VDATUM MANUAL FOR DEVELOPMENT AND SUPPORT OF NOAA'S VERTICAL DATUM TRANSFORMATION TOOL, *VDATUM*

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NATIONAL OCEAN SERVICE

Office of Coast Survey
National Geodetic Survey
Center for Operational Oceanographic Products and Services

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1. INTRODUCTION

1.1. INTRODUCTION TO VDATUM

The National Ocean Service (NOS) of the National Oceanic and Atmospheric Administration (NOAA) uses a variety of vertical reference elevations, i.e. vertical datums, in its geographical data. For example, NOS requires tidal datum information such as Mean High Water (MHW) and Mean Lower Low Water (MLLW) to support nautical charting, navigational safety, shoreline photogrammetry, marine boundary determination, and inundation mapping for coastal storms (tsunamis and hurricanes) and sea level rise. In addition, tidal datum information is needed for referencing NOS' older bathymetric data from Mean Low Water (MLW) to the current standard datum, MLLW, for charting purposes and related activities. To create seamless bathymetric-topographic Digital Elevation Models (DEM), all of the bathymetric/topographic data must be converted from various vertical datums to one common datum. Such a DEM can be used for a variety of coastal GIS applications (Parker et al., 2001; Gesch and Wilson, 2001; Tronvig, 2005). Vertical datum transformation information will also be needed for carrying out the kinematic-GPS hydrographic surveying that NOS is researching (Hess et al., 2003).

VDatum, a software tool under development at NOS, is designed to transform elevations among approximately 27 vertical reference datums (Milbert, 2002; Parker, 2002). These datums fall into three categories: three-dimensional (i.e, the ellipsoidal reference frames used by GPS such as the North American Datum of 1983 [NAD 83]), orthometric (e.g, the North American Vertical Datum of 1988 [NAVD 88]), and tidal datums (e.g., Local Mean Sea Level [LMSL]: see Appendix A). Figure 1.1 shows the datums and linkages that are a part of this software.

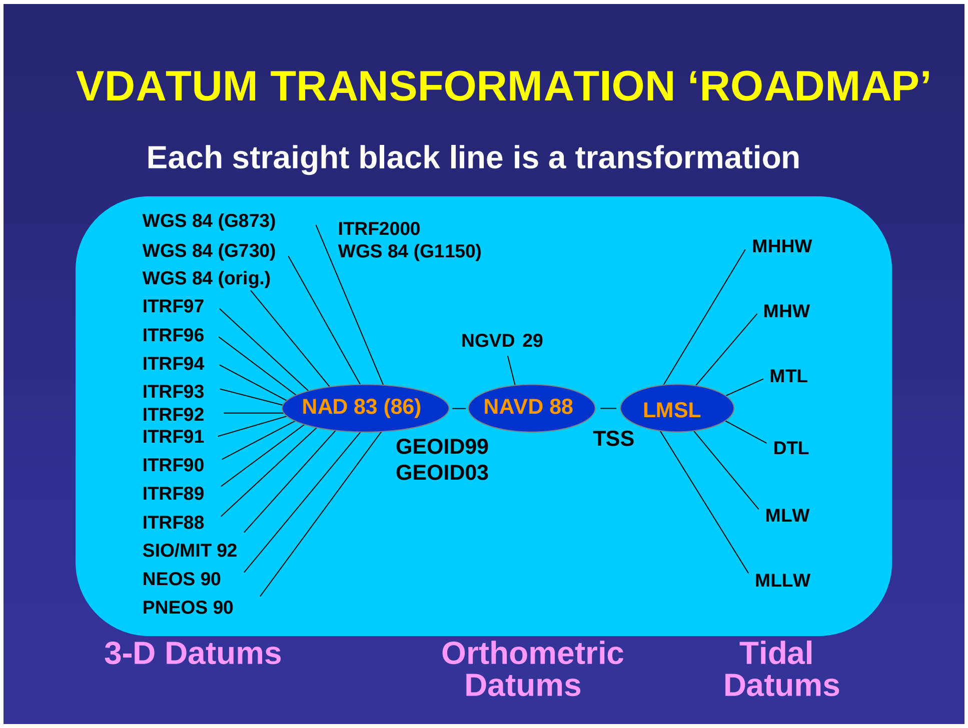


Figure 1.1. Vertical Datum (VDatum) transformation roadmap.

The VDatum software operates through a series of individual transformations that are referenced to three fundamental elevation datums: the NAD 83 ellipsoid, the NAVD 88 orthometric height, and LMSL. (Note: NAD 83 was affirmed as the official horizontal datum for the United States by a notice in the Federal Register {Vol. 54, No. 113 page 25318} on June 14, 1989, and 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.) The software can convert any ellipsoidal elevation to NAD 83 by parametric models, NAD 83 to NAVD 88 by a gridded geoid model, NAVD 88 to the LMSL by a gridded sea surface topography model, and LMSL to any tidal datum with a set of gridded tidal datum transfer fields. The philosophy is to employ the most accurate transformation method for each of the individual steps. Data for the parametric models was obtained from the literature, and the gridded data are generated by spatial interpolation of known values at a limited number of locations or by the use of dynamic models.

The goal of the VDatum project is to have complete coverage of U.S. coastal waters from the landward (i.e., navigable) reaches of estuaries and charted embayments out to 25 nmi offshore, and to include all tidal datum and sea surface topography transformations over the water and all transformations between the ellipsoidal and orthometric datums over the water and the land. VDatum has already been produced by NOS for the entire coast in the continental U.S. Figure 1.2 shows the completed regions and the projects in progress (Puerto Rico and the U.S. Virgin Islands). The coasts of Alaska and Hawaii are scheduled to be next.

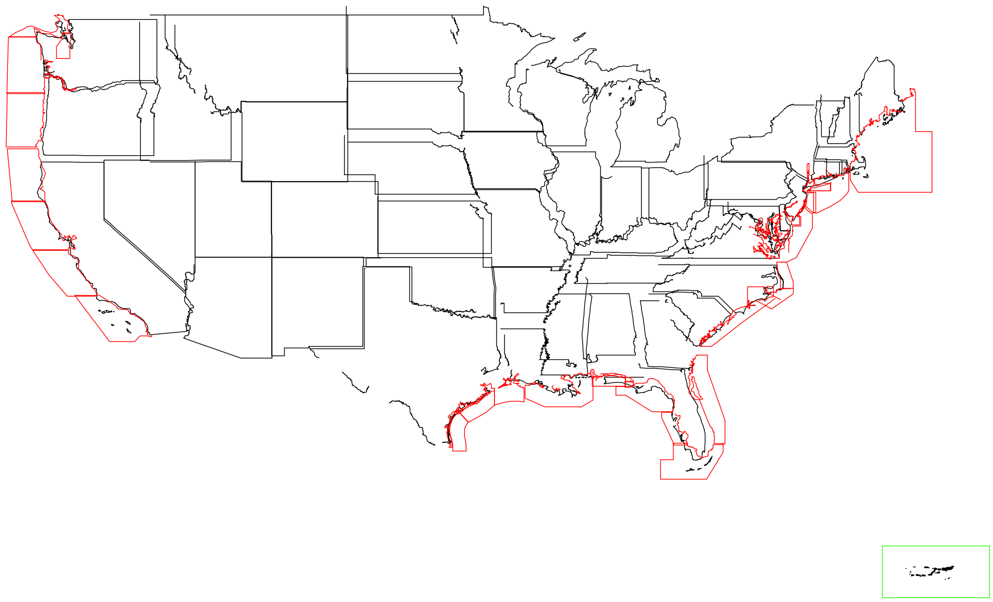


Figure 1.2. Map of the United States and adjacent waters with the bounding polygons of existing VDatum coverage (red) (as of September 2011) and areas in development (green).

The development of VDatum for a region has been documented after the work was completed. The regions and their technical reports, listed in approximate order of completion, include Tampa Bay (Hess, 2001); coastal southern Louisiana (Hess et al., 2004); the New York Bight (Hess, 2001), central coastal California and San Francisco Bay (Myers and Hess, 2006); Delaware Bay (Hess et al., 2003); Puget Sound (Hess and Gill, 2003; Hess and White, 2004); Lake Charles and Lake Calcasieu, Louisiana (Spargo and Woolard, 2005); the Outer Banks area of North Carolina (Hess et al., 2005); the Strait of Juan de Fuca and an update of the Puget Sound (Spargo and Hess, 2006); Long Island Sound and New York Bight (Yang et al., 2008); the northeast Gulf of Mexico including Mobile Bay, Pensacola Bay, and St. Joseph Bay (Dhingra et al., 2008); New Jersey, Delaware, and Virginia, including Chesapeake Bay (Yang et al., 2008); Southern California (Yang et al., 2009); Great South Bay and New York Harbor (Yang et al., 2010); eastern coastal Louisiana and Mississippi (Yang et al., 2010); the Pacific Northwest including Northern California, Oregon and the west coast of Washington (Xu et al., 2010); Florida, South Carolina, and southern North Carolina (Yang et al., in preparation); the northwest Gulf of Mexico from western Louisiana and Texas (Xu et al., in preparation); and the Gulf of Maine (Yang et al., in preparation).

With the large variety of vertical datums that are incorporated into this tool, the VDatum project has been a joint effort by several different parts of NOS, including the Office of Coast Survey (OCS), the Center for Operational Oceanographic Products and Services (CO-OPS), and the National Geodetic Survey (NGS). The U.S. Geological Survey (USGS) has provided additional technical support for this project.

1.2. VDATUM ACCURACY

Accuracy requirements for VDatum, which are based on user needs, are in the process of being established. The expected accuracy of the VDatum conversions is also being analyzed.

Required Accuracy - For the purposes of this manual, accuracy requirements are based on the uses to which the software is to be put. These include hydrographic surveying, shoreline mapping, and creation of digital elevation models.

For hydrographic surveying, the accuracy requirement for an Order 1 survey (typically used by NOAA for nautical charting) is that 95% of all depth values have a total error less than or equal to the following:

$$\varepsilon = \sqrt{0.5^2 + (0.013d)^2} \tag{1.1}$$

where d is the depth in meters (IHO, 1998). For a near-shore depth of 5 m, ε equals 0.504 m. Note that error contributions in extrapolation of tidal characteristics can be significant contributors to the total error budget, with an estimated contribution (95% confidence level) of between 0.20 and 0.45 m. (Sec. 5.2.3.5, NOS, 2010).

For shoreline mapping, LIDAR elevations over a swath of coastal land and water are collected and referenced to an ellipsoid by the sensor system using a blended solution from GPS and Inertial Measurement Unit (IMU) technology. A MHW or MLLW shoreline can then, in principle, be defined by the intersection of the appropriate tidal datum plane with the LIDAR elevation data. Therefore, the LIDAR elevation data needs to be transformed from ellipsoid to a tidal datum (MHW or MLLW), for contour extraction. Required accuracies for vertical datum transformations (reported by NGS staff) are on the order of 0.02 m to 0.04 m for this methodology.

Accuracy requirements for DEMs are based on the expected use of the DEM. For example, a DEM has been developed for coastal North Carolina using LIDAR data collected by the State. The elevation data was processed to represent the bare earth, to an estimated vertical accuracy of 0.15 to 0.20 m. The intended use of the DEM is for the study of the impacts on long-term sea level rise of coastal ecosystems. Requested accuracies were on the order of 0.05 to 0.10 m, although it is not firmly known what accuracy is necessary for the simulation of ecosystems such as marshes.

The USACE is presently revising its requirements for project datums. Preliminary target values for levees and flood control projects are ±8 cm for 95% of readings.

Expected Accuracy - In contrast to the required accuracy, the expected accuracy (or uncertainty) from VDatum is based on the uncertainty in the input data and in the transformation fields. For the evaluation of VDatum, the standard deviation (SD) is the primary statistical variable used to quantify the random uncertainty in both the vertical datums (i.e., the source data) and of the transformations between them. SD is a simple measure of the average size of the errors in a data set (when errors are normally distributed), and is denoted by the Greek letter sigma (σ). Uncertainties for the source data and transformations in the Chesapeake Bay VDatum region are shown in Figure 1.3 as an example. Uncertainty may also include systematic errors such as those due to land subsidence or sea level rise, although VDatum currently does not include these systematic errors.

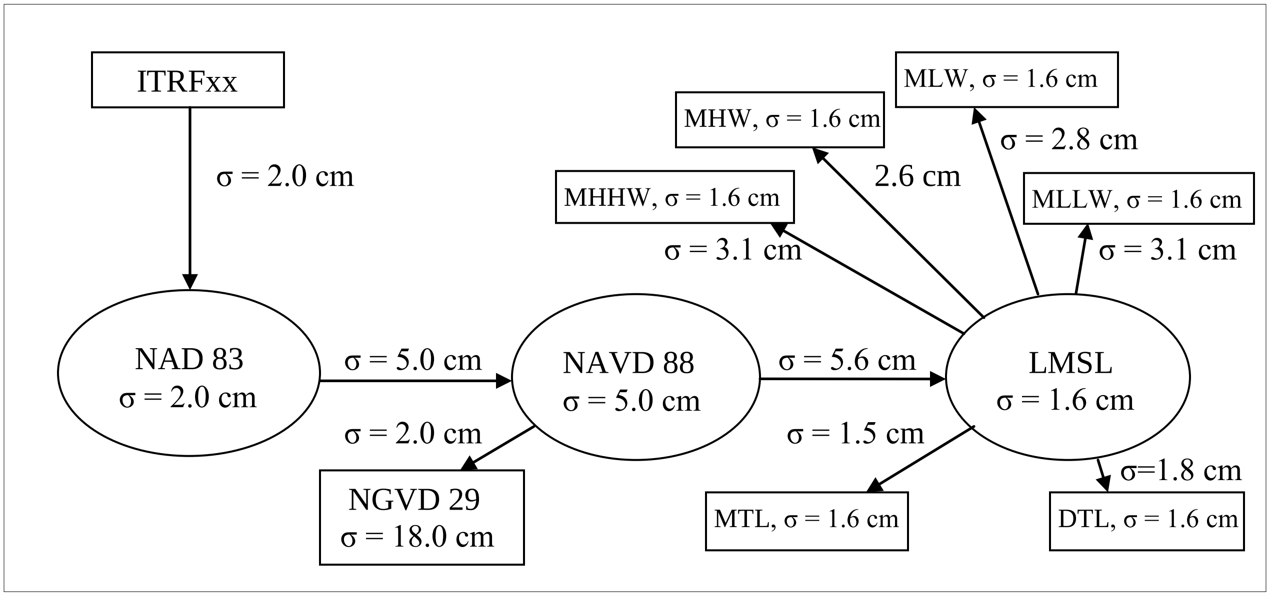


Figure 1.3. Schematic showing how VDatum handles the transformation (arrows) of a value from an ITRFxx ellipsoid to the several tidal datums (boxes) through the core datums (ovals). Estimated errors in the transformations for the Chesapeake Bay VDatum region are shown as standard deviation values (σ) and are placed next to the arrow relating to each transformation. Also included are the estimated uncertainties for each individual vertical datum, shown as the σ values inside the ovals/boxes.

Cumulative uncertainty for a sequence of conversions such as those used in VDatum is obtained by taking the square root of the sum of the squares of the individual uncertainties in both the data and the transformations.

As an example, consider the transformation of an elevation in the ITRF datum into an elevation relative to MLLW using the values shown in Figure 1.3. The cumulative uncertainty, expressed as σ (cm), will be

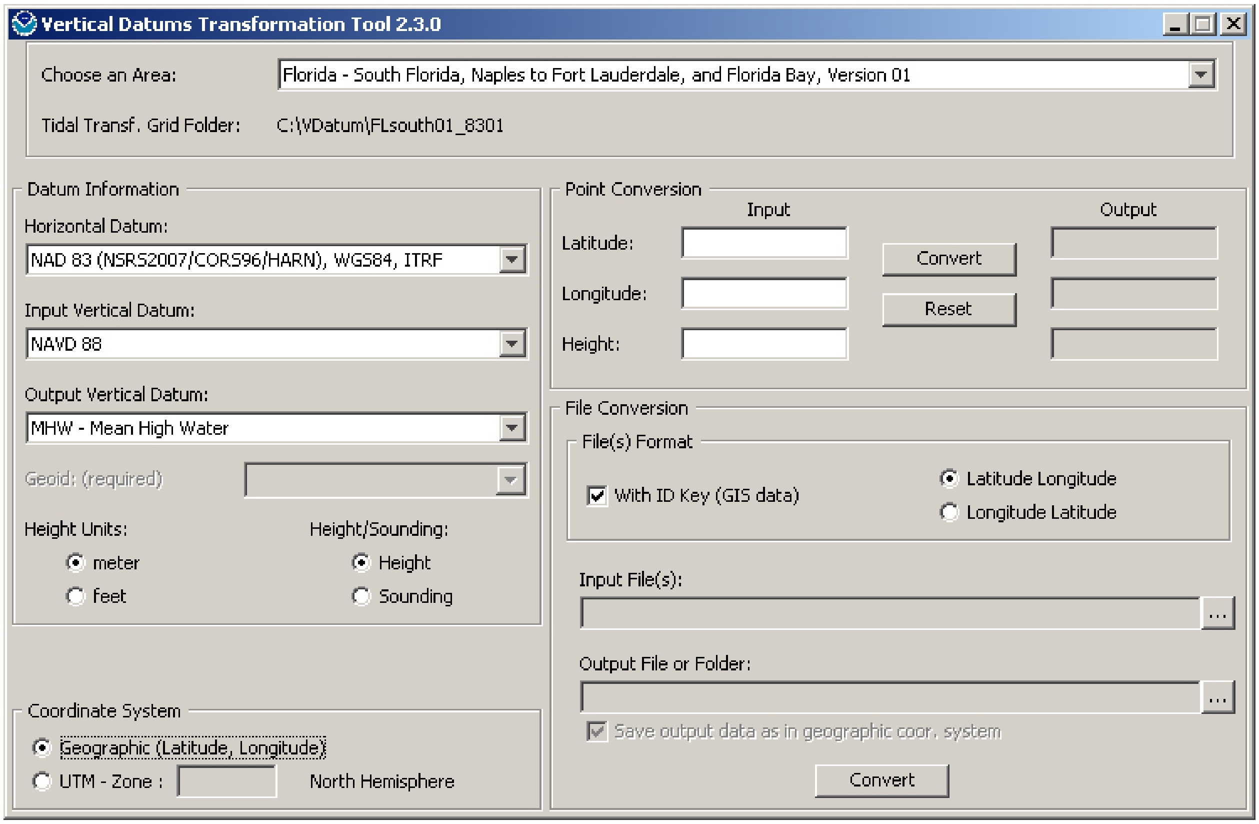
$$\sigma = [2^2 + 2^2 + 5^2 + 5^2 + 5.6^2 + 1.6^2 + 3.1^2 + 1.6^2]^{1/2} = 10.20 \tag{1.2}$$

An in-depth discussion of the methodology and the uncertainty parameters for all the VDatum regions appears on the VDatum web site.

1.3. HOW VDATUM WORKS

VDatum transforms a user-supplied input elevation in specified vertical and horizontal reference frames to an output elevation in a selected vertical reference frame using code and data files downloaded to a user's PC. A graphical user interface (GUI) (see in Figure 1.4) is employed to run the underlying Java code (VDatum requires the latest version of the Java Runtime Environment, or JRE). The user enters a position (latitude and longitude) and elevation (height), and then selects a horizontal datum, input datum, output datum, elevation units, and whether the elevation is a height (positive upward) or sounding (positive downward). The solution appears when the 'Convert Vertical Datum' button is pushed. Data can be entered either point by point, or in batch mode when the data resides in a file. Since the data files cover only a limited geographic region, the output for a point lying outside the region will be a null value (−999999.). All points lying within the region will support a conversion between geodetic datums, but only points lying within water areas will support a conversion involving LMSL or a tidal datum. Each region defined by a polygon in Figure 1.2 has a unique set of data files.

An outline of the code from Milbert (2002) is as follows. The datum transformation algorithms can be considered as traversing a minimal spanning tree, whose nodes represent individual datums. The datums are conceptually grouped into three subsets: three-dimensional datums, orthometric datums, and tidal datums. Each subset has a principal member: NAD83 for three-dimensional datums, NAVD 88 for orthometric datums, and LMSL for tidal datums. The logic begins with the source and target datums, extracts their categories, encodes the traversal path through the principal members, and also applies the transformations to go between the source and target datums and their associated principal members. The transformations between the three-dimensional datums are provided by seven-parameter Helmert transformations (three translations, three rotations, and a scale change) calibrated through global networks of satellite and extra-terrestrial measurements. Transformations between NAD 83 (86) and NAVD 88 are performed by interpolation of the latest NGS geoid height grid (e.g. GEOID09). Transformations between NAVD 88 and LMSL are performed by interpolation of a sea surface topography grid. This grid was estimated by comparison of measured tidal values, NAVD 88 datum values, and tidal model predictions at tide benchmarks throughout the region. Transformations between the tidal datums are performed by interpolation of grids computed from either a hydrodynamic model or by spatial interpolation.



Choose an Area: Florida - South Florida, Naples to Fort Lauderdale, and Florida Bay, Version 01

Tidal Transf. Grid Folder: C:\VDatum\FLsouth01_8301

Datum Information

Horizontal Datum: NAD 83 (NSRS2007/CORS96/HARN), WGS84, ITRF

Input Vertical Datum: NAVD 88

Output Vertical Datum: MHW - Mean High Water

Geoid: (required)

Height Units: ● meter ○ feet

Height/Sounding: ● Height ○ Sounding

Coordinate System: ● Geographic (Latitude, Longitude) ○ UTM - Zone : North Hemisphere

☑ With ID Key (GIS data)

● Latitude Longitude ○ Longitude Latitude

☑ Save output data as in geographic coor. system

Figure 1.4. The VDatum graphical interface for either individual point or batch mode data conversion.

1.4. DEVELOPMENT OF THE DATUM TRANSFER FILES

Transformation between NAD83 and other ellipsoids is by means of a 7-parameter (Helmert) conversion, while the other transformations are by the use of spatial interpolation of values from gridded fields (the files of which have the extension `gtx`). Although the GTX files for some of the geodetic fields are created by simply extracting a subset of the arrays that cover the continental U.S., the major effort in creating the VDatum files for a region has been the development of the gridded tidal datum and sea surface topography values. In addition, there is an on-going project to create updated geoids for the U.S.

1.4.1. Tidal Datum Modeling

Tidal datum fields are developed, preferably, by applying a hydrodynamic model to simulate tidal propagation in a geographic area. These models require detailed bathymetry and coastline information to produce an accurate representation of the flow of water. Tidal simulations are carried out by forcing the open ocean boundaries with an astronomical tidal signal. A sample of a hydrodynamic model grid used for the North Carolina simulations is shown in Figure 1.5.

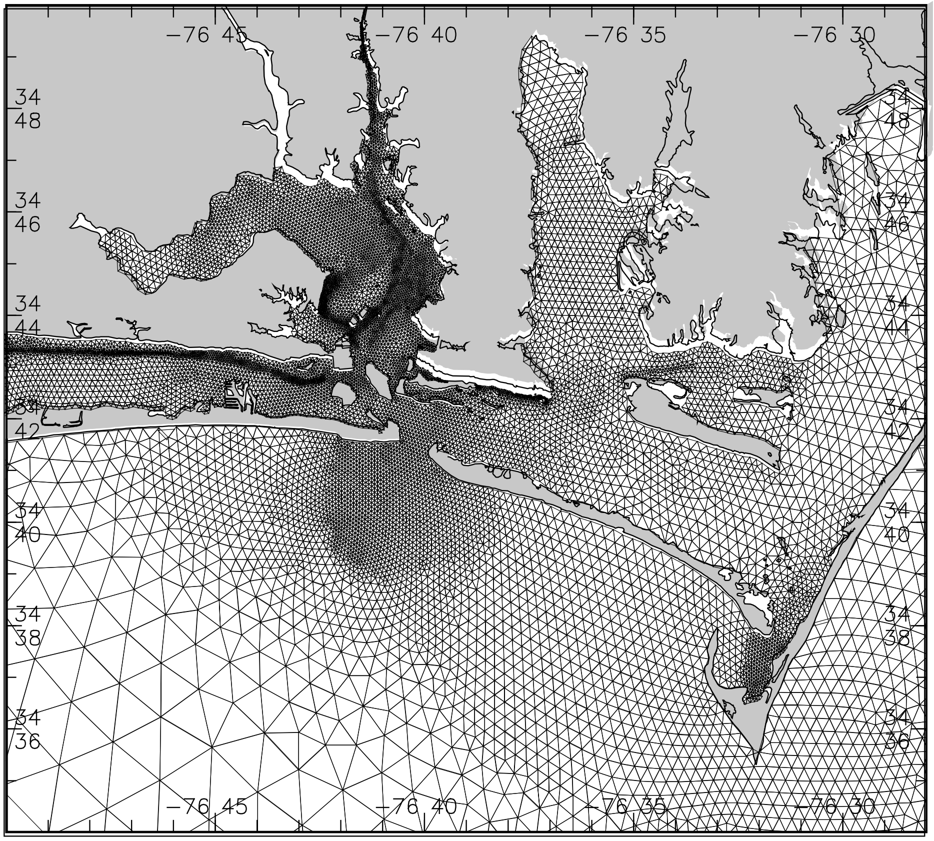


Figure 1.5. Hydrodynamic model grid in the vicinity of Beaufort, North Carolina.

From the hydrodynamic model's simulated water level time series at each point in the model grid, time series of water levels can be analyzed to determine the MHHW, MHW, MLW, and MLLW values. These datum values are compared to the NOAA accepted values (as determined by CO-OPS' analysis of observed water levels), and the differences at each water level station are interpolated over the model domain to produce the final, corrected tidal datum fields.

The tidal datum fields can also be created by generating time series from a database of harmonic constants. Such databases have been created by the use of ocean-scale hydrodynamic models. Using the simulated water levels, the tidal datum fields are extracted as they would be from a modeled time series.

In cases where a hydrodynamic model is not available, the tidal datum fields can be created directly by spatial interpolation. The interpolation can be done on a rectangular grid or a finite-element grid using the Tidal Constituent And Residual Interpolation (TCARI) method. This method takes land-water boundary values into account and assumes a solution that satisfies Laplace's equation.

1.4.2. The Tidal Marine Grid

Creation of the Marine Grid For the next step, a VDatum tidal marine grid is created. The marine grid is defined by the origin (latitude and longitude), the uniform horizontal and vertical spacing, and the number of rows and columns. Digitized coastline data are used to determine which points in this grid are water and which are land. Points located within water, or within a distance of approximately one-half a marine grid element size of water, are set to water. A sample marine grid for Delaware Bay is shown in Figure 1.6.

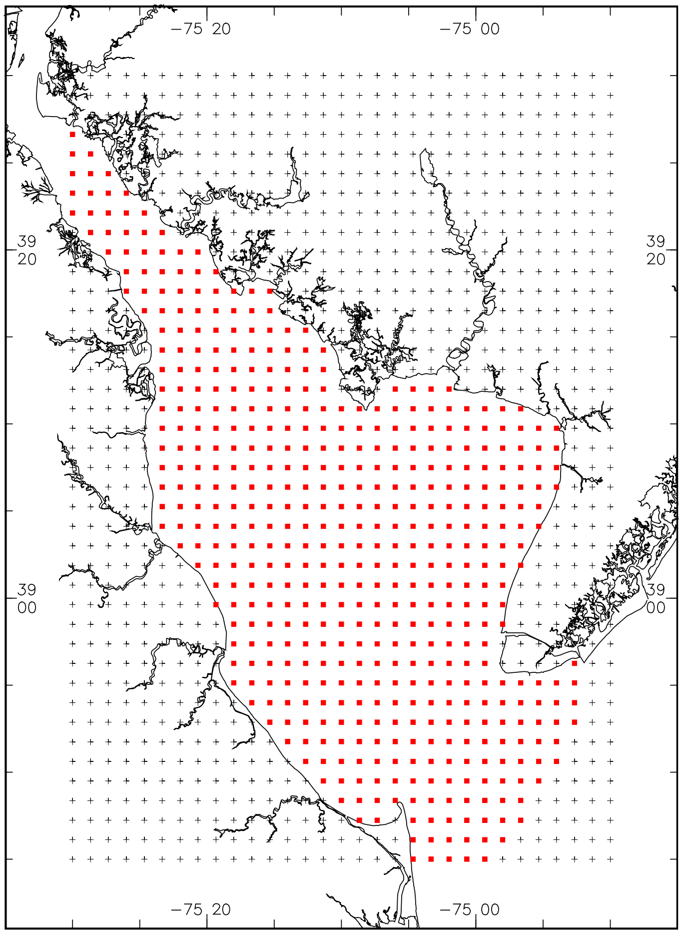


Figure 1.6. VDatum marine grid in Delaware Bay. Solid red squares show locations of non-null values and plus signs (+) show locations of null values. Note: this particular grid has been superseded and is shown for explanation purposes only.

Population of the Marine Grid In the next step, values from the tidal datum fields are used to populate the VDatum marine grid. Since the marine grid points are uniformly spaced, and hydrodynamic model grid points usually are not, an interpolation procedure is required. If the marine grid point falls within a hydrodynamic model element (i.e., a triangle or quadrilateral), a linear interpolation of the values at the element's nodes is used. If the marine grid point falls outside all elements, an inverse-distance weighted mean of the values from the two closest nodes is usedSimilar interpolation is used for the tidal datum fields created by the harmonic constant database and TCARI methods. The data are stored in a standard format in GTX files. A sample of a populated grid is shown in Figure 1.7.

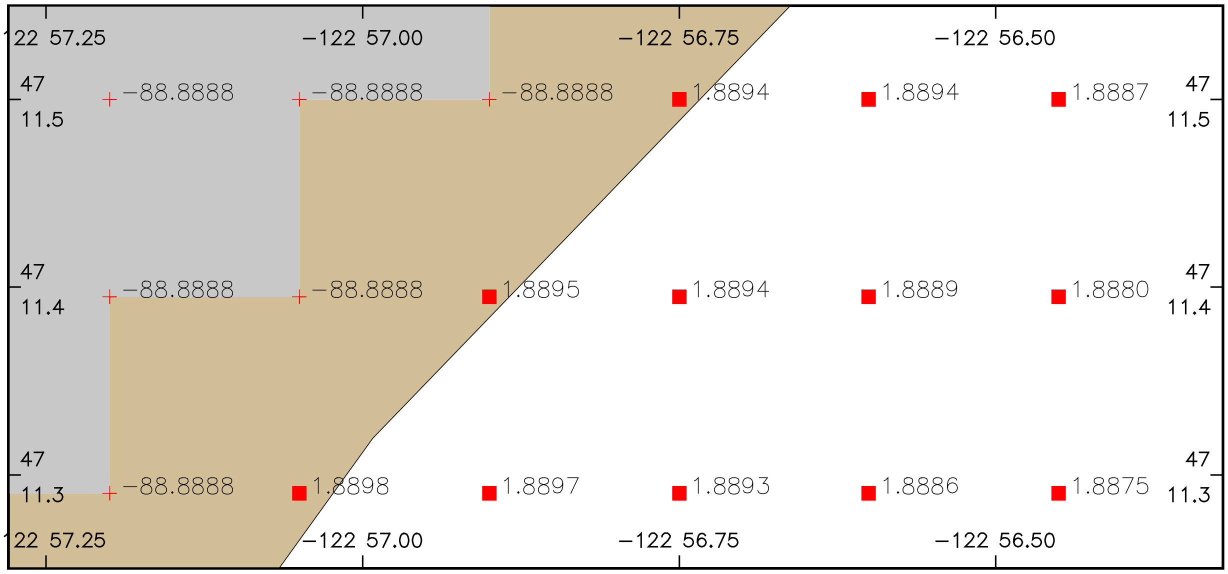


Figure 1.7. Portion of the marine grid in Puget Sound. The white area represents water, the tan area represents land, and the gray area represents areas where a null value will be returned for a conversion involving a tidal datum. Values at the grid points are MHHW relative to MSL (meters), and null values are shown as -88.8888.

When the user enters a latitude-longitude location, the conversion value is computed by interpolating the values at the corners of the surrounding rectangle (see Section 7), provided that one or more of the four values is non-null. If all four values are null values (i.e., the gray area in Figure 1.7), a conversion value of -999999 is returned.

Problems at Barrier Islands Occasionally, problems in populating the marine grid can arise when there are narrow barrier islands separating two coastal regions, such as a lagoon and the open ocean, having greatly varying tidal conditions. Specifically, a marine grid point representing water may lie outside the hydrodynamic model grid for each region, in which case the two closest nodes are identified. If one node represents the ocean and the other the lagoon, an inverse distance-weighted mean will mix ocean and lagoon values, creating an unrepresentative value. This possibility can be avoided if (a), in the marine grid, the spacing of nodes is so small that at least one null value separates the two non-null values (in both latitude and longitude) representing the ocean and the lagoon, or (b) some method is used to exclude the unrepresentative hydrodynamic model points. The first option would lead to extremely large arrays, so the second option is usually the better choice. This was done in the North Carolina VDatum (Hess et al., 2005) by the employment of an *excluding polygon*, by which any hydrodynamic model nodes lying outside the polygon were automatically excluded from selection.

Bounding Polygons In some regions, such as those in North Carolina, Louisiana, and Puget Sound, the tidal marine grids actually overlap, resulting in ambiguity in the selection of the correct grid. Therefore, the use of a *bounding polygon* is necessary. Given a latitude-longitude point in the overlap region, a check is made of whether the point falls within a specific bounding polygon; if so, the marine grid for that region can be used. If not, additional polygons are checked. Figure 1.8 shows the bounding polygons and the rectangle limits for three tidal marine grids in North Carolina. When national VDatum coverage is complete, the entire U.S. coast will be covered by a set of non-overlapping bounding polygons.

