A Tampa Bay Bathymetric/Topographic Digital Elevation Model With Internally Consistent Shorelines for Various Datums

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Abstract

In a joint demonstration project for the Tampa Bay region, the National Oceanic and Atmospheric Administration (NOAA) and the U.S. Geological Survey (USGS) have blended their bathymetric and topographic data sets (respectively) into a digital elevation model (DEM) with all data initially referenced to the ellipsoid. A datum transformation tool allows easy transformation of elevations with respect to any of 26 orthometric, 3-D, or tidal datums. The geographic distribution of particular tidal datums (relative to mean sea level) was produced using a calibrated and verified numerical hydrodynamic model of Tampa Bay. This datum transformation tool was used to transform all bathymetric data from a mean lower low water datum (or from a mean low water datum for older data) to the ellipsoid. For areas where low water and high water shorelines are significantly different, an ultimate objective will be to incorporate a higher-resolution "shoreline zone" into the DEM, so that various internally consistent "shorelines" can be generated by moving the water level in the DEM to the desired tidal datum heights. The bathymetric/topographic DEM will not only solve the problem of inconsistency between NOAA and USGS shorelines that have caused difficulty for a variety of mariners and coastal managers, but it will also provide a standard DEM on which other third-party bathymetric and topographic data can be appended, as well a great variety of geospatial data layers. The applications benefitting from the bathy/topo DEM range from electronic nautical charts to improved storm surge modeling to better sea grass (and other habitat) restoration projects.

1. Introduction

In recent years increased attention has been paid to the use of bathymetric data for coastal applications in addition to its use in the traditional production of nautical charts for safe navigation. It has also been realized that, for a variety of coastal zone uses, increased benefit could be gained by blending these bathymetric data with topographic data to provide a single seamless elevation surface. In the United States there was an additional motivation for blending bathymetric and topographic data, namely, obvious inconsistencies between the products of its two primary domestic mapping agencies, the National Oceanic and Atmospheric Administration (NOAA) and the U.S. Geological Survey (USGS). The most glaring inconsistency was that the shorelines of the topographic products of USGS often did not match the shorelines of the nautical charts from NOAA. Although part of this inconsistency could be traced back to data that has been obtained at different times (with shoreline changes having subsequently occurred), much of the problem was due to the use of different tidal datums. The problem was serious enough that representatives from the coastal resources user community, participating in a Users Needs Workshop in St. Petersburg, Florida, in December 1999, expressed the view that data *consistency* was more important than data *accuracy* for many of their applications (in which a great number of different demographic and environmental data types must be georeferenced).

For similar reasons it has been extremely difficult for state and local agencies to blend their own data with data of NOAA and/or USGS or with data produced by neighboring agencies. Again the problem could usually be traced back to their use of a number of different reference datums. 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, as well as by universities. However, to be able to do this, all these various data sets must all be transformable to a common datum, and they must fit into an accepted national geospatial framework.

2. The Tampa Bay Demonstration Project

As a first step toward solving the above problems, NOAA's National Ocean Service (NOS) and the USGS's National Mapping Division (NMD) have begun a joint demonstration project in which they have 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 Datum Transformation Tool. This tool allows transformations among any of 26 orthometric, 3-dimensional (3-D), or tidal datums and is being provided as a user-friendly tool to the coastal user community. A fully calibrated hydrodynamic model of Tampa Bay was used to determine the geographic distribution of the tidal datums. Recent high-resolution third-party bathymetric and topographic data are being incorporated into the DEM, also making use of the Datum Transformation Tool. A number of visualizations (including fly-throughs) have been created.

Up-to-date high-resolution shorelines are being developed using data from various airborne and satellite remote sensing sources and referenced to agreed upon tidal datums. Where data permits, attempts will be made to produce a higher-resolution "shoreline zone" in the DEM, from which various internally consistent "shorelines" can be generated by moving the water level in the DEM to the desired tidal datum heights. The product will include a vector GIS layer that contains the various shoreline delineations

A great variety of other types of marine and terrestrial geospatial data will be added to the bathymetric/topographic DEM. The DEM, shorelines, additional data layers, and visualizations will be available from a Web-accessible database and on CD-ROMs. The Web-accessible bathy/topo DEM and accompanying shorelines will not only solve the problem of inconsistency between NOS and USGS products that has caused difficulty for coastal managers, but it will also provide a standard DEM onto which others can append their bathymetric and topographic data. The Datum Transformation Tool and metadata standards will be made available to all users to facilitate this process.

