertical datums, among a choice of 27 vertical datums, which can be categorised as three general types: (1) orthometric, (2) tidal, and (3) 3-D or ellipsoid datums (see Figure 1). A fully calibrated hydrodynamic model of Tampa Bay was used to determine the geographic distribution of the tidal datums. VDatum was programmed as a Java application, with both interactive and batch modes. The source code and algorithms are open, and VDatum is being made available to the coastal user community.

## Types of Vertical Datums

Vertical datums have traditionally come in two categories: those based on a form of mean sea level (MSL), called *orthometric datums*, and those based on tidally-derived surfaces of high or low water, called *tidal* *datums*. In addition, there is a recently added third category, consisting of *3-dimensional* or *ellipsoid datums* realised through space-based systems such as the Global Positioning System (GPS). Topographic maps (e.g., from USGS) generally have elevations referenced to orthometric datums, either the North American Vertical Datum 1988 (NAVD 88) or to the older North American Geodetic Vertical Datum 1929 (NGVD 29). All GPS positioning data are referenced to a 3-D/ellipsoid datum. NOAA's nautical charts have depths referenced to mean lower low water (MLLW), and bridge clearances are referenced to mean high water (MHW). The legal shoreline in the U.S., which is the shoreline represented on NOAA's nautical charts, is the MHW shoreline, that is, the land-water interface when the water level is at an elevation equal to the MHW datum.

*Orthometric datums* are essentially equipotential (gravitational) surfaces of the Earth with one or more tide stations used as control points. They have often been viewed as being based on a form of MSL. The National Geodetic Vertical Datum of 1929 (NGVD29), which was originally called the 'Sea Level Datum of 1929', has 21 tide station control points in the U.S. and 5 in Canada. MSL, however, departs from an equipotential surface through the effects of winds, atmospheric pressure, water temperature, salinity, and currents. This caused unacceptable inconsistencies in NGVD29 and a new national orthometric datum, the North American Vertical Datum of 1988 (NAVD88) was established with only one control point (Father Point, Quebec, Canada). The differences between these two orthometric datums can be up to 2.2 metres.

*3-D or ellipsoid datums*, which have become so important since the development of GPS, are based on a geometric model, an ellipsoid that approximates the earth's surface (without the topography). There can be different 3-D datums depending on how the origin of the ellipsoid is defined. For example, there is a 2 metre difference between two of the most frequently used 3-D datums, the North American Datum of 1983 (NAD83) and the World Geodetic System of 1984 (WGS84). VDatum uses only the vertical component of the 3-D datum, which, as the name implies, is a complete 3-D coordinate system.

The *geoid* is a specific gravitational equipotential surface which best fits (in the least squares sense) global sea level. Since this equipotential surface includes the effects of topography, it will significantly differ (by as much as 100 metres) from a geocentric ellipsoid because of the Earth's irregular mass distribution, being higher than the ellipsoid where there is a greater mass. GEOID99, the latest geoid model developed by NOS, specifically relates NAD83 ellipsoid heights to NAVD88 orthometric heights. It was calibrated against GPS ellipsoid heights on leveled benchmarks throughout the conterminous United States.

*Tidal datums* are based on averaged stages of the tide, such as MHW and MLLW (see Figure 1). To minimise all the significant tidal daily, monthly, and yearly variations, a tidal datum such as MHW is defined as the average of all the high water elevations over an 18.6-year period (often rounded to 19 years). Tidal datum elevations vary with horizontal (geographic) distance, especially in shallower waters, and they can vary more rapidly than the horizontal variation in orthometric or 3-D/ellipsoid vertical datums. In Tampa Bay the separations between the tidal surfaces and the NAD 83 (and other 3-D/ellipsoid datums) are in excess of 24 metres. The relationship of NAVD 88 to local mean sea level is calibrated from tide model comparisons with leveled tidal benchmarks, and is approximately a constant 0.163 metres in Tampa Bay.