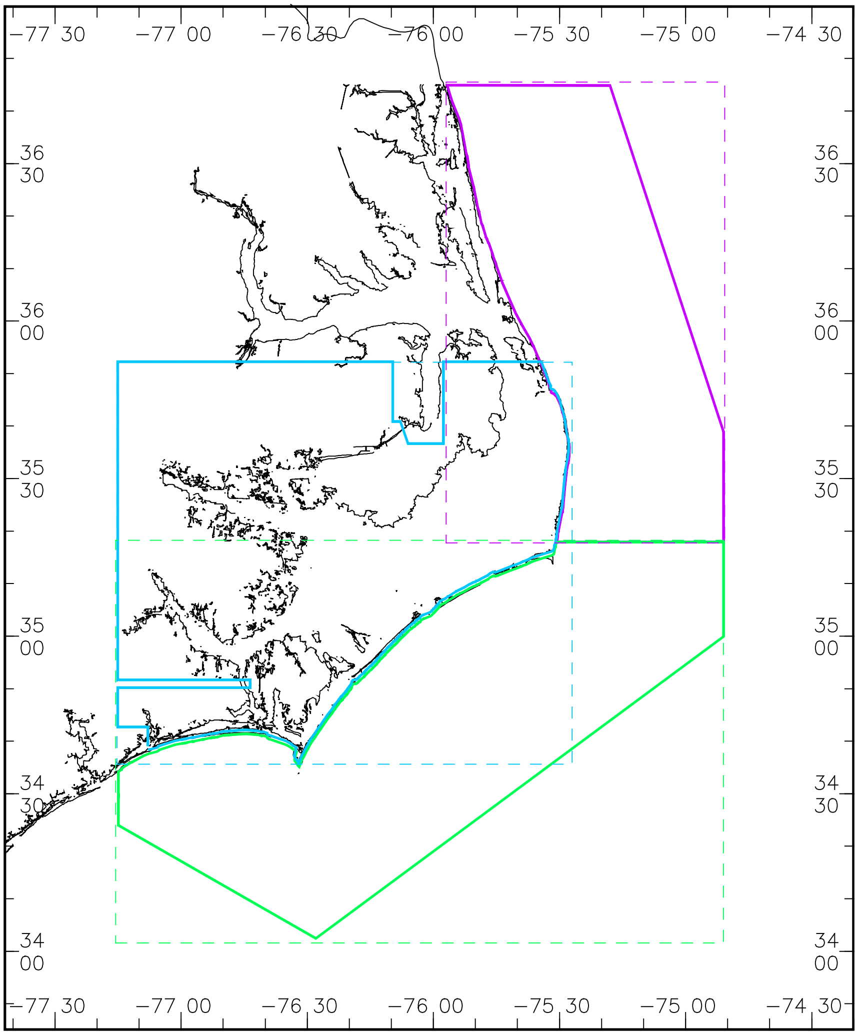


Figure 1.8. North Carolina region showing the bounding polygons of selection (solid line) and the mesh borders (dashed lines) for Pamlico Sound (light blue), the central coast (green) and the northern coastal (purple) regions.

1.4.3. Sea Surface Topography

Once the tidal marine grids are populated, the location and land/water designations are used to create the sea surface topography grid. This grid is populated with commercially available interpolating software and using values of the difference between NAVD 88 and LMSL at the locations of water level stations and of geodetically-measured benchmarks.

1.4.4. Compatibility of New Regions with Existing Data

To cover large sections of the coast, numerous individual VDatum regions are necessary to reduce the size of the arrays that are needed. Whenever VDatum files for a new region are developed, they may be adjacent to, or even overlap, existing regions. Care must therefore be taken to (a) define the bounding polygons of selection so that they overlie each other at the boundaries, and (b) ensure that values extracted from adjacent marine grids show consistency across the common boundary.

1.4.5. Testing

The tidal and sea surface topography GTX files are tested for accuracy and continuity with adjacent regions. Accuracy is tested by comparing values at water level stations with the values obtained by interpolation from the marine grids. Continuity is tested by comparing values interpolated from VDatum at points along lines perpendicular to the bounding polygon where adjacent regions meet.

1.4.6. Data Archival

Tidal data, model input and output, test results, reports and documents, and final VDatum transfer fields are stored in an archive (Appendix B), and are the computer programs used (Appendix C). The objective is to save all the data that was used for generating the final GTX fields, both to document the steps in the process and to make the inevitable task of updating results easier. Storage in an archive also makes retrieval faster and helps in the testing process.

1.4.7. Resources

NOS has developed or acquired numerous tools, computer programs, and databases to apply to the VDatum project. These include the VDatum data itself (Appendix B) as well as computer programs for processing digitized coastline data, extracting datums, and generating marine grids (Appendix C). These include databases of regional and global tidal harmonic constants (Section 4.3.2, Appendix D) and tidal datums at U.S. water level stations (Section 3.3.1), as well as hydrodynamic models (Appendices E and F). Finite-element mesh grids are generated using the Surface-water Modeling System (SMS) commercial software.

1.5. ORGANIZATION OF THIS REPORT

The following sections of this report describe the details of procedures for developing VDatum for a selected geographic area.

- Section 2 describes the formal procedures to be followed when creating a VDatum grid and accompanying files for each new area.

- Section 3 describes how the essential data for VDatum are gathered. These data include digital shoreline, tidal datums and other water level data, geodetic data, and bathymetric data.

- Section 4 describes the techniques used to create the tidal datum transfer fields. These techniques include spatial interpolation, use of harmonic constant databases, and hydrodynamic modeling.

- Section 5 describes how the tidal marine grids are produced and populated. These grids form the basis for the VDatum operational files.

- Section 6 describes geodetic data modeling.

- Section 7 explains how VDatum works, and how the GTX data files are created, integrated, tested and transferred to the NOS web site for dissemination to the public.

- Section 8 discusses areas of further research.

- Appendix A describes tides and tidal datums

- Appendix B describes the VDatum data archive.

- Appendix C describes the various computer programs used in the development of VDatum.

- Appendix D describes global tide databases and models.

- Appendix E describes methods of averaging soundings to a grid.

- Appendix F describes the use of the ADCIRC hydrodynamic model.

2. STANDARD OPERATING PROCEDURES

As NOS continues to develop programs and data files for VDatum, it is important to establish standards for VDatum coverage and accuracy, to inform users and interested parties of the methods used, and to train new staff working on the project. To meet these goals, a well-defined set of Standard Operating Procedures (SOPs) has been produced. The processes in the SOP are discussed in this Section.

2.1. OVERVIEW OF THE STANDARD OPERATING PROCEDURES

The creation of the web-based VDatum software and the files used to support it is a complex action requiring many activities and the making of numerous decisions. Because of this complexity, it is desirable to develop Standard Operating Procedures (SOPs) for this action. As described by the U.S. Environmental Protection Agency (EPA, 2001),

> "An SOP is a set of written instructions that document a routine or repetitive activity. SOPs describe both technical and administrative operational elements of an organization that would be managed under a Quality Assurance Project Plan and under an organization's Quality Management Plan.
>
> The development and use of SOPs is an integral part of a successful quality system. It provides individuals with the information to perform a job properly and facilitates consistency in the quality and integrity of a product or end-result through consistent implementation of a process or procedure within the organization. SOPs can also be used as a part of a personnel training program, since they should provide detailed work instructions. When historical data are being evaluated for current use, SOPs can be valuable for reconstructing project activities. In addition, SOPs are frequently used as checklists by inspectors when auditing procedures. Ultimately, the benefits of a valid SOP are reduced work effort, along with improved data comparability, credibility, and legal defensibility".

As a start in developing an SOP, the total action in creating VDatum files is broken down into five separate processes:

- Selecting the region of application,
- Creating VDatum files,
- Placing VDatum files on the Web,
- Updating existing VDatum files, and
- Researching future developments.

There is an SOP for each process. Each process is broken down into several major procedures, and each procedure has several steps. In the description below, the NOS Management Team (MT) consists of the Chiefs, or their Deputies, of OCS/CSDL, CO-OPS, and NGS/RSD. Similarly, the NOS Technical Team (TT) consists of management and staff personnel from the same three organizations. NOTE: the following is meant as a general description and may not accurately reflect the most recent management policy.

2.2. PROCESS V01: SELECTING THE REGION OF APPLICATION

The final product produced by this process is the selection and definition of the geographic region for which the VDatum data sets will be developed or revised.

1. Reception of requests - The NOS MT and the TT will collect, archive, and report on (as needed) the reception of requests from user groups, NOAA partners, and other interested parties.

2. Establishment of priority of requests – The NOS MT will decide or approve the specific location where VDatum is to be developed, taking into account available funding, Congressional incentive, user requests, potential partnerships, and/or other criteria.

3. Assessment of requirements and resource needs – With the approval of the NOS MT, the NOS TT will (1) assess their resources to determine whether personnel are available and when the project can be scheduled. (2) The assessment will also include the possibility of updating existing VDatum files from adjacent, overlapping, or included regions. (3) The results of the assessment will be reported to the NOS MT, and (3) a determination of project feasibility will be made by the MT.

4. Coordination among OCS, NGS, CO-OPS and other partners – Once approval has been gained, the NOS TT will (1) discuss the project requirements and assign tasks as necessary with the NOS partners. The TT will (2) notify relevant external partners (PMEL, USGS, USACE, etc.) of the plans. Final plans will incorporate comments from partners and management. Process V02 can begin.

2.3. PROCESS V02: CREATING VDATUM FILES

The final product produced by this process is a set of files which can be placed on the NOS VDatum website. The files consist of six tidal datum transfer files, topography of the sea surface file, geoid conversion files, two NAD 83-to-NAVD 88 conversion files, and an NAVD 88-to-NGVD 29 conversion file, as well as a digitized bounding polygon and the VDatum Java code.

1. Data Acquisition

1.a. Establishing geographic limits – The NOS TT will determine the specific geographic boundaries of the project, based on the outcome of Process V01. This step is important for assessing the adequacy of the other data types.

The following five steps (1.b to 1.f) may be carried out simultaneously.

1.b. Coastline data – the NOS TT will (1) acquire the digital shoreline for MHW. If available, the Electronic Navigational Chart's (ENC's) digitized shoreline will be used. If the ENC shoreline is not available, the Extracted Vector Shoreline (EVS) will be assessed by comparing sections to digitized charts, and used if it is deemed to be of sufficient accuracy. If the EVS data set is not sufficiently accurate, it will be revised manually using digitized charts to correct it. If the manually revised EVS data are not of sufficient accuracy, other digitized data such as the medium resolution 1:70,000 shoreline or the World Vector Shoreline may be used.

Once a digitized data set is available, the data will (2) be processed to create a file containing multiple line segments representing the main coastline and all islands. All segments will be joined (i.e., the first point and last point will be identical) and will be numbered counterclockwise.

1.c. Tidal Data – The NOS TT will acquire and assess data pertaining to tidal datums, harmonic constants (HCs), tidal epochs, water level time series, and other relevant information for water level stations in and near the geographic area of interest.

Specifically, CSDL will (1) make a preliminary selection of the tide stations and their data within a specific geographic area from the available databases. CSDL will (2) assess the data and contact CO-OPS if questions arise. CO-OPS will (3) review CSDL's selected data and (4) make recommendations as necessary as to the validity of the selected datums and HCs, provide updated tidal information at specified locations as needed, and determine whether additional water level stations and their data should be used.

1.d. Benchmark data (ellipsoidal, geodetic) - The NOS TT will acquire and assess data pertaining to geodetic datums. Specifically, NGS will (1) review the availability and accuracy of existing benchmark data.

1.e. Hydrographic survey areas - The NOS TT will acquire and assess data pertaining to bathymetric survey data. Specifically, CSDL will (1) create plots showing the coverage of the sounding data and (2) the age and source of the data. If NOS sounding data are unavailable, bathymetry for nearshore areas will be acquired from ENCs or digitized directly from NOAA Raster Charts. For offshore areas where NOS survey data are not available, bathymetry is acquired in gridded format from global databases at the National Geophysical Data Center (NGDC) such as the Earth Topography 2-minute (ETOPO2) dataset or from the U.S. Navy's Digital Bathymetric Database – Variable Resolution (DBDB-V) gridded database.

1.f. Hydrodynamic model results - The NOS TT will acquire and assess data pertaining to previous hydrodynamic models of the region under consideration. Data include HC databases and model grids (including bathymetry).

1.g. Data quality assessment – Once the previous five steps have been completed, the NOS TT will (1) assess the quality of the data in the above five categories and decide whether they are sufficient for continuing the project. If they are not sufficient, the TT will (2) report its findings to the NOS MT for further action.

2. Tidal Datum Modeling

2.a. Selection of specific area - The TT will (1) finalize the specific geographic area to be studied, including the generation of a digitized bounding polygon for the VDatum fields. Since there may be narrow barrier islands in the region of interest, there may be more than one bounding polygon. In the case of nearby, previously modeled regions or polygons, (2) the TT will assess what boundary conditions will be needed to assure that the VDatum fields are continuous and smooth across the common boundaries between polygons.

2.b. Selection of method – The TT will (1) assess the quality of the data and select the method to be used for tidal datum modeling. The available methods are (a) spatial interpolation of existing datums, (b) determination of datums from reconstructed water level time series reconstructed from a database of HCs, and (c) hydrodynamic modeling of water levels. In general, the first method is the quickest, the second method is appropriate for regions which have been modeled previously, and the third requires the most time but usually produces the most accurate results. The reasons for selecting the method (2) shall be explained in the written documentation. Depending on the choice, one of the following three steps will come next.

2.c. Application of method of spatial interpolation – The TCARI method of spatial interpolation is to be used. The first step is (1) to select or generate the grid. If a mesh of triangular elements exists, the finite-element form of TCARI can be used. If not, a mesh of square cells is generated by program `pa.f`. Then, the (2) points in the mesh will be initialized using a data file of applicable datums. Next, the grid (3) will be populated with datums using either the MatLab program `tcari.m` for the finite element form or the program `pb.f` for the square cell form.

2.d. Application of method of HC database – First, (1) the database must be selected. It usually will be the one with the best match of the data in the region and the HC data, based on the analysis conducted in step 1.f, above. Following the selection of the tidal database, (2) if the database is larger than the VDatum area, the HC data within the region of interest will be subset. Then, (3) the HC results are converted into time series data and analyzed using the program `adcdf2datum_mpi.f90`. The next step (4) is to compare the datum results from the analyzed time series data to the NOS station data throughout the domain. (5) The error between the model results and the NOS station data are interpolated throughout the domain to create an error field for each of datums using the TCARI method of spatial interpolation. Finally, (6) the error field is used to correct the results from the database to create at datum field that matches the NOS station data at those locations.

2.e. Application of method of hydrodynamic modeling – Any two-dimensional hydrodynamic model can be used for this method. The first step (1) is to create a grid of the domain and (2) populate the domain with bathymetry data. The bathymetric data is converted to a common vertical datum (i.e., Model Zero, or MZ, which is not necessarily MSL), based on an initial estimate of the datum differences from local NOS tide gauges. Before the model is run, (3) the input files must be created including the open boundary forcing from a larger-scale model. (4) Initial runs are conducted to insure model stability and demonstrate a close match with HC data in the region. After these initial runs, (5) the model is run iteratively and the results are used to correct the original bathymetric data to the common vertical datum MZ after each iteration. Once the model results have converged to a repetitive solution, (6) the difference between the modeled datums and the NOS station datums are used as input to the TCARI method of spatial interpolation to create an error field. Finally, (7) the error field is used to correct the results from the model to create at datum field that matches the NOS station data at those locations.

2.d. Error analysis – An analysis of the errors in the tidal datum fields will be performed using standard procedures. For the TCARI method (2.c), a comparison of datums can be made by withdrawing one station at a time and comparing the predicted datum at the station with the data.

For the other methods (2.d, 2.e), the uncorrected modeled and observed datums at the stations can be compared directly.

3. Creation of the VDatum Gridded Tidal Datum Fields

3.a. Creation of a marine grid – The NOS TT will create a regularly spaced marine grid consisting of points that represent either water or 'non-water.' The non-water, or null, points represent land, non-tidal water, tidal waters for which datums have not been determined, or points outside the bounding polygon. The grid and the water/non-water designations can be created using the program `vgridder.f`.

Since there are limits on the size of data files that the VDatum software can handle, and because there may be narrow barrier islands in the region of interest, there may be more than one bounding polygon. Each bounding polygon constitutes a unique VDatum region, and there will be a separate set of files for each bounding polygon.

3.b. Creation of the tidal datum transformation files – The marine grid is to be used (1) to generate six output files, each populated with a tidal datum transformation. The transformations are MHHW minus LMSL, MHW minus LMSL, MLW minus LMSL, MLLW minus LMSL, MTL minus LMSL, and DTL minus LMSL. Each file will consist of a header record and will be followed by datum transformation records. Each file is created by the program `vpop.f`. (2) The standard naming convention (see Table 7.1) will be used for the file names.

3.c. Transfer populated grid to NGS/RSD – A sample tidal datum transformation file will be sent from CSDL to NGS so that the gridded sea surface topography can be started.

3.d. Error analysis - An analysis of the errors in the tidal datum transfer fields will be performed using standard procedures. These include inspection of the bounding polygon (`test_poly.f`), comparison of datums from VDatum with observed values at the water level stations (`test_sta.f`), and comparison of datum values across boundaries with adjacent regions (`test_cont.f`).

4. Generation of the Gridded Topography of the Sea Surface (TSS)

4.a. Apply methodology for making gridded fields – After reception of a sample gridded tidal datum field from CSDL, the NOS TT, (i.e., the NGS/RSD members) will apply the standard method for developing the sea surface topography field. The standard method (see Section 6.3.1) consists of generating a continuous surface of the LMSL-to-NAVD 88 offset by a best fit to (a) values at the NOS benchmarks produced by minimizing differences to each of the four tidal datums by an iterative process, and (b) values at the tide stations obtained from CO-OPS. NGS/RSD may also assess the accuracy and appropriateness of the sample tidal datum fields.

4.b. Create other VDatum gridded data – The NOS TT will create the additional fields (i.e., Geoid99, Geoid03, NADCON, and VERTCON) by extracting subsets of data from the national grid so as to cover the VDatum region.

4.c. Error analysis - An analysis of the errors in the TSS fields will be performed by standard methods. These include inspection of the bounding polygon (`test_poly.f`), comparison of datums from VDatum with observed values at the water level stations (`test_sta.f`), and comparison of datum values across boundaries with adjacent regions (`test_cont.f`).

4.d. Transfer of data to CSDL – The gridded TSS and other gridded data will be transferred to CSDL for inclusion in the final VDatum package. CSDL may also assess the accuracy and appropriateness of the fields.

5. Quality Control and Archival

5.a. Create and maintain archive – The NOS TT will create and maintain an archival database (Appendix C), and will save the appropriate files, data, and documents produced for the VDatum region. The purpose of the archive is to allow easy access to the files for rapid updates and for independent assessment of the data.

5.b. Writing a report – The NOS TT will be responsible for the completion of a written report describing the data and processes of creating the VDatum files. The report should conform to any required standards and should include (at a minimum) a description of the VDatum region, a discussion of the tidal datum modeling method, a discussion of the sea surface topography modeling, and the tidal and benchmark data used. The report will also include graphics showing the location of the tidal and benchmark data and the resulting datum fields with a spatial resolution sufficient for assessment of overall quality.

5.c. Transfer of data to archive – When the GTX files for the tidal datum transfer, sea surface topography, and other gridded datums have been completed, the NOS TT will (1) add them to the archive (Appendix C) for testing purposes. Also, the NOS TT will (2) transfer all auxiliary data and files sufficient to allow updates of the fields when additional data become available.

5.d. Independent assessment of data, files, and methods - An analysis of the methods and results saved in the archive will be performed by independent scientists (i.e., not the developers) using the standard procedures (see 3.d and 4.c). If potential problems are detected, the developers will be informed. If a problem is confirmed, the developers will need to repeat this entire process (V02), starting at some previous step.

5.e. Formal approval – (1) After review of the final report and results of the independent assessment, the NOS TT leader will either approve the data files for dissemination or request a change. (2) If a change is requested, activity will resume from a previous step in the process. (3) If no change is recommended, the report will go to the CSDL Project Leader.

5.f. Update of performance metrics – Following formal approval by the CSDL Project Leader, the metrics describing the progress of VDatum (e.g., percentage of the coast completed) will be updated.

5.g. Transfer of data to web page developer - Following formal approval by the CSDL Project Leader, the files will be transferred to the web page developer and Process V03 begins.

2.4. PROCESS V03: PLACING VDATUM FILES ON THE WEB

The final product of this process is a functioning VDatum web page which allows the user to access VDatum for a newly-developed region.

1. CSDL will maintain the VDatum web site, acting in coordination with NGS and CO-OPS.

2. Creation of test web page with new region – After the approval from Process V02, a test (i.e., non-operational) web page or equivalent that incorporates the new region will be created. Note that this step may require major revisions in the format of the existing web site.

3. Testing the website – The NOS TT will test and evaluate the revised web site using standard methods [to be developed]. When testing by standard methods is completed satisfactorily, the NOS TT leader will be notified.

4. Transition to operations – The NOS TT leader will notify the OCS Web team that the new web page and files are ready for operational status. They will then transfer the data to the OCS web server.

5. Dissemination by other means – CSDL, NGS, and CO-OPS will coordinate the dissemination of VDatum data in revised formats and other media (e.g., CD).

2.5. PROCESS V04: UPDATING VDATUM FILES AND DOCUMENTS

The product of this process is a set of updated VDatum files for a particular region.

1. Track changes in tidal data – On a monthly basis, the NOS TT will monitor CO-OPS tidal datum and harmonic constant data and save the most recent values in a database.

2. Periodic review – On a periodic basis, or in response to user comments, or when significant changes in data occur (e.g., a new NTDE, GEOID, etc.), the NOS TT will assess the impact of such changes. If the potential change is great, or when significant errors can be corrected, the NOS TT will make a recommendation to the NOS MT. Then the Process V01 can begin.

2.6. PROCESS V05: RESEARCH AND FUTURE DEVELOPMENTS

The product of this process is improved methodology for the development and distribution of VDatum results.

1. Improve tide and/or datum models – The NOS TT will continually assess the accuracy and efficiency of its tide and datum models and will incorporate improvements as they become available. This activity may lead to the initiation of Process V04.

2. Adaptation of models for other regions/purposes - The NOS TT will continually assess models and data sets produced by outside organizations with the goal of adapting completed results to the VDatum project. This activity may lead to the initiation of Process V04.

3. Data delivery services - The NOS TT will continually assess its data delivery services and will strive to make data more accessible. The NOS TT will investigate updates, developments, and enhancements to the stand-alone version (and other versions when available) of the VDatum software tool. This might include updates to geoids, three-dimensional, and orthometric datum fields. Enhancements from outside users of the software will also be entertained.

4. Contact with potential partners - The NOS TT will seek out new partners from other agencies or geographic areas with the intent of increasing awareness of our products and supporting the missions of other agencies.

5. Reports on technical work - The NOS TT will disseminate technical reports on its achievements and will make presentations at scientific meetings to increase awareness and improve methodology.

3. DATA ACQUISITION

The acquisition of data is usually one of the first steps in the process of developing the tidal datum fields. The process is much more efficient when the region of interest is well-defined, especially (a) the precise area to be covered by VDatum's marine grid and (b) the area (larger than the marine grid) to be covered by the tide model (hydrodynamic or otherwise).

There are several types of data that are essential for input to and evaluation of the VDatum fields. These include:

- digitized shoreline,
- bathymetric data,
- tidal data, including tidal datums, harmonic constants, and water level time series, and
- geodetic data at tide station benchmarks.

These data will be discussed, and instructions on how to collect these data are given below. Information on which sources are considered more reliable is also included.

3.1. DIGITAL SHORELINE DATA

Digital shorelines are used to define the coastal boundary of a hydrodynamic model. NOS' Office of Coast Survey (OCS) defines the MHW boundary on their nautical charts, and when available, the MLLW boundary. In general, the tidal datum fields incorporated into the VDatum tool should be defined up to the MHW boundary. On nautical charts, the MHW line defines the end of bathymetric data. Any elevation points in the model above the MHW line must be collected from a source that supplies topographic information rather than the bathymetric soundings. Nautical charts in the United States do not mark the line of the highest astronomical tide, so the MHW line is the closest approximation of the extent of the tide. There are several sources from which this shoreline can be obtained. These include, in decreasing order of quality,

- Electronic Navigational Chart (ENC) data,
- Extracted Vector Shoreline (EVS) data,
- Raster Navigational Chart (RNC) data,
- Medium Resolution Shoreline (MRS), and
- World Vector Shoreline (WVS) data.

Figure 3.1 shows an example of the differences between the ENC, EVS, and MRS data types. The chart shown in (a) is #11383 in the Pensacola, Florida, region, and is at a scale of 1:30,000. The ENC displays the best MHW shoreline at this scale. Shown in (b) is the same coastline against a different chart (#11382), which is at a scale of 1:80,000.

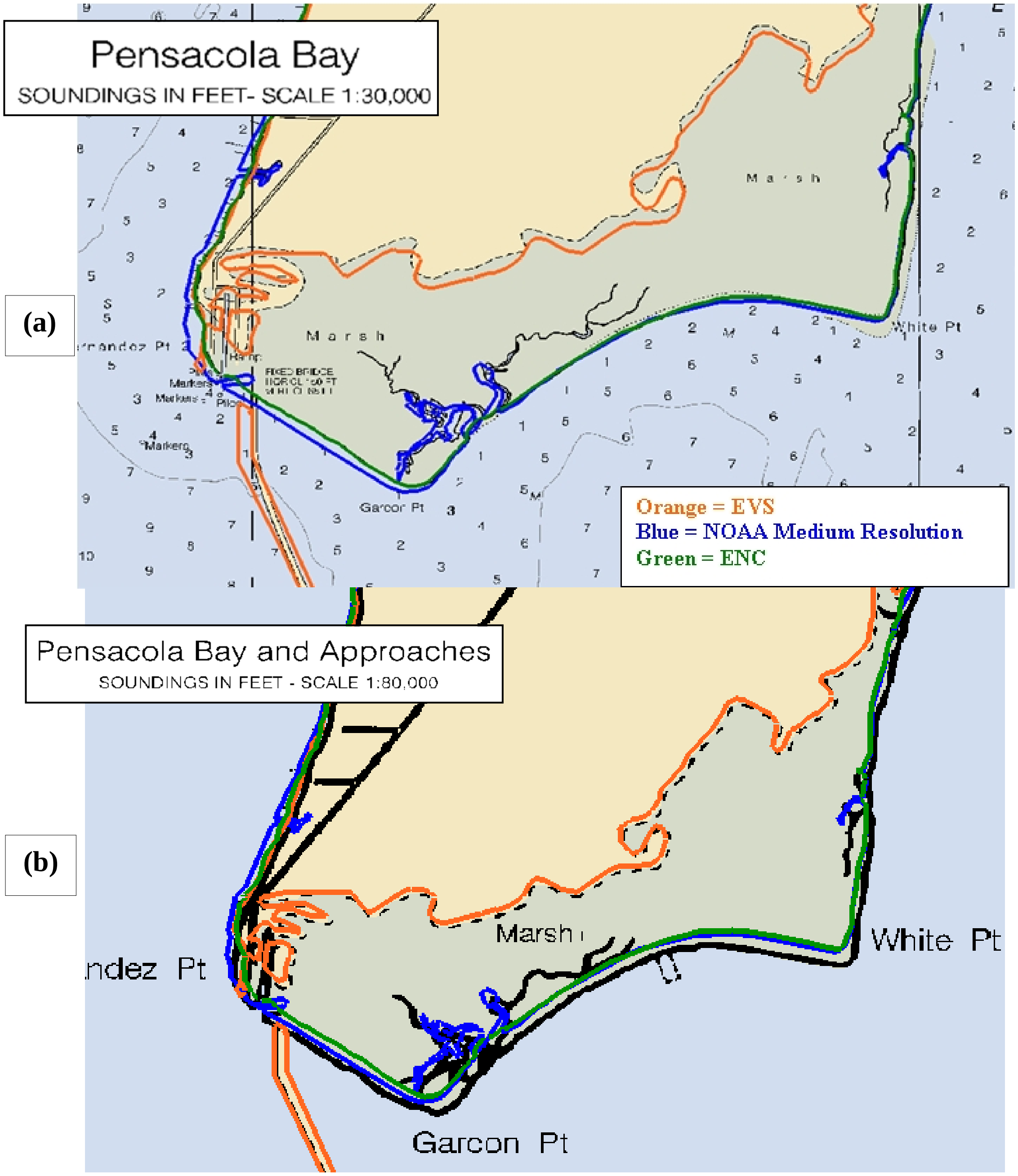


Figure 3.1. Comparison between different MHW shorelines with (a) a chart of the scale 1:30,000 and with (b) a chart of the scale 1:80,000.

3.1.1. Electronic Navigation Chart (ENC) Data

The best available shoreline data comes from NOAA's Electronic Navigational Charts (ENCs). This shoreline is a vector-based file of the MHW shoreline on NOAA nautical charts and they are available at map scales up to 1:5000. ENCs are produced and distributed in IHO S-57 format, the international data standard format used for navigational purposes. ENCs are horizontally referenced to the World Geodetic System of 1984 (original) (WGS 84). It is recommended that the highest resolution ENC shoreline be used where it is available, but as there are many NOAA charts that have not yet been converted to this electronic form, other sources will probably have to be used as well.

NOAA ENCs in their native standard IHO S-57 data format are freely available from http://nauticalcharts.noaa.gov/mcd/enc/index.htm. Complete ENC cells are selected either by chart number or by using the interactive map service. Each ENC cell contains hundreds of charted S-57 object classes referenced to WGS 84 (original). After downloading the selected ENC cells, the digital coastline file is extracted from the S-57 COALNE object class, and converted into ASCII or any number of projected vector-based formats and geographic coordinate systems using a spatial ETL (Extract, Transform, and Load) software engine such as Safe Software's FME.

The *ENC Direct to GIS* web portal interactively distributes the data of most ENCs. ENC data are selected, converted into several digital formats, and downloaded directly from the web at http://nauticalcharts.noaa.gov/csdl/ctp/encdirect_new.htm. Each S-57 ENC object class is mapped and attributed as a separate layer within one or more scale categories. ENC data can be visualized at higher resolutions by SQL query or by zooming into a geographic area at the selected chart scale. When the coastline data becomes visualized and activated, the user selects the area by entering geographic coordinates in latitude-longitude, selects the format and geographic coordinate system of the data to be extracted, and downloads the digital product.

3.1.2. Extracted Vector Shoreline (EVS) Data

The Extracted Vector Shoreline (EVS) is derived from NOAA nautical charts published between 1984 and 2003, at scales between 1:10,000 and 1:80,000 with emphasis on the larger scales (highest resolution). As a result of the automated method that was applied to extract data from raster nautical charts, EVS files named "gd20" designate the presumed MHW coastline. The Merged Extracted Vector Shoreline was created by merging data from the best scale of the EVS series. EVS must be used with caution as there are problems with this data along the boundary between tan and green areas depicted on the charts. In these areas, the MHW line is often incorrectly depicted by the “buff tint boundary” (the edge of the tan land areas), instead of the heavy black MHW line on NOAA charts. Some of the EVS data named with the "mar" prefix may be applied to edit the problem areas because the officially charted MHW shoreline may exist at the edges of the EVS "mar" areas. In places where the charts depict buff-colored areas adjacent to extensive green areas such as marshes, tidal flats, ledges, gravel, mud, uncovered rocks, and vegetation, this shoreline should be checked against the RNC shoreline (Section 3.1.3) because the buff tint boundary is likely to be the incorrect MHW line. In areas where discrepancies between the EVS and RNC shoreline are significant, the EVS must be edited by manually digitizing the RNC coastline.

EVS and Merged EVS are available from http://nauticalcharts.noaa.gov/csdl/ctp/cm_vs.htm, the NOAA website. Because the EVS data files named with the prefix "gd20" and the Merged EVS do not always follow the charted MHW line, they must be corrected or edited from the corresponding RNC. EVS data files named with the "mar" prefix may need to be included to edit the shoreline, especially in places where the heavy black MHW line depicted on nautical charts exist along the boundary of the "mar" data.

3.1.3. Raster Navigational Chart (RNC) Data

A raster navigational chart is an electronic picture of the paper chart which is suitable for use in computer-based navigation systems and geographic information systems. Under an exclusive agreement with MapTech (formerly BSB Electronic Charts), digital raster charts of the entire NOAA suite of charts are available. These charts include every detail of the official paper charts. New editions of the raster charts are available simultaneously with the new edition of the paper charts. RNC data are available from http://nauticalcharts.noaa.gov/csdl/ctp/cm_vs.htm, the NOAA website.