This is the first step toward the development of a mutually agreed upon "national shoreline". For NOAA and USGS it 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 applications benefitting from the bathy/topo DEM include: improved hurricane evacuation plans (based on improved storm surge modeling); improved and consistent geospatial data for county planners; better located habitat restoration projects; and detailed electronic nautical charts, to name just a few. The nature of this project also promotes metadata standards and therefore the reliable use of data from many different sources. This project will be viewed as a "demonstration" in the broadest sense, and will include a variety of promising new technical and scientific techniques. (This is an ongoing project and the material presented in this paper represents the status as of September 30, 2000.)

3. Datum Transformation Tool (VDatum)

VDatum is a tool for the transformation of elevation data from one vertical datum into another. Such transformations are necessary when data from diverse sources are to be combined or compared. Informally, a datum can be considered as the "coordinate system" of geospatial data. Artificial steps or discontinuities can appear in maps and charts if they are built from data based on inconsistent datums. This problem can be particularly acute in coastal areas. For example, on a gently sloping beach, an offset in elevation information will change the depiction of the shoreline – it can shift the shoreline and change its shape on a map.

VDatum has been implemented initially for the region of Tampa Bay, Florida, as part of the bathymetric/topographic/shoreline demonstration project. The source code and algorithms are open. And, if this project is successful, the vertical datum transformation methodologies could conceivably be incorporated into various commercial Geographic Information System (GIS) packages.

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 distinct new third category, consisting of 3-dimensional datums realized through space-based systems such as the Global Positioning System (GPS), referred to as *3-D Datums*. Topographic maps (from USGS, for example) generally have elevations referenced orthometric datums, either the North American Vertical Datum 1988 (NAVD 88) or to the older North American Geodetic Vertical Datum 1929 (NGVD 29). The NAVD 88 was affirmed as the official vertical datum for the United States (by a notice in the Federal Register, Vol. 58, No. 120 page 34245) on June 24, 1993. Nautical charts have depths referenced to different tidal surfaces, which may vary from chart to chart. In the United States mean lower low water (MLLW) is the typical low water reference surfaces. To support harbor and river navigation, bridge clearances are referenced to a mean high water (MHW), not to MLLW.

VDatum converts elevation data among the 26 different vertical datums shown in Table 1 below. In practice, a user will only have to transform between a few datums. The 26 varieties of tidal and 3-D datums supported by VDatum are supplied merely to be complete. The relative position of a few of these datums is shown in Figure 1. In Tampa Bay the separations between the tidal surfaces and the NAD 83 (and other 3-D datums) are in excess of 24 meters. The relationship of NAD 83 to NAVD 88 is defined by the GEOID99 height model (Smith and Roman, 2000). The relationship of NAVD 88 to local mean sea level (LMSL) is calibrated from tide model comparisons with leveled tidal benchmarks, and is assumed to be a constant 0.163 meters in Tampa Bay.

Table 1. *26 different vertical datums included in VDatum.*

Orthometric Datums	
NAVD 88	North American Vertical Datum 1988
NGVD 29	North American GeodeticVertical 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 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
ITRF97	International Terrestrial Reference Frame 1997
3-D Datums (continued)	
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

--- WGS 84 (G873)

--- NAD 83(86)

(large offset)

--- MHHW

--- MHW

--- NAVD 88

--- LMSL

--- MLW

--- MLLW

Figure 1. *Schematic of selected vertical datum reference surfaces at Tampa Bay (approximate B not to scale)*

4. Geographic Distribution of Tidal Datums

Tidal datum transfer fields for Tampa Bay were generated using a numerical hydrodynamic model of the bay, a version of the Princeton Ocean Model that was previously developed by NOS (Hess, 1994). It is a three-dimensional, free-surface, sigma-coordinate baroclinic hydrodynamic model with a curvilinear grid. Typical grid spacing is from 100 to 1000 meters. 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.