## Geographic Distribution of Tidal Datums

Tidal datum transformation fields for VDatum for Tampa Bay were generated using a numerical hydrodynamic model of the bay, a version of the Princeton Ocean Model that was previously developed in NOS (Hess, 1994). It is a three-dimensional, free-surface, sigma-coordinate baroclinic hydrodynamic model using a curvilinear grid with typical grid spacing from 1,000 to 100 metres. For calibration purposes the model was forced with coastal water levels, inputs from seven rivers, winds and air temperature, and coastal salinity and temperature. The typical standard deviation of the differences between model predictions and data was approximately 2.7 cm. For the purpose of determining the geographic distribution of tidal datums the model was forced at the Bay entrance with accepted tidal harmonic constants and run for one year, with the various stages of the tide picked off and averaged for every grid point of the model. The one-year averages were corrected for the 18.6-year lunar nodal cycle by comparison to the St. Petersburg

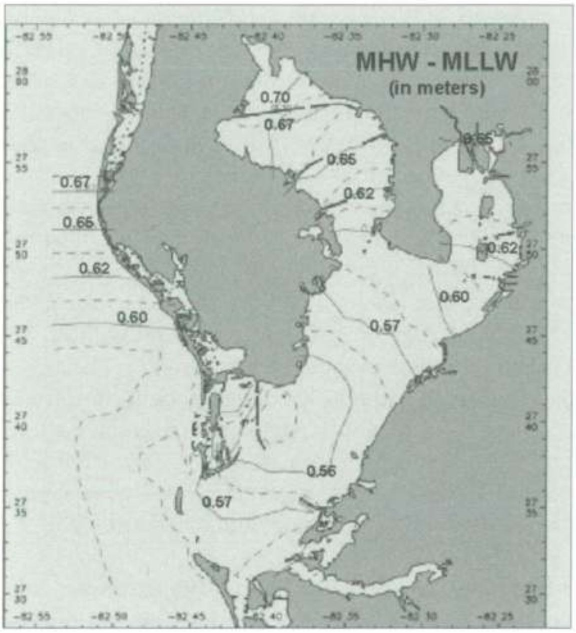


*Figure 2: Geographic distribution of the MHW datum (relative to the MLLW datum) in Tampa Bay produced by a tidally forced hydrodynamic model (produced by Kurt Hess).*

tide gauge. The hydrodynamic model was used to generate a set of fields representing the difference between MLLW and: Mean Low Water (MLW), Diurnal Tide Level (DTL), Mean Tide Level (MTL), Mean Sea Level (MSL), Mean High Water (MHW), and Mean Higher High Water (MHHW). Figure 2 shows the geographic distribution of the MHW datum. (Datum fields for locations outside the Bay along the Gulf coast were generated by interpolating between shore-based tide gauges and the hydrodynamic model output near the entrance to the Bay, and extrapolating seaward.)

For bays or estuaries where a fully calibrated hydrodynamic model is not available, a technique for spatial interpolation among locations with tide gauge data has been developed (Hess, 2002). This method, the Tidal Constituent And Residual Interpolation (TCARI) method, uses a set of weighting functions (generated by solving numerically Laplace's Equation) to quantify the local contributions from each of the tide gauges. TCARI does this in a manner that considers distances from gauges by over-water paths only, and thus includes the effects of islands and bending shoreline.

## Building the Bathymetric-Topographic DEM

### Bathymetric Data

The bathymetric data used for the Tampa Bay DEM were taken from the 47 most recent NOAA hydrographic surveys covering the Tampa Bay project area. Data in and around navigation channels came from surveys carried out in 1994-96, but the most recent data near the shore and in other shallower areas came from surveys back in 1950-58. Some data outside the entrance to Tampa Bay came from a 1975 survey. The 1994-96 and 1975 data were referenced to MLLW, while the data from the 1950s were referenced to MLW. Approximately 800,000 soundings were extracted and loaded into ArcView 3.2 GIS software. Soundings were sorted based on (1) vertical datum, (2) date of the survey and (3) survey identification number (Gesch and Wilson, 2001). Additional statistics were compiled to develop a strategic plan to identify and locate spurious soundings (old soundings that fall on land), to reject nautical charting features (e.g., obstructions, navigation aids, landmarks) and soundings with excessive depth or elevation values that fall outside a minimum-maximum range, and to assess the spatial and temporal qualities of the archived soundings for near in-shore areas. The transformation of the bathymetric data to the NAD83 datum with VDatum was verified using special hydrographic survey transects carried out in February 2000 using RTK-GPS vertical referencing, i.e., the depth soundings were directly measured with respect to NAD83.