3.1.4. NOAA's Medium Resolution Digital Vector Shoreline (MRS) Data

If an area has no ENC shoreline data and if the EVS data does not accurately show the MHW line, another option is NOAA's Medium Resolution Digital Vector Shoreline. This shoreline was created by NOAA's Special Projects Office (SPO) in the late 1980s, with data taken manually from topographic charts (called T sheets) created between 1988 and 1992. The compilation map scale is nominally 1:70,000. The actual scales of chart sources range from 1:20,000 to 1:600,000, with the majority of charts concentrated between 1:80,000 and 1:40,000. According to the SPO documentation, the shoreline's horizontal datum is the North American Datum of 1983 (Geodetic Reference System 1980) (NAD 83), while the controlling vertical datum is the North American Vertical Datum of 1929 (NAVD 29). When compared to the EVS or ENC data, this shoreline may differ slightly (around 0.1 nmi) due in part to actual physical changes in the shoreline, but mostly because the newer charts digitized for the EVS project have been updated with positions revised using GPS.

This digital coastline is available from http://rimmer.ngdc.noaa.gov/coast/getcoast.html, a NOAA website, by entering a latitude-longitude window and selecting the appropriate data source. Output is available in Mapgen, Arc/Info, Matlab, and Splus formats, and the data can be downloaded to a PC. A variety of compression formats are available.

Figure 3.1 illustrates that the ENC shoreline (shown in green) matches the higher resolution (1:30,000) charted MHW shoreline exactly. The NOAA Medium Resolution shoreline (shown in blue) is slightly offset from this line, but is much closer than the EVS shoreline (shown in orange) that follows the tint boundary instead of the heavy black MHW line.

3.1.5. World Vector Shoreline (WVS) Data

In areas outside the U.S., the extents of three previously mentioned shoreline types will be limited. For international shoreline, the World Vector Shoreline (WVS) can be used. The shoreline is at a nominal scale of 1:250,000, much coarser than any of the other shoreline data sources. This MHW shoreline was originally compiled in the late 1980s by the Defense Mapping Agency (DMA), which is now the National Geospatial-Intelligence Agency (NGA).

This digital coastline is available from http://rimmer.ngdc.noaa.gov/coast/getcoast.html, a NOAA website, by entering a latitude-longitude window and selecting the appropriate data source. Output is available in Mapgen, Arc/Info, Matlab, and Splus formats, and the data can be downloaded to a PC. A variety of compression formats are available.

3.1.6. Processing Shoreline Data

Shoreline data can be formatted for use in a variety of software packages, including Mapgen, SMS, Matlab, XYI, and xmgredit. A Fortran processing program, `fc4.f90`, is available to convert between these formats.

Shoreline data often consists of numerous short line segments, which may be listed in no particular order. Some programs are available to make the data more usable.

The program `concat.f` reads a coastline data file (in XYI format: east longitude, north latitude, and pen command {0 or 1}) and concatenates the segments into longer strings. After running the program, the resulting data should contain one long, unconnected (i.e., the end points do not match) string followed by numerous, smaller connected (i.e., the end points match) strings that represent islands. The program `cleancoast.f` reads a coastline file and removes segments consisting of two points, repeated points, three or more points located along a constant latitude or longitude. Input data are in the XYI format.

The SMS program can also be used to read and clean up coastline data files, using a NOAA nautical chart as a guide.

3.2. BATHYMETRIC DATA

Good bathymetric data are essential for stable hydrodynamic model runs and reliable model output. Care should be taken to find the most recent and accurate bathymetric soundings for the modeling area of interest. Unfortunately, this is not a simple task as the available data throughout the U.S. are not all of the same resolution or age. This section will focus mainly on how to find all of the available data for an area and determine the best source. Information on adjusting the data to a common datum and combining data from different sources will be discussed in Section 3.4.4 on hydrodynamic modeling of the tidal datums.

In general, the sources of data, in decreasing order of quality, are:

- U.S. Army Corps of Engineers,
- NOAA NOS hydrographic survey sounding data,
- Depths published in NOAA NOS Electronic Navigational Charts,
- Depths published on NOAA NOS Raster Navigational Charts,
- NOAA Coastal Relief Model data, and
- World Bathymetric Databases.

Table 3.1 lists details on these bathymetric data sources.

Table 3.1. Sources and reported accuracy of bathymetric data.

Sources	Horizontal Resolution	Reported Horizontal Accuracy	Vertical Resolution	Reported Vertical Accuracy	Horizontal Datum	Vertical Datum
Soundings from USACE surveys of channels, inlets, rivers, canals, and dredged areas; updated with new data depending on survey priority	1:1200 to 1:48,000 usually	2 – 5 m [1]	coarser than 1 m [1]	0.25 – 1.0 ft at depths less than 15 ft 1.0 – 2.0 ft at depths greater than 15 ft [1]	NAD 83	MLLW MLW, MLG, MLT
Soundings from NOAA NOS Hydrographic Survey Database Warehouse; updated with new data depending on survey priority	1:5000 to 1:80,000 [2]	IHO and U.S. standards [3]	~0.1 m reported	IHO and U.S. standards [3]	original datums transformed to NAD 83	MLLW, MLW, usually
Soundings digitized from NOAA Navigational Charts; updated with data from new USACE and NOS surveys	subsampled from survey source	less accurate than survey sources	~0.1 m reported	less accurate than survey sources	NAD 83 WGS 84	MLLW on charts after 1980 [4]
NGDC Coastal Relief Model (CRM); interpolated from soundings data before 1995	various data resolutions interpolated to ~90 m	undetermined; less accurate than source soundings	various data resolutions interpolated to 0.1 – 1 m	undetermined; less accurate than source soundings	nonuniform [5]	nonuniform [5]
Naval Research Laboratory's Digital Bathymetry Gridded Database (DBDB-Variable) [6]	various data resolutions interpolated to 0.05 – 0.5 minutes	undetermined; less accurate than any source data	various data resolutions interpolated to averaged depth per grid cell	undetermined; less accurate than any source data, especially in areas shallower than 200 m [6]	nonuniform source datums have been interpolated as WGS 84 [6]	nonuniform source datums interpolated to global MSL [6]
ETOPO2 ERS-1 and Geosat altimeter data merged with soundings from shipborne surveys before 1995 [7]	various data resolutions interpolated to 2 minutes	undetermined; less accurate than any shipborne soundings data included as "ground truth"	various data resolutions interpolated to averaged depth per grid cell	undetermined; less accurate than any source data; unreliable in areas shallower than 200 m [7]	nonuniform source datums have been interpolated as WGS 84 [7]	nonuniform source datums interpolated to global MSL [7]

[1] Table 3-1, U.S. Army Corps of Engineers Hydrographic Survey Manual, 2002.

[2] 1 cm spacing between sounding lines and 5-6 mm sounding density along lines at the scale of the survey. Soundings are twice as dense along lines than across lines.

[3] See Table 3.2.

[4] Original MLW and other tidal datums are designated as MLLW on NOAA navigational charts.

[5] Depth values that were used to generate the CRM were non-uniformly georeferenced.

[6] Performance Specification Digital Bathymetric Database – Variable Resolution (DBDB-V), U.S. Naval Oceanographic Office and U.S. National Imagery and Mapping Agency, 1998.

[7] Smith, W.H.F. and D.T. Sandwell, 1997, Global Sea Floor Topography from Satellite Altimetry and Ship Depth Soundings, *Science* 277 (5334), p.1956-1962.

3.2.1. U.S. Army Corps of Engineers (USACE) Data

Because U.S. Army Corps of Engineers (USACE) soundings data are usually the densest and the most recent, these should be the primary source of bathymetry. However, these data are only available in navigation channels, canals, rivers and other areas where the USACE is responsible for dredging, which will only cover a small fraction, if any, of the total model domain area. The vertical datum information will be included as metadata and can be MLW, MLLW, Mean Low Gulf (MLG used by the New Orleans District, USACE, in Louisiana only), or Mean Low Tide (MLT used by the Galveston District, USACE, for Galveston Bay). USACE is presently working to establish and use the same vertical datums as NOS.

If the NOAA Chart datum tables do not show the differences between MLLW and the USACE special datums, then CO-OPS should be contacted to get the estimated elevation differences. MLT and MLG are fixed datums established decades ago from historical tide station measurements and have not been updated to account for sea level change as is the case for MLLW. MLT and MLG are approximately 1.0 foot below MLLW in those regions.

Information about the USACE hydrographic surveys is available from OCS' Marine Chart Division, NGS' Remote Sensing Division, or directly from Corps of Engineer district offices.

3.2.2. NOS Sounding Data

Since the Army Corps data cover limited areas, the NOS sounding data should be used to fill in the gaps. The NOS sounding data originate from NOAA hydrographic surveys should cover the majority of areas at the highest resolution in most coastal and estuarine model domains. NOAA's Office of Coast Survey and the National Geophysical Data Center (NGDC) are updating and maintaining this bathymetry data warehouse to distribute digital sounding data from nearly 7,000 hydrographic surveys conducted between 1850 and 2006.

Each survey in the NOS hydrographic survey database (NOSHDB) includes metadata in `*.h93` header format. Header fields include the survey identification, parameters (soundings, features, or both), file creation date, file modification date, source institution, platform, start and end years of field data collection, survey scale, general and specific geographic areas, position determination, original horizontal datum, calculated horizontal datum, original vertical (tidal) datum, average tide range during the survey, original sounding units, sounding method, method of sound velocity correction applied to the acoustic depth measurements, data archival processing methodology, geographic coordinates of the survey's minimum bounding rectangle, cartographic code, additional documentation. The survey identifier acts as the primary key to relate each survey's parameters to metadata fields recorded in the survey's `*.h93` header.

The NOSHDB contains soundings digitized from smooth sheets processed from hydrographic surveys that were completed between the years 1851 and 1965, as well as digital soundings acquired by survey ships since 1965. The surveys were carried out using a variety of sounding methods including lead-line soundings from the late 1800's until the 1930's, single beam echosounder from the 1930's until to the 1990's, and multibeam sonar from the 1980's to present. The sonar systems utilized a wide-range of frequencies with varying beam widths.

A wide range of navigation methods are also associated with the surveys. Visual navigation (three-point sextant fixes to objects on shore) was the most common method of survey positioning (navigation) until the 1930's and continued to be used for nearshore positioning until the 1980's. Radio waves were first used for offshore positioning in the 1930's and electronic positioning evolved over the years, becoming more accurate and reliable until being replaced by GPS in the mid 1990's.

Sounding and navigation techniques have changed over the more than 150 years of NOS hydrographic data collection. As a consequence, the required horizontal and vertical accuracy standards for NOAA surveys have changed over time (Table 3.2). Accuracy requirements were prescribed on a case-by-case basis for individual survey projects carried out before 1957. Differential GPS has improved the level of accuracy considerably for the most recent survey data. NOS surveys are plotted at map scales that range from 1:5,000 for harbors and channels to 1:80,000 for open ocean surveys, with 1:20,000 being the most commonly used scale.

The nominal accuracy of the survey measurements is usually much better than the minimum standards specified in Table 3.2. Almost all modern surveys, including those carried out in deep water and open ocean, will meet IHO Order 1 standards or better. The actual accuracy of historical data depends on the age of the survey, depth, seafloor rugosity, horizontal positioning, platform, field conditions, water level variability, original processing methodology, and archival processing methodology. Compared to the survey measurements, greater significant sources of error are the unknown depths between sparse soundings.

The various original horizontal datums of older surveys are transformed to North American Datum 1983(1986) [NAD 83(86)] using the North American Datum Conversion utility (NADCON) developed at NOS. For surveys before 1927, horizontal coordinates are transformed using a single pair of datum latitude/longitude shift values for the entire survey that approximates its location referenced to the North American Datum 1927 (NAD 27), which NADCON further transforms to NAD 83(86).

The soundings' original vertical datum can be MLW, MLLW, or Low Water Datum (LWD, for coastal non-tidal areas). The original processed survey depth units (feet, fathoms and feet, fathoms and tenths, meters) are converted into metric units during assimilation into the NOSHDB. Depth measurements collected before 1980 are referenced to MLW along the Atlantic Coast, whereas MLLW is the usual vertical reference used by surveys conducted after 1980 and for surveys along the Pacific coast. Planned and processed for navigational safety, the NOS soundings are shoal biased, i.e. they were analyzed and filtered so as to over-emphasize shallower depths.

Processed as data sources for navigational products, the NOS soundings and their subsequently charted depths are shoal-biased. For each survey, sounding depths are initially cleaned to eliminate invalid measurements of objects that are not part of the seafloor (e.g., fish, kelp). Other invalid soundings result from measurement angle effects, interference, or instrument effects. Until 2006, when the Combined Uncertainty Bathymetry Estimator algorithm (CUBE; Calder, 2003) became the standard method to process MBES data, soundings that exceed the desired measurement error tend to be over-cleaned as hydrographers typically rejected depth data in deeper areas while favoring data in shallower areas.

Table 3.2. The required horizontal and vertical accuracy standards for NOAA surveys. Accuracy requirements before 1957 were prescribed on a case-by-case basis for individual survey projects.

Survey Year*	Horizontal Accuracy	Vertical Accuracy	Standard
1998 – present	**Order 1:** 1 – 100 m depth: 5.0 m + 5% of depth **Order 2:** 100 – 200 m depth: 20 m + 5% of depth **Order 3:** 100 – 200 m depth: 150 m + 5% of depth	**Order 1:** 1 – 100 m depth: 0.5 – 1.4 m **Order 2:** 100 – 200 m depth: 2.5 – 4.7 m **Order 3:** > 100 m depth: same as Order 2	IHO S-44 [1] and NOAA [2]
1988 – 1998	95% probability that the true position lies within a circle of radius 1.5 mm, at the scale of the survey	0 – 30 m depth: 0.3 m > 30 m depth: 1% of depth	IHO S-44 [1] and NOAA [2]
1982 – 1988	probable error shall seldom exceed twice the plottable error (1.0 mm) at the scale of the survey	0 – 20 m depth: 0.3 m 20 – 100 m depth: 1.0 m > 100 m depth: 1% of depth	IHO S-44 [1] and NOAA [2]
1957 – 1982	maximum error of plotted positions shall seldom exceed 1.5 mm at the scale of the survey	0 – 20 m depth: 0.3 m 20 – 100 m depth: 1.0 m > 100 m depth: 1% of depth	IHC [3] NOAA [2] and IHO S-44 [1]
before 1957	undetermined	undetermined	undocumented

* end of field collection

[1] International Hydrographic Organization (IHO) Standards for Hydrographic Surveys, Special Publication 44, (First Edition, 1968; Second Edition, 1982; Third Edition, 1987; Fourth Edition, 1998).

[2] U.S. Department of Commerce Coast and Geodetic Survey Hydrographic Manual (1931, 1942, 1960, 1976)
NOAA NOS Office of Coast Survey Specifications and Deliverables, 1999 – 2006.
NOAA was established in 1970.

[3] International Hydrographic Conference, 1957.

Traditionally, the depth measurements were down-sampled into shoal-biased 5 m bins to generate the archive data sources for navigational products, until the Navigation Surface processing (Smith, 1993) became operational after 2005. The binned shoal-biased depths were down-sampled further (with additional shoal bias) as they were selectively plotted at prescribed scales to create the survey smooth sheets. Even with Navigation Surface processing, shoal-biased depths are inevitable for NOS survey data when the metric units of the original depth measurements are converted to English units for navigational charts using NOAA rounding rules (*Nautical Chart User's Manual, 1997*).

For detailed information and to download the NOS survey data products, including soundings, metadata, Descriptive Reports (DRs), smooth sheet images, sonar images, and reprocessed multibeam data, go to NGDC's website http://www.ngdc.noaa.gov/mgg/bathymetry/hydro.html.

3.2.3. NOAA Electronic Navigational Chart Data

NOAA sounding data are published as ENCs or digitized directly from raster versions of the paper charts. While the accuracy of charted soundings are about the same as the survey source at the location of the sounding point, they are sub-sampled from survey measurements that are collected at higher resolutions than the most detailed chart of the area. Consistent with NOS hydrographic processing to ensure safe navigation, the nautical chart data are shoal-biased, meaning that the shallowest (as opposed to the median or mean) soundings are selected for the chart bathymetry. To add another margin of safety, the charted soundings, depth areas, and bathymetry contours along the coast are conservatively designated as being referenced to MLLW since 1989, in compliance with the NOS chart datum convention of 1980. Regardless of the original vertical datum of the survey depths, the charted NOS coastal bathymetric data are published as being referenced to MLLW on NOAA nautical charts.

In the same manner as for downloading ENC coastline, ENC cells in their native standard IHO S-57 data format are selected by using the interactive map service, from the Office of Coast Survey web site, http://nauticalcharts.noaa.gov/mcd/enc/index.htm. After downloading the selected ENC cells, the digital soundings are extracted from the S-57 SOUNDG and DRGARE object class, and converted into ASCII or any number of projected vector-based formats and geographic coordinate systems using Safe Software’s FME spatial ETL (Extract, Transform, and Load) software engine.

The *ENC Direct to GIS* web portal interactively distributes the data of most ENCs. ENC data are selected, converted into several digital formats, and downloaded directly from the web at http://nauticalcharts.noaa.gov/csdl/ctp/encdirect_new.htm. When the desired data are visualized and activated on the interactive web map, the user selects the area by entering geographic coordinates in latitude-longitude, selects the format and geographic coordinate system of the data to be extracted, and downloads the digital products such as SOUNDG and DRGARE.

3.2.4. Coastal Relief Digital Elevation Model Data

NOAA’s National Geophysical Data Center (NGDC) has created the Coastal Relief Digital Elevation Model (CRM), which merges bathymetry and coastal land topography as coarse grids (about 90m x 90m horizontal resolution). The coastal bathymetry grids are interpolated from all the combined historic NOS soundings from the 1850s until about 1995. Additional bathymetry data sources include the U.S. Geological Survey (USGS), Monterey Bay Aquarium Research Institute (MBARI), U.S. Army Corps of Engineers LIDAR (SHOALS), and various academic institutions. Each of the CRM raster grids was initially produced at one degree of latitude by one degree of longitude. The vertical resolution is 1 m along the coast in order to merge with the terrestrial grids created by the U.S. Geological Survey. Offshore bathymetry elevations are gridded at 0.1 m resolution or higher.

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 interpolated from soundings merged from all dates. Grids are referenced to the sources' various horizontal datums. Although the soundings' original vertical datums vary, the CRM bathymetry is reportedly referenced to MLW. It is important to note that in this data set, the delimiters for no data are “0.0” and “-9999.0”. CRM data with these values should be disregarded.

Description about the coastal digital elevation model grid development, software to create custom-sized grids, grid images, metadata and gridded data are available for download in binary raster, ASCII raster, and ASCII XYZ (longitude, latitude, depth) from NGDC's website, http://www.ngdc.noaa.gov/mgg/coastal/coastal.html.

3.2.5. Global Bathymetric Databases

Because the regional hydrodynamic water level models do not extend a great distance into the deep ocean waters, the bathymetry data sources listed above should be sufficient. But if there is a need, ETOPO2 or the Navy's Digital Bathymetric Database – Variable (DBDB-V) are available as coarse grids that are derived from satellite altimetry merged with the ship-borne soundings (included to help calibrate the satellite data). Information about ETOPO2 can be found at the NOAA NGDC website: http://www.ngdc.noaa.gov/mgg/global/global.html. Information about the Naval Research Laboratory’s gridded bathymetry is available from the web and from the Coast Survey Development Laboratory's data library. For DBDB-V, difficulties with geo-referencing cause these primarily deep ocean bathymetric data to be unreliable around coastal areas.

Bathymetric data may also be available for other countries, especially Canada and Mexico. The staff of the Coast Survey's Hydrographic Surveys Division will be able to provide contact information.

3.3. TIDAL DATUMS AND ASSOCIATED WATER LEVEL DATA

Data derived from recorded water level time series are used to run spatial interpolation models, and provide benchmarks for the hydrodynamic model’s validation and correction. These data include tidal datum values, time series of elevations and derived values such as mean values of water levels, and harmonic constants.

3.3.1. Types of Available Water Level-Derived Data

NOS’ Center for Operational and Oceanographic Products and Services (CO-OPS) is NOAA’s clearing house for all of the water level time series data and the data derived from these records (http://tidesandcurrents.noaa.gov). The two most important derived datasets for tidal datum modeling are tidal datums and harmonic constants. For other purposes, the actual water level records and the NAVD 88-to-MLLW data are also available.

Tidal Datums A vertical datum is a reference plane used as the basis for a vertical measurement. A tidal datum is a reference plane that is determined by a characteristic of the astronomical tides. Tidal datums are calculated by extracting and averaging the high and low water values from a time series. The primary tidal datums discussed in this paper are listed and defined below based on CO-OPS' Tide Glossary (NOS, 2001) (also see Appendix A):

- Mean higher high water (MHHW): The average of the higher high water heights of each tidal day observed over the National Tidal Datum Epoch (NTDE).
- Mean high water (MHW): The average of all the high water heights observed over the NTDE.
- Mean low water (MLW): The average of all the low water heights observed over the NTDE.
- Mean lower low water (MLLW): The average of the lower low water heights of each tidal day observed over the NTDE.
- Mean tide level (MTL): The arithmetic mean of mean high water and mean low water.
- Diurnal tide level (DTL): The arithmetic mean of mean higher high water and mean lower low water.
- Mean sea level (MSL): The arithmetic mean of hourly heights observed over the NTDE.

The National Tidal Datum Epoch, as defined by CO-OPS (NOS, 2001), is a "specific 19-year period adopted by the National Ocean Service as the official time segment over which tide observations are taken and reduced to obtain mean values for tidal datums". Updates to the NTDE reflect changes in local MSL due to global sea level change and the effects of long term local land movement due to subsidence or glacial rebound. The current NDTE is 1983 to 2001. Previous tidal epochs were determined for 1924 to 1942, 1941 to 1959, and 1960 to 1978. Note that in practice tidal datums have uncertainties based on the length of series of observation. For stations in less than 19-years, equivalent 19-datum values are computed through simultaneous comparison with a nearby long-term control tide station. The uncertainties of these equivalent NTDE datums at short-term stations are also dependent on the geographic distance to the control station and the difference in time of tide and range of tide from the control station (Swanson, 1974; Bodnar, 1981).

Note: NGS often uses mean sea level to refer to a hypothetical global surface that approximately coincides with the ocean's mean level. Therefore, the term Local Mean Sea Level (LMSL) was introduced to refer to the mean sea level value that is determined by CO-OPS for any individual water level station.

Harmonic and Non-harmonic Constants CO-OPS derives harmonic constants (amplitudes and phases of the harmonic constituents) from water level time series (Appendix A). If more than 29 days of data is available, programs developed at CO−OPS can solve for up to 175 tidal constituents using least squares harmonic analysis. For only 29 days of data, a Fourier harmonic analysis can be done to solve for 10 constituents and infer an additional 14 tidal constituents (Zervas, 1999). Auxiliary, non-harmonic constants include Greenwich Intervals, mean and great tropic tide ranges, constituent speeds, and the equilibrium arguments and lunar node factors for the years 1900 to 2025.

Harmonic constants are also available from a limited number of global tide models. These are listed in Appendix D.

3.3.2. Acquiring Tidal Datums

CO-OPS data can be acquired in a variety of ways. The CO-OPS website provides links to the tidal datums (http://tidesandcurrents.noaa.gov/station_retrieve.shtml?type=Datums) and (http://tidesandcurrents.noaa.gov/station_retrieve.shtml?type=Harmonic+Constituents) for harmonic constant data.

On occasion, when a new project area is begun, CO-OPS has generated a spreadsheet of the latest data for the region. The spreadsheet can be read and reformatted using the program `unpack_datums.f` in the VDatum subdirectory `vdatum/T/CO`. For example, the following three lines are the first three records in the file `msf_usa20100218.dat`.

```
 0 5 -9.999  CO-OPS tidal datums
 1611347  21.903300 -159.592000   0.307   0.185  -0.194  -0.254  -9.999 PORT ALLEN, KAUAI
 1611400  21.954444 -159.356111   0.306   0.182  -0.191  -0.252  -9.999 NAWILIWILI HARBOR, KAUAI
```

The first line contains the numbers containing a dummy value, the number of datums, and the value used to represent a missing datum. The following lines contain data for each tide station, including the 7-digit NOS station number; the north latitude and east longitude (decimal degrees); the MHHW, MHW, MLW, and MLLW tidal datums relative to MSL (meters); the NAVD88 elevation relative to MSL (meters); and the station name (abbreviated here).

In addition, CSDL has created a shell program, `makelist.sh`, that reads the CO-OPS website and creates a spreadsheet of tidal data in the above format and has the naming convention `'msf_usaYYYYMMDD.dat'`. This file may then be transferred to the CSDL archive.

3.4. GEODETIC DATA

The NGS routinely collects geodetic data at the benchmarks that are installed around NOS water level stations (Figure 3.1). These data are used to generate the TSS field and to perform accuracy checks on the VDatum tidal datum fields. The topography of the sea surface (TSS) is a gridded field containing the difference between the MSL at the water level stations and the NAVD 88 elevation.

Geodetic datum (NAVD88) elevation relationships to tidal datums are found in the *Accepted Datums* area of the CO-OPS web-site, if there has been a level connection between two or more geodetic bench marks. Alternatively, the geodetic data for individual bench marks at an individual water level station are available in a NGS database. These should be used if a value from a CO-OPS datums file is not available. Geodetic to tidal datum elevation relationships should be estimated using more than one bench mark at each station as a validation check. These can be extracted after a request to the NGS web-site of the CO-OPS published sheet web-site. NGA and CO-OPS bench mark databases are hyperlinked via the bench mark PID number.

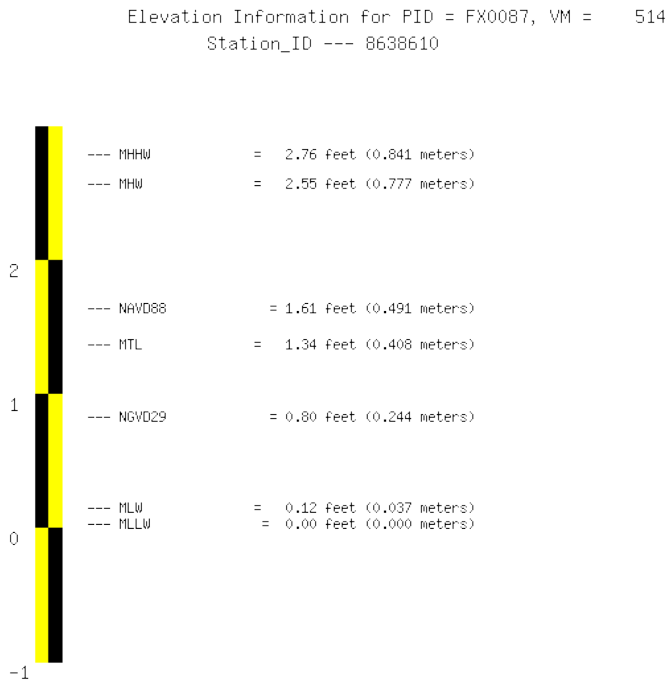


Figure 3.2. Schematic of geodetic data at an NGS benchmark.

4. TIDAL DATUM MODELING

4.1. INTRODUCTION TO CREATING THE TIDAL DATUM FIELDS

Historically, the need to supply a tidal datum offset for a given location was met by simply using the offset at the nearest water level station. This approach assumes that the offsets are spatially constant, when it is known that each offset, much like the tide range, varies from place to place. The VDatum approach has been to predict the tidal variations using a variety of methods, including:

- hydrodynamic tide models,
- harmonic constants, and
- spatial interpolation of datums.

First, the most complicated and time consuming method, but often the most accurate, is to create a regional hydrodynamic model and use the time series results from this model to compute the tidal datums throughout the VDatum domain. This is the approach preferred by NOS. The results are corrected using a spatial interpolation program to insure that the modeled datums match the datums at the NOS tide gauges. The second method uses the harmonic constants generated by a pre-existing hydrodynamic model output to compute the tidal datums throughout the VDatum domain. The harmonic constants (as many as are available) are used to generate a time series, and the series is analyzed to extract the high and low waters. These results are corrected using a spatial interpolation program to insure that the datums from the model results match the NOS tide gauge data. The third method is a simplified approach which uses the tidal datum data provided at the NOS tide gauges and to apply spatial interpolation to create tidal datum fields for the entire VDatum domain.

We note in passing an alternative method of generating tidal datum offsets using harmonic constants, called the Harmonic Constant Datum (HCD) method (Mofjeld et al., 2004), has been developed and may be worth pursuing. In this method, a limited number of constituents are used to make an estimate (accurate to within a few cm) of the tidal datum using formulae originally set forth in the Coast and Geodetic Survey’s Form 180 (Coast and Geodetic Survey, 1952), a table designed for the manual analysis of tidal data. The datum values are computed by two sets of formulae, the set being determined by whether the value of the ratio R,

$$R = (K1 + O1)/M2 \tag{4.1}$$

is greater than 4.0. In (4.1), $K1$, $O1$, and $M2$ are the amplitudes of the K_1, O_1, and M_2 tidal constituents, respectively. In application, however, the formulae yield a discontinuity in all datum values at $R = 4$, so one of three methods must be used to adjust the original estimate.

4.2. HYDRODYNAMIC MODELING

The goal of developing and running a hydrodynamic model is to generate tidal datum fields in a regional area. This section gives a general standard operating procedure to follow when using a hydrodynamic model. Details of how to set up and run specific models can be found in the appendices.

4.2.1. Overview

The first method is by applying a hydrodynamic model to a region, simulating water levels at all nodes, and extracting the datums from the simulated series. Unlike the spatial interpolation method, a regional model can capture the hydrodynamics of the region. An advantage over the harmonic constant database method is that the user is allowed to specify the domain and the grid resolution. A limitation is that this process is time consuming and is not as straightforward as the other two methods.

To compute accurate tidal datums, it is essential that accurate bathymetry be supplied to the model. This is more complicated than one may first suppose. Beyond collection of the most accurate bathymetry (first from NOS sounding databases and then from other sources), the data must be referenced to a common vertical datum. But these transformations are unavailable in the region of interest as the VDatum tool is the output of the modeling study.

The first step, then, is to identify the vertical datum of each sounding. Once this is done, these data can be transformed to the model datum, which is usually a geopotential surface such as NAVD 88 or a generic "model zero" (MZ). The initial transformation is done based on data from the NOS tide gauges in the region. If the tide range is nearly invariant throughout the region, a constant datum transformation can be applied. If there is a large difference in the datums throughout the domain, a spatial interpolation of the datums will provide a sufficient initial guess at the datum transformations.

After a stable model run has been established with the initially adjusted bathymetry data, the tidal datum fields can be calculated from the model output. Generally, water levels are recorded at all nodes in the grid every 6 minutes. The high and low waters are picked off from these time series, and the tidal datums are computed. Now it is these tidal datum fields that are used to adjust the original bathymetry data to a common datum. The model is run again and the datums are again calculated from the model output. The datums will converge such that the output from one model run to the next is essentially the same.

The results will not converge to the exact values of the tidal datums at the stations located throughout the domain as the datums from the model reflect only the astronomical tide and do not account for the meteorological effects that are included in the computation of the datums from the NOS water level time series. As with the results from a tidal datum database discussed above, the correction to match the NOS tide gauge data is done with the TCARI spatial interpolation method. Again, the errors between the modeled datums and the NOS tide gauge data are the input values for TCARI. The spatial interpolation of the error is applied to correct the modeled results to ensure that the final datum values match the NOS tide gauge data. An example of the use of this method is with the creation of the Outer Banks, North Carolina VDatum tool (Hess et al., 2005).

4.2.2. Choosing a Hydrodynamic Model

NOS has run several types of hydrodynamic models for tidal simulation and in the development of nowcast/forecast systems. For purely tidal simulations, the use of an unstructured grid offers great advantages in modeling common coastal features such as curving and irregular coastlines, small embayments, and narrow channels. By contrast, structured grids, which typically have rectangular elements of fixed size, often are less satisfactory in aligning their land-water boundaries with coastal features. NOS is experienced in running several unstructured grid models, namely the Advanced Circulation model (ADCIRC), which is at present the preferred model to use, the Eulerian-Lagrangian Circulation model (ELCIRC), the Semi-implicit Eulerian-Lagrangian Finite Element model (SELFE), and the Finite Volume Coastal Ocean Model (FVCOM). For a list of the available ADCIRC models, see Appendix C.

4.2.3. Setting up the Hydrodynamic Model

Domain Definition The domain of the model corresponds to the geographic region being modeled. It will be extremely useful to establish the precise boundary of the new VDatum marine grid, since this will set the minimum extent of the hydrodynamic model's domain. Also, some hydrodynamic model overlap with existing VDatum model grids is advisable to allow for more flexibility when merging these areas in the future.

In the models currently being designed for the VDatum tide modeling projects, the model open boundary is extended into the open ocean waters that have slowly-varying (in space) tidal constituent amplitudes and phases. It is also important that the open boundary be located as far away as possible from amphidromic points or other areas of rapidly changing phase in the tidal constituents, and from locations of large bathymetric gradients.

Finally, the open ocean boundary conditions will be in the form of tidal harmonic constants which are taken from a tidal database (see Section 4.3). It is therefore important to examine the available data for sufficiency and coverage.

Once the domain has been established, the necessary modeling data, namely the bathymetric data and the digitized shoreline, must be acquired.

Grid Development The mesh that represents the actual physical domain is a key component of every hydrodynamic model. The mesh can be regular, orthogonal, or unstructured, depending on the model. No matter which type of mesh is used, it is important to have sufficient resolution to capture key hydrodynamic features such as the continental shelf break (if the model extends that far), inlets, rivers, etc. Several advantages of unstructured grids are that they allow the elements to conform very closely to the coastline and also to provide increased resolution in areas of the domain where more complex physics dominate (such as inlets). In the deep ocean where tides vary linearly, relatively larger elements will provide sufficient resolution to capture all the important flow features. In areas with high bathymetric gradients (such as over the continental shelf break), in shallow waters, and in narrow inlets, increased resolution is necessary to resolve the important flow features. For regular meshes, the element information is usually implicit, but with triangulated meshes, there needs to be an element connectivity table listing which nodes compose a given element.