NOS hydrographic data obtained in 1994-96 and 1975 were referenced to MLLW, but data obtained in 1950-58 were referenced to MLW. 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). The model generated more than one year's worth of water levels, which were then analyzed to pick off high and low waters and average them according to accepted standards in order to generate the datum transfer fields. Figure 2 shows the geographic distribution of MSL relative to MLLW. (Datum fields for locations outside the Bay along the coast were generated by interpolating between shore-based tide gauges and the hydrodynamic model output near the entrance to the Bay, and extrapolating seaward.)

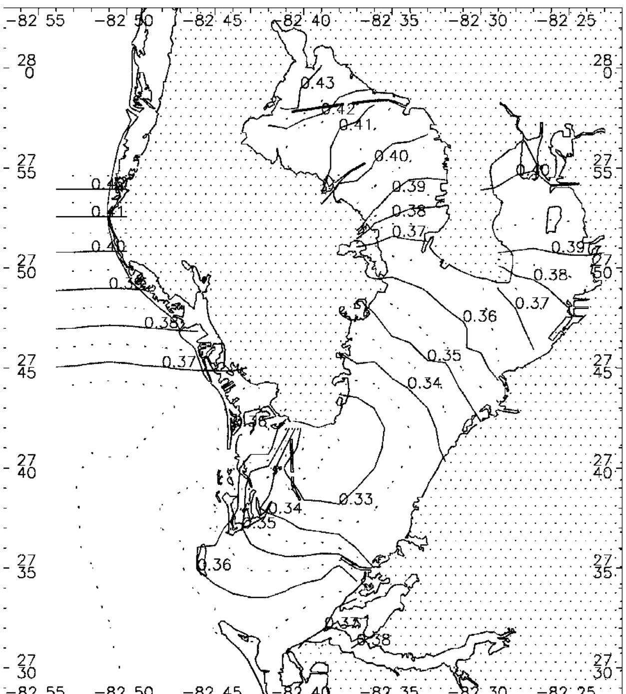

Figure 2. MSL(m) relative to MLLW.

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, 1999). 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.

5. Bathymetric Data

Sounding data 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, while data near the shore and in other shallower areas came from surveys carried out in 1950-58. Some data outside the entrance to Tampa Bay came from a 1975 survey.

Approximately 800,000 soundings were extracted and loaded into ArcView 3.2 GIS software. Soundings were sorted based on (1) vertical datum (MLW or MLLW), (2) date of the survey and (3) survey identification number. 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.

Spatial polygons for each of the 47 NOAA hydrographic surveys were employed in ArcView, sorted by date, merged with other survey polygons for a given year and clipped based on the survey date. An Avenue script was developed to ensure a polygon topological consistency and to remove polygon slivers for surveys that overlapped or intersected. As a result of this process, 15 new master spatial-temporal polygons were developed. Each new polygon represents the spatial location of the most current NOAA soundings in Tampa Bay. About 99% of the project area for Tampa Bay had digital sounding data at variable data densities. The soundings identified as most recent from the polygon processing were merged into a single file and sorted based on the vertical datum. Soundings were then converted from either MLW or MLLW to NAD 83 (86) using VDatum. Approximately 300,000 soundings (for each datum) were converted in less than 4 minutes running on a 550mhz NT computer with 2 GB of RAM. After completing the datum conversion, NOAA soundings were merged into a single data file. The datum transformation will be verified using special hydrographic survey transects carried out with on-the-fly GPS referencing.

6. Topographic Data

The best available topographic data for the Tampa Bay region were selected from the USGS National Elevation Dataset (NED), an implementation of the National Spatial Data Infrastructure (NSDI) concept of “framework” data, i.e., those spatial data sets that are fundamental to many applications. NED is a seamless raster elevation data set that provides national coverage at a horizontal grid spacing of 1-arc-second (approximately 30 meters). NED is derived from USGS map-based DEMs, each covering the area of a standard 7.5-minute topographic quadrangle map. Large-scale 7.5-minute DEMs such as these are gridded elevation data that is interpolated from USGS hydrographic and hypsographic digital line graph (DLG) data. The original USGS DEMs are relative to NGVD 29 (in the continental US). Typically the grid spacing (horizontal resolution) is 30 meters, however, more data are now being added to the database with 10-meter spacing. 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 meters 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.