### Topographic Data

The best available topographic data for the Tampa Bay region were selected from the USGS National Elevation Dataset (NED), a seamless raster elevation data set that provides national coverage at a horizontal grid spacing of 1-arc-second, approximately 30 metres, with some data for some locations also at 10-metre spacing. NED is derived from USGS map-based DEMs, each covering the area of a standard 7.5-minute topographic quadrangle map. Each DEM consists of gridded elevation data interpolated from USGS hydrographic and hypsographic digital line graph data, originally referenced to NGVD 29 (in the continental US). The maximum root-mean-squared error for all of the DEMs used in this project was one-third of the contour interval. NED production includes the following processing steps performed on the individual source 7.5-minute DEM files: datum and coordinate unit conversion (horizontal and vertical), projection transformation and resampling, filtering (for removal of production artifacts), mosaicing, edge matching, and metadata generation. The resulting 50-gigabyte dataset includes an elevation value (expressed in decimal metres referenced to NAVD 88) posted every 1-arc-second on a latitude/longitude grid (referenced to the NAD 83 horizontal datum). Standard tools and datasets (VERTCON and GEOID99) from NOS were used to transform the elevation data into the common ellipsoid vertical reference frame. (Gesch and Wilson, 2001)

**Blending the Bathymetric and Topographic Data**

NOAA and USGS exchanged their gridded bathymetric and topographic data sets and each agency separately blended them into a seamless bathy/topo DEM for comparison purposes and quality control.

At NOAA, the soundings were gridded in Spatial Analyst at multiple resolutions (10m, 20m and 30m), but the 30m result was used initially in order to match the resolution of the topographic 30m DEM GRID model from USGS. Both raster GRID models were merged into a single bathy/topo 30m GRID in Spatial Analyst. Other types of GIS data in both vector and raster formats were produced to assess the accuracy and reliability of the merged GRID data. For example, shoreline data were extracted from the production plates for the largest-scale nautical chart in Tampa Bay, (using a new technique that converts raster shoreline data to a vector shoreline file) for overlay on the bathy/topo 30-m DEM in order to help assess bathymetric and topographic data overlaps. The bathy/topo DEM was also compared with: a series of USGS digital orthoquads (DOQs) for select areas in Tampa Bay; high-resolution vector shoreline data extracted from original NOAA source manuscripts; and six NOAA raster nautical charts that cover Tampa Bay which were reprojected to a geographic projection so that all raster and vector data would align correctly in the GIS. Vector channel data already developed for an Electronic Navigational Chart (ENC) were also used to assess sounding data inside the main shipping channels in the Tampa Bay area. Other miscellaneous GIS data layers containing demographic, environmental and biological data, employed as secondary GIS layers, were overlaid on top of the bathy/topo GRID model. A large number of visualisations were produced of the bathy/topo DEM, including a 3-dimensional fly-through produced at the NOAA-University of New Hampshire Joint Hydrographic Center using the Fledermous software. (See Figure 3 for one visualisation of the DEM.)

At USGS the interface of zero and non-zero elevations in the NED (an approximate 'shoreline') was used to select the bathymetry and topography points for merging. All land elevations within 600 metres of the shoreline were converted from raster format to xyz point data. All bathymetry points coinciding with areas of zero elevation in NED were selected. Some of the depth soundings were withheld from further processing if it was believed that those water areas had been filled and so that those points were now on dry land. The selected topography and bathymetry points were gridded to produce a raster surface model with a 1-arc-second grid spacing to match the resolution of NED, making use of the ANUDEM thin plate spline interpolation algorithm. To avoid introduction of any interpolation edge effects in the merged elevation model, the output grid from the interpolation was clipped to include only land elevations within 300 metres of the shoreline. The final processing step involved the mosaicing of the bathymetry grid and the NED elevation grid to produce a seamless bathymetric-/topographic model covering the Tampa Bay region at a grid spacing of 1-arc-second. The vertical coordinates represent elevation in decimal metres relative to the NAD 83 (86) datum which uses the GRS80 ellipsoid, and the horizontal coordinates are decimal degrees of latitude and longitude referenced to the NAD 83 (86) horizontal datum. A series of visualizations were also produced for this bathy/topo DEM.

In both the NOAA and the USGS methods for producing the bathy/topo DEM, there was a problem in how to handle accurately the area where the bathymetric data and the topographic data meet, namely, the shoreline zone. Near the shoreline both sets of data were too coarse, too old, and obtained at different times, so that overlap of topographic and bathymetric data was inevitable. The use of high-resolution Lidar data flown over the shoreline zone (i.e., in and landward of the intertidal zone) helps solve the problem of joining the two data sets (although there is always the problem of discontinuities owing to the different ages of the data sets). As we shall see in the next section, Lidar data from the shoreline zone, in combination with the VDatum, provides us with a means for producing a true consistently defined shoreline.

## A Consistently Defined Shoreline Derived from a DEM

The shoreline presently depicted on nautical charts for the Tampa Bay region (the U.S. legal shoreline) is a MHW shoreline derived from 1977 T-Sheets (based on tide-controlled black-and-white, infrared aerial photographs) with updates to man-made shoreline areas determined from satellite imagery such as SPIN-2 and IKONOS. However, natural shorelines depicted on nautical charts or other mapping products all suffer from the same problem – the difficulty in measuring a true MHW shoreline, with the result that shorelines measured by different agencies usually do not match (Parker, 2001).