CSDL uses the Surface-water Modeling System (SMS), developed by Environmental Modeling Systems, Inc. (www.ems-i.com/SMS/cms.html) to generate its unstructured meshes. The goal with the grid setup is to have sufficient resolution to resolve the important flow features, but not so high than it increases the model run time beyond practicality. This optimization has been explored at length with the localized truncation error analysis (LTEA) method (Hagen, 2001; Hagen and Parrish, 2004), which has been incorporated into the SMS software. In addition, other criteria such as the dimensionless wavelength and Courant number should be used as guides when creating a grid. A sample regional model grid is shown in Figure 4.1.

Adding Bathymetry To compute accurate tidal datums, it is essential that accurate bathymetry be supplied to the model. First, details on how to adjust the bathymetry data to a common vertical datum will be described. Then, notes on how to combine data from different sources will be given. Methods for interpolating data to a grid (with notes if the technique is for structured grids, unstructured grids, or both) are listed in Appendix E.

For the hydrodynamic models, the so-called model zero (MZ) is an equipotential surface which represents the undisturbed ocean surface. This is the surface of the water when the model is at rest. Note that, in general, MZ is not the same as MSL because of non-linear dynamic effects. All of the bathymetry data should be referenced to this common datum. There are three methods that can be used to make this adjustment from the bathymetric datum (usually MLLW or MLW) to MZ. These methods are discussed below.

> **Constant Adjustment -** A constant adjustment is the easiest way to adjust bathymetric data from the original datum to MZ. Although it is not spatially accurate, it can provide a reasonable initial field at the start of a series of model runs. The constant is the average of the differences between the datum and MSL as measured at the NOS water level tide gauges located throughout the model domain. Although MSL and MZ are not the same, it is safe to assume that they are equivalent for an initial guess at the datum adjustment.
>
> **Spatial Interpolation Adjustment** - Using the TCARI program (see Section 4.2), the difference between the datum the bathymetric data is referenced to (such as MLLW or MLW) and MSL as recorded at NOS water level stations can be spatially interpolated throughout the model domain to create a field of the datum adjustment. Although MSL and MZ are not the same, for an initial guess at the datum adjustment, it is safe to assume that they are equivalent.
>
> **Hydrodynamic Model Output Adjustment** - Usually an initial guess is made at the adjustment from the original bathymetric datum to MZ using a constant adjustment or a spatially interpolated field as discussed above. After the model has been run with this initial MZ-referenced bathymetry, the tidal datum fields from the analyzed hydrodynamic model output can be used to adjust the original bathymetric data to MZ. This is the most accurate method for adjusting the bathymetry.

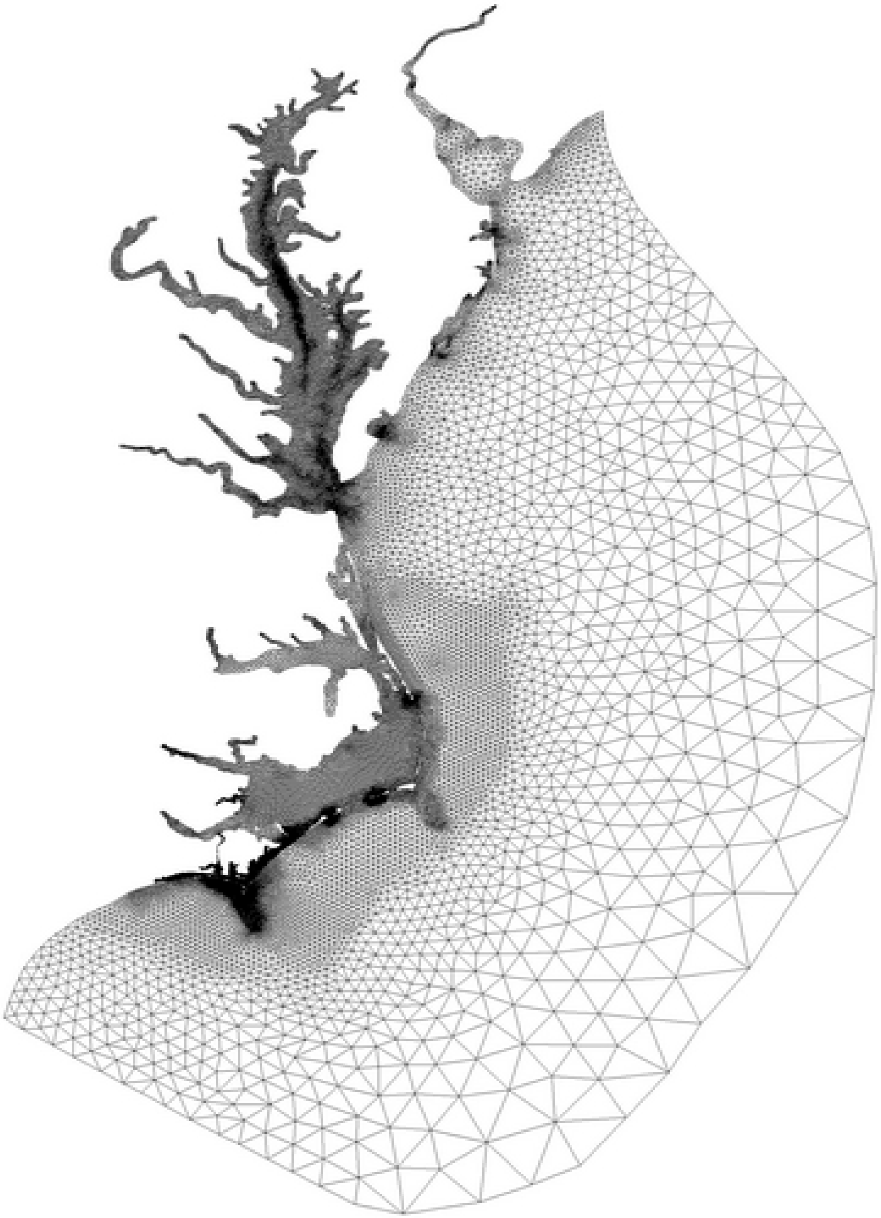


Figure 4.1. Unstructured grid representing Delaware Bay, Chesapeake Bay and the Pamlico and Albemarle Sounds.

Since it is unlikely that one data source will provide all of the data needed to populate the hydrodynamic grid, data from different sources will need to be combined (see Section 3.1 on bathymetric data sources and quality). There are two ways to approach this problem. The first solution is to adjust all of the raw bathymetry data from the original datum to the common MZ datum. After that is completed all of the soundings can be incorporated into the model grid (using the interpolation methods discussed above). Another approach would be to populate the grid with data referenced to like datums to create several different grids. For example, one model grid could have data from the MLLW surveys where those data are available and a separate grid could have data from MLW surveys where those data are available. Next, the adjustment from the original datum to MZ is made at the grid nodes. Finally, the two grids, which are now referenced to MZ, can be combined.

4.2.4. Running the Hydrodynamic Model

This section will discuss the general steps involved in running the hydrodynamic models (see also Appendix F). Methods for calculating the tidal datum fields from hydrodynamic model results will be discussed first. In general, the six (6) steps in running the model are:

1. assume initial MLLW- and MLW-to-MZ fields
2. adjust bathymetry to MZ
3. make a model run of a length sufficient for tidal datums (e.g., 37 days)
4. extract tidal datum values from analysis of time series at each node
5. compare new and previous MLLW, MLW, MHW, MHHW fields
6. if differences exceed allowable values, generate new MLLW- and MLW-to-MZ fields, then return to step 2. If not, finish

An initial set of runs (steps 1 through 6) is made to check for stability. If the water levels do not settle into the repetitive semidiurnal tidal pattern, all inputs must be examined. After the model stability has been established and adjustments have been made to the model grid and input parameters to produce the best matches to the station data, the model is ready for the final set of iterative runs. The final set of runs will produce the tidal datum fields. Hopefully, through good initial adjustments, the model results match closely with the tidal datums at the NOS stations, but since the model disregards meteorological effects, the model results will never exactly match the data. At this point the final adjustments can be made using the method described in Section 4.3.4.

4.2.5. Constructing the Tidal Datum Fields

For a model run of 37 days (5 days of spin-up, with the last 32 days being analyzed), the tidal datums are extracted from the 6-minute water levels at each node. The datums are computed by the Fortran program `lv.f` (see Appendix C). Analysis of past results indicate that, once the model has stabilized, the computed datums after 60- and 90-day runs show little difference.

The above approach yields datum fields from a small set of relatively short model runs. Another approach, which requires longer model runs, is based on extracting the harmonic constants from the water level time series. Once the HCs are known, the harmonic constant database method (Section 4.3) can be used. Table A.1 (Appendix A) describes the length of a time series needed to separate each constituent.

4.2.6. Wetting and Drying

The extraction of tidal datums from a hydrodynamic model-generated time series is complicated if there are shallow regions in the grid domain that are ‘wet’ (i.e., have appreciable water) but that occasionally go ‘dry’ (i.e., the water depth drops to or below some minimum, user-defined value, h_0) during part of the tidal cycle. When this happens, the node is temporarily removed from the computations until the water from adjacent nodes is high enough to flood the element and for the node to become wet. During this time, the water level at the node is given an artificial value (-9999.0) in the output file. A related condition, ‘ponding’, occurs at nodes that are isolated from the larger body of wet nodes and the node's water level, although not small enough to go dry, remains constant for several timesteps because no water is flowing into or out of the cell. Since the water level at the node is prevented from falling below a certain level and is thus artificially altered, it is important to understand that the attempted calculation of the mean water level and other tidal datums cannot yield valid values.

Although simple in concept, the occurrence of drying or ponding is not always easy to determine from the time series record. As explained in Appendix C, the computer program that extracts the tidal datums, `lv.f`, will not return valid datum values if the default value is detected or one or more of several conditions are not met. These include the requirement that the minimum water depth is greater than h_0, the difference between the maximum and minimum value in the series is above a user-defined number, and that the number of consecutive repeated values of water level (during low tide) is below a small, user-defined number. When these conditions are not met, a set of default datum values (either 9.999 or 0.0) is returned.

Model nodes representing the shallows where no valid datums are generated are not used in the population of the marine grids (Section 5.2). However, some estimate of MLW and MLLW must be made so that the bathymetric data can be adjusted to MZ. This normally accomplished by 'paving', wherein values are filled in an iterative process. At each iteration, an unfilled node is filled by the mean value of the nodes in the cells surrounding the node, providing the surrounding node was not filled at the present iteration.

4.2.6. Final Corrections to Match Published Datums

The standard approach to error analysis is a comparison of predicted tidal datums with those based on observed water levels. The comparison can include RMS and maximum error for the MHHW, MHW, MLW, and MLLW datums. The error is defined here as the value based on the model minus the value from the observations.

Using the results of the error analysis, the datum fields can be 'corrected' by interpolation with TCARI (see Section 4.4). In the application of TCARI, the error values are interpolated over the domain to produce a smooth error field. When this field of error (model minus observation) for a particular datum is subtracted from the original modeled field, it will exactly match the values at the water level stations.

4.3. HARMONIC CONSTANT DATABASES

Data from harmonic databases are used to generate time series from which datums are computed, and also to provide boundary conditions for the hydrodynamic models.

4.3.1. Overview

The second method of creating a tidal datum field is by extracting tidal datums from water level time series generated by the harmonic constants for specific geographic locations saved in a database. The harmonic constants usually are produced by a hydrodynamic model and values were saved at grid nodes. Creating tidal datum fields from a pre-existing harmonic constant database is a relatively easy process, but depends on the availability and accuracy of the underlying hydrodynamic model. The inputs for this method are the hydrodynamic model harmonic constants and a matching model grid from a previously-developed model. The harmonic constant data is reconstituted into water level time series. The highs and lows are picked off of these time series and used to calculate the datum values. As the harmonic constants are listed at the nodes of the grid, the datum values are given at the nodes, as well. NOS's Center for Operational Oceanographic Products and Services (CO-OPS) publishes datum values based on water level time series that include meteorological effects. Also, the harmonic constant databases often have less than the 37 main NOS constituents (Table A.1, Appendix A). Therefore, the results from a strictly astronomical reconstruction of the water levels will never exactly match the NOS tide gauge datums, and the tidal datum fields derived from the harmonic constant database will need to be corrected. This is done using TCARI to spatially the error between the modeled datums and the NOS tide gauge data. The spatial interpolation of the error is applied to correct the modeled results to insure that the final datum values match the NOS tide gauge data.

Although this method is relatively easy and the datum fields reflect the general hydrodynamic characteristic of the region, the model grid is predetermined so there is no opportunity to change the model domain or increase spatial resolution of the solution nodes. An example of the use of this method is with the creation of the Strait of Juan de Fuca VDatum files (Spargo et al., 2006).

4.3.2. Methodology

This method is based on generating a water level time series using a set of harmonic constants, extracting the high and low waters, and finally computing the tidal datums. The harmonic constants are inserted into a water level prediction equation such as (4.2) to generate a time series.

$$H = h_o + \sum f_n A_n \cos(\omega_n t + [Vo + u]_n - \kappa_n) \tag{4.2}$$

Here H is the total water level, h_o represents a constant offset (here taken to be zero), and the remaining term represents the astronomical tide. The lunar node factor is f_n, A_n is the constituent amplitude, ω_n is the constituent speed, t is the time relative to some reference time, $[Vo + u]_n$ is the equilibrium angle, and κ_n is the phase relative to Greenwich time. A set of such constants is shown in Table 4.1.

The program `adcdf2datum_mpi.f90` was created to generate tidal datum fields from an HC database. For the simulation of water levels, a specific 19-year time period is selected, and a series is generated with a 6-minute interval. From this series, for each tidal day the high and low water level values are extracted and saved and the higher highs and lower lows are identified. The means are then computed from the daily values. The database must be in netCDF format.

Table 4.1. Sample of tidal constituents and their harmonic constants.

Constituent	A_n , Amplitude (m)	κ_n, Phase (deg)
K_1	0.091433	177.978
O_1	0.068979	191.636
Q_1	0.012528	177.459
M_2	0.408000	351.313
S_2	0.074515	10.154
N_2	0.096141	336.247
K_2	0.017007	16.020

4.3.3. Available Databases

Typically, existing databases contain, for each grid node, a set of harmonic constants for a number of constituents. For the East Coast and the Gulf of Mexico, the two best shelf-scale model results currently available are the East Coast Inversion model (Myers, unpublished) and the EastCoast2001 model (Mukai et al., 2001). The Inversion model generally provides more accurate forcing, but each model should be examined for a given region. An older version of the East Coast model results, EC1995 (Scheffner, 1994) is available, as are the model results for three eastern north Pacific shelf-scale models (ENPO, ENPAC 2003, and the North Pacific Assimilation; see below) and for the central North Carolina region (Hess et al., 2005). Additional data are available from several global databases (see Appendix D). The databases are summarized in Table 4.2, and a plot of the regions covered by the models is shown in Figure 4.2.

Table 4.2. Tidal databases available in CSDL. NC is the number of harmonic constants.

MODEL	DIRECTORY	TIDAL DATA FILE	GRID FILE	NC
East Coast 2001	ec2001	ec2001.tdb	ec2001.grd	9
East Coast 2001, NOS	ec2001_nos	ec2001_NOS.tar.gz	ec2001.grd	37
East Coast 1995	ec1995	ec_95d.tdb	ec_95d.grd	7
East Coast Inversion	Edinv			
Western North Atlantic Inversion	WNATInv	fort.53	fort.14	15
Coastal North Carolina	northcarolina	nc19r04.tdb	nc19d_final.grd	37
Eastern North Pacific Inversion (ENPO)	enpo_ed	enpo.tct	enpo_ll.gr3	37
North Pacific Assimilation	Foreman	mf_fort.53	mf.grd	8
ENPAC 2003	Enpac	enpac2003.tdb	enpac2003.grd	10
Global Tides	Leprovost	(constituent).legi	-	13

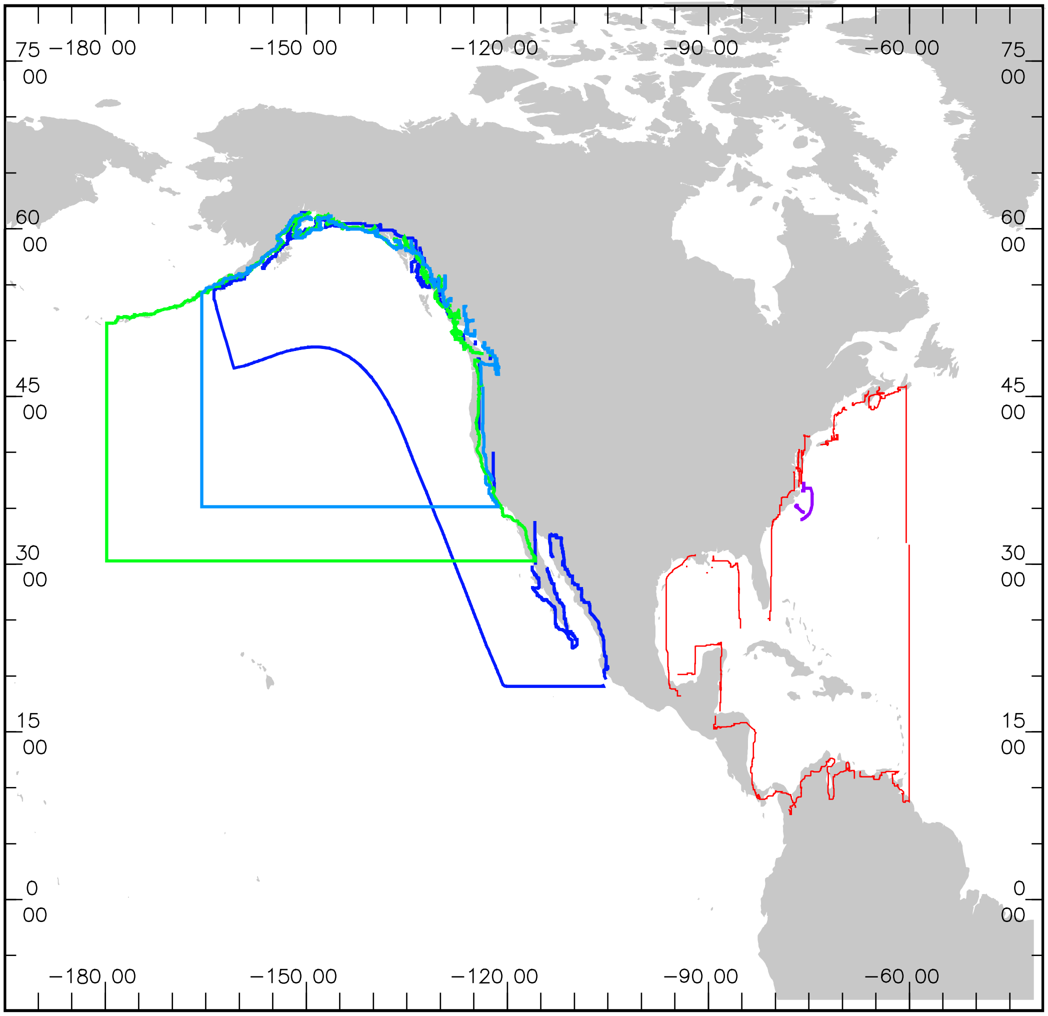


Figure 4.2. Areas covered by tidal databases available in CSDL. The East Coast 2001 grid boundaries are shown in red, the North Carolina boundary in purple, the ENPAC in dark blue, the ENPO in light blue, and the Foreman in green.

For the west coast, three shelf-scale models are available. These are the Eastern North Pacific model ENPAC2003 (Spargo et al., 2004), the Northeast Pacific Assimilation model (Foreman et al., 2000), and the Eastern North Pacific Inversion model (Myers and Baptista, 2001). The Northeast Pacific Assimilated model does, in general, provide more accurate results.

There are other global tide models whose output may be available. In addition, CSDL has developed nowcast/forecast models for many coastal regions, and harmonic constants may be available for some of them.

4.3.4. Final Corrections to Match Published Datums

Final correction is as described in Section 4.2.6.

4.4. SPATIAL INTERPOLATION

4.4.1. Overview

The third method of creating a tidal datum field is by spatially interpolating datum values at water level stations. Currently, all spatial interpolation of tidal datums is done using the Tidal Constituent And Residual Interpolation (TCARI) program (Hess, 2002). This program solves the Laplace Equation taking landforms into account. The most recent version solves equation using the finite element method. This program requires an unstructured, triangulated grid and an array of tidal datum data as input. The program computes a tidal datum field with information at the nodes of the unstructured grid and it matches the input datum data at those locations.

Note that this method is presently used primarily to generate the datum error fields that are used to correct the hydrodynamic modeled fields (Figure 4.3).

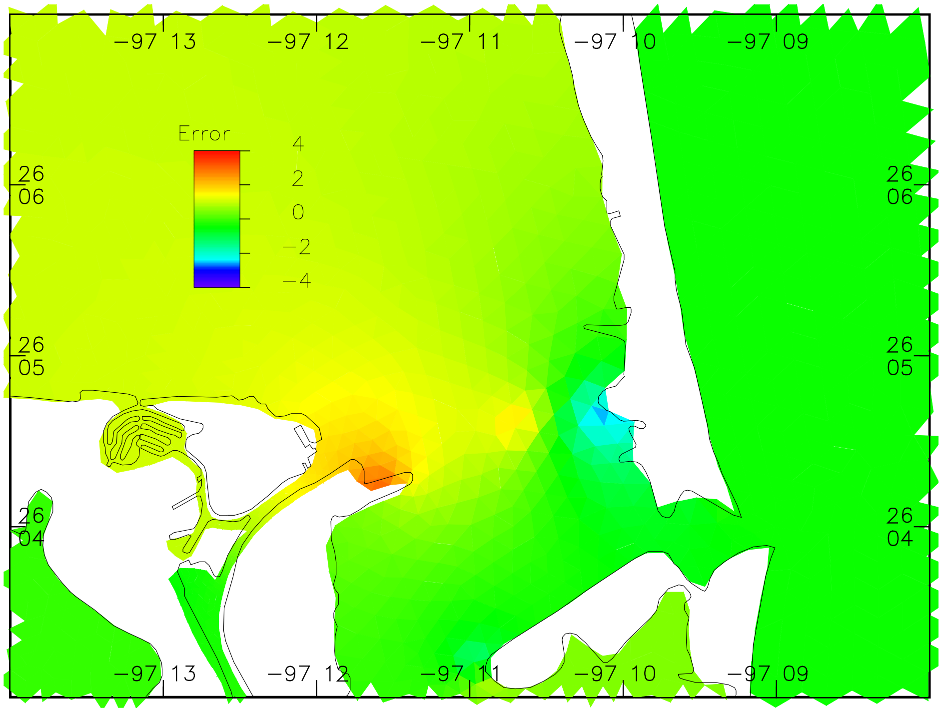


Figure 4.3. Error field (cm) for MLLW in a portion of Laguna Madre, Texas.

This method of creating tidal datum fields works best with a dense and evenly distributed array of tide gauges in a bay. The spatial interpolation does not solve the shallow water equations, and therefore does not reflect the actual hydrodynamics of the region, but with a dense network of tide gauges this method can do a good job of creating accurate tidal datum fields. The fields exactly match the tidal datum values at the gauges and the method is more advanced than traditional tidal zoning work in that it does not create discrete and sometimes discontinuous boundaries. An example of the use of this method is the creation of the Puget Sound VDatum files (Hess and White, 2004).

4.4.2. How TCARI Works

TCARI creates a two-dimensional field by interpolating values at water level stations. The values can represent either tidal datums or errors in tidal datums. If the value at each station represents the error, then the error field can then be added to the computed field to create an updated field. Suppose that f represents the interpolated field, and F_i represent values at water level stations. Then the TCARI interpolated field satisfies the Laplace Equation

$$\nabla f = 0 \tag{4.3}$$

and f is subject to the boundary conditions

$$\frac{\partial f}{\partial n} = \alpha \overline{\frac{\partial f}{\partial n}} \tag{4.4}$$

where n is the outward normal direction, α is a constant, the overbar denotes spatial averaging (of nearby values), and at water level stations

$$f(x_i, y_i) = F_i\,. \tag{4.5}$$

The above set of equations can be solved on a rectangular grid mesh (finite difference version) or a triangular grid mesh (finite element version). Details of the method as applied on a rectangular mesh can be found in Hess et al. (1999) and Hess (2002, 2003a, 2003b). Note that, for numerical stability, the value of α must be limited as follows:

$$0 < \alpha < 1.0 \tag{4.6}$$

In practice, a value of α close to, but less than, 1.0 should be used. For both rectangular and triangular grids, a value of 1.0 was best in test cases that attempted to match the computed and analytic solutions in a simple region (Hess, 2002). For the simulation of tidal constituent phases on a rectangular grid representing Galveston Bay, a value of 0.90 was found to be satisfactory (Hess et al., 1999). The use of large values of α (0.9 to 1.0) produces solutions that have gradients that are approximately uniform through the region (which is the desired outcome), while small values of α (< 0.3) produce solutions that have large gradients close to the water level stations and much smaller gradients elsewhere.

4.4.3. How to Run the Python Version

The solution by TCARI has been programmed in a Python-language program that uses the elliptical equation solver Ellip2d. The input consists of an ADCIRC-formatted file containing the datum field and boundary specification, and a file containing the values or errors at the three nodes representing a tide station cell. The user specifies the maximum number of steps and the value of α.

A user’s guide for this application is in the planning stage.

5. GENERATION OF TIDAL MARINE GRIDS

The tidal datum transformations in the VDatum software are designed to relate each tidal datum to local MSL. These datums are MHHW, MHW, MLW, MLLW, MTL, and DTL. The VDatum software requires regularly spaced grids called "marine grids" that contain the datum information at the water nodes and null information at the land nodes.

5.1. CREATION OF THE VDATUM MARINE GRID

The VDatum marine grid for a specific region consists of points with uniform spacing in the longitude and latitude directions. Points designated as water are populated by tidal datum or TSS conversion values, while other points are designated as land and given the default, or null, value of -88.8888. The datum values are spatially interpolated to the points in the marine grid.

It is important to note that, in the VDatum software, the final datum conversion values at any geographic point within the marine grid are determined by a distance-weighted average of the datum values at the surrounding four points (see Section 1.2). Therefore, if even one of the four surrounding points is non-null, a datum value will be returned. Hence, the marine grid's point spacing puts a limit on the size of geographic features that can be recognized.

The locations of the points in each marine grid are defined by the geographic coordinates of the origin (i.e., the most southwesterly point), the latitude and longitude spacing between points, and the maximum number of points in the eastward and northward directions. The grid origin is at $latitude_0$ and $longitude_0$, and extends to $latitude_1$ and $longitude_1$. The longitudinal spacing between points is *delx*, and the latitudinal spacing is *dely*. The VDatum grid consists of points as defined by

$$longitude_i = longitude_0 + (i - 1)delx \tag{5.1}$$

$$latitude_j = latitude_0 + (j - 1)dely \tag{5.2}$$

where the index *i* denotes longitude and index *j* denotes latitude. The range of *i* is 1 to *imax* and the range of *j* is 1 to *jmax*, where

$$imax = 1 + (longitude_1 - longitude_0)/delx \tag{5.3}$$

$$jmax = 1 + (latitude_1 - latitude_0)/dely \tag{5.4}$$

In the GTX files, the longitude is always positive; for western hemisphere (i.e., negative) longitudes, this condition can be met by adding 360 deg to $longitude_o$. Also, for higher precision, it is desirable that the latitude and longitude limits be rational numbers and integral multiples of *delx* and *dely*, and that the reciprocals of *delx* and *dely* be integers. The preferable spacing of grid points is on the order of 0.1 nautical miles, which corresponds to a *dely* value of 0.0020 deg (1/500 deg) or 0.12 nautical miles. Width will change with latitude, but for a *delx* of 0.0025 deg (1/400 deg), values range from 0.136 nmi in south Florida (latitude 25 deg) to 0.098 nmi in northern Washington (latitude 49 deg).

The final marine grid specifies each point in the domain as simply water or land. The tidal datum transformations can only be computed on the water points. (Attempted transformations at a point surrounded by "land" will result in an error message from the VDatum software.) In the grid generating software (`vgridder.f`, Appendix C), points are determined to be water or land as follows. A rectangle is constructed around each marine grid point. This rectangle's bottom has a latitude equal to the mean of the latitude of the marine grid point and the point immediately to the south. Likewise, the top of the rectangle has a latitude equal to the mean the latitude of the marine grid point and the point immediately to the north. The sides of the rectangle have longitudes that are determined similarly. Then, several points along each of the four sides (at present, points located at intervals of one tenth the length of the side) are tested. If any of these points lies in water, the marine grid point is set to water; otherwise, the point is set to land.

In the final marine grid, therefore, the water cells will cover some of the land area, as shown in Figure 5.1.

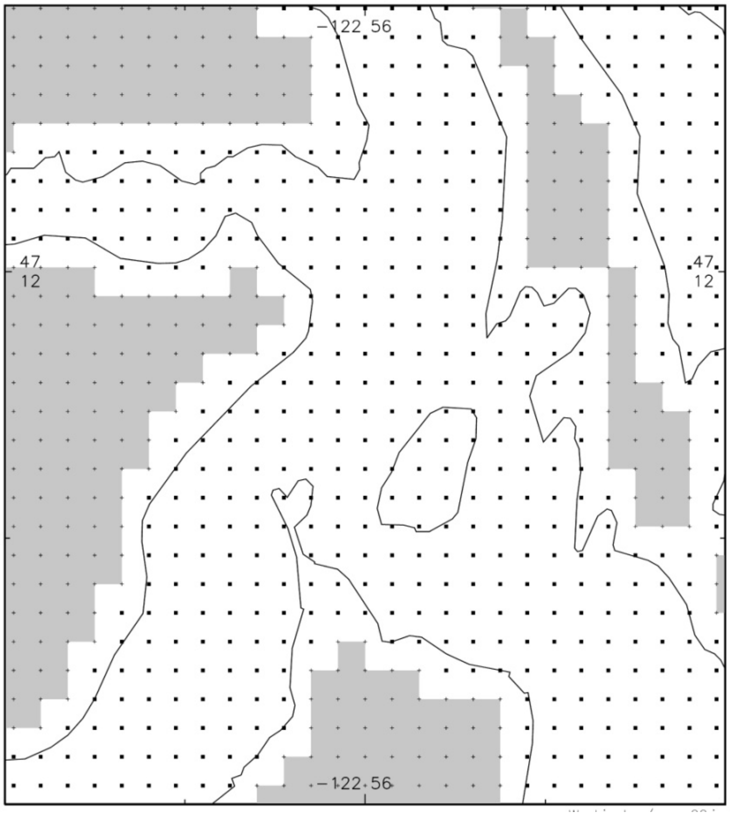


Figure 5.1. Final marine grid showing land (gray) and water areas (white). Water areas consist of rectangles with at least one active (i.e., non-null) VDatum point (small dark squares) at a corner.

Note that for any one marine grid, its use by VDatum has two requirements:

- only geographic locations that lie on or within the outer bounds of the marine grid (as defined by ***latitude$_0$*** and ***longitude$_0$, latitude$_1$*** and ***longitude$_1$)*** will return a number interpolated from the mesh, and

- if a marine grid exists for an adjacent area, continuity dictates that the adjacent marine grid must either (a) have an identical border latitude or longitude, or (b) overlap the new marine grid. For the case of overlapping grids, the bounding polygon will determine which mesh is to be used.

5.2. POPULATION OF THE VDATUM MARINE GRIDS WITH TIDAL DATUMS

The water points of the VDatum marine grid are populated with the tidal datum information interpolated from the final tide model results using the program `vpop.f` (Appendix C). The tide model results, which include seven tidal datum fields (MHHW, MHW, MSL, DTL, MTL, MLLW, and MLLW), are output on either an unstructured (e.g., ADCIRC) grid or a structured (e.g., TCARI) grid.

For an unstructured grid, the program examines each water point in the marine grid, then searches the unstructured hydrodynamic model grid for the closest two nodes. (Recall that each element is defined by three nodes, and each node is the vertex of one or more elements.) If the water point lies within one of the elements surrounding the closest node, the datum value is computed by an interpolation of the three values at the nodes. Otherwise, the same procedure is applied to the second closest node. Note that for the selection of the two closest nodes, only nodes lying within the bounding polygon (BP) are examined, provided a BP is specified; if a BP is not specified, all nodes are searched. Also, if a node in a surrounding element is outside the BP but at least one node of that element is inside the BP, then all nodes are used for the interpolation. Finally, if at least one node in the element has the default value (-88.8888), signifying that no datums could be computed, the element is not used for interpolation.

If the marine grid point lies outside all unstructured grid elements, the datum value is computed by an inverse-distance weighted mean of the surrounding non-null values in the marine grid. However, if the closest node in the unstructured grid has the default value, the grid is not filled.

For a structured final tidal model grid, the marine grid value at water points is determined by an inverse-distance-squared weighting of the surrounding non-land values. Since at present, hydrodynamic models are routinely used to generate tidal datum fields, this approach is rarely used.