7. 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. 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 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. The extracted shoreline data provided a temporal framework for the shoreline data. It was used in part to locate and validate shoreline in the 30m DEM. The bathy/topo DEM was also compared with a series of USGS digital orthoquads (DOQs) for select areas in Tampa Bay, and high-resolution vector shoreline data extracted from original NOAA source manuscripts. Raster nautical charts were also employed in ArcView to assess the temporal quality of the hydrography as represented on the most current large-scale nautical chart. Six NOAA raster nautical charts that cover Tampa Bay 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 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 were also provided and employed as secondary GIS layers which can easily be overlaid on top of the bathy/topo GRID model. An integrated X, Y, Z data set that contained both the NOAA depth sounding data and the USGS topographic data was converted at the NOAA-University of New Hampshire Hydrographic Center to a 3-dimensional fly-through model using the Fledermaus software. The high-resolution 3-D fly through of the Tampa Bay blended bathymetric and topographic elevation data (stored in a standard .mpg format) provided a rich data visualization.

At USGS the NED “shoreline” (interface of zero and non-zero elevations) was used to make the final selection of bathymetry and topography points for merging. All land elevations within 600 meters of the shoreline were converted from raster format to X, Y, Z point data. All bathymetry points coinciding with areas of zero elevation in NED were selected. Because of the age of some of the hydrographic surveys, some of the depth soundings were located on areas that had been filled and are now on dry land in the DEM. These points were withheld from further processing. The selected topography points within the shoreline buffer zone and the bathymetry points were gridded to produce a raster surface model with a 1-arc-second grid spacing to match the resolution of NED. The points were input to an implementation of the ANUDEM thin plate spline interpolation algorithm (Hutchinson, 1989), which is optimized for generation of topographic surfaces. The bathymetry points could have been gridded independently of the topographic data, but the shoreline zone land elevations were included in the interpolation to ensure a better match of the bathymetric and topographic surfaces for the subsequent mosaicing step. To avoid introduction of any interpolation edge effects into the merged elevation model, the output grid from the interpolation was clipped to include only land elevations within 300 meters of the shoreline. The final processing step involved the mosaicing of the bathymetry grid and the NED elevation grid. The values in the 300-meter overlap area were blended by weighted averaging, where the weights for each grid are determined on a cell-by-cell basis according to the cell's proximity to the edges of the overlap area (Franke, 1982). The resulting final merged product is 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 meters 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) datum. A series of visualizations were also produced for the bathy/topo DEM (see Figure 3).