The main difficulty in measuring a true MHW shoreline has been the use of measurement techniques that capture the land-water interface at an 'instant in time'. Each point on a MHW shoreline should represent the horizontal position of the land-water interface at the time when the water level at that point is at a height equal to MHW elevation value at that point. However, at the time of measurement any deviation of the water level height from the MHW value will shift the horizontal position of the land-water interface seaward or landward. Such water level variations have made it almost impossible to capture with a camera, on a plane or satellite, the image of an land-water interface which is a true MHW line. MHW is a statistical quantity, the average of all the high water elevations over the most recent 18.6-year period. Since the height of each high water varies throughout the month, the year, and the 18.6-year lunar nodal period, there are only limited days when a particular high water will be close to the MHW datum value. Also, since

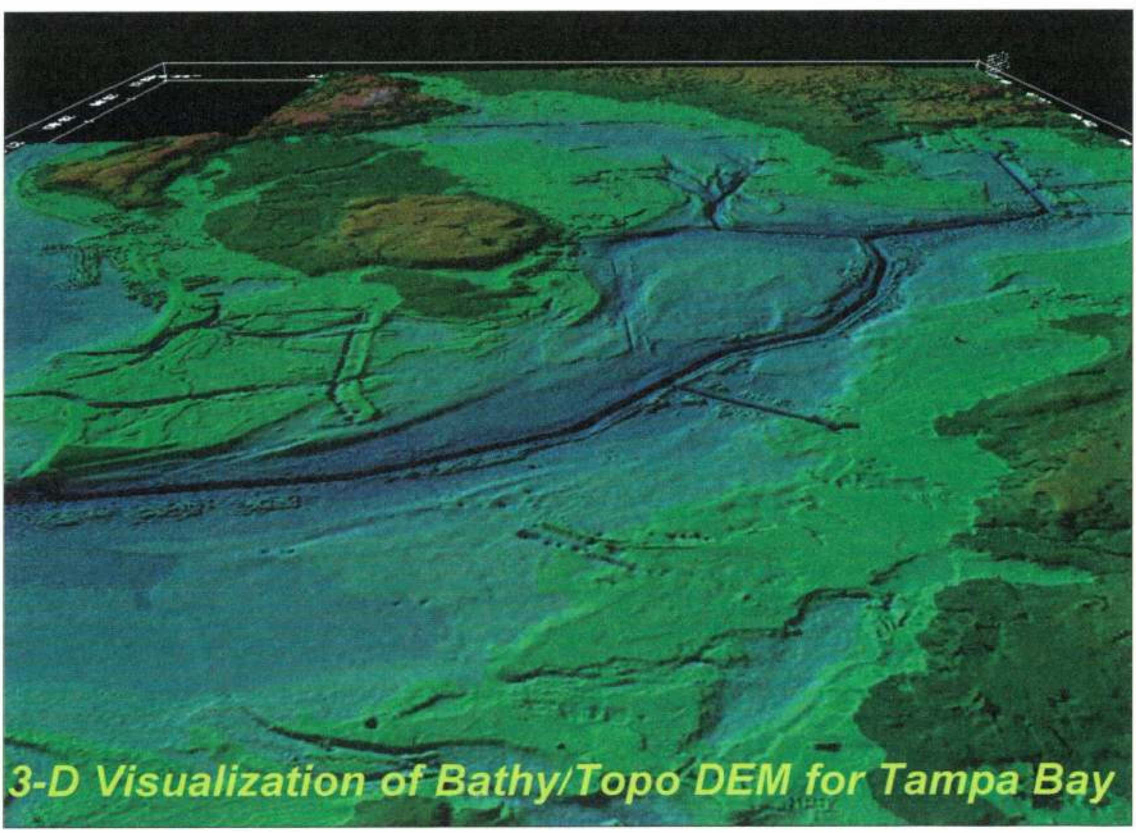


*Figure 3: A 3-dimensional visualisation of the Digital Elevation Model (DEM) for Tampa Bay produced from the blending of bathymetrical and topographic data that were first transformed to a common datum using NOS' Vdatum*

the tide regime changes over distance (and often quickly in shallower waters), it is never really high water (much less MHW) everywhere along a shoreline at exactly the same time (to be conveniently captured by a camera). Without having a huge number of tide gauges to cover the entire shoreline, we cannot even know what the MHW value is at all points along the shore. Meteorological effects add greatly to the problem. Water level is affected by a number of non-tidal phenomena, the most important being wind, but also including atmospheric pressure, river discharge, and steric effects due to changing water density (from both changing salinity and temperature). So even if one was lucky enough to capture a land-water interface image on a clear day when the high water elevation is close to the MHW datum value, a moderate wind could still raise or lower the water level, thus moving the land-water interface away from its hoped for MHW horizontal position.