5.3. ERROR ANALYSIS

The final tidal datum results as represented on the VDatum marine grid must be checked in several ways. First, the data are checked against tidal datum station information to confirm that the datums match at the stations. The average root mean square (RMS) error at each station should be small (e.g., less than 1 or 2 cm. This comparison is carried out by the program `test_msf.f` (Appendix C). The program reads the master station file originally used to construct the datum fields and creates a table of errors.

A second test using the program, `test_sta.f` (Appendix C), compares data in the GTX files with that in the CO-OPS spreadsheet. In the future, this program will be modified so that the datums in the GTX files exactly match those in the CO-OPS spreadsheet.

If there are adjacent tidal datum grids, there must be a check for continuity of values across the common boundaries. This is done with program `test_cont.f` (Appendix C).

6. GEODETIC DATUM MODELING

The National Geodetic Survey (NGS) supports the VDatum program through the creation of the ellipsoidal and orthometric datum transformations and the geoid models that transform between NAD 83(86) and NAVD 88 and the topography of the sea surface (TSS) model to transform between NAVD 88 and LMSL.

6.1. ELLIPSODIAL DATUMS

There are many reference ellipsoids to select from in the VDatum software. Elevations referenced to an ellipsoidal datum which is not NAD 83 can be translated to NAD 83 by Helmert transformations. Each transformation is accomplished with three translations (along the X-axis, Y-axis, and Z-axis), three rotations (around the X-axis, Y-axis, and Z-axis), and a scale change between the two reference frames. These transformations and their values are coded into the VDatum software and do not need to be generated for each new VDatum region. More rigorous approaches to these datum transformations could include a time-dependent component, but it was determined that the typical VDatum user would not have access to the metadata describing the times used to establish positioning, and thus would not need the final time-dependent transformations (Milbert, 2002). However, if the time-dependent transformations are necessary, NGS' full Horizontal Time Dependent Positioning software can be used (Snay, 1999).

6.2. ORTHOMETRIC DATUMS

The current official vertical orthometric datum for the United States is the North American Vertical Datum of 1988 (NAVD 88). This datum is based on an adopted elevation at Father's Point, Rimouski, Québec. Also in this sub-category of datums is the superseded National Geodetic Vertical Datum of 1929 (NGVD 29). The translation between NAD 83 and NAVD 88 is accomplished by using a geoid model. A geoid is an equipotential surface, that is, a surface to which the gravity vector is everywhere normal and which has a constant gravity value; this surface approximately represents the global mean sea level. The models in use by NOAA are Geoid99, Geoid03, Geoid06, and the most recent Geoid09. In VDatum, conversion is by use of the gridded files such as `g03.gtx` and `g09.gtx`.

Transformations between NAVD 88 and NGVD 29 are performed by interpolation of the VERTCON 2.0 vertical datum grid (`vcn.gtx`). More detail on the VERTCON model can be found in http://www.ngs.noaa.gov/TOOLS/program_descriptions.html#VERTCON. Conversion in VDatum is by use of the gridded file `vcn.gtx`.

The readjustment of the North American Datum of 1927 (NAD 27), the old Hawaiian Datum, and the Puerto Rico Datum to the North American Datum of 1983 (NAD 83 (1986)) in July 1986 was both a change in reference ellipsoid and a "clean up" of nearly 200 years of surveying data held by NGS. Based on this readjustment and redefinition, positions of points can change between 10 and 100 meters in the conterminous United States; by more than 200 meters in Alaska, Puerto Rico, and the Virgin Islands; and in excess of 400 meters in Hawaii. In VDatum, bi-quadratic interpolation is used to interpolate the NADCON horizontal datum transformations in files `ncla.gtx` and `ncla.gtx` (http://www.ngs.noaa.gov/TOOLS/Nadcon/Nadcon.shtml).

6.3. TOPOGRAPHY OF THE SEA SURFACE (TSS) MODELS

NGS has the responsibility of creating the topography of the sea surface (TSS) grid for the VDatum region. This grid provides the spatial variations between a mean sea-level surface and the NAVD 88 geopotential surface. A positive value specifies that the NAVD 88 reference value is further from the center of the Earth than the local mean sea-level surface. In VDatum, the data are saved in file `sst.gtx`.

Tidal benchmark elevation information is obtained through the Tidal and Orthometric Elevations tool located on the NGS Geodetic Tool Kit (http://www.ngs.noaa.gov/TOOLS/). Tidal data is obtained from CO-OPS database (http://tidesandcurrents.noaa.gov). All data for both methodologies are based on the most recent NTDE (1983-2001).

6.3.1. Methodology for Creation of the TSS Grid

At each NGS benchmark location, there is a set of TBM_{datum} values, which is the elevation at the Tidal Benchmark of a datum relative to MLLW (i.e., Datum – MLLW). Also, from the four tidal datum grids (see Section 5), there is a set of VD_{datum} values, which is the difference between the tidal datum and MSL (i.e., Datum – MSL).

The first step is the computation of four residuals. The residual, R, for each datum is defined as:

$$R_{datum} = TBM_{navd88} - TBM_{datum} + VD_{datum} \qquad (6.1)$$

Note that the VD values are interpolated to the location of the benchmark. The four residuals at the benchmark are averaged to produce the mean. Note that this mean is an estimate of the quantity (MSL – NAVD88).

Next, a gridded sea surface topography field is generated. The mean residuals at all benchmarks are merged with values of the quantity (NAVD88 – MSL) at CO-OPS' water level stations to produce input data for contouring. A mesh covering the entire area of benchmarks and water level stations with a spatial resolution similar to that of the tidal marine grids is created. Breaklines are inserted to represent the influence of land. A sea surface topography field is generated using the Surfer© software's minimum curvature algorithm to create a surface that honors the data as closely as possible. The maximum allowed departure value used is 0.0001 meters. To control the amount of bowing on the interior and at the edges of the grid, an internal and boundary tension value of 0.3 is utilized. Once the gridded topography field has been generated, null values are obtained from the marine tidal grids and are inserted to denote the presence of land.

Then a set of 'Delta' values are computed. Delta represents the difference between the observed tidal datum and the datum as computed by the gridded fields. If S represents the value of the quantity NAVD88 – MSL obtained from the topography of the sea surface grid, then Delta (D) for each tidal datum is computed as:

$$-D_{datum} = TBM_{navd88} - TBM_{datum} + VD_{datum} - S \qquad (6.2)$$

The averaged Delta at each benchmark should be less than 0.01 m. If it is not, the input data and grids are checked, appropriate changes are made, and the Deltas are recomputed until the criterion is met.

6.3.2. Quality Control and Error Analysis of the TSS Grid

Quality control is carried out by comparing observed benchmarks values to those predicted. After the TSS is created, it is incorporated into VDatum. For the first test, conversions between NAVD 88 and the tidal datums MLLW, MLW, MHW, and MHHW at tidal benchmarks were computed. All Delta values are tabulated and examined.

For the second test, the mean differences between known NAVD 88 to MSL values and those predicted by VDatum is computed. The mean is examined and evaluated.

7. INTEGRATION WITH THE VDATUM TOOL

7.1. HOW VDATUM WORKS

As discussed in Section 1.3, the transformations between the tidal datums and between LMSL and the NAVD 88 surface are performed by interpolation of gridded data. These files have the extension `.gtx`. The set of gridded data files must be generated for each separate region, and they are listed in Table 7.1.

Table 7.1. Gridded data files for a single region of VDatum with names in the standard format. The Type indicates whether the file contains null values denoting land (Tidal) or contains all non-null values (Geodetic).

NAME	DESCRIPTION	TYPE
dtl.gtx	Diurnal tide level	Tidal
gNN.gtx	Geoid model, GeoidNN	Geodetic
mhhw.gtx	Mean higher high water	Tidal
mhw.gtx	Mean high water	Tidal
mllw.gtx	Mean lower low water	Tidal
mlw.gtx	Mean low water	Tidal
mtl.gtx	Mean tide level	Tidal
ncla.gtx	NADCON latitude shifts	Geodetic
nclo.gtx	NADCON longitude shifts	Geodetic
tss.gtx	Sea surface topography	Tidal
vcn.gtx	VERTCON 2.0 vertical shifts	Geodetic

7.1.1. Development of the Datum Transfer Files

The gridded data contain values at equally-spaced locations in a rectangular coordinate system, which is defined by an origin (latitude and longitude), horizontal and vertical spacing, and number of rows and columns. The tidal model grids (`dtl.gtx, mhhw.gtx, mhw.gtx, mtl.gtx, mlw.gtx, mllw.gtx, and sst.gtx`) contain values of the difference between the datum and MSL, where positive values denote that the datum is above MSL. The tidal grids contain null values that represent the presence of land. The Geodetic grids (`gNN.gtx, ncla.gtx, nclo.gtx,` and `vcn.gtx`) contain no null values. The North American Datum Conversion (NADCON) grid is a subset of data used on the NGS website (http://www.ngs.noaa.gov/cgi-bin/nadcon.prl) for horizontal datums. VERTCON computes the difference in orthometric height between NAVD 88 and NGVD 29.

The conversion value at any location is determined by interpolation using the surrounding values. For the godetic grids, a set of nine points are used with a bi-quadratic interpolation (Figure 7.1).

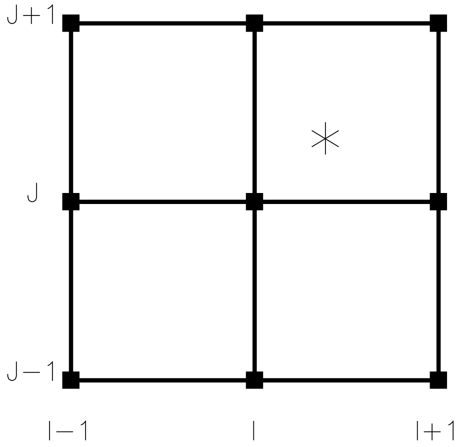


Figure 7.1. Location of the nine VDatum points used for interpolation on the geodetic grid to a point (*). Points with indices I-1, I, and I+1, and J-1, J, and J+1 are used. If, for example, the column I+1 is outside the grid, then column I-2 is used (i.e., I-2, I-1, and I); and similarly for J.

For points in the tidal grid, two methods are used. If the four surrounding VDatum points are non-null, bilinear interpolation is used. If one to three points are a null value, inverse-distance-squared weighting is used for the non-null values (Figure 7.2).

Figure 7.2. Location of the four points used in the interpolation of tidal data to a point (*). For the left rectangle (a), the four values are non-null (filled squares), so the bilinear interpolation method is used. For the right (b), since one of the values is null (open square), an inverse-distance-squared weighting method is used.

Each GTX file has the same format. The first record contains the origin (latitude and longitude), the uniform horizontal and vertical spacing, and the number of rows and columns. The remaining records contain the conversion values (in meters), with the value -88.8888 representing the null value. For the tidal datums, the conversion value is added to MSL to get the tidal datum value. For the topography of the sea surface file, the conversion value is added to MSL to get NAVD 88. A sample of the Delaware data is shown in Figure 7.3. Notice that the origin longitude, 284.5, is a positive value obtained by adding 360 deg to the mathematical longitude value of -75.5. Presently, the data are stored in binary format.

```
38.7500000  284.5000000  0.0187500 0.0222222222222   41   31
-88.8888
-88.8888
  0.3897
  0.3893
-88.8888
-88.8888
(etc)
```

Figure 7.3. Sample ASCII GTX file. Values in the header line are Y0, X0, DY, DX, JMAX, and IMAX. The records that follow contain the datum transfer values, with -88.8888 being the null value.

For an origin at (*X0, Y0*), a grid spacing of *DX* and *DY*, and *IMAX* columns and *JMAX* rows, the header line is: *Y0 X0 DY DX JMAX IMAX*

Also, the longitude of any point I in the grid is

$$X = X0 + (I-1)DX \tag{7.2}$$

and the longitude of point J is

$$Y = Y0 + (J-1)DY. \tag{7.3}$$

If N is the number of the record past the header line, then

$$I = 1 + MOD(N-1,IMAX) \tag{7.4}$$

$$J = 1 + (N-1)/IMAX \tag{7.5}$$

and

$$N = I + (J-1)IMAX. \tag{7.6}$$

For more accurate interpolation, the vertical and horizontal spacing should both be approximately 0.1 when converted to nautical miles.

7.1.2. Datum Transfer Files in Adjacent Regions

The set of GTX files shown in Table 7.1 applies to a single VDatum region. The use of the marine grid restricts the individual VDatum region to the area within the latitude-longitude rectangle defined by the six parameters described above. When a specific conversion is requested and a location outside the rectangle for that GTX file is entered into the VDatum software, a default value of −999999.0 is returned. The default value is also returned if the location is within the rectangle but on land and the requested conversion involves a tidal or TSS datum.

7.2. ACCEPTANCE PROCEDURES FOR NEW DATA FILES

7.2.1. Working Directory

After the tidal datum GTX files have been developed by CSDL and the geodetic GTX files have been developed by NGS, these files are ready for integration. First, a temporary subdirectory is created in the VDatum archive (Appendix B). Then, all 11 of the GTX files (i.e., the `mhhw.gtx, mhw.gtx, mlw.gtx, mllw.gtx, dtl.gtx, mtl.gtx, gNN.gtx, ncla.gtx, nclo.gtx, tss.gtx`, and `vcn.gtx`) are loaded on that directory, as are the bounding polygon and the `msf` files.

7.2.2. Testing

At this time the GTX files must be tested. The approach here is to use a sequence of tests, performed in order, that inspect the data in the working directory (Section 7.2.1) for validity. The files must pass each step in the testing sequence before going on to the succeeding test. All 12 files for each bounding polygon must be tested. Programs mentioned below are saved in the P (programs) subdirectory of the VDatum Archive (Appendix C); use the most recent version of each program. It is recommended that the developer perform these tests during the creation of the GTX files, and that a second person perform the tests after the GTX files have been transferred to the working directory. The person carrying out the final tests should keep notes and prepare a short write-up of the tests performed, the results, and any problems encountered.

Polygon Test - The first test is for compatibility of the area wthin the GTX grid and the bounding polygon. That is, program `test_poly.f` inspects each GTX grid to insure that it completely covers the area within the bounding polygon. That is, the bottom row must have a latitude that is below the lowest point in the bounding polygon, the uppermost row must have a latitude that is above the topmost point in the bounding polygon, and so on. Otherwise an input location may request a grid mesh that does not contain any datum transfer data. If the files do not pass this test, either the bounding polygon or the GTX mesh, or both, must be corrected before any subsequent tests can be performed.

Overlap Test - The second test is for potential overlap of bounding polygons using the program `test_ovlp.f`. This program checks each vertex in a bounding polygon to see whether it falls within another bounding polygon. Note that vertices are allowed to lie upon the side of another polygon, or to coincide with another vertex. There should be no overlap between polygons, but they may share sides.

Station Datums Test - The next test is for compatibility with the official tidal datums at each water level station in the VDatum region. This is accomplished using the program `test_sta.f`, which reads the entire U.S. file from CO-OPS. The program will compare the value of the tidal datum obtained by interpolation from the VDatum GTX files with the corresponding value from the observations. If there are significant mismatches between the GTX values and the datums at tide stations, then the GTX files should be regenerated.

Continuity Test - This test applies when a new region is adjacent to another VDatum region, or more specifically, when the bounding polygon of the new region has any side in common with the bounding polygon of an existing region. Here the program `test_cont.f` is used to compare transformations across the water regions of interface between the two regions.

Tidal Order Test – In this test, values of the tidal datums at each non-null point in the GTX file are examined to determine whether the magnitudes are in the logical order; i.e., whether the MHHW value is greater than the MHW value, the MHW value is greater than the MLW value, and the MLW value is greater than the MLLW value. The number of occurrences of situations where the order is not as it should be is reported.

7.2.3. Transfer to the Web

Following the passing of all tests and the approval of the Team Leader, the files can be uploaded to the VDatum website. The standard procedures for modifying the OCS website will be adhered to. Once transferred, these files should be tested again [procedure to be developed]. Project team members, administrators, and potential users should be notified of the operational status of the new VDatum region.

7.2.4. Updating the Archive

Once the region becomes operational, a new permanent subdirectory should be created and the appropriate files saved therein. New subdirectory names have a standard, 10−character format. The general format is

SSaaaaaaNN

where SS is the two-character postal zip code for the primary state covered by the VDatum region, aaaaaa is a six-character string that further defines the region (such as ‘ncentr’ for north central), and NN is a two-digit number specifying the version number of the data files. Existing directories are shown in Appendix B, Table B.1.

7.3. UPDATES TO VDATUM

The most recent tidal data is contained in the CO-OPS spreadsheet (Section 3). All U.S. stations have been updated to the most recent NTDE, 1983 – 2001. Occasionally, station datums are re-computed or station position data are updated by CO-OPS. When informed of these changes by CO-OPS, CSDL will examine existing VDatum data files and determine whether a revision is needed. Also, sea surface topography may change due to sea level rise or land subsidence or rebound, so the NAVD 88-to-LMSL data need to be monitored by NGS and CO-OPS.

8. FUTURE DIRECTIONS

Several areas of potential improvement to VDatum are under consideration at NOS. They include:

Updating the Web Interface – Examining different ways to get data from the web, such as downloading data for each region vs. getting transformations via an interactive web site. In addition, expand the options for user selection of geoids, tidal epochs, etc.

Software Bridge over NAVD 88 – In some U.S. coastal waters, namely in the Hawaiian Islands and Alaska, the NAVD 88 datum has not been determined. It may be necessary to bridge this datum and translate directly between LMSL and NAD 83. A possibility is substituting a geoid or an ellipsoid for NAVD88 as part of the VDatum roadmap.

Uncertainty Estimates – Generate spatially-varying uncertainty estimates for each transformation, and save output in a GTX format. Provide an estimate of error for the requested transformation within the VDatum GUI.

Inland Coverage – For now, VDatum covers primarily coastal areas of the continental U.S. methods of expanding coverage landward to include non-coastal areas (i.e., where tidal datums would all be undefined) are being discussed.

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REFERENCES

Bodnar, A.N., 1981: Estimating accuracies of tidal datums from short term observations. Tides and Water Levels Division, National Ocean Survey, Draft Report, 44 pp.

Brennan, Lt. R. T., 2005: An Uncertainty Model for the Tidal Constituent And Residual Interpolation (TCARI) Method of Water Level Correction. M.S. Thesis, University of New Hampshire, Department of Ocean Engineering, Ocean Mapping Option. Durham, New Hampshire. 90 pp.

Coast and Geodetic Survey, 1952: Manual of Harmonic Constant Reductions. U.S. Department of Commerce, Coast and Geodetic Survey, Special Publication 260. 74 pp.

Dhingra, E. A., K. W. Hess, and S. A. White, 2008: VDatum for the Northeast Gulf of Mexico from Mobile Bay, Alabama, to Cape San Blas, Florida: Tidal Datum Modeling and Population of the Marine Grids . NOAA Technical Memorandum NOS CS 14, pp 64.

EPA, 2001: Guidance for Preparing Standard Operating Procedures (SOPs). Environmental Protection Agency, Office of Environmental Information, Washington DC. *Quality System Series* EPA/240/B-01/001.

Foreman, M.G.G., W.R. Crawford, J.Y. Cherniawsky, R.F. Henry and M.R. Tarbotton, 2000: A high-resolution assimilating tidal model for the northeast Pacific Ocean. *Journal of Geophysical Research*, 105(C12), 28629-28651.

Gesch, D. and R. Wilson, 2001: Development of a Seamless Multisource Topographic / Bathymetric Elevation Model for Tampa Bay. *Marine Technology Society Journal*, 35(4): 58-64, Winter 2001/2002.

Gill, S. K., and J. R. Schultz. Tidal Datums and Their Application. U.S Department of Commerce, National Oceanic and Atmospheric Administration, Special Publication NOS CO−OPS 1, 111 pp + Appendices.

Hagen, S.C., "Estimation of the Truncation Error for the Linearized, Shallow Water Momentum Equations", Engineering With Computers, 17, 354-362 (2001).

Hagen, S.C. and D.M. Parrish, "Meshing Requirements for Tidal Modeling in the Western North Atlantic," International Journal of Computational Fluid Dynamics, 18 (7), 585-595 (2004).

Hess, K. W., R. A. Schmalz, C. Zervas, and W. C. Collier, 1999 (revised 2004). Tidal Constituent And Residual Interpolation (TCARI): A New Method for the Tidal Correction of Bathymetric Data. *NOAA Technical Report* NOS CS 4, 99 pp.

Hess, K. W., 2000: Tidal Constituent And Residual Interpolation (TCARI): User’s Guide to the Programs. Unpublished Manuscript, 46 pp.

Hess, K. W, 2001: Generation of Tidal Datum Fields for Tampa Bay and the New York Bight. U.S. Department of Commerce, National Oceanic and Atmospheric Administration, Silver Spring, Maryland, *NOAA Technical Report* NOS CS 11, 43 pp.

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(2), 175-192.

Hess, K.W., 2003a: Water level simulation in bays by spatial interpolation of tidal constituents, residual water levels, and datums. *Continental Shelf Research,* 23(5), 395-414.

Hess, K. W., 2003b. Tidal Constituent And Residual Interpolation (TCARI): User's Guide to the Programs. Unpublished Manuscript, 48 pp.

Hess, K.H., D. G. Milbert, S.K. Gill, and D.R. Roman, 2003: Vertical Datum Transformations for Kinematic GPS Hydrographic Surveys. *Proceedings, U.S. Hydrographic Conference*, March 24 – 27, 2003. Biloxi, MS. 8 pp.

Hess, K.W., and S. K. Gill, 2003: Puget Sound Tidal Datums by Spatial Interpolation. *Proceedings, Fifth Conference on Coastal Atmospheric and Oceanic Prediction and Processes*. Am. Meteorological Soc., Seattle, August 6-8, 2003. Paper 6.1, 108 - 112.

Hess, K.W., and S. A. White, 2004: VDatum for Puget Sound: Generation of the Grid and Population with Tidal Datums and Sea Surface Topography. U.S. Department of Commerce, National Oceanic and Atmospheric Administration, Silver Spring, Maryland, *NOAA Technical Memorandum* NOS CS 4, 27 pp.

Hess, K.W., E. A. Spargo, A. Wong, S. A. White, and S. K. Gill, 2005 : VDatum for Central Coastal North Carolina: Tidal Datums, Marine Grids, and Sea Surface Topography. U.S. Department of Commerce, National Oceanic and Atmospheric Administration, Silver Spring, Maryland, *NOAA Technical Report* NOS CS 21, 46 pp.

Hess, K.W., and E.A. Spargo, 2006: TideSheet: an Astronomical Tide Database File. Unpublished manuscript.

International Hydrographic Organization, 1998. IHO Standards for Hydrographic Surveys. Special Publication No. 44, 23 pp.

Luettich, R.A., J.J. Westerink, and N.W. Scheffner, 1992: ADCIRC: an advanced three-dimensional circulation model of shelves, coasts, and estuaries, Report 1: theory and methodology of ADCIRC-2DDI and ADCIRC-3DL. *U.S. Department of the Army, Technical Report* DRP-92-6, XXp.

Luettich, R.A. and J.J. Westerink, 2004: Formulation and numerical implementation of the 2D/3D ADCIRC finite element model version 44.XX. (www.marine.unc.edu/C_CATS/adcirc).

Mojfeld, H. O., A. J. Venturato, F. I. González, V. V. Titov, and J. C. Newman, 2004: The Harmonic Constant Database Method: Options for Overcoming Datum Discontinuities at Mixed-Diurnal Tidal transitions. *Journal of Atmospheric and Ocean Technology,* v. 21, 95 – 104.

Milbert, D.G., 2002: Documentation for VDatum (and VDatum Tutorial); Vertical Datum Transformation Software. Ver. 1.06 (http://nauticalcharts.noaa.gov/csdl/vdatum.htm).

Mukai, A.M., J.J. Westerink, and R.A. Luettich, 2001: Guidelines for using the Eastcoast 2001 database of tidal constituents within the Western North Atlantic Ocean, Gulf of Mexico and Caribbean Sea. *Department of the Army Technical Note*, IV-XX.

Myers, E.P., and K. W. Hess, 2006:.Modeling of Tidal Datum Fields in Support of VDatum for the North and Central Coast of California. NOAA Technical Memorandum NOS CS 6, 15 pp.

Myers, E.P. and A.M. Baptista, 2001: Inversion for tides in the Eastern North Pacific Ocean. *Advances in Water Resources*, 24, 505-519.

Myers, E.P. (unpublished): Tidal Datum Inversion Model of the East Coast of the United States.

National Ocean Service, 2001: Tidal Datums and Their Applications. *NOAA Special Publication* NOS CO-OPS 1, 111 pp + appendix.

National Ocean Service, 2003: Computational Techniques for Tidal Datums Handbook. *NOAA Special Publication* NOS CO-OPS 2, 89 pp + appendix.

National Ocean Service, 2010: National Ocean Service Hydrographic Surveys Specifications and Deliverables, NOS Office of Coast Survey, 2010 Edition, 149 pp.

Parker, B. P., A. M. Davies, J. Xing, 1999: Tidal Height and Current Prediction. *Coastal and Estuarine Studies* 56, 277-327.

Parker, B.P., D. Milbert, R. Wilson, J. Bailey, and D. Gesch. (2001): “Blending bathymetry and topography: the Tampa Bay demonstration project.” *Proceedings, U.S. Hydrographic Conference 2001*, Norfolk, VA.

Parker, B. P., 2002: The integration of bathymetry, topography, and shoreline, and the vertical datum transformations behind it. *International Hydrographic Review* (3) 3 (November 2002).

Parker, B., K. W. Hess, D. Milbert, and S. K. Gill, 2003: A national vertical datum transformation tool. *Sea Technology*, v. 44. no. 9 (Sept. 2003), 10 - 15.

Scheffner, N. W., 1994. Tidal Constituent Database East Coast, Gulf of Mexico, and Caribbean Sea. U.S. Army Corps of Engineers, U.S. Army Engineer Research and Development Center, Environmental Laboratory. Dredging Research Program Technical Note DRP-1-13 , 13 pp.

Snay, R., 1999: Using the HTDP Software to Transform Spatial Coordinates Across Time and Between Reference Frames. *Surveying and Land Information Systems*, 59(1), 15-25.

Spargo, E.A., J.J. Westerink, R.A. Luettich, D.J. Mark, 2004: ENPAC 2003: A Tidal Constituent Database for the Eastern North Pacific Ocean. *Department of the Army Technical Note* TR-04-12.

Spargo, E.A., and J.W. Woolard, 2005: VDatum for the Calcasieu River from Lake Charles to the Gulf of Mexico, Louisiana: tidal datum modeling and population of the grid. U.S. Department of Commerce, National Oceanic and Atmospheric Administration, Silver Spring, Maryland, *NOAA Technical Report* NOS CS 19, 26 pp.

Spargo, E.A., K.H. Hess, and S.A. White, 2006: VDatum for the San Juan Islands and Juan de Fuca Strait with Updates for Southern Puget Sound: Tidal Datum Modeling and Population of the VDatum Marine Grids. U.S. Department of Commerce, National Oceanic and Atmospheric Administration, Silver Spring, Maryland, *NOAA Technical Report* NOS CS 25, 50 pp.

Swanson, R.L., 1974: Variability of Tidal Datums and Accuracy in Determining Datums from Short Series of Observations. U.S. Department of Commerce, National Oceanic and Atmospheric Administration, Silver Spring, Maryland, *NOAA Technical Report* NOS 64, 41 pp.

Tronvig, K.A., 2005: Near-shore Bathymetry. *Geospatial products and ecological applications. Hydro International*, (9)5, June 2005, pages 24-25.

Xu, J., E. P. Myers, and S. A. White (2010): VDatum for the Coastal Waters of North/Central California, Oregon and Western Washington: Tidal Datums and Sea Surface Topography. U.S. Department of Commerce, National Oceanic and Atmospheric Administration, Silver Spring, Maryland, *NOAA Technical Memorandum* NOS CS 22, pp 68.

Xu, J., E. P. Myers, and S. A. White (in preparation): VDatum for the Coastal Waters of Texas and West Louisiana: Tidal Datums and Sea Surface Topography. *NOAA Technical Memorandum*.

Yang, Z., E. A. Dhingra, K. W. Hess, A. Wong, E. P. Myers, and S. A. White, 2008: Vdatum for the Long Island Sound, Narragansett Bay, and New York Bight: Tidal Datums, Marine Grids, And Sea Surface Topography. U.S. Department of Commerce, National Oceanic and Atmospheric Administration, Silver Spring, Maryland, *NOAA Technical Memorandum* NOS CS 16. 61 pp.

Yang, Z., E. P. Myers, A. M. Wong, and S. A. White, 2008: VDatum for Chesapeake Bay, Delaware Bay, and Adjacent Coastal Water Areas: Tidal Datums and Sea Surface Topography. U.S. Department of Commerce, National Oceanic and Atmospheric Administration, Silver Spring, Maryland, *NOAA Technical Memorandum* NOS CS 15, pp 109.

Yang, Z., E. P. Myers, E. A. Dhingra, A. M. Wong, and S. A. White, 2009: VDatum for Southern California: Tidal Datums and Sea Surface Topography. U.S. Department of Commerce, National Oceanic and Atmospheric Administration, Silver Spring, Maryland, *NOAA Technical Memorandum* NOS CS 17, pp 59.

Yang, Z., E. P. Myers, A. M. Wong, and S. A. White, 2010: VDatum for Great South Bay, New York Bight and New York Harbor: Tidal Datums, Marine Grids and Sea Surface Topography. U.S. Department of Commerce, National Oceanic and Atmospheric Administration, Silver Spring, Maryland, *NOAA Technical Memorandum* NOS CS 21, pp 55.

Yang, Z., E. P. Myers, and S. A. White, 2010: VDatum for Eastern Louisiana and Mississippi Coastal Waters: Tidal Datums and Sea Surface Topography U.S. Department of Commerce, National Oceanic and Atmospheric Administration, Silver Spring, Maryland,. *NOAA Technical Memorandum* NOS CS 19, 56 pp.

Yang, Z., E. P. Myers, and S. A. White, (in preparation): VDatum for the Florida Shelf and the Southern Atlantic Bight: Tidal Datums, Marine Grid and Sea Surface Topography. *NOAA Technical Memorandum.*

Yang, Z., E. P. Myers, and S. A. White, (in preparation): VDatum for the Gulf of Maine: Tidal Datums and Sea Surface Topography. *NOAA Technical Memorandum.*

Zervas, C., 1999: Tidal Current Analysis Procedures and Associated Computer Programs. U.S. Department of Commerce, National Oceanic and Atmospheric Administration, Silver Spring, Maryland, *NOAA Technical Memorandum* NOS CO-OPS 21, 102 pp.

APPENDIX A. TIDAL DATUMS AND HARMONIC CONSTANTS

Tidal Datums

Tidal datums at water level stations are elevation values that are determined from a time series of observations. For stations located along the coasts of the U.S. (except for the Great Lakes), the analysis starts with the identification of all the tidal extrema (highs and lows) in the record, and continues with the selection (within a 25-hour time period) of the higher of the two highs and the lower of the two lows. If only one high water is present in the time period, it is categorized as a higher high. Thus, for high water (for example), each day has either a high and a higher high, or a single higher high. The average of all the highs and the higher highs is called the Mean High Water (MHW), and the average of just the higher highs is called the Mean Higher High Water (MHHW). The process for producing Mean Low Water (MLW) and MLLW from the low waters is similar. The average of the MHW and the MLW is called the Mean Tide Level (MTL) and the average of the MHHW and the MLLW is called the Diurnal Tidal Level (DTL). Mean Sea Level (MSL) is the average of the hourly water levels. Where MSL is not computed, the MTL or DTL can be used as approximations. Equivalent NTDE tidal datums computed from short series of observations have higher uncertainties than those computed form 19-years of data. For further information on tidal datums, see Gill and Schultz (2001).

Additional datums that are not in general usage but may be encountered include: the Mean Water Level (MWL), which represents the mean level of the sea surface over the time of measurement; Low Water Datum (LWD), which is equal to 0.5 ft below MWL and has been used by NOS in Pamlico Sound, NC; Gulf Coast Low Water Datum, which is used by USACE and seems to be defined locally; and Lowest Astronomical Tide (LAT) and Highest Astronomical Tide (HAT), which are defined as the lowest and highest elevation of the predicted tide, respectively, and which are used by survey agencies in Canada and Europe.

The present NTDE of 1983-2001 was implemented in April 2003 and replaced the previous 1960-1978 NTDE period. Older epochs include 1924-1942 and 1941-1959. Use of the most recent epoch will give more accurate datums for locations where apparent sea levels are changing rapidly due to local land subsidence caused by mineral and ground water extraction, isostatic rebound following the last ice age, or tectonic motion. Many of the NOS Tide Table 2 station values are from very old data from short time series.

Tidal datum values at NOS water level stations are routinely computed and are available to the public in the form of the station benchmark sheets. Data are available from the web at: http://tidesandcurrents.noaa.gov.

Harmonic Constants

A list of the NOS constituents is shown in the table.

Table A.1. Thirty-seven tidal constituents (the NOS standard constituents) that can be calculated from a one-year series, listed in order of length of data time series needed to resolve each constituent from a nearby larger constituent, and size (from Parker et al., 1999).