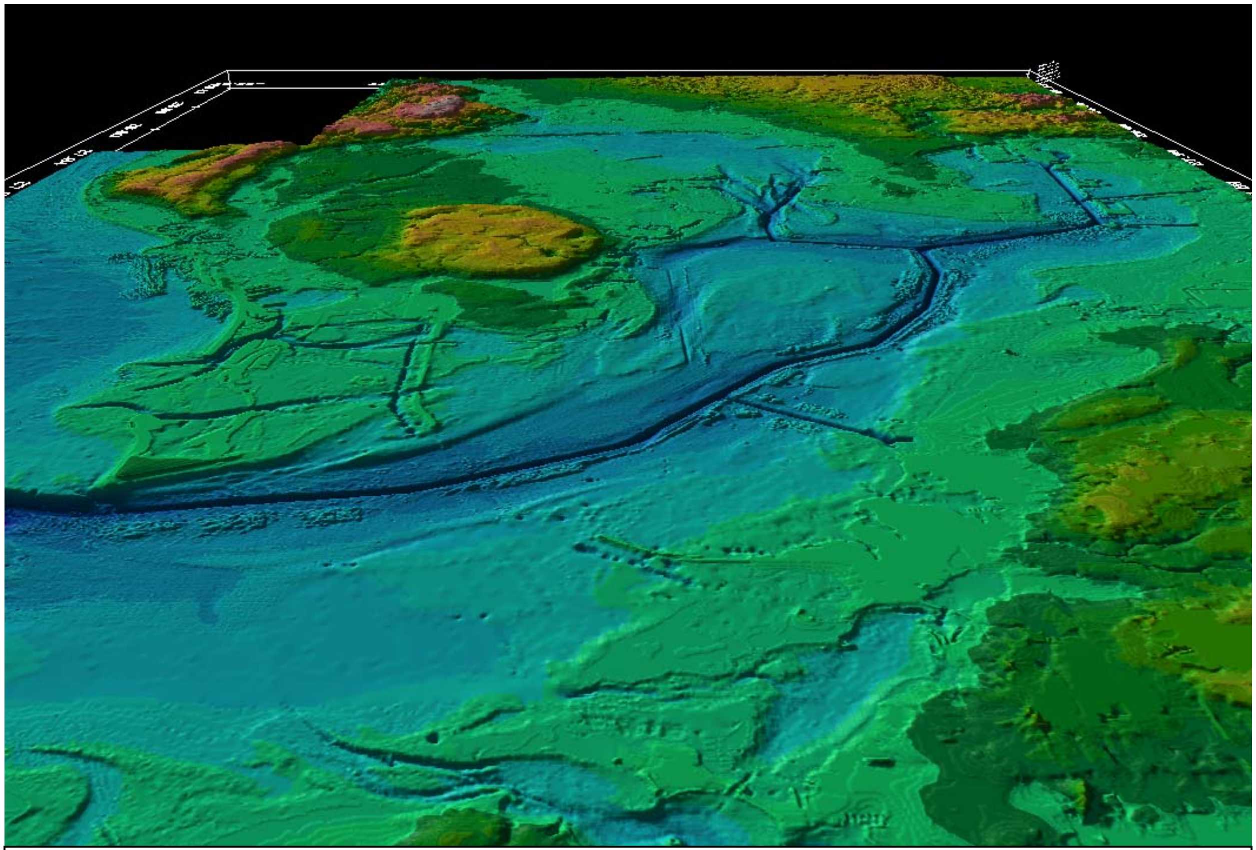

Figure 3. 3-D visualization of the Tampa Bay bathymetric/topographic digital elevation model.

8. Shoreline

A number of shoreline data sets are in the process of being compared for the Tampa Bay region. High-resolution photogrammetric mapping from aircraft continues to be the standard by which other technologies are measured. The most recent complete NOS photogrammetric survey of shoreline for Tampa Bay was carried out in 1977. Recently these topographic manuscripts were scanned, digitized, georeferenced, topologically structured, and quality checked to derive a composite digital shoreline. In addition, the shoreline displayed on the most recent NOAA raster nautical chart (which is based on the 1977 data, but may include subsequent man-made changes) was converted to vector form. These composite data sets serve as a base with which to register new high-resolution satellite images and other sources of shoreline such as Light Detection and Ranging (LIDAR) systems, hyperspectral imaging and more recent photogrammetric data.

The T-sheet data from the October-November 1977 survey consisted of shoreline manuscripts at 1:10,000 scale. The lines of MHW, Mean Water Level, and MLLW were compiled from tide-controlled black-and-white, infrared aerial photographs. The shoreline meets National Map Accuracy Standards (better than 27.8 feet for the 1:10,000 scale). Aerotriangulated 1:30,000-scale photogrammetric imagery from an aircraft was also taken in April 1999 for most (but not all) of the Tampa Bay shoreline.

SPIN-2 satellite imagery was taken February 18, 1998, at 20:20:02 GMT with a KVR-1000 camera system with a ground sample distance of 1.56 meters. The images for certain port areas were georeferenced to the 1977 1:10,000-scale vectorized shoreline manuscripts. The geopositioning of the georeferenced SPIN-2 had an average of 3.7 meter shift from the aero-triangulated 1:30,000-scale imagery taken in April 1999. Figure 4 shows shorelines near Hookers Point in the Port of Tampa derived from 1977 and 1999 photogrammetric data, along with the nautical (electronic) chart shoreline (based on the 1977 data plus some updates from permits), shown on top of a 1998 SPIN-2 satellite image. Here the differences are not due to different tidal datums, but to man-made changes including dredge-filled areas.