These factors are an important cause of the inconsistency between shoreline measured by different agencies and institutions, including NOAA and USGS. But the consistency we seek in a shoreline representation can be provided by the stability of the statistically determined MHW if we have a means of determining the horizontal position of the land-water interface that has an elevation equal to (the horizontally varying) MHW at all points along the shore. This means is provided by the combination of a DEM covering the intertidal zone and a vertical datum transformation tool whose tidal datum distribution has been accurately determined by a hydrodynamic model.

Rather than observing the shoreline directly from above, one instead measures the shore elevation profiles along the shore and then raises the water level to a MHW elevation for each profile. The geographic distribution of MHW along a coast (and throughout a waterway) is provided by the numerical hydrodynamic model, which essentially creates a MHW elevation surface. A closely spaced sequence of elevation profiles, i.e., a Digital Elevation Model (DEM), can be produced from airborne Lidar data. The intersection of the MHW elevation surface from the hydrodynamic model with the Lidar-produced DEM covering the intertidal zone produces the consistent MHW shoreline we desire.

One thus produces a true MHW shoreline by essentially using the hydrodynamic model to raise the water

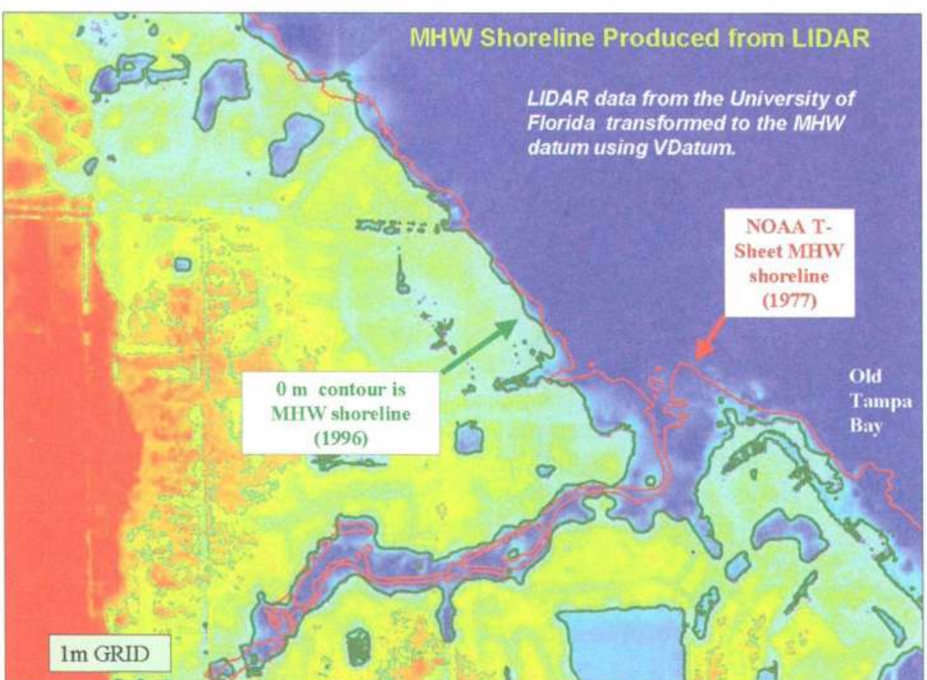


*Figure 4: A MHW shoreline produced from Lidar data that was transformed to the MHW datum using VDatum, for the Long Branch creek area on the northwestern side of Old Tampa Bay. The green line is the MHW shoreline derived from the Lidar data and the red line is the MHW shoreline from 1977 T-Sheets. See text for explanation of differences*

level to the correct MHW elevation value for each of the continuous beach profiles produced by the Lidar. However, this is most easily accomplished through a vertical datum transformation of the high-resolution elevation data, in and landward of the intertidal zone. Such data, whether from airborne Lidar surveys or from surveys carried out with land vehicles or on foot, are now routinely referenced to an accepted ellipsoid datum using RTK-GPS. If one simply transforms these elevation data from the ellipsoid datum to the MHW datum, then the zero elevation values will be the MHW shoreline. Both the chosen ellipsoid datum and the MHW datum vary in horizontal (geographic) space, and these variations must be accurately known. Such ellipsoid datums are known accurately for the entire U.S., and the geographic distribution of MHW and other tidal datums, as mentioned above, can be produced by a numerical hydrodynamic model. A vertical datum transformation tool incorporates both datum fields. Not only does this method allow a consistent representation of the MHW shoreline for an area, one can also produce shorelines for other vertical datums as well, all of them consistent with each other through the DEM.