Const.	Speed (Deg/Hour)	Origin	Days Needed to Separate	From:
M_2	28.984104	Lunar	--	--
M_4	57.968208	Shallow-water	0.5	M_2
M_6	86.952313	Shallow-water	0.5	M_4
M_8	115.936417	Shallow-water	0.5	M_6
K_1	15.041069	Lunisolar	1.1	M_2
S_6	90.000000	Shallow-water	4.9	M_6
S_4	60.000000	Shallow-water	7.4	M_4
O_1	13.943036	Lunar	13.7	K_1
MK_3	44.025173	Shallow-water	13.7	$2MK_3$
$2MK_3$	42.927140	Shallow-water	13.7	MK_3
OO_1	16.139102	Lunar	13.7	K_1
$2Q_1$	12.854286	Lunar	13.8	O_1
S_2	30.000000	Solar	14.8	M_2
MS_4	58.984104	Shallow-water	14.8	M_4
$2SM_2$	31.015896	Shallow-water	14.8	S_2
M_3	43.476156	Lunar	27.3	MK_3
M_1	14.492052	Lunar	27.3	K_1
N_2	28.439730	Lunar	27.6	M_2
MN_4	57.439730	Shallow-water	27.6	M_4
Mm	0.544375	Lunar*	27.6	Mm
Q_1	13.398661	Lunar	27.6	O_1
J_1	15.585443	Lunar	27.6	K_1
$2MN_2/L_2$	29.528479	Shallow-water/lunar	31.8	S_2
$2MS_2/\mu_2$	27.968208	Shallow-water/lunar	31.8	N_2
MSf	1.015896	Lunar*	182.6	Mf
Mf	1.098033	Lunar*	182.6	MSf
P_1	14.958931	Solar	182.6	K_1
K_2	30.082137	Lunisolar	182.6	S_2
ν_2	28.512583	Lunar	182.6	N_2
λ_2	29.455625	Lunar	205.9	$2NM_2$
$2NM_2/2N_2$	27.895355	Shallow-water/lunar	205.9	$2MS_2$
ρ_1	13.471514	Lunar	205.9	Q_1
Sa	0.041069	Solar*	365.2	Ssa
Ssa	0.082137	Solar*	365.2	Sa
S_1	15.000000	Solar	365.2	K_1
T_2	29.958933	Solar	365.3	S_2
R_2	30.041067	Solar	365.3	S_2

*Values are determined predominantly by long-term meteorological effects and thus vary from year to year.

APPENDIX B. THE VDATUM ARCHIVE

All VDatum data, files, reports, and auxiliary data are entered into the archive. The archive is presently located on the OCS computers in the directory /disks/NASWORK/vdatum. The archive has five main directories, named M, O, P, T, and V. The contents of each are as follows, where the bullets denote subdirectories:

- **M** contains (by region) hydrodynamic and interpolation *model* codes, grids, and data
    - Region No. 1
        - Data
        - Model results
        - Test results
        - VDatum files
        - Reports and presentations
    - Region No. 2
    - Etc.
- **O** contains *other* data that apply to all VDatum projects and regions
    - Data
    - Etc
- **P** contains computer *programs* used to process data
    - Program No. 1
    - Program No. 2
    - Etc.
- **T** contains *tidal* database information
    - TideSheet
    - CO-OPS spreadsheet database
    - Harmonic Constants
- **V** contains the final *VDatum* GTX files and related documents
    - Region No. 1
    - Region No. 2
    - Etc.

The contents of the P directory are computer programs; these are explained in Appendix C. The remaining directories are described below.

B.1. THE M DIRECTORY

The M directory is organized by geographic regions and parallels the development of a single project grid. The geographic regions are explained in Table B.1 and the contents are explained in Table B.2.

Table B.1. Contents of the M (model data) directory, listed in alphabetical order. Each directory contains data for a specific geographic region as defined by a hydrodynamic model or TCARI grid. Structure and files in each directory are discussed in Table B.2.

DIRECTORY	DESCRIPTION
CAcentral01	Central coastal California and San Francisco Bay
CAsouth01	Southern California model produced for the Coastal Storms project
DEdelches01	Delaware Bay and Chesapeake Bay
FLpanhan01	Hydrodynamic model for the northeast Gulf of Mexico storm surge project
FL_SAB_01	Florida coast from Georgia to Pensacola
FL_tampa01	Tampa Bay project for DEM
GAkingsb01	Special project for Kings Bay, GA for USACE
LAcalc01	Hydrodynamic model for Lake Calcasieu and Lake Charles
MEgulfme01	Gulf of Maine, Massachusetts Bay project
MSneworlea01	Louisiana, New Orleans project
NCcentral01	Hydrodynamic model for the central coastal North Carolina project (sea level rise)
NYsndbght01	New York Bight project for USGS
NYsndbght02	Revised New York Bight and Long Island Sound
PacificNW01	Pacific Northwest, including No. California, Oregon, and coastal Washington
TXcoast01	Coast of western Louisiana and Texas, including bays
WAjuandefuca01	Harmonic constant data for the Strait of Juan de Fuca model
WAnpugsnd01	Northern Puget Sound harmonic constant database model
WAspugsnd02	Revised southern Puget Sound TCARI model
WAspugsnd01	Original southern Puget Sound TCARI model

Table B.2. Typical directory structure and files for a region in the M directory. Contents represent the minimum type of files. * means each subdirectory should include a README file describing the contents, † means if necessary (i.e., if more than one marine grid is generated). T = TCARI, D = harmonic constant database, H = hydrodynamic model, A = all three.

DIRECTORY	SUBDIRECTORY	CONTENTS*	APP.
DA (data)	Bathy	Soundings data sets	H
	Shore	Digitized coastline	A
	Station	Tide station datum data, input file for select.f or celect.f	A
MR (model results)	IN (input)	Model grid(s), model input files	D,H
	MO (model output)	Uncorrected tidal datum fields	D,H
	TC (TCARI input and output)	TCARI input (e.g., error) files, gridded output TCARI error fields	A
	DC (datums corrected)	Final corrected datum fields	A
	VP (vgridder and vpop)	Input and output files for vgridder.f, input files for vpop.f, hydro bounding polygon(s)	A
	WA (working tidal datums for region A)	Final corrected gridded tidal datum fields on a marine grid (GTX files) , vdatum bounding polygon	A
	†WB (working tidal datums for region B)	Final corrected gridded tidal datum fields on a marine grid (GTX files) , vdatum bounding polygon	A
TS (testing)		Results of test_poly.f, test_ovlp.f, test_msf.f, test_cont.f	A
VD (VDatum data)	RA (Region A)	Tidal GTX files, geodetic GTX files, vdatum bounding polygon	A
	†RB (Region B)	Tidal GTX files, geodetic GTX files, vdatum bounding polygon	A
RP (reports)		Technical reports, power-point presentations	A

Table B.3. Organization of the V (VDatum data) directory, including Current and Superseded subdirectories. Each directory holds the data applicable to a single region as defined by the bounding polygon. The directory name conforms to SSaaaaaaNN, where SS is a two-letter state postal abbreviation, aaaaaa is a six-character descriptor, and NN is a two-digit version number.

CURRENT				
CAmontby01	DEnjshor01	FL_stjoe01	NCccentr01	WAjdfuca01
CAoregon01	FL_andrw01	GAFLking01	NCcnorth01	WApugets02
CA_sfbay01	FL_cedar01	FLtampab01	NCpamlis01	WAscoast01
CAsouthn01	FL_charl01	GAkingsb01	NYgrsoby01	TX_cbays01
DEchesby01	FL_flbay01	LAcahchc01	NYharbor01	TX_cshelf01
DEdelbay02	FL_moble02	LAcalche01	NYlisnyb01	TX_sbays01
DEmdshor01	FL_negom02	LAcalchw01	OR_coast01	TX_sshef01
DEmidatl01	FL_pcola01	LAnomiss01	SCGAsap01	TXlousi01

SUPERSEDED				
CAncentr01	FL_moble01	FLtampab01	LAfourch01	WApugets01
DEdelbay01	FL_negom01	GAkingsb01	NYjbight01	

Table B.4. Organization of the V (VDatum data) directory (SSaaaaaaNN) for a single region. The directory name conforms to SSaaaaaaNN, where SS is a two-letter state postal abbreviation, aaaaaa is a six-character descriptor, and NN is a two-digit version number.

DIRECTORY	CONTENTS
SSaaaaaaNN	GTX files, bounding polygon
SSaaaaaaNN /Docs	VDatum software documentation
SSaaaaaaNN /Sample	Sample input file for batch processing
SSaaaaaaNN /Programmr	Java bat files
SSaaaaaaNN /Source	VDatum Java code

APPENDIX C. COMPUTER PROGRAMS

Table C.1. The following lists the various computer programs that can be used to generate and test tidal datum fields.

DIRECTORY	PROGRAM NAME(S)	FUNCTION

ADCIRC	`adc44_15`
	`adc45_11`
	`padcirc90_v44.19t_20040618`
	`adc46_32jgf`
		Codes and directories for recent versions of the ADCIRC model

CELECT	`celect.f`	Extract water level station datums from the CO-OPS database (see SELECT)
CLEAN	`cleancoast.f`	Remove small segments and repeated points from a concatenated coastline dataset (see CONCAT)
CONCAT	`concat.f`	Concatenate the multiple coastline segments on the NOAA medium shoreline into a single long segment and multiple island segments
EPOCH	`compare_epoch.f`	Compare the ranges at stations in an MSF file with ranges from earlier National Tidal Datum Epochs

HARMCON1	`adcirceuv2netcdf.f90`
	`tides_netcdf.f`
	`Makefile`
		Programs to read the ADCIRC model output and create a database of HCs in netCDF format

HARMCON2	`Makefile`
	`comm_lvl_1by1.f`
	`adcdf2datum_mpi.f90`
	`datum_runScript_i_jet.sh`
		Create tidal datum fields from harmonic constants at nodes in a database

LEVELS	`lv4.f`	Extract individual high and low waters from a 6-minute water level time series, and compute MHHW, MHW, MLW, and MLLW
REFORMAT	`fc4.f90`	Reformat digitized coastline data between several formats
SELECT	`select.f`	Extract water level station datums from the TideSheet database (see CELECT)
TCARI_M	`tcari.m`	Compute spatially-interpolated error for an unstructured grid using MatLab
	`tcari_all.m`	Compare observed error at station with interpolated error by selectively removing one station at a time

TEST_CONT	`test_cont.f`	**Compare tidal datums across the interface between to adjacent VDatum polygon regions**
TEST_MSF	`test_msf.f`	**Compare datums at water level stations (from TideSheet) with those produced by VDatum at the same locations**
TEST_ORDER	`Test_order.f`	**Compare datums at each point in GTX grid, checkof MHHW>MHW, MHW>MLW, MLW>MLLW**
TEST_OVLP	`test_ovlp`	**Make sure bounding polygons do not overlap each other**
TEST_POLY	`test_poly.f`	**Insure bounding polygon is completely inside marine grid**
TEST_STA	`test_sta.f`	**Compare tidal data at water level stations (from CO-OPS) with those produced by VDatum at the same locations**
VGRIDDER	`vgridder.f`	**Create a marine grid using coastline file, and identify land and water points**
VPOP	`vpop.f`	**Populate a marine grid using tidal datum fields**

C.1. PROGRAM CLEANCOAST

1. Latest Version `cleancoast.f` December 2005

2. Programmer(s) Kurt Hess, Emily Spargo

3. Purpose

The Fortran 90 program `cleancoastnn.f`, where nn is the version number, creates a cleaned up, digitized coastline file from a concatenated coastline file. The output consists of a long, either closed or unclosed segment representing the uninterrupted shoreline and a set of closed segments representing only islands. The output file is suitable for plotting a coastline or generating a tidal marine grid.

4. Methods

A processed coastline file for a given latitude-longitude window usually contains a multitude of small segments, each consisting of a string or latitude-longitude pairs and some delimiter, and each representing a portion of the coast such as an island. The program cleancoast.f reads in the data in a variety of formats and then looks for, in each segment, consecutive identical points or three adjacent points with identical latitudes or longitudes. Redundant points are removed. The program removes segments comprised of only two points, or of three points with identical ends. The program also finds ‘folded’ series of points (i.e., a set of points that repeat, but in reverse order, a previous, adjacent set of points). The program find points repeated in different segments. The program also determines whether a closed segment is inside another segment (or segments), and whether the segment represents an island, a lake within an island, or an island within a lake.

5. Programs and Files

The Fortran 90 program is contained in file `cleancoastnn.f`, where nn is the version number. The program contains all common variables in a module. To compile the program, enter:

```
f90 cleancoastnn.f –o cleancoast.x
```

To run the program, enter:

```
cleancoastnn.x < cleancoast.in
```

6. Input Files

Input data consist of a digitized, concatenated coastline file (see `concatnn.f).` The input file, cleancoast.in, contains six records and looks like:

```
Title
Input_file_name
1         input format:  1=mapgen, 2=x,y,i 3=y,x,I, 4=SMS
2         output format: 1=x,y,i  2=y,x,i
Output_file_name
3  100 105 125  number of segment to print, followed by points
```

The first record contains the input file name, and the format of the input, *iformi*, is given in the second record. Mapgen format (from the Coastline Extractor website) is as follows:

```
ï»¿<!DOCTYPE HTML PUBLIC "-//W3C//DTD HTML 4.0 Transitional//EN">
<!--                              saved                              from
url=(0046)http://rimmer.ngdc.noaa.gov/coast/tmp/1282.dat -->
<HTML><HEAD>
<META http-equiv=Content-Type content="text/html; charset=utf-8">
<META content="MSHTML 6.00.2900.2769" name=GENERATOR></HEAD>
<BODY><PRE># -b
-76.960122      34.991660
-76.960864      34.992118
-76.961671      34.992705
-76.964165      34.994099
# -b
-76.435027      36.978201
-76.434513      36.976954
-76.434587      36.976734
-76.434880      36.976514
</PRE></BODY></HTML>
```

The format x,y,i looks like:

```
-77.359680      34.550180  1
-77.359386      34.550180  0
-77.359313      34.549960  0
-77.359386      34.549520  0
(etc.)
```

The SMS (.map) format looks like:

```
MAP VERSION7
BEGCOV
COVNAME "Merge coverage 2"
COVELEV 0.000000
COVID 15562
COVATTS VISIBLE 1
COVATTS ACTIVECOVERAGE Merge coverage 2
COVATTS ADCIRC 0
NODE
XY -69.844082999999998 44.023415000000000 0.000000000000000
ID 3362080
END
ARC
ID 10845
ARCELEVATION 0.000000
DISTNODE 0
NODETYPE 0
ARCBIAS 1.000000
MERGED 0 0 0 0
```

```
NODES  3362080  3362080
ARCVERTICES 6
-69.843880999999996 44.023415000000000 0.000000000000000
-69.843451000000002 44.023780000000002 0.000000000000000
-69.843451000000002 44.023980000000002 0.000000000000000
-69.843653000000003 44.024161999999997 0.000000000000000
-69.843880999999996 44.024053000000002 0.000000000000000
-69.844082999999998 44.023415000000000 0.000000000000000
ADCIRCARC 0 0 0.000000 0.000000 0.000000 0.000000
GENADCARC
END
ENDCOV
BEGTS
LEND
```

7. Outputs

The output consists of a data file such as (*y*,*x*,*i*):

```
34.308890  -77.699999 1    1
34.311316  -77.697477 0    1
34.313076  -77.695351 0    1
34.315423  -77.692857 0    1
34.325031  -77.681563 0    1
34.325324  -77.681270 0    1
34.325837  -77.681049 0    1
34.326864  -77.680976 1    1
34.327231  -77.681049 1    2
34.327524  -77.681416 0    2
(etc.)
```

The first column contains the north latitude, the second the east longitude, the third an index for start or end of the segment, and the fourth the number of the segment.

8. Related Programs

An initial coastline file is obtained from `concatnn.f`. Once the cleaned coastline file has been created, further processing for VDatum is carried out by program `vgridder.f`.

C.2. PROGRAM CONCAT

1. Latest Version concat.f December 2005

2. Programmer(s) Kurt Hess, Emily Spargo

3. Purpose

The Fortran 90 program concatnn.f, where nn is the version number, creates a cleaned up, digitized coastline file from a raw coastline file obtained from Coastline Extractor, Extracted Vector Shoreline, or other source. The output consists of a long, either closed or unclosed, segment representing the uninterrupted shoreline and a set of closed segments representing islands.

4. Methods

A raw coastline file for a given latitude-longitude window usually contains a multitude of small coastline segments, each consisting of a string or latitude-longitude pairs and some delimiter. Usually, the segments are not arranged in any particular order. The program concat.f reads in the data in a variety of formats and then looks for matches between end points of segments. Some segments have their end points close to each other (i.e., the separation is within a small, user-defined distance, *dista*); these are defined to be islands, and the end points are then joined. All segments which are not islands are examined in an end-point matching process. That is, the first point in a segment is compared (by computing the distance between them) to the first and last points of all other segments, and then the last point in a segment is compared to the first and last points of all other segments. If a match is found, the two segments are joined into a single new segment. Segments continue to be concatenated until the minimum separation between ends, which is constantly increasing, reaches a limiting distance (a user-defined distance, *distb*), and the process stops.

5. Programs and Files

The Fortran 90 program is contained in file `concatnn.f`, where nn is the version number. The program contains all common variables in a module. To compile the program, enter:

```
f90 concatnn.f –o concat.x
```

To run the program, enter:

```
concatnn.x < concat.in
```

6. Input Files

Input data consist of a digitized coastline file (from the Coastline Extractor, the Extracted Vector Shoreline, the Electronic Navigation Chart, or other source), as well as various other parameters. The input file, concat.in, contains nine records and looks like:

```
Title
/disks/NASUSER/khess/Data/Coastline/Test/A/1216_dat.htm
1              input format:  1=mapgen, 2=x,y,i 3=y,x,I, 4=SMS
2              output format: 1=x,y,i  2=y,x,i
0.030000       dista(deg): max dist between segments that can be connected
0.000010       distb(deg): smallest separation that can be considered zero
1              iclose: 1=close the loop on longest segment
1              iconnect: 1=connect all remaining segments
0              keepnpt: keep segments greater than this length
```

The first record contains the input file name, and the format of the input, *iformi*, is given in the second record. Mapgen format (from the Coastline Extractor website) is as follows:

```
ï»¿<!DOCTYPE HTML PUBLIC "-//W3C//DTD HTML 4.0 Transitional//EN">
<!--                            saved                             from
url=(0046)http://rimmer.ngdc.noaa.gov/coast/tmp/1282.dat -->
<HTML><HEAD>
<META http-equiv=Content-Type content="text/html; charset=utf-8">
<META content="MSHTML 6.00.2900.2769" name=GENERATOR></HEAD>
<BODY><PRE># -b
-76.960122      34.991660
-76.960864      34.992118
-76.961671      34.992705
-76.964165      34.994099
# -b
-76.435027      36.978201
-76.434513      36.976954
-76.434587      36.976734
-76.434880      36.976514
</PRE></BODY></HTML>
```

The format x,y,i looks like:

```
-77.359680      34.550180  1
-77.359386      34.550180  0
-77.359313      34.549960  0
-77.359386      34.549520  0
(etc.)
```

The SMS (.map) format looks like:

```
MAP VERSION7
BEGCOV
COVNAME "Merge coverage 2"
COVELEV 0.000000
COVID 15562
COVATTS VISIBLE 1
COVATTS ACTIVECOVERAGE Merge coverage 2
COVATTS ADCIRC 0
```

```
NODE
XY -69.844082999999998 44.023415000000000 0.000000000000000
ID 3362080
END
ARC
ID 10845
ARCELEVATION 0.000000
DISTNODE 0
NODETYPE 0
ARCBIAS 1.000000
MERGED 0 0 0 0
NODES  3362080  3362080
ARCVERTICES 6
-69.843880999999996 44.023415000000000 0.000000000000000
-69.843451000000002 44.023780000000002 0.000000000000000
-69.843451000000002 44.023980000000002 0.000000000000000
-69.843653000000003 44.024161999999997 0.000000000000000
-69.843880999999996 44.024053000000002 0.000000000000000
-69.844082999999998 44.023415000000000 0.000000000000000
ADCIRCARC 0 0 0.000000 0.000000 0.000000 0.000000
GENADCARC
END
ENDCOV
BEGTS
LEND
```

7. Outputs

The output consists of a data file such as (*y*,*x*,*i*):

```
34.308890  -77.699999 1    1
34.311316  -77.697477 0    1
34.313076  -77.695351 0    1
34.315423  -77.692857 0    1
34.325031  -77.681563 0    1
34.325324  -77.681270 0    1
34.325837  -77.681049 0    1
34.326864  -77.680976 1    1
34.327231  -77.681049 1    2
34.327524  -77.681416 0    2
(etc.)
```

The first column contains the north latitude, the second the east longitude, the third an index for start or end of the segment, and the fourth the number of the segment.

8. Related Programs

Once the concatenated coastline file has been created, further processing is carried out by program `cleancoast.f.`

C.3. PROGRAM LEVELS

1. Latest Version `lv8g.f` February 2010

This version has numerous improvements over earlier versions in how it treats the portions of the time series where the ADCIRC model has drying or ponding, and in some of the output formats.

2. Programmers Kurt Hess, Jiangtao Xu

3. Purpose

This Fortran 95 program is designed to extract the high and low waters from a time series of water levels, categorize them into higher highs and lower highs and higher lows and lower lows, then compute the tidal datums, including MHHW, MHW, MSL, MTL, DTL, MLW, and MLLW.

4. Methods

The method for extracting the highs and lows is based on the approach used by CO-OPS (Gill and Schultz, 2001), which is coded in the C language in the CO-OPS Data Processing and Analysis System (DPAS). This program is not well documented, so for the VDatum effort the new Fortran program `levels.f` (or `lv.f`) was written to duplicate the CO-OPS methodology. The program is based examination of the original program TAB.C (see the VDatum Programs Archive, in Misc), and discussions with various members of CO-OPS.

The program reads successive files, computing extrema (highs and lows) and datums for each record by the multi-step process outlined below.

- Read in the data file,
- Check for too small a signal, for drying or ponding, and for repeated values,
- Compute the ½-hourly averages,
- Compute the precise peak using Singular Value Decomposition,
- Sort the peaks in higher and lower highs, and higher and lower lows, and
- Compute and print the tidal datums.

First, the water level record is read and the times converted into hours if they are in days. The water level (assumed to be in units of meters) can be either an observed signal or a hydrodynamic-model generated series, but has a uniform time increment of 0.1 hr and is assumed to have no gaps.

The initial series of water levels is checked for several conditions. If a node in the model goes dry (i.e., the water depth drops below some specified value h_0), the model code automatically substitutes a value of -9999.0 for the output elevation. Therefore, the first check is for water level values below a user-defined level *h99*. If this situation has occurred, the analysis is skipped and output values of the datums are set to the default (9.999 in the datums summary file and -88.8888 in the GTX file). Another check is made on the minimum water depth. If the minimum water depth, defined as the bathymetric depth at the node below the model zero elevation minus the minimum value in the water level time series, is less than the ADCIRC input value h_0, the datums are also set to default values. (The parameter h_0 causes the hydrodynamic model to stop recalculation flow when water depth at a node falls below h_0.) Next, the gross tide range is checked. If the gross range, defined as the difference between the maximum and minimum water levels in the series, is below a user-defined value *rgross*, datums are also set to default values. Finally, the negative water levels are checked for repeated values. An occurrence of repeated values is defined as three consecutive equal values. If the total number of occurrences exceeds a user-defined fraction of the total number of data values *fmaxreps*, the datums are also set to default values.

The tidal peaks are computed next. First, the average water levels for each half-hourly period (centered on the hour and half-hour) are computed to estimate the times of the peaks. Each peak is tagged as a high water if it is greater than or equal to the two adjacent values, or as a low water if it is less than or equal to the two adjacent values. Then, the method of singular value decomposition (SVD) is applied in an attempt to compute the specific times and values of the peaks. SVD involves fitting a 5-th order polynomial through the values within a 6.4-hr window around the time of the preliminary peak (i.e., 32 points on each side), the selecting the maximum or minimum, depending on whether a high or low is sought, closest to the preliminary time. If a peak with the correct sign cannot be found within this window, the window is halved and the search repeated. If the window falls below a user-defined minimum value, *minwindow*, the datums for that series are set to default values. Peaks are then put into chronological order and any repeated peaks are eliminated.

Next, the peaks are screened and those pairs that do not fit the separation criteria are eliminated. CO-OPS' criteria are that the amplitudes must differ by at least *delhr* in time (hours) and *delamp* in amplitude (meters), where the nominal values are *delhr* = 2.0 and *delamp* = 0.03 (i.e., 0.1 ft). However, for additional flexibility, the amplitude requirement can be set to a fixed value (*iopta* = 1), a fraction (*delfrc*) of the difference of the maximum and minimum water levels in the series (*iopta* = 2), or a fraction (*delfrc*) of the difference of the mean maximum and mean minimum water levels in the series (*iopta* = 3). First, extrema pairs are screened and those too close in time are eliminated. At this point, a check of the tide range is made. The mean range is computed as the difference between the mean of the high waters minus the mean of the low waters. If this range is lower than a user-specified value *rangemin*, datums for that series are set to default values. Then, extrema pairs are screened and those too close in amplitude are eliminated. At this point, another check of the tide range is made.

In the next step, the highs and lows are separated into higher highs, lower highs, higher lows, and lower low values. This is accomplished by applying the '25 hour algorithm' developed by CO-OPS. For example, in simple terms three successive highs in a 25-hour window are examined to determine the maximum value. The window is then centered on this peak, which becomes the higher high; the peaks ahead and behind become lower highs. Finally, in the last step all the higher highs are averaged to determine the Mean Higher High Water (MHHW), all the lower highs are averaged to determine the Mean Lower High Water (MLHW), and all the peaks are averaged to become the Mean High Water (MHW). The calculations for low water are analogous. The Mean Tide Level (MTL) is the mean of MHW and MLW, and the Diurnal Tide

Level (DTL) is the mean of MHHW and MLLW. Mean Sea Level (MSL) is the mean of the 6-min values. An example is shown in Figure C.3.

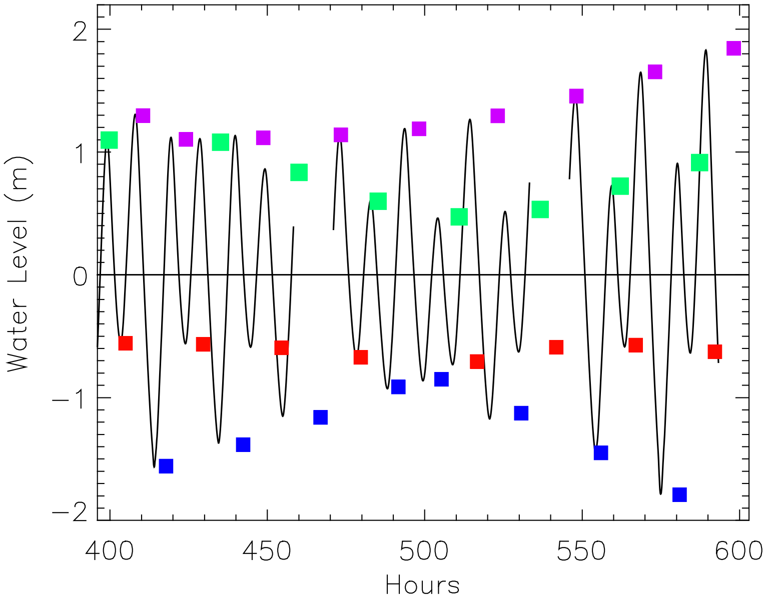


Figure C.3. Water level time series showing HHs (purple), LHs (green), HLs (red), and LLs (blue).

5. Programs and Files

The program, `lv_XX.f`, is compiled by the command

```
lf95 lv_XX.f -o lv_XX.x
```

and is executed by the command

```
lv_XX.x < lv_XX.in.
```

6. Input Files

A. Lv_XX.in A sample of the input file appears below. Most of the input variables have been described above. The print switches in the fourth record (`ipr0` to `ipr6`) can be set to 0 (no printing) or 1 (print the data and some calculations) for each of the six steps in the process for each file read in. (i.e., `ipr0`=signal number to print ; `ipr1`=water depth; `ipr2`=original series; `ipr3`=checks; `ipr4`=1/2-h avgs; `ipr5`=peaks w/SVD; `ipr6`=sort into HH,LL).

```
Descriptive text
1    number of files to process
outputfile.dat        name for datums output file
1 2 1                 date col, wl col, date index (1=hr, 2=day)
000 1 0 0 1 0 0       print switches: ipr0,1,2,3,4,5,6
0.0                   dummy
0.010  -99.           h0, h99
0.01   .004           rgross, fmaxreps
0.10     1            rangemin, minwindow
2.0  0.03 .03  3      delhr, delamp, delfrc, iopta
0  0                  dummy1, dummy2
depths.dat            file with bathymetric depths
2  4                  lskip, lrec (for reading depths file)
1  8                  WL index(1=ascii,2=bin),bin record length
water_levels.dat      input data file
```

B. water_levels.dat A sample of the input ASCII water level time series data is as follows.

```
202.1      -1.6730
202.2      -1.6854
202.3      -1.6989
 ..           ..
```

The first column is the time (here shown in hours, but can be in days) and the second column is the water level value (meters) relative to model zero.

C. depths.dat A sample of the input ASCII water depths file is given below.

```
grid with bathy adjustment to MZ based on run23
    4528    2452
       1     -0.123782895000E+03      0.462409610000E+02      0.350400000000E+01
       2     -0.123783213000E+03      0.462461650000E+02      0.905400000000E+01
       3     -0.123782751000E+03      0.462446380000E+02      0.743200000000E+01
       4     -0.123782362000E+03      0.462432100000E+02      0.554600000000E+01
       5     -0.123782086000E+03      0.462420460000E+02      0.495000000000E+01
       6     -0.123780866000E+03      0.462411900000E+02      0.470200000000E+01
       7     -0.123781736000E+03      0.462396890000E+02      0.286600000000E+01
       8     -0.123780584000E+03      0.462382430000E+02      0.250500000000E+01
```

To read this file, the first two records are skipped `(lskip = 2)`, then for each successive record, the 4th value `(lrec = 4)` is the depth value.

7. Output Files

Outputfile.dat This file contains the datums for each tide series analyzed, followed by the code for each. A sample is shown below. These datums are then read in by another program and the values are assigned to the proper nodes.

```
 178   1.4074   1.1434   0.1592   0.1780   0.1511  -0.7873  -1.1051   0
 179   9.9990   9.9990   9.9990   9.9990   9.9990   9.9990   9.9990  10
 180   9.9990   9.9990   9.9990   9.9990   9.9990   9.9990   9.9990  10
 181   9.9990   9.9990   9.9990   9.9990   9.9990   9.9990   9.9990  10
 182   9.9990   9.9990   9.9990   9.9990   9.9990   9.9990   9.9990  11
 183   1.4083   1.1443   0.1617   0.1829   0.1593  -0.7785  -1.0897   0
 184   1.4078   1.1438   0.1614   0.1827   0.1593  -0.7783  -1.0892   0
 185   1.4085   1.1445   0.1612   0.1828   0.1592  -0.7789  -1.0901   0
```

The first number is the node (actually the number of the time series analyzed), followed by the seven tidal datums (MHHW, MHW, MSL, MTL, DTL, MLW, MLLW), then a code. The codes (or flags) are explained below in the table.

CODE	EXPLANATION
0	Datums processed successfully
10	Value of -9999.0 was detected (i.e., a value was less than *h99*)
11	Minimum water level was less that h_0
12	Maximum minus minimum water level was less than *rgross*
13	Fraction of repeated values was greater than *fmaxreps*
14	Mean range was less than *rangemin*
15	SVD window was less than *minwindow*

8. Related Programs

See TAB.C, the original peak extraction program from CO-OPS, in the VDatum Programs Archive.

C.4. PROGRAM VGRIDDER

1. Latest Version `vgridder10.f` February 2010

2. Programmer Kurt Hess

3. Purpose

This Fortran 95 program creates the structured GTX marine grid which distinguishes between points that represent land and those that represent water, using a coastline and a bounding polygon file to make the determination (see Section 5.1). The program sets up the grid parameters such as the latitude-longitude origin, the point spacing, and the number of rows and columns. The marine grid can then be populated using gridded hydrodynamic model output fields of tidal datums using the program `vpop.f`.

4. Methods

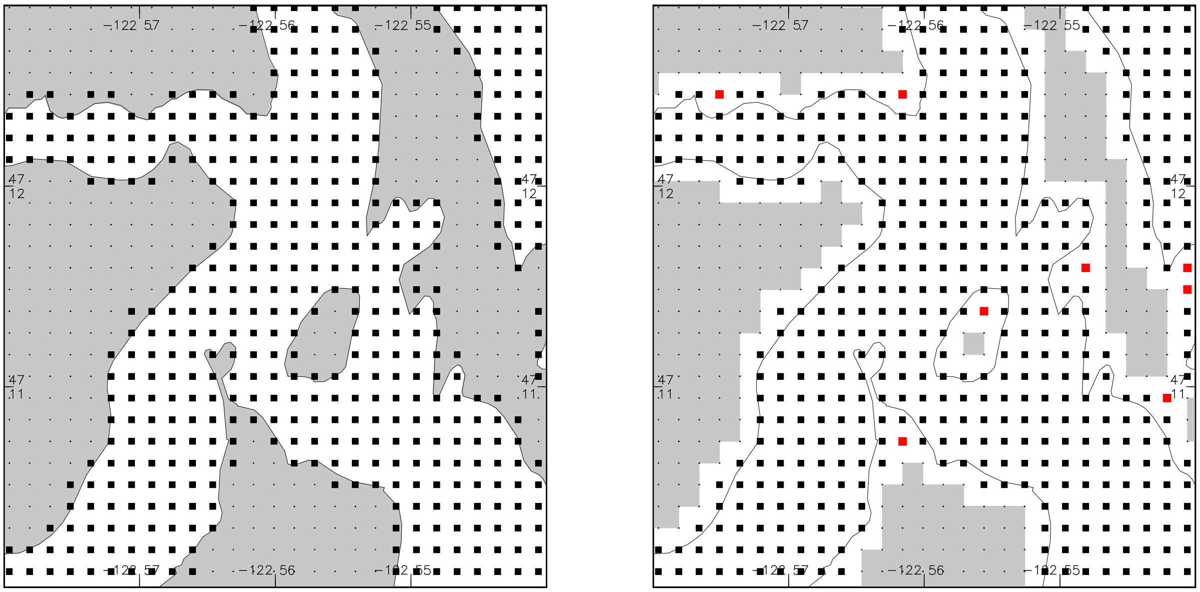
The program basically runs through five steps to create the marine grid. They are:

- Read in the grid parameters, coastline and other file names,
- Generate the grid origin and point spacing,
- Check each point in the grid to determine if it is land or water,
- Optionally, add one or more layers of water points around the original water area, and
- Write out the results.