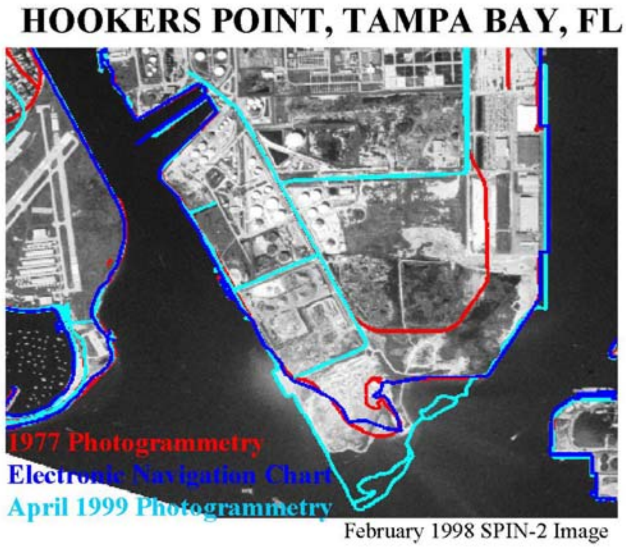

Figure 4. 1977 (red) and 1999 (light blue) shoreline from photogrammetry, and shoreline from nautical chart (red) superimposed on a 1998 SPIN-2 satellite image.

IKONOS satellite imagery will also be purchased for areas of Tampa Bay; it should have a ground sample distance of 1 meter. Shoreline will also be extracted from LIDAR data flown last year at 1-m resolution by the University of Florida and NASA over Pinellas County (on the west side of Tampa Bay), as well as from hyperspectral data expected to be flown in November 2000 on NOAA's Citation with resolution on the order of 2-4 meters.

For areas with sloping beaches, where low water and high water shorelines are significantly different, an ultimate objective will be to incorporate a higher-resolution "shoreline zone" into the DEM. Then various internally consistent "shorelines" can be generated by moving the water level in the DEM to the desired tidal datum heights. Data with sufficient horizontal resolution to produce such a shoreline zone could conceivably be obtained from LIDAR (flown at low water) or from SHOALS (flown at high water) or possibly from stereo-photogrammetry. Or, if several photographic or satellite images show shorelines at lower low water, at higher high water, and at some mid-tide level, that might be sufficient with appropriate interpolation techniques. At the very least, the goal is to come up a common shoreline agreed to by both NOAA and USGS.

9. GIS Users and Their Applications

Although visualizations 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 maximizes 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 need to be made aware of the spatially varying quality of the merged model. Likewise, the vertical accuracy of the model varies spatially, due mainly to the wide variety of dates and data collection technologies used for source data acquisition. A merged raster model at a uniform grid cell spacing 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 model 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. This index will be helpful for indicating to users the inherent accuracy of the source data, and thus the derived merged model. Without such labeling, 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 minimized, and the vertical units are expressed to sub-meter precision.

Providing a consistent DEM to the coastal user community, onto which they can append recent higher-resolution bathymetric and/or topographic data for use in their own applications (ranging from storm surge modeling to better sea grass habitat restoration projects), also has advantage for NOAA and USGS. With more than 95,000 miles of U.S. coastline to map (and to map frequently in order to keep up with natural and man-made changes) and with severe shortages in the resources needed to do this mapping, NOAA and USGS must be able to begin using quality data obtained by a state and local agencies, as well as by universities. To be able to do this, all these various data sets must all be transformable to a common datum, and they must fit into an accepted national geospatial framework.

LIDAR and SHOALS type data sets should be especially useful, since they provide combined bathymetric/topographic data of high resolution where the need is the greatest: at the land/water interface. High-resolution and high-accuracy data that cover both near-shore bathymetry and near-shore topography is ideal because it would serve as the reference dataset to which the inland topographic data and the offshore bathymetric data would be matched. The merging process could be the same as that used for the current model: surface interpolation across the overlap area by including points from all three data sources, followed by raster mosaicing with weighted average data blending to minimize discontinuities at data source transition zones.

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