This is demonstrated for a section of coastline in Tampa Bay. A MHW shoreline was produced by using VDatum to transform Lidar data (flown by the University of Florida) to the MHW water datum. Figure 4 shows the Lidar data (a 1-metre DEM) and the MHW shoreline, i.e., the zero-metre contour (the green line), since the elevation data is now referenced to the MHW datum. Also shown in this figure is a red line, which represents the MHW shoreline as determined from NOS T-Sheets back in 1977. In some locations the two lines are reasonably close considering they were observed 19 years apart. The larger difference at the mouth of Long Branch creek is due to the presence of mangrove swamps which the Lidar saw through, but the 1977 NOS field party was influenced by the presence of the mangroves and they chose the waterside edge of the mangrove swamp as the designated shoreline.

## GIS Users and Their Applications

Although visualisations of the DEM (including fly-throughs) are useful for data understanding and interpretation, a remaining key issue is how to provide the coastal zone user with the full DEM in a convenient digital form (usable in a GIS) that maximises available data resolutions. This is especially important because recent data will generally be of greater resolution than the NOAA and USGS data used to create the basic DEM. The DEM is still important since it provides the basic framework (taking care of datum and other issues) for these newer data to be superimposed onto or blended into. However, these newer higher-resolution data must not be forced to be gridded down to lower resolutions just to fit in with the DEM. One approach is to treat newer data sets as 'independent objects', and one question is how easily could separate GIS layers with these newer data sets be used in conjunction with the basic DEM database in the GIS.

Since the source bathymetric and topographic data vary in density and accuracy, users also need to be made aware of the spatially varying quality of the merged model. The vertical accuracy of the DEM varies spatially due mainly to the wide variety of dates and data collection technologies used for source data acquisition. A merged uniformly spaced grid cell model was originally produced because most users require such a product for their computer mapping systems. Current work involves generating spatial indices of data quality and accuracy that are co-registered with the DEM to help users better judge the applicability of the model for their application in a specific location. One index will be a representation of the density (point spacing) of the input sounding data. Another index will portray the estimated vertical accuracy of the bathymetric and topographic data. Without such labelling, users may assume more accuracy than is actually present, especially because the data are presented in a seamless fashion where discontinuities among data sources have been intentionally minimised, and the vertical units are expressed to sub-metre precision.

To encourage use of the Tampa Bay DEM (and other DEMs being developed), and most importantly to encourage feedback, a bathy/topo Website (http://chartmaker.ncd.noaa.gov/bathytopo) and a bathy/topo CD product have been developed. The CD product, designed specifically with the GIS user in mind, has four levels of sophistication built into it. The first level is primarily introductory, with project overview, visualisations, background and history information, including explanatory movies. The second level is aimed at the beginning GIS user, with tutorials and sample hands-on project examples. The third level includes technical applications aimed at the more experienced GIS user and includes tutorials on VDatum and DEM creation, with sample VDatum and DEM datasets. The fourth level links directly with the Tampa Bay high-resolution datasets on the bathy/topo web-site, and allows for the creation of customised data sets. The bathy/topo website also has a number of explanatory papers, tutorials, and visualisations.

## One Other Application of VDatum - Hydrographic Surveys with Vertical Referencing using RTK-GPS

An additional benefit of NOS's vertical datum transformation tool is its use in making hydrographic surveys more efficient and accurate by eliminating the need for real-time water level gauges installed during the survey and time-consuming water level corrections, as well as eliminating the need for vessel settlement and squat corrections. Since the transducer of a shallow-water multibeam is at a known position below a GPS receiver on the hydrographic survey ship, the depth measurements can be taken referenced to a 3-D/ellipsoid datum. Using VDatum, which includes the geographic variation of the chart datum (MLLW) produced by the hydrodynamic tidal model, and its relationship to the ellipsoid, the measured depths can thus be directly referenced to the chart datum. This eliminates the need for water level corrections and settlement and squat corrections, usually done as time-consuming post-processing. The depth soundings are actually measured 'on the fly' already referenced to chart datum. This was proposed in Parker and Huff (1998) but without specific reference to an overall vertical datum transformation tool like VDatum.