After reading in the data, `vgridder.f` first sets up the grid origin and point spacing using the parameters from the input file (see Section 5.1). The grid is structured and is defined by the origin (*x0*, *y0*), the horizontal and vertical point spacing (*dx* and *dy*, in arc-degrees), and the number of points in the horizontal and vertical directions (*imax* and *jmax*). Note that the origin (*x0*, *y0*) is defined by the minimum latitude and longitude values, and that *imax* and *jmax* are defined so that the rightmost longitude (*x0+{imax-1}*delx*) and topmost latitude (*y0+{jmax-1}*dely*) equal or exceed the input boundaries.

Next, the programs loops through each point in the grid and checks on whether the point is inside or outside of a polygon representing land or the bounding polygon (if there is one). For details on the coastline and bounding polygons, see below. If the point is in water, it becomes an active point and is to be filled with a tidal datum value (by `vpop.f`). Each point in the marine grid is checked as follows. Since the actual grid point may not be representative of the presence of land, several points surrounding the grid point are checked instead. These secondary points form a rectangle and are located along parallels and meridians located halfway between the actual grid points (see Figure D.4.a). The secondary points have horizontal and vertical spacing equal to *dx/(llmax-1)* and *dy/(llmax-1)*, respectively; thus there will be *llmax* points along each side, including the corners, of the rectangle. If any of the secondary points are in water, the grid point is considered water. In the program, to speed up the process the secondary points are inspected to see if they were checked previously, then checked at the corners first, and then are checked around the perimeter last. At least one secondary point must also be inside the bounding polygon to be considered water. By using the secondary points, some grid points that actually lie on land will be considered to be water; this is desirable since users may want to have tidal datum information on the land that is near the shoreline. The results for a small area in Puget Sound are shown in Figure C.4.a.

Figure C.4.a. Schematic showing marine grid points (*), the grid point being checked (X), and the secondary points that are actually tested (+), as well as the coastline (solid line) and land (gray areas). Here *llmax* = 5. If any of the secondary points are in water (as is the case shown), the grid point is considered water.



(a) (b)

Figure C.4.b. (a) Points in the marine grid representing water (black squares) and land (.). The gray areas show land. (b) Points in the marine grid representing water (black squares), water points added to remove barriers (red squares), and land (.). The gray areas show locations where VDatum cells are inactive.

The coastline and bounding polygon must have certain characteristics. The coastline file must consist of groups of latitude-longitude points wherein the first and last points in each group are identical, so that each group represents a polygon that describes an island or other land mass. Similarly, the bounding polygon must also be a closed polygon. A test point is considered to be inside a polygon if, at the latitude of the point, there are an odd number of crossings of the polygon at longitudes greater than the longitude of the test point.

It is helpful here to define an 'active' VDatum cell. Consider a cell to be the rectangular area defined by the four corners which are points in the marine grid. Since the VDatum software interpolates a value at any point inside the cell if at least one corner is a water point, a cell can be considered active if one or more corners are water points. Otherwise, it is 'inactive'.

The method of identifying water points described above can lead to artificial 'barriers' which have discontinuities. The situation for four adjacent active cells is shown in Figure D.4.c. At point A, the VDatum values will be computed by interpolation the values at the single water point in the upper left rectangular cell. At point B, the VDatum values will be computed by interpolation the value at the single water point in the upper right rectangular cell. Hence at the border between the two cells there is the potential to have a discontinuity of values. To avoid this situation, the land point closest to A and B is turned into water; in general, if a land point lies at the corner of four active cells, that point is switched to water. In `vgridder.f`, after the initial generation of the marine grid, there is an option to check for and remove artificial barriers (by setting *nobarr1* = 1) in the land/water field by switching a land point to a water point. Figure C.4.c above shows the effect (as red squares) of switching these land values to water. Note that switching does not alter whether the cells containing that corner are active in VDatum.

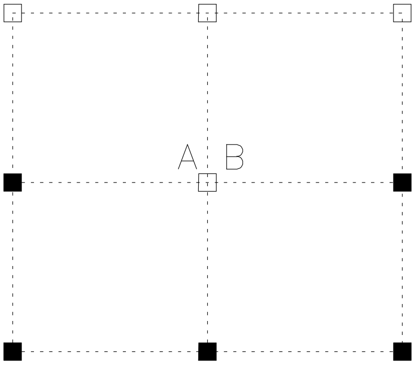


Figure C.4.c. Four active VDatum cells (rectangles bounded by dashed lines) defined by the four marine grid points at the corners. Solid squares at the corners represent water locations and open squares represent land locations. Since at least one of the corner points in each cell is water, all cells are active; i.e., the VDatum software will interpolate a value to any point inside either cell. Interpolated values at locations A and B may show a discontinuity.

It is sometimes desirable to expand the active area covered by the marine to include more active cells inland. This can be accomplished by the input parameter *layers*. For example, by setting *layers* = 1, one additional layer of water points is added to the existing field. Any number of additional layers is possible. Each new layer is implemented by switching land points to water if at least one of the four adjacent points is water and has not been switched to create this layer.

The result of adding one layer of water points to the marine grid depicted in Figure D.2a is shown in Figure C.4.d.

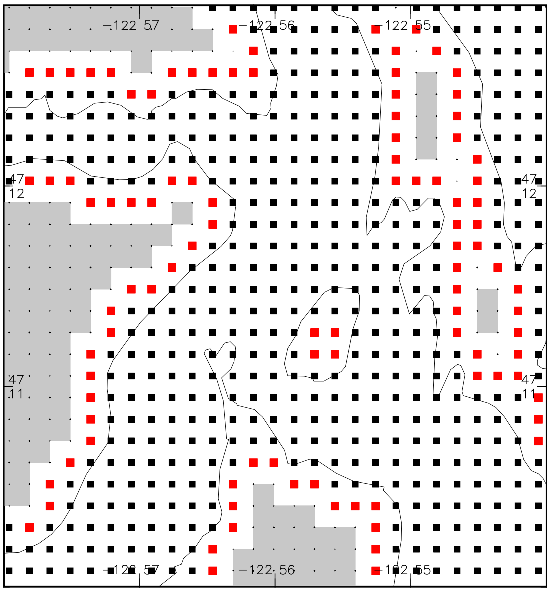


Figure C.4.d. Marine grid after adding a layer of water points to the previous water points (Fig. C.4.c). The red squares are those that were added, and gray areas show inactive VDatum cells. Artificial barriers, if any, were not removed after the layer was added.

During the addition of extra layers, it is possible that the new water points could lead to more artificial barriers. To remove these, set *nobarr2* = 1; any other value will leave the barriers in place. However, it is possible that leaving the barriers in may give more realistic results, since discontinuities in the datums may occur when, for example, interpolating over a barrier island. Another option in adding layers is whether to exclude points that are outside of the bounding polygon. Setting the parameter *icheckbp* = 1 will use the BP to exclude points.

5. Programs and Files

The program, `vgridder.f`, is compiled by the command

```
lf95 vgridder.f –o vgridder.x
```

and is executed by the command

```
vgridder.x < vgridder.in.
```

6. Input Files

The following are descriptions of the input files required for `vgridder.f`.

A. vgridder.in Below is a typical input file for `vgridder.f`. This file is read during program execution.

```
vgridder.in for Puget Sound          title
4  47.01  48.11  -123.11  -121.00    lat/lon window
0.001   0.001                        delx,dely (degrees)
5   0                                llmax,layers
1   0   0                            nobarr1,nobarr2,icheckbp
1  162  658                          mpr,iprt(),jprt()
puget_coastline.dat                  coastline data
bounding_polygon.dat                 bounding polygon
vgrid_ps01.dat                       output marine grid file
vgrid_marine.gtx                     output marine GTX file
```

The data in this file are as follows. The first record contains descriptive text. The second record has the number of values to follow, then two values of latitude, and finally two values of longitude. These are the bounds of the marine grid. The third record has the horizontal and vertical grid point intervals. The fourth record gives *llmax*, the number of secondary points (along a constant latitude or longitude - see Figure D.1.) to be checked, and *layers*, the number of additional layers of water points to be added. The next record holds the parameter *nobarr1*, which (if equal to 1) removes barriers in the land/water field (see Figure D.4.c); the parameter *nobarr2*, which (if equal to 1) removes barriers after a layer of water points has been added; and *icheckbp*, which (if set to 1) will not add layer points if they are outside the bounding polygon. Record six has the indices for print calculations that determine whether a grid point is inside a land or bounding polygon. Here, *mpr* is the number of grid points, followed by *mpr* pairs of *i* and *j* indices of points to print, *iprt* and *jprt*. The last four records contain the file names for the coastline file, the bounding polygon file (or ‘none’ if no polygon is specified), the output file containing the water points (for use by `vpop.f`), and a similar file but in GTX format.

B. Coastline File This file appears in `vgridder.in` .

```
34.308890  -77.699999 1
34.311316  -77.697477 0
34.313076  -77.695351 0
34.315423  -77.692857 0
34.325031  -77.681563 0
34.325324  -77.681270 0
34.325837  -77.681049 0
34.326864  -77.680976 1
34.327231  -77.681049 1
34.327524  -77.681416 0
 etc.
```

The first column contains the latitude (positive northward), the second the longitude (positive westward), and the third an index for the segment. An index value of 1 denotes the start or end of a segment.

C. Bounding Polygon File The bounding polygon file contains the active region of the marine grid, and has a form identical to that of the coastline file. It contains only one segment.

7. Output Files

A. Marine Grid This file gives information on the marine grid, including for each point the longitude, latitude, land/water indicator (0 = land, 1 = water), horizontal grid index *i*, and vertical grid index *j*. The first record also contains the maximum horizontal and vertical indices, *imax* and *jmax*.

```
-123.710000  46.267000 0    1    1   51   19
-123.709000  46.267000 0    2    1
-123.708000  46.267000 0    3    1
-123.707000  46.267000 0    4    1
-123.706000  46.267000 0    5    1
-123.705000  46.267000 0    6    1
-123.704000  46.267000 0    7    1
-123.703000  46.267000 0    8    1
-123.702000  46.267000 0    9    1
  etc.
```

B. Marine GTX Grid This is simply the output of the marine grid transformed into the GTX file format.

```
 46.267000  236.290000    0.001000    0.001000      19      51
-88.8888
-88.8888
-88.8888
-88.8888
  0.1000
  0.1000
  0.1000
  etc.
```

The first record contain the latitude and longitude of the lower left corner of the marine grid (*y0* and *x0*), the vertical and horizontal points spacing *dy* and *dx* (in degrees), and the number of rows (*jmax*) and columns (*imax*) in the grid. The following records (numbering *imax*jmax*) contain either the default value (-88.8888) for land, or 0.10 for water.

8. Related Programs

The output marine grid is used as input to the populating program, `vpop.f.`

C.5. PROGRAM VPOP

1. Latest Version	vpop17.f	February 2010
2. Programmers	Kurt Hess, Jiangtao Xu	

3. Purpose

This Fortran 95 program reads a marine grid (as created by the program `vgridder.f`) and ADCIRC hydrodynamic model output (and possibly a TCARI output file), and creates tidal datum transfer fields on the marine grid (the GTX files).

4. Methods

The populating of the marine grid is accomplished through a five step process:

- Read in the input data and files,
- Initialize the mean sea level (MSL) field,
- Loop through each tidal datum and filling the marine grid, and
- Writing the output to files.

In the first step, the input parameters in the file `vpop.in` (see below) are read in, and then the marine grid and bounding polygon (if any) are read in. In the next step, the MSL grid (if any) is read in. Usually, the datum output file from `levels.f` (see Appendix D.3, section 7) is used to create a datum field that is referenced to MSL already, so the MSL field is not needed.

In the third step, the ADCIRC nodes are tagged as being either inside or outside the bounding polygon. A node is inside the BP if the number of crossings of the BP with longitudes greater than that of the node is an odd number. If there is no BP, all nodes are inside. However, if a node is outside the BP, but at least one of the remaining nodes in an adjacent cell is inside the BP, the node is considered to be inside. After tagging, all water points in the marine grid are examined. If the point lies within an ADCIRC cell, the value at the point is found by interpolating the values at the cell's nodes using a two-dimensional plane. Water points outside any cells are filled iteratively. At each iteration, a point value is the weighted sum of values at all adjacent points (either latitudinally, longitudinally, or diagonally) that have been filled either by interpolation or on a previous iteration. The weighting is by the inverse of the distance to the node, and at least one adjacent point has to have been filled for the interpolation to proceed. Finally, the interpolated values in the marine grid are written out in standard GTX format.

Note that if a node has the default value (-88.8888), its tidal datums could not be computed because of drying or ponding. In this case, the marine grid is filled with the default value; i.e., it becomes a land point.

Also note that the program was written originally to fill a marine grid using a structured (TCARI) source file. This feature has not been used in several years and the code has not been updated, so this option should be used with care.

5. Programs and Files

The program is compiled by the command

```
lf95 vpop.f –o vpop.x
```

And executed by the command

```
vpop.x < vpop.in
```

6. Input Files

A. vpop.in A sample input file is shown below.

```
title
2                            model(1=tcari,2=adcirc)
2   15 17    20 31           nprt,iprt(),jprt()
bounding_polygon.dat
none                         MSL file
vgridder_marine.dat          input marine file
1                            nfmax = number of sets to follow
adcirc_mhhw.dat
mhhw.gtx
```

Here the first record contains a text description. The next record contains an index to denote whether a TCARI file (*model* = 1) or an ADCIRC file (*model* = 2) is providing the source datums. The third record contains the number of points (*nprt*) and the locations (*iprt*, *jprt*) at which the filling calculations will be printed (the maxim record contains the bounding polygon file name,um of *nprt* is 100). The fourth record contains the bounding polygon file name, and the fifth record contains the MSL file name; both are optional and can be skipped by inserting the four-letter word 'none' in its place. The sixth record is the name of the marine grid file as produced by the program `vgridder.f`. The next record contains the number of sets to follow, *nfmax*; *nfmax* can be as large as 7. In each set there is the name of an ADCIRC file for a particular tidal datum, followed by the name of the output file in GTX format.

B. Bounding Polygon See the description in Appendix D.3.

C. MSL File This file contains the MSL relative to the hydrodynamic model's zero elevation. The format is an ADCIRC file (see Appendix F, Section 1.1).

D. Marine Grid File This file, created by `vgridder.f`, is described in Appendix D.4.

E. ADCIRC Datum File This file contains the field for a single tidal datum. The format is an ADCIRC file (see Appendix F, Section 1.1).

7. Output Files

A. Output GTX File This file contains the resulting tidal datum filed in GTX file format (see Appendix D.3, Section 7.

8. Related Programs

The program `vgridder.f` is used to create the marine grid.

APPENDIX D. GLOBAL TIDAL DATABASES

Many global tide modeling solutions have been developed in recent years, particularly ones that make use of satellite altimetry data. Schwiderski (1980) pioneered the development of global tide models and demonstrated with a 1° x 1° gridded model the ability to simulate the ocean tides to within a 10 cm root mean square error in the open ocean. Below is a summary of some of the more recent global tide models that are available.

If a global model is to be used to either derive datums for VDatum or to provide boundary conditions to tidal models supporting VDatum, it is recommended that either the FES99 for TPX06.2 models be used. Also, these models usually do not cover the entire water surface of the Earth. Figure D.1 shows the areas not covered by each database.

NAO.99

This is a global ocean tide model developed by Japan's National Astronomical Observatory. The model has 0.5° resolution and assimilates approximately 5 years of TOPEX/POSEIDON altimeter data. Tidal constituents available from the model include the M2, S2, K1, O1, N2, P1, K2, Q1, M1, J1, OO1, 2N2, Mu2, Nu2, L2, and T2. A separate model developed by the same group for long-period tides, NAO.99L, can provide tidal constituent model results for the Mtm, Mf, Mm, Ssa, and Sa constituents.

Website: http://www.miz.nao.ac.jp/staffs/nao99/index_En.html

Reference: Matsumoto, K., T. Takanezawa, and M. Ooe, Ocean Tide Models Developed by Assimilating TOPEX/POSEIDON Altimeter Data into Hydrodynamical Model: A Global Model and a Regional Model Around Japan, Journal of Oceanography, 56, 567-581, 2000.

FES99

C. Le Provost and collaborators have developed a fininte element model that uses inversion techniques to optimize solutions with respect to tide gauge data and assimilates TOPEX/POSEIDON data to improve the results. This model has evolved over time and includes versions named FES94.1, FES95.2, FES98 and FES99. The last of these, FES99, provides results on a 0.25° by 0.25° grid. Modeled tidal constituents are provided for the following tidal components: M2, S2, N2, K2, 2N2, K1, O1, Q1, m2, n2, L2, l2, T2, e2, h2, P1, 2Q1, r1, s1, J1, c1, M11, M12, OO1, j1, p1, and q1.

Website: http://www.jason.oceanobs.com/html/donnees/produits/auxiliaires/fes_uk.html

Reference: Lefèvre, F., F. Lyard, C. Le Provost, and E.J.O. Schrama, FES99 : a tide finite element solution assimilating tide gauge and altimetric information, JTECH, submitted, 2001.

CSR4.0

Developed by the University of Texas' Center for Space Research, CSR4.0 and CSR3.0 use TOPEX/POSEIDON data to make long wavelength adjustments to the FES94.1 model on a 0.5° by 0.5° grid. For the coastal waters of the United States, this model should be identical to FES94.1.

Website: ftp://ftp.csr.utexas.edu/pub/tide/

Reference: Eanes, R. J. Diurnal and semidiurnal tides from TOPEX/POSEIDON altimetry. Eos Trans. AGU, 75(16):108, 1994.

GOT00.2

Also a long wave adjustment to the FES94.1 model and should be identical to FES94.1 in U.S. coastal waters. Results are provided on a 0.5° by 0.5° grid.

Website: ftp://geodesy.gsfc.nasa.gov/dist/ray

Reference: Ray, R. D. A Global Ocean Tide Model From TOPEX/POSEIDON Altimetry: GOT99.2. *NASA Technical Memorandum 209478*, 1999.

TPXO6.2

Inverse theory is used to provide a least squares best fit of TOPEX/POSEIDON data to the Laplace tidal equations. Regional tidal solutions are also available on their website that makes use of the Oregon State University Tidal Inversion Software (OTIS). The TPXO.6 global solution has about the same residual magnitudes as the regional inverse solutions for the open ocean, but the regional inverse solutions fit the data significantly better for complex topographic areas. The tides are provided as complex amplitudes of earth-relative sea-surface elevation for eight primary (M2, S2, N2, K2, K1, O1, P1, Q1) and two long period (Mf, Mm) harmonic constituents, on a 1440x721, 1/4 degree resolution full global grid. Note that TPXO7.0 is in the process of being released.

Website: http://www.coas.oregonstate.edu/research/po/research/tide/

Reference: Egbert, G. D. and Erofeeva, L. Efficient inverse modeling of barotropic ocean tides. *Journal of Atmospheric and Oceanic Technolgy,*, Vol. 19, 2002.

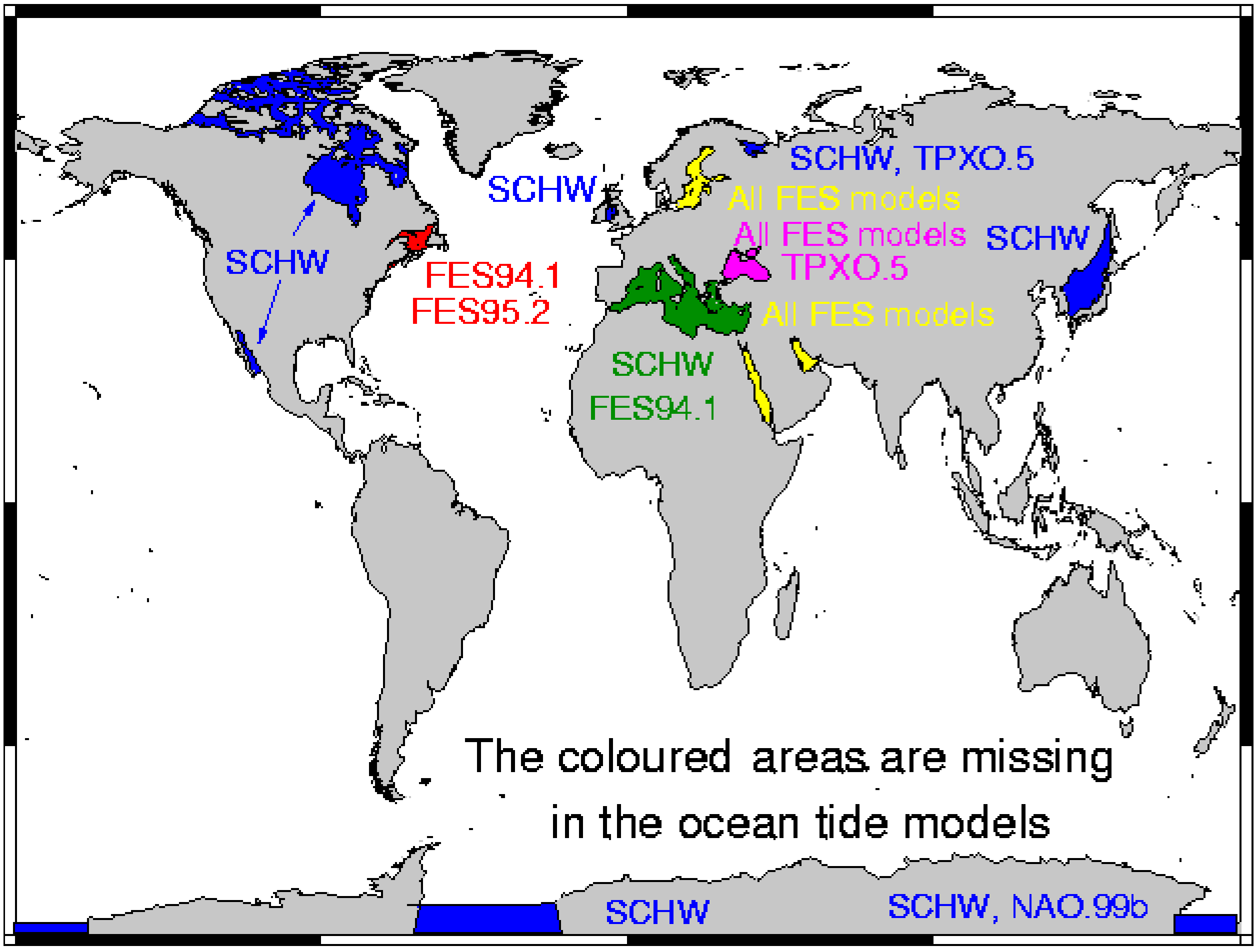


Figure D.1. Areas not covered by the various global tide models.

APPENDIX E. INTERPOLATION OF BATHYMETRY TO A GRID

There are several methods for interpolation of bathymetric values to a node. These include

- cluster averaging,
- the quadrant method, and
- the SMS methods.

E.1. CLUSTER AVERAGING

For unstructured, triangulated grids, a simple and effective method to incorporate bathymetry into the grid at the grid scale is a method called "cluster-averaging". This method allows the data to be filtered onto the mesh at the grid scale. Cluster averaging can be demonstrated using Figure E.1 on an unstructured, triangular mesh.

In this figure, the bathymetric sounding data locations are shown as red squares. The node where the bathymetry will be averaged is highlighted with a blue circle. The elements (or the "cluster") that surround that node are labeled "1" through "6". To calculate the cluster-averaged bathymetry at the highlighted node, the bathymetric depths are totaled from all of the sounding points located within the cluster of elements surrounding the node and averaged. Variations on this method can include searching through a larger cluster area (i.e. the elements that surround the highlighted node and all the elements that touch the original cluster) or using an inverse distance weighted method to weight the bathymetric data by distance to the node. Data points

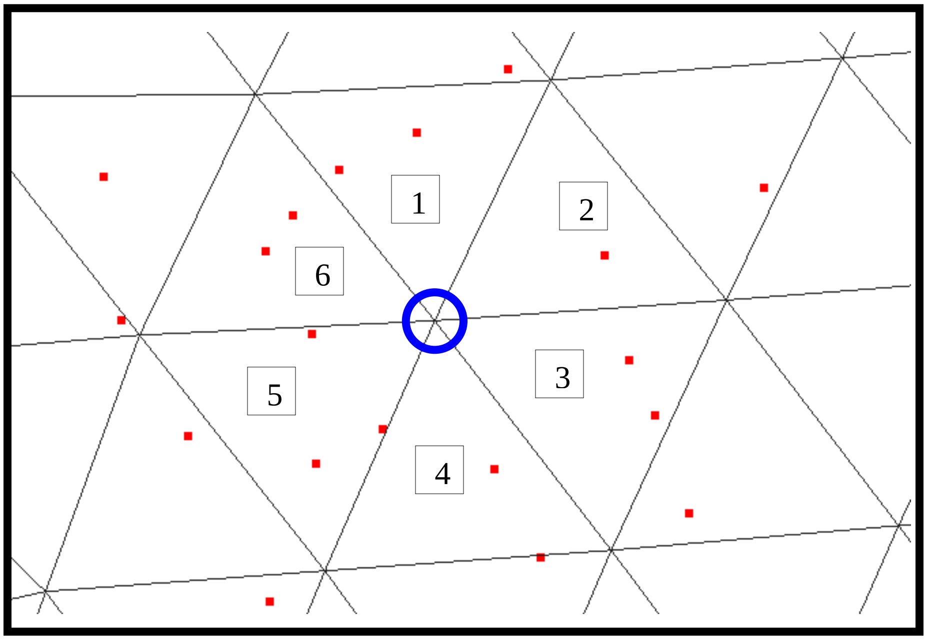


Figure E.1. Sample element configuration of an unstructured mesh with reference node highlighted with a blue circle and the elements labeled '1' to '6'. Sample bathymetry data locations shown as red squares.

that vary more than one standard deviation from the mean of the data in the cluster region could be eliminated, also, for a more complex way of using that bathymetry data. Initial tests have shown that using the regular cluster-average approach produces smooth and reasonably realistic bathymetric data sets at the nodes in the mesh. The averaging in the cluster approach inherently filters noise that would exist in linear interpolation from a triangulated interconnected network (TIN) of bathymetry at a higher resolution that the grid. However, it does weight points of differing distance from a node with the same importance.

E.2. QUADRANT METHOD

For any node in a structured or unstructured grid, an interpolation based on the nearest neighbors within four quadrants surrounding the node can be done. First, a box of a user-determined width is drawn around the grid node. The box is divided into quadrants and the nearest neighbors are used to bi-linearly interpolate the bathymetric depth at the grid node. Figure 4.3 shows the grid node as the black center dot and the sounding points (crosses) within the box around that node. The nearest neighbors in each quadrant are highlighted in red. This method is advantageous since it honors the values of the bathymetry closest to the nodal point. However, it can be susceptible to creating a noisy bathymetric field as localized bathymetric variations are applied to a larger grid area. It can also be misleading if the soundings are not regularly distributed or if the nearest neighbors aren't representative of the values of adjacent sounding points.

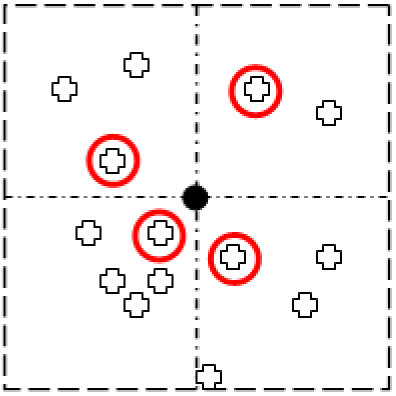


Figure E.2. Example of how the quadrant method works.

E.3. INTERPOLATION USING SMS

The Surface-water Modeling System (SMS) program allows users to add bathymetry data to any of the grids supported in their software (including ADCIRC unstructured grids) using one of three different interpolation options: linear, inverse distance weighted (IDW) or nearest neighbor (NN). The following paragraphs are directly from the SMS help documentation:

> If the linear interpolation scheme is selected, the 2D scatter points are first triangulated to form a temporary TIN. If the surface is assumed to vary linearly across each triangle, the TIN describes a piecewise linear surface which interpolates the scatter points. Since a TIN only covers the convex hull of a scatter point set, extrapolation beyond the convex

hull is not possible with the linear interpolation scheme. Any points outside the convex hull of the scatter point set are assigned the default extrapolation value entered at the bottom of the Interpolation Options dialog.

One of the most commonly used techniques for interpolation of scatter points is inverse distance weighted (IDW) interpolation. Inverse distance weighted methods are based on the assumption that the interpolating surface should be influenced most by the nearby points and less by the more distant points. The interpolating surface is a weighted average of the scatter points and the weight assigned to each scatter point diminishes as the distance from the interpolation point to the scatter point increases. Several options are available for inverse distance weighted interpolation. The options are selected using the Inverse Distance Weighted Interpolation Options dialog. This dialog is accessed through the Options button next to the Inverse distance weighted item in the 2D Interpolation Options dialog. SMS uses Shepard's Method for IDW.

Natural neighbor interpolation is also supported in SMS. Natural neighbor interpolation has many positive features. It can be used for both interpolation and extrapolation and it generally works well with clustered scatter points. SMS uses nodal functions with IDW. The nodal function can be selected using the Natural Neighbor Interpolation Options dialog. The difference between IDW interpolation and natural neighbor interpolation is the method used to compute the weights and the method used to select the subset of scatter points used for interpolation. Natural neighbor interpolation is based on the Thiessen polygon network of the scatter point set. The Thiessen polygon network can be constructed from the Delauney triangulation of a scatter point set. A Delauney triangulation is a TIN that has been constructed so that the Delauney criterion has been satisfied.

APPENDIX F. USING THE ADCIRC MODEL

The ADCIRC hydrodynamic model allows for a wide variety of user-specified parameters. It is important that the parameters be set in a manner that is both physically realistic for the problem at hand as well as ensures model stability and efficiency. Additional help on ADCIRC is available at: http://www.adcirc.org. The model user should be aware that the ADCIRC model is under continuing development by the community and ensure that the input files they use are valid for newer releases of the code. These input files are acceptable for ADCIRC versions 44 through 45 at a minimum.

F.1. MODEL INPUT FILES

In order to run the ADCIRC model to simulate tidal processes, there needs to be an input mesh file called fort.14 and an input parameter control file called fort.15. Files fort.67 and fort.68 are model-generated files that contain values of water levels and velocities, respectively, at all nodes and that can be used for a 'hot start'. File fort.21 contains (optional) spatially-varying bottom friction information. Additional input files are available as optional input but generally do not apply to tidal modeling scenarios.

F.1.1. Grid File (fort.14)

Having had experience with the ADCIRC model is helpful when designing a grid to be used with the model, but without that exposure, the SMS tool can help even a novice develop usable grids. Some general rules to keep in mind when designing a grid will be listed first and then tutorials on using SMS will follow.

As with any unstructured grid, the goal is to have sufficient resolution – meaning the element sizes are small enough to resolve the important flow features, but not smaller than they need to be in order to optimize the model run time. This optimization has been explored at length with the localized truncation error analysis (LTEA) method (Hagen, 2001; Hagen and Parrish, 2004). A summary of this method can simply be stated that resolution should increase as bathymetry decreases, and additionally increased resolution should be placed in areas of large bathymetric gradients.

Based on the grids that have been developed for contemporary ADCIRC model runs (Hess et al., 2005; Spargo and Woolard, 2005; Yang et al.), the average node-to-node spacing has been 20-40 km in deep ocean waters and 50-100 m in the near-shore areas. Also, fine features such as inlets and rivers should have at least three nodes across the width of the opening/channel and preferably four to six, depending on the physical width of the area. But if sufficient discretization of the inlet or channel would require the element sizes to be less than 50-100 m each, then this feature should be left out of the grid. A shortened version of a fort.14 file appears in Figure F.1.

```
 MZ/la5c_finalMZ.grd
 36931 20575
       1    -93.147680     29.341250   12.9007
       2    -93.169560     29.359200   12.7823
       3    -93.187640     29.339560   12.7905
       4    -93.254880     29.340680   12.6546
       5    -93.274030     29.367200   12.5363
       6    -93.302630     29.344660   12.5219
       7    -93.340060     29.348070   12.2660
          (etc.)
   20573    -93.333097     30.015240   11.1825
   20574    -93.338460     29.923175   11.1714
   20575    -93.329720     30.059400    1.5897
     1 3 1 2 3
     2 3 4 5 6
     3 3 7 6 8
     4 3 1 9 10
     5 3 9 11 12
     6 3 1 10 2
        (etc.)
 36929 3 9981 9988 9958
 36930 3 7266 7310 7320
 36931 3 7266 7320 7257
1       ! no. of open boundary (water elev.) segments
54      ! total no. of points on all open boundary segments
54 0    ! no. of points on first segment, type
1275
1193
  (etc.)
474
498
567     ! last point on o.b.
16      ! no. of other boundaries (e.g., land, river)
4192    ! total no. of boundary points
3132 1  ! no. of points on first boundary segment, type
527
545
547
   (etc.)
```

Figure F.1. Sample input grid file (fort.14). First record is a title, second lists the number of cells and number of nodes. What follows is the node data (number, longitude, latitude, and value), the cell data (number, number of nodes at vertices, the node numbers), the open boundary nodes, and the land-water boundary nodes.