## Conclusions

There are many coastal applications that can benefit greatly from a bathymetric-topographic digital elevation model with an accurate and consistently defined shoreline. One major benefit will be an eventual consistency between the coastal mapping and charting products of USGS and NOAA, especially the shoreline. For NOAA and USGS it also represents the beginning of a new way of doing business with each other that will reduce duplication of effort and better meet the needs of state and county agencies. The nature of this co-operation also promotes metadata standards and therefore the reliable use of data from many different sources, increasing the chances of being able to use quality bathymetric and/or topographic '3rd-party' data.

In addition to the Tampa Bay Demonstration Project, several other related projects have taken place all which have resulted in a populated VDatum for those regions. These include: another NOAA-USGS bathy/topo project for a section of Louisiana near Port Fourchon, the creation of a blended bathymetric elevation surface off the coast of California for a marine sanctuaries application, a blended bathymetric elevation surface for the New Jersey coast for an offshore aggregates study, a VDatum implementation for a special hydrographic survey in Delaware Bay with RTK-GPS vertical referencing, and several areas for determining MHW shoreline from Lidar data.

In particular, it appears that the use of a vertical datum transformation tool will be a cornerstone of the new way that NOS will acquire, handle and process bathymetric and shoreline data and efficiently use these data to produce NOAA nautical chart and electronic vector products. Thus, the development and population of national *vertical datum transformation database* ('National VDatum'), with its tidal datum fields produced by tidal modelling techniques, is now an important goal of NOS. Some very important applications for which National VDatum is critical (Figure 5) include:

(1) The implementation of a seamless National Bathymetric Database. VDatum will transform all the historical data sets to a common datum (MLLW). This database will be the source of bathymetric data for the Vector Product Database from which electronic navigational chart (ENCs) products will be produced or updated

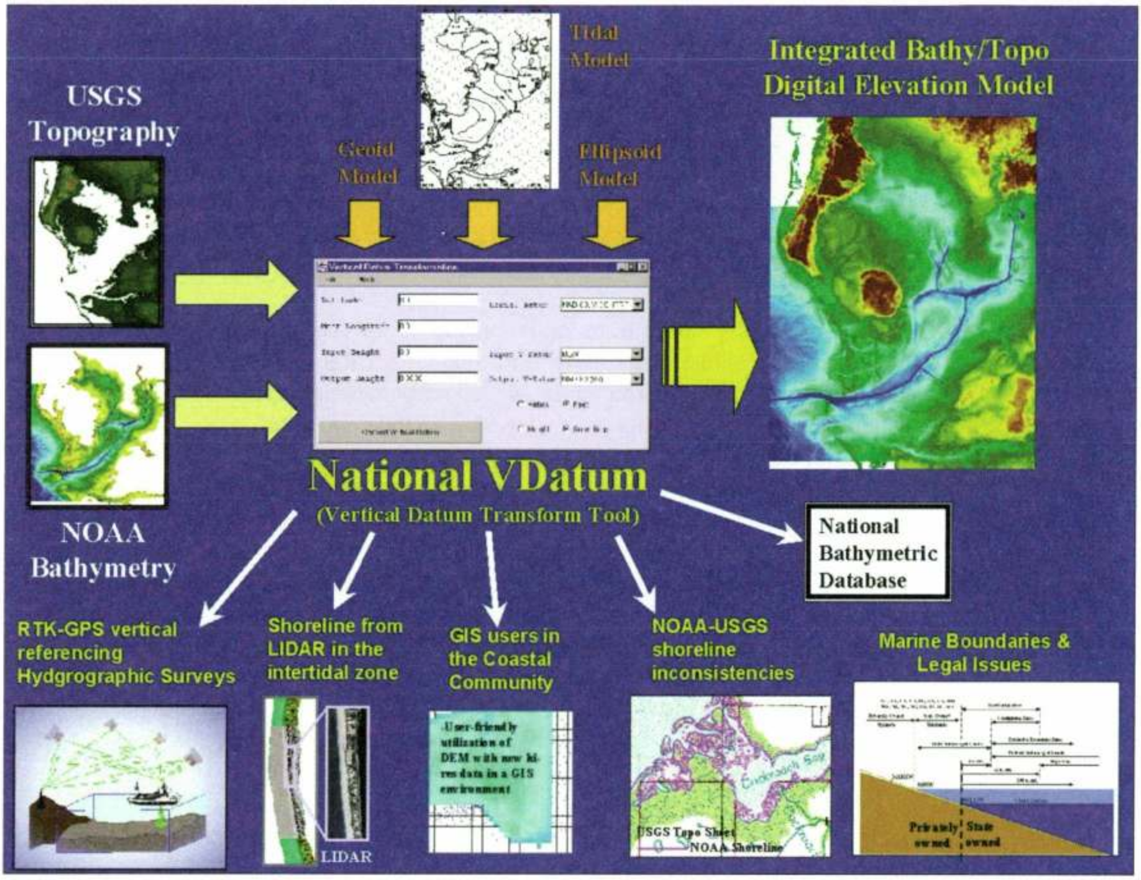


*Figure 5: Applications of a vertical datum transformation tool such as NOS's VDatum*

(2) The improved efficiency and accuracy of hydrographic surveys with vertical referencing from RTK-GPS by eliminating the need for time-consuming water level corrections (requiring real-time water level gauges installed during the survey) and vessel settlement and squat corrections. The bathymetric data will be measured on the fly relative to chart datum (MLLW) using VDatum to transform the RTK-GPS referenced data to MLLW

(3) The measurement of *consistently* defined MHW shoreline from RTK-GPS-referenced Lidar elevation data from the intertidal zone, transformed with VDatum to the MHW datum, with the zero line then being the shoreline

(4) The ability to use high-quality 3rd-party bathymetric data (from universities, companies, and state, county, and city agencies) in NOAA nautical chart products, with VDatum solving the datum incompatibility problems that have prevented this

(5) Meeting local coastal user needs for being able to blend their bathymetric data with that obtained by other groups (local users are requesting a National VDatum for this reason)

(6) The implementation of a full National Bathy/Topo Program with the U.S. Geological Survey, VDatum being required for the blending of USGS's topographic data with NOAA's bathymetric data after their transformation to a common datum

(7) Marine boundary applications

The development of a National VDatum has two major activities. First, is the database design and implementation, taking into consideration all future applications and user-friendly access requirements via the internet, including the ability to handle multiple grids with different resolutions. Second, the geographic distribution of the various tidal datums must be produced with either hydrodynamic tidal models or a dynamic interpolation technique (such as TCARI); in some areas additional tide gauges will need to be installed for a short time period. This second activity is a huge undertaking considering the 95,000 miles of coastline to be covered. Based on what resources are available, the National VDatum database will be populated area by area, with priorities based on a number of considerations, including: areas with high quality Lidar data from which shoreline is to be derived; planned hydrographic surveys; high priority areas to be added to the National Bathymetric Database; future joint NOAA-USGS bathy/topo projects; areas with high-quality 3rd-party data; user requests from the coastal zone community; and homeland security needs.

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## References

Gesch, Dean and Robert Wilson,( 2001). Development of a seamless multisource topographic/bathymetric elevation model of Tampa Bay. *Marine Technology Society Journal*, Winter 2001/2002, 35(4):58-64

Hess, Kurt, (1994). *Tampa Bay Oceanography Project: Development and Application of the Numerical Circulation Model*, NOAA Technical Report: NOS OES 005, National Ocean Service, NOAA, 90 pages

Hess, K. W., (2002). Spatial interpolation of tidal data in irregularly-shaped coastal regions by numerical solution of Laplace's equation. *Estuarine, Coastal and Shelf Science*. 54, 175-192

Milbert, Dennis, (2002). VDatum Transformation Tool (New Version 1.05), The GeoCommunitiy Spatial News, http://spatialnews.geocomm.com/features/vdatum/

Parker, Bruce,( 2001). Where is the shoreline? *Hydro INTERNATIONAL*, July/August 2001, pages 6-9

Parker, Bruce B. and Lloyd C. Huff, (1998). Modern under-keel clearance management. *International Hydrographic Review*, **LXXV**(2):143-165

## Biography

Dr. Bruce Parker is Chief of the Coast Survey Development Laboratory in the National Ocean Service in NOAA. His lab carries out oceanographic, hydrographic, and cartographic research and development, especially in areas supporting safe navigation, environmental protection, and coastal zone management. In September 2000 Dr. Parker was awarded the Department of Commerce Gold Medal for Scientific

Leadership for development of a new program to implement real-time and forecast oceanographic model systems. In May 2000 Dr. Parker and a lab colleague were awarded the Commodore Cooper Medal by the IHO for a paper published in IHR in 1998. Dr. Parker received his Ph.D. in physical oceanography from Johns Hopkins University, an M.S. in physical oceanography from the Massachusetts Institute of Technology, and B.S./ B.A. in biology/physics from Brown University. Dr. Parker is also a former Director of the World Data Center A for Oceanography, and former Chair of the Research and Technology Subcommittee of the Interagency Committee for the Marine Transportation System, which represents 18 Federal agencies.

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