F.1.2. Model Input Parameters (fort.15)

This section will discuss the parameters in the order that they appear in the input file, fort.15. The names of the parameters will be given as they appear in the User's Manual website: http://www.adcirc.org/document/ADCIRC_title_page.html. A shortened version of the fort.15 file appears in Figures F.2 and F.3.

```
la12r23.inp la5c_finalMZ.grd - RUN WITH ADCIRC V42.19T  !RUNDES: a 36-CHAR. DESCRIPTOR
ffactor=0.003,hbreak=1,fgamma=0.33,ESL=2  ! RUNID: a 24-CHAR RUN DESCRIPTOR
 1                ! NFOVER - NONFATAL ERROR OVERRIDE OPTION
 1                ! NABOUT - ABREVIATED OUTPUT OPTION PARAMETER
 1                ! NSCREEN - UNIT 6 OUTPUT OPTION PARAMETER
 0                ! IHOT - HOT START PARAMETER
 2                ! ICS - COORDINATE SYSTEM SELECTION PARAMETER
 0                ! IM - MODEL SELECTION PARAMETER
 2                ! NOLIBF - BOTTOM FRICTION TERM SELECTION PARAM
 2                ! NOLIFA - FINITE AMPLITUDE TERM SELECTION PARAMETER
 1                ! NOLICA - SPATIAL DERIVATIVE CONVECTIVE SELECTION PARAMETER
 1                ! NOLICAT - TIME DERIVATIVE CONVECTIVE TERM SELECTION PARAMETER
 0                ! NWP - VARIABLE BOTTOM FRICTION AND LATERAL VISCOSITY OPTION PARAMETER
 1                ! NCOR - VARIABLE CORIOLIS IN SPACE OPTION PARAMETER
 1                ! NTIP - TIDAL POTENTIAL OPTION PARAMETER
 0                ! NWS - WIND STRESS AND BAROMETRIC PRESSURE OPTION PARAMETER
 1                ! NRAMP - RAMP FUNCTION OPTION
 9.81             ! G - ACCELERATION DUE TO GRAVITY - DETERMINES UNITS
 -0.02            ! TAU0 - WEIGHTING FACTOR IN GWCE
 2                ! DT - TIME STEP (IN SECONDS)
 0.00             ! STATIM - STARTING TIME (IN DAYS)
 0.00             ! REFTIM - REFERENCE TIME (IN DAYS)
 37.0             ! RNDAY - TOTAL LENGTH OF SIMULATION (IN DAYS)
 5.0              ! DRAMP - DURATION OF RAMP FUNCTION (IN DAYS)
 0.35 0.30 0.35   ! A00, B00, C00 - TIME WEIGHTING FACTORS FOR THE GWCE EQUATION
 0.10 25 0 0.05   ! H0, NODEDRYMIN, NODEWETRMP, VELMIN
 235.0 31.0       ! SLAM0,SFEA0 - CENTER OF CPP PROJECTION (NOT USED IF ICS=1, NTIP=0, NCOR=0)
 0.003 1.0 10.0 0.33333   ! FFACTOR, HBREAK, FTHETA, FGAMMA
 2.0                      ! ESL - LATERAL EDDY VISCOSITY COEFFICIENT; IGNORED IF NWP =1
 0.0                      ! CORI - CORIOLIS PARAMETER - IGNORED IF NCOR = 1
 2       ! NTIF - NUMBER OF TIDAL POTENTIAL CONSTITUENTS BEING FORCED
 K1     ! TIPOTAG - ALPAHANUMERIC DESCRIPTION OF TIDAL POTENTIAL CONSTIT.
  0.141565  0.000072921158358  0.736  1.000  0.000  ! TPK, AMIGT, ETRF, FFT, FACET
 O1
  0.100514  0.000067597744151  0.695  1.000  0.000
 2      ! NBFR - TOTAL NUMBER OF FORCING FREQUENCIES ON OPEN BOUNDARIES
 K1     ! BOUNTAG - ALPHANUMERIC DATA FOR OPEN OCEAN FORCING
  0.000072921158358   1.000  0.000  ! AMIG, FF, FACE
 O1
  0.000067597744151   1.000  0.000
   K1                                  ! ALPHA – CONSTITUENT NAME
   0.18864E+00    25.373               ! EMO, EFA (AMPLITUDE, PHASE)
   0.18838E+00    25.329
        (etc)
 110.0             ! ANGINN : INNER ANGLE THRESHOLD
 1 6.0 36.0 180      ! NOUTE,TOUTSE,TOUTFE,NSPOOLE:ELEV STATION OUTPUT INFO (UNIT  61)
 6                ! NSTAE - TOTAL NUMBER OF ELEVATION RECORDING STATIONS
    -93.098335   29.756666     !#8767577 MERMENTAU_R_1/2_MI_FROM_MOUTH_LA
    -93.221664   30.225000     !#8767816 LAKE_CHARLES_CALCASIEU_RIVER_LA
    -93.273331   30.026667     !#8767916 GRAND_LAKE_CALCASIEU_RIVER_LA
    -93.275002   30.183332     !#8767919 PRIEN_LAKE_CALCASIEU_RIVER_LA
    -93.320000   30.136667     !#8768012 L_CHARLES_WATERWAY_CALCASIEU_R_LA
    -93.328331   29.840000     !#8768044 CALCASIEU_PASS_NORTH_END_LA
 0 0.0 10.0  8      ! NOUTV,TOUTSV,TOUTFV,NSPOOLV - VEL STATION OUTPUT INFO (UNIT  62)
 0                  ! NSTAV - TOTAL NUMBER OF VELOCITY RECORDING STATIONS
 1 6.0 36.0  180    ! NOUTGE,TOUTSGE,TOUTFGE,NSPOOLGE : GLOBAL ELEVATION OUTPUT INFO (UNIT  63)
 0 6.0 36.0  180    ! NOUTGV,TOUTSGV,TOUTFGV,NSPOOLGV : GLOBAL VELOCITY  OUTPUT INFO (UNIT  64)
 38                 ! NFREQ
 STEADY             ! NAMEFR
 0.000000000000000   1.000   0.000      ! HAFREQ, HAFF, HAFACE
 MN
 0.000002639203296   1.000   0.000
               (etc)
 6.0  36.0 180  0.0  ! THAS,THAF,NHAINC,FMV - HARMONIC ANALYSIS PARAMETERS
 0 0 0 0            ! NHASE,NHASV,NHAGE,NHAGV - CONTROL HARMONIC ANALYSIS & OUTPUT TO UNITS 51-54
 1 2400              ! NHSTAR,NHSINC - HOT START FILE GENERATION PARAMETERS
 1  0  1.E-6  25 0   ! ITITER, ISLDIA, CONVCR, ITMAX, ILUMP - ALGEBRAIC SOLUTION PARAMETERS
 36                  ! MNPROC
------------------------------------------------------------------
RUN WITH ADCIRC V42.19T
```

Figure F.2. Sample fort.15 input file (also see Figure F.3).

```
 7      ! NTIF - NUMBER OF TIDAL POTENTIAL CONSTITUENTS BEING FORCED
 K1     ! ALPHA - ALPAHANUMERIC DESCRIPTION OF TIDAL POTENTIAL CONSTIT.
  0.141565  0.000072921158358  0.736  1.000  0.000
 O1
  0.100514  0.000067597744151  0.695  1.000  0.000
 Q1
  0.019256  0.000064958541129  0.695  1.000  0.000
 M2
  0.242334  0.000140518902509  0.693  1.000  0.000
 S2
  0.112841  0.000145444104333  0.693  1.000  0.000
 N2
  0.046398  0.000137879699487  0.693  1.000  0.000
 K2
  0.030704  0.000145842317201  0.693  1.000  0.000
 7      ! NBFR - TOTAL NUMBER OF FORCING FREQUENCIES ON OPEN BOUNDARIES
 K1     ! ALPHANUMERIC DATA FOR OPEN OCEAN FORCING
  0.000072921158358   1.000  0.000
 O1
  0.000067597744151   1.000  0.000
 Q1
  0.000064958541129   1.000  0.000
 M2
  0.000140518902509   1.000  0.000
 S2
  0.000145444104333   1.000  0.000
 N2
  0.000137879699487   1.000  0.000
 K2
  0.000145842317201   1.000  0.000
```

Figure F.3. Extended version of the tidal data in fort.15.

The parameters in the order that they appear in the input file, fort.15, are as follows.

I.) RUNDES, RUNID, NFOVER, NABOUT, NSCREEN, IHOT

The first and second records of the input file are a brief description of the run. It is usually helpful to give each run a distinct name and list, in one of the first two lines, the name of the mesh used for this run. These parameters are called *RUNDES* (run description) and *RUNID* (run identification).

The third parameter is *NFOVER* (non-fatal error override) and should be set to 1 so that the program will not automatically stop if input parameters are inconsistent, but rather give a warning in the screen output.

The next two parameters (*NABOUT* and *NSCREEN*) are parameters that control the output of diagnostic information. This is often helpful for initial model runs when the user is still testing for model stability, but they should be turned off (set to 0) if the mesh is larger than about 100,000 nodes after model stability is proved since the large grids produce prohibitively large output files.

The hot start parameter (*IHOT*) is available if computational time is not sufficient to complete one run. This parameter should be set to 0 for a cold start and 67 or 68 for a hot start (depending on the input file the user wants to use – fort.67 or fort.68; the file written most recently is generally chosen).

II.) ICS, IM

The *ICS* parameter should be set to 2 to indicate that spherical coordinates will be used. (*ICS*=1 selects Cartesian coordinates, which are generally not applicable at the scale of coastal ocean models). In the ADCIRC program, the spherical coordinates are transformed into Cartesian coordinates prior to discretization using a map projection (Carte Parallelo-grammatique Projection, or CPP). Coordinates in the input mesh file should be in decimal degrees longitude and latitude.

The model selection parameter (*IM*) allows the model to be run in 2DDI (two-dimensional, depth-integrated velocity) or 3D. All of the model runs done for the VDatum project are currently being run in 2-dimensions by setting this parameter to 0.

III.) NOLIBF, HBREAK, FFACTOR, FTHETA, FGAMMA

The bottom friction law used in ADCIRC is determined by the *NOLIBF* parameter. Generally, bottom stress is expressed as $\tau_{bx}=U\tau_*$ and $\tau_{by}=V\tau_*$, where *U* and *V* are the velocity terms and τ_* is the bottom friction coefficient.

For the linear friction option, where the *NOLIBF* parameter is set to 0, $\tau_* = C_f$, where C_f is the user specified bottom friction coefficient, and that term is constant in time, but may vary in space.

For the quadratic friction option, where the parameter *NOLIBF* is set to 1, a general quadratic formula is used for τ_* such that

$$\tau_* = \frac{C_f (U^2 + V^2)^{1/2}}{H} \qquad \text{(F.1)}$$

where *H* is the bathymetric depth at the node and C_f is the user specified bottom friction coefficient.

For the so-called hybrid friction, where the *NOLIBF* parameter is set to 2, the same formula for τ_* is used as was defined for the quadratic friction option, but C_f is not assigned by the user. Rather, it is calculated by the following formula:

$$C_f = C_{f\,\min} \left[1 + \left(\frac{H_{break}}{H} \right)^{\theta} \right]^{\gamma/\theta} \qquad \text{(F.2)}$$

In this equation, *H* is again the bathymetric depth at a specified grid node and H_{break} (the so-called break depth called *HBREAK*) is a depth specified by the user such that in waters deeper than H_{break} (where $H > H_{break}$), C_f quickly approaches C_{fmin} (called *FFACTOR*), and in shallower waters (where $H < H_{break}$) C_f approaches $C_{fmin}(H_{break}/H)^{\gamma}$ The exponent, θ (called *FTHETA*) , determines how quickly C_f approaches the asymptotic limit and γ (called *FGAMMA*) determines how quickly the friction coefficient increases as the water depth decreases. This formulation increases the value of bottom friction coefficients in very shallow water, as defined by Manning's formula.

It is recommended that the quadratic (*NOLIBF* = 1) or hybrid bottom friction laws (*NOLIBF* = 2) be used. If the hybrid law is used, it is recommended that all parameters be set to typical values to mimic Manning's quadratic bottom friction (unless there is some prevailing reason to increase the friction dramatically in the very shallow waters). For *NOLIBF* = 2, the user is required to specify C_{fmin}, H_{break}, θ, and γ. These associated parameters are listed on line twenty eight where C_{fmin} = *FFACTOR*, H_{break} = *HBREAK*, θ = *FTHETA*, and γ = *FGAMMA*. In the hybrid bottom friction formulation, it is common to use *HBREAK* = 1.0 m (or the smallest number possible that results in stable model runs), *FTHET*A= 10, and *FGAMMA* = 1/3. Again, these parameters are on line twenty-eight. If the linear (*NOLIBF*=0) or quadratic (*NOLIBF*=1) bottom friction law is used), only the *FFACTOR* parameter is necessary and should be set to the desired C_f. Typical values of *FFACTOR* for either nonlinear formulation are between 0.002 and 0.004; the recommended value of *FFACTOR* is 0.0025.

IV.) NOLIFA, NOLICA, NOLICAT

The non-linear finite amplitude terms should be included; when the *NOLIFA* parameter on line ten is set to 2 they are enabled and wetting and drying is also activated in the model. Sometimes, though, when a model is first being set up and tested for stability, this term should be set to 0 for the linear option; after model stability has been proven, it can be changed back to 2 for the non-linear option. (Setting this parameter to 1 allows the non-linear finite amplitude terms to be included, but wetting and drying to be deactivated.)

The advective terms should be included in the calculations and this is done by setting the *NOLICA* and *NOLICAT* parameters to 1. However, the model tends to be very sensitive to instabilities generated by the explicitly handled advection terms. It is not uncommon for these terms to be disabled as model stability is being established during initial testing.

V.) NWP, NCOR, NTIP, NWS

The parameter controlling whether the bottom friction coefficient is constant in space or specified to be spatially varying is called *NWP*. This parameter is generally set to 0 to indicate constant bottom friction parameter (which is set in the *FFACTOR* parameter). This can be changed to 1 to allow spatially varying bottom friction coefficients, in which case there needs to be a "fort.21" file. This file is in the standard grid format and instead of the z-value lists the *FFACTOR* for each node in the grid. However, if *NWP* is set to 1, the hybrid friction option cannot be chosen.

The *NCOR* parameter controls whether the Coriolis parameter is constant in space and read in below (*NCOR*=0) or spatially varying (*NCOR*=1*)*. The read-in value, *CORI* , is defined in section IX below. The model will automatically calculate the spatially variable Coriolis parameter for grids in latitude/longitude coordinates.

The tidal potential option parameter (*NTIP*) is usually set to 1, indicating that tidal potential forcings are used as defined later in the input parameter control file. If this parameter is set to 0, neither tidal potential nor self attraction/load tide forcings will be used. If this parameter is set to 2, both the tidal potential and self attraction/load tide forcings will be used, and the self attraction/load tide information will be read in for each constituent at each node in the grid from a separate forcing file, “fort.24”.

Wind stress and barometric pressure options are available using the *NWS* parameter. These options will not be discussed, since they are not used for datum modeling exercises, and this parameter should be set to 0.

VI.) NRAMP, DRAMP, G, TAU0

The ramp option parameter (*NRAMP*) should be set to 1. This allows a hyperbolic tangent ramp function to be applied to the surface elevation specified boundary conditions, nonzero flux boundary conditions, tidal potential terms, wind and atmospheric pressure forcing, and wave radiation stress. The number of days this ramp function is specified as the *DRAMP* parameter. For the domains used for tidal datum modeling, 5 days should be sufficient for the *DRAMP* parameter. For the initial test runs, the water surface elevation should be recorded for the first 10 days at several nodes in the mesh to insure that this is a sufficient amount of ramp time. This time series can be plotted to show that the tidal response in the domain has successfully ramped up to the full value of the tidal signal without the generation of spurious oscillations.

The gravity factor, “G”, should be set to 9.81 to indicate SI units of m/s^2. It could be set to 32.2 to indicate ft/s^2, if the user needs the results in English units. Care should then be taken to adjust other terms in the model input in SI units to English units (e.g., tidal amplitude, bathymetry).

This parameter (called *TAU0)* sets the balance between the wave equation and the primitive continuity equations in the Generalized Wave Continuity Equation (GWCE) formulation of the shallow water equations that is the foundation of the ADCIRC model. Using any negative number allows optimum *TAU0* values to be selected by the model according to water column depth. It is strongly suggested that -0.02 be used, which selects a value of 0.005 for depths greater than 10 m and 0.02 for depths less than 10 m in ADCIRC 44.19.

VII.) DT, STATIM, REFTIM, RNDAY, DRAMP

The size of the time step is set with the *DT* parameter. For the ADCIRC model, the stability is generally Courant number-based, and the time step should be selected to keep the Courant number less than 1. The Courant number describes the relationship between physical and numerical wave propagation speeds, and is calculated by $\mathbf{C} = v*dt/dx$, and can be approximated by $\mathbf{C} = 1*DT/dx_{min}$. This can also be computed in SMS using the “Data Calculator” (found in the “Mesh Module” in the “Data” menu). For tidal models where the smallest elements are about 50 m, a DT of 3 seconds should be fine. The starting time (*STATIM*) and reference time (*REFTIM*) allow the user to simulate specific time periods, but for the datum modeling, these can be generic and should be set to 0.

The run time (*RNDAY*) is the total number of days that the model should run. This needs to include the ramp period (defined with the *DRAMP* parameter). To get a 31 day time series with a 5 day ramp period the *RNDAY* parameter should be set to 37 to allow the first 5 days for the ramp, 1 day to insure model stability and the last 31 days to record the time series.

VIII.) A00, B00, C00, HO, NODEDRYMIN, NODEWETMIN, VELMIN

The weighting factors that apply to the GWCE formulation are called *A00, B00,* and *C00*. These should be left at 0.35, 0.30, and 0.35.

The *H0*, *NODEDRYMIN*, *NODEWETMIN*, and *VELMIN* parameters apply to the wetting and drying algorithm in ADCIRC. When wetting and drying is turned on (*NOLIFA* = 2), all four of these parameters need to have values listed. If wetting and drying is turned off (*NOLIFA* = 0 or 1), then only the *H0* parameter will be read in. If wetting and drying is active (as is generally the case for VDatum tidal model runs), the *H0* parameter is the minimum water depth allowed before a node dries. Typically, this is set to 0.1 m. If wetting and drying is turned off, *H0* sets the minimum bathymetric depth (to allow all the nodes in the grid to stay wet); typically this is set to 1.0 m. If this is not large enough to be deeper than minimum tidal water levels the model will crash. Since the tidal datum models should be run with wetting and drying on, *H0* should be set to 0.1 m to specify the minimum depth that will be allowed before the node dries. The next two parameters, *NODEDRYMIN* and *NODEWETMIN*, set the number of time steps a node must stay dry before it can wet again and the number of time steps it must stay wet before it can dry again. These parameters should be set to 0 and are in fact obsolete in later versions of the code. The *VELMIN* parameter sets the minimum velocity needed for wetting an element and a typical value is 0.05 m/s.

IX.) SLAM0, SFEA0, ESLMM, CORI

Since the coordinate system parameter *ICS* is (usually) set to 2, the *SLAM0* and *SFEA0* parameters should be set to the longitude and latitude that is at or near the center of the model domain. An approximation is sufficient.

The spatially constant horizontal eddy viscosity parameter for the momentum equations (*ESLM*) should be set as low as possible to maintain model stability. In fact, too large of a value will also lead to instability due to the use of the explicit solver. Generally, this value is between 1 and 5 m^2/s.

The constant Coriolis coefficient (*CORI*) is only used if *NCOR* = 0. When NCOR is 0, this indicates that a spatially constant Coriolis coefficient will be used and that value is read in from the fort.15 file. This generally would only be the case if the grid was in Cartesian coordinates, which is not likely to occur in VDatum applications. If *NCOR* = 1, a spatially variable Coriolis coefficient is computed; CORI is read in, but ignored.

X.) NTIF, TIPOTAG, TPK, AMIGT, ETRF, FFT, FACET

Although tidal potential forcing is more important for large domains than the small regional areas which are the focus of the tidal datum modeling efforts for the VDatum project, the tidal potential terms are usually included in the model runs for consistency and completeness. A series of parameters describe the tidal potential forcing used in the ADCIRC model.

First the number of tidal potential constituents (*NTIF*) is given. Usually this is 7 or 8. Then, for each tidal potential constituent, first a line with the alphanumeric description (*TIPOTAG*) such as

"M2", "K1", etc. is listed followed by a line that gives tidal potential amplitude in meters (*TPK*), tidal frequency (*AMIGT*), earth tide potential reduction factor (*ETRF*), nodal factor (*FFT*) and equilibrium argument (*FACET*) in degrees. Currently, the ADCIRC tidal datum modeling efforts have set the nodal factors and equilibrium arguments to match the values at the middle of 1992 (the half-way point of the 1983 to 2001 NTDE). In Table F.1., the eight major astronomical constituents and the tidal potential amplitude, frequency, and earth tide potential reduction factors are given. The nodal factors and equilibrium arguments associated with the middle of 1992 are also listed.

Table F.1. List of the eight major astronomical constituents and the tidal potential amplitude, frequency, and earth tide potential reduction factors. The nodal factors and equilibrium arguments associated with the middle of 1992 are also listed.

Constituent	Tidal Potential Amplitude (m)	Tidal Potential Frequency (radians/sec)	Earth Tide Potential Reduction Factor	Nodal Factor	Equilibrium Argument (degrees)
K1	0.141565	0.000072921160387	0.7360	1.0337	18.3864
O1	0.100514	0.000067597746032	0.6950	1.0552	79.6041
P1	0.046843	0.000072522947993	0.7060	0.9984	350.7977
Q1	0.019256	0.000064958542936	0.6950	1.0544	326.8412
M2	0.242334	0.000140518906419	0.6930	0.9941	101.3723
S2	0.112841	0.000145444108380	0.6930	1.0004	359.8745
N2	0.046398	0.000137879703323	0.6930	0.9900	348.9695
K2	0.030704	0.000145842321259	0.6930	1.0637	217.2271

XI.) NBFR, BOUNTAG, AMIG, FF, FACE, ALPHA, NETA, EMO, EFA

The number of forcing frequencies used along the open boundary is listed as the *NBFR* parameter. Generally this number matches the *NTIF* listed above. Following the *NBFR*, each constituent is listed with an alphanumeric description (*BOUNTAG*) followed by the forcing frequency (*AMIG*), nodal factor (*FF*), and equilibrium argument (*FACE*) for tidal forcing on elevation specified boundaries. The *AMIG*, *FF*, and *FACE* should be the same as the *AMIGT*, *FFT*, and *FACET* used with the tidal potential forcing. Again, the nodal factors and equilibrium arguments are set to match the values at the middle of 1992 (for 1992, the *FF* value for the M2 constituent is 1.00).

Following these parameter declarations, for the number of constituents (*NBFR*), the alphanumeric description (*ALPHA*) is listed followed by the constituent amplitude (*EMO*) and constituent phase (*EFA*) for the number of nodes along the open boundary (*NETA*), which is listed in the fort.14 grid file.

In the ADCIRC model, the open boundary is forced with periodic water level variations to astronomical tides. The water level, relative to the model's zero elevation, at the outer boundary is:

$$H = h_o + \sum f_n \, A_n \cos \left(\omega_n + [Vo + u]_n - \kappa_n \right) \qquad \text{(F.3)}$$

where H is the total water level (m), h_o represents a constant offset (here taken to be zero), and the remaining term represents the astronomical tide. A_n is the constituent amplitude (m), ω_n is the constituent speed (degrees/hr), $[Vo + u]_n$ is the equilibrium angle (degrees), and κ_n is the phase relative to Greenwich time (degrees). There is a unique set of harmonic constants at each grid node along the coastal boundary.

XII.) ANGINN

The inner angle threshold (*ANGINN*) applies to the flow boundary nodes which are set up to have a normal flow essential boundary condition. If the nodes have an inner angle less than *ANGINN* (specified in degrees), the nodes will have the tangential velocity zeroed. The recommended value is 100.0 degrees.

XIII.) NOUTE, TOUTSE, TOUTFE, NSPOOLE, NSTAE, XEL, YEL

ADCIRC can record data at particular locations (like NOS water level station locations). The water surface elevation time series at specified locations are recorded in the output "fort.61" file. To create this file, the parameter *NOUTE* should be set to 1. If *NOUTE* is set to 0, no fort.61 file will be printed. The parameter *TOUTSE* is the starting time (in days) of the time series and *TOUTFE* is the ending time (in days). The *NSPOOLE* parameter is the number of time steps at which the elevation data is recorded. This should be set to record data every 6 minutes in order to match CO-OPS data standards, so *NSPOOLE* is calculated by dividing 360 seconds by *DT*. The number of user specified stations (*NSTAE*) is listed and the coordinates of the station locations follows (*XEL*, *YEL*). Stations that are located outside the model grid will be extrapolated from the nearest model node.

XIV.) NOUTV, TOUTSV, TOUTFV, NSPOOLV, NSTAV, XEV, YEV

The depth-averaged velocity can also be recorded at specified stations. The output is recorded in a "fort.62" file. To create this file, the *NOUTV* parameter should be set to 1. If *NOUTV* is set to 0, no fort.62 file will be created. The parameter *TOUTSV* is the starting time (in days) of the time series and *TOUTFV* is the ending time (in days). The *NSPOOLV* parameter is the number of time steps at which the elevation data is recorded. The number of user specified stations (*NSTAV*) is listed and the coordinates of the station locations follows (*XEV*, *YEV*). Stations that are located outside the model grid will be extrapolated from the nearest model node.

XV.) NOUTGE, TOUTSGE, TOUTFGE, NSPOOLGE

To record elevation time series data at every node in the grid, the global elevation parameter *NOUTGE* must be set to 1. If *NOUTGE* is set to zero, no global output elevation time series file will be written. This output file is called "fort.63". The starting time in days and the ending time in days are set with the *TOUTSGE* and *TOUTFGE* parameters, respectively. The *NSPOOLGE* parameter sets the time step interval at which this data is recorded. This should be set to record data every 6 minutes in order to match CO-OPS data standards, so *NSPOOLGE* is calculated by dividing 360 seconds by *DT*.

XVI.) NOUTGV, TOUTSGV, TOUTFGV, NSPOOLGV

If the parameter NOUTGV is set to 1, the velocity will be recorded every NSPOOLGV time steps into the output “fort.64” file. The TOUTSGV and TOUTFGV parameters set the starting time and ending time (in days) for the data output. If NOUTGV is set to 0, no output will be recorded.

XVII.) NFREQ, NAMEFR, HAFREQ, HAFF, HAFACE

A least squares harmonic analysis program is included in the ADCIRC model. This analysis is done “on the fly” and can be done for the elevation or velocity results for the number of frequencies specified with the NFREQ parameter. For each frequency, the name of the associated constituent (NAMEFR) is listed. Following the alphanumeric description of the constituent, the frequency (HARFREQ), nodal factor (HAFF), and equilibrium argument (HAFACE) are listed. (These constituents that duplicate the tidal potential and boundary forcing should have the same frequency, nodal factor and equilibrium argument listed previously in the input file.)

XVIII.) THAS, THAF, NHAINC, FMV

The harmonic analysis parameters *THAS* and *THAF* set the number of days after which the analysis begins and ends, respectively. The number of time steps at which information is harmonically analyzed is listed in the *NHAINC* parameter. The parameter *FMV* sets the fraction of the analysis period (extending back from the end of the period) to use for comparing the water elevation and velocity means and variances from the raw model time series with corresponding means and variances of a time series synthesized from the harmonic constituents. If this parameter is set to 0, nothing will be computed. The entire time period will be used for this calculation if *FMV* is set to 1. A fraction of the time period will be used for any number between 0 and 1. For example, if *FMV* is set to 0.1, 10% of the period will be used to compute the means and variances.

XIX.) NHASE, NHASV, NHAGE, NHAGV

For all of the following parameters, if they are set to 0, no harmonic analysis will be done and no data will be recorded to output files. If the analysis is computed, the time series is that specified with the *THAS* and *THAF* parameters listed above. If *NHASE* is set to 1, harmonic analysis will be performed at the selected elevation recording stations specified earlier in the input parameter file. The output is in a “fort.51” file. If *NHASV* is set to 1, harmonic analysis will be performed at the selected velocity recording stations specified earlier in the input parameter file. The output is in a “fort.52” file. If *NHAGE* is set to 1, harmonic analysis will be performed at every node in the grid based on the water level elevation time series. The output is in a “fort.53” file. If *NHAGV* is set to 1, harmonic analysis will be performed at every node in the grid based on the velocity time series. The output is in a “fort.54” file.

XX.) NHSTAR, NHSINC

To generate hot start files, the NHSTAR parameter must be set to 1, and the number of time steps at which that output is generated is specified with the NHSINC parameter. If NHSTAR is set to 0, no output will be generated. . Generally it is advisable to generate hot start files on an hourly basis so *NSHINC* can be determined by 3600 divided by the time step *DT*.

XXI.) ITITER, ISLDIA, CONVCR, ITMAX

To optimize the speed of the ADCIRC code, the following parameters should be set: ITITER = 1 (to use the iterative JCG solver), ISLDIA = 0 (to allow only fatal error messages from the ITPACKV 2D solver), CONVCR = $1.0\text{x}10^{-6}$ (to set the absolute convergence criteria for 64 bit machines) or CONVCR = $1.0\text{x}10^{-5}$ (to set the absolute convergence criteria for 32 bit machines), and ITMAX = 25 (for the maximum number of iterations for each time step).

F.2. COMPILING ADCIRC

The versions of ADCIRC code being used for VDatum projects is archived in the VDatum directory. In order to compile the ADCIRC program on the platform of choice, enter the program's 'work' subdirectory and open the 'cmplrflags.mk' file. This file lists appropriate compiler flags for many different computing systems. Uncomment out the appropriate one for your system if necessary. Then the program can easily be compiled in the 'work' directory by issuing the command 'gmake all'. This produces all executables included in the ADCIRC package: metis, adcirc, padcirc, adcprep, adcprep2, and adcpost. In order to run ADCIRC in a parallel environment three of these programs are necessary: adcprep, adcpost and padcirc. The adcprep program is the preprocessor for the parallel code that requests the input files (fort.14 and fort.15) and the number of processors in order to construct subdirectories for the parallel run. Once completed, the parallel version of adcirc (named padcirc) can be submitted to the job queueing system on the parallel computer. The procedure for this submission generally requires a script and commands specific to that system's implementation; please see the system administrator for this information. Following the run's completion the adcpost program will gather the results distributed over multiple directories and combine them into a global result.

VDatum model implementations for NOS are primarily run on the Earth System Research Laboratory's High Performance Computing System (HPCS). As of this document's publishing, the system is composed of two distinct Beowulf-type cluster supercomputers named 'ijet' and 'ejet'. However, as with all computing technologies details are likely to rapidly change and a prudent user will check with both his or her fellow users and the system administrator for the latest information. The 'ijet' system is composed of 32-bit Intel Xeon dual processor machines operating at 2.2 GHz, while 'ejet' is built from 64-bit Intel Xeon dual processor machines operating at 3.2 GHz. Login to the system requires the user to request an account and corresponding SILVER Safeword password device. Remote access is accomplished through ssh and file transfer via scp. Both systems have implemented the Intel FORTRAN compiler (ifort), and the compiler setup below has been found to be successful. With these flags chosen by the user in 'cmplrflags.mk', the 'gmake all' command will generate all ADCIRC executables (Figure F.4).

The ESRL HPCS operates a batch job submission system that manages execution of all submitted jobs. This system is the SUN Grid Engine (SGE) and requires users to submit a job script with appropriate commands for running on the HPCS. Accounts for VDatum users are currently limited to 128 processors and 8 hour run times. A sample job script is shown in Figure

F.5. In order to submit the job, the user must issue the ‘$qsub *scriptname*’ command. Job status can be examined by ‘$qstat –u *username*’ and job deletion is executed by ‘$qdel *jobID*’.

```
########################################################################
# Intel-Linux computers using Intel compiler
# These flags have been tested on NOAA FSL IJET and EJET
#
# ***NOTE*** User must select between various Linux setups
#            by commenting/uncommenting these sections
#
#ifeq ($(MACHINE)-$(OS),i686-linux-gnu)
  FC            :=  ifort -Qoption,link,--noinhibit-exec -zero -w -save -tpp7
  PFC           :=  mpif90 -Qoption,link,--noinhibit-exec -zero -w -save -tpp7
  FFLAGS1      :=  -O2  -Vaxlib
  FFLAGS2      :=  -O2  -Vaxlib
  FFLAGS3      :=  -O2  -Vaxlib
  FFLAGS4      :=  -O2  -Vaxlib
  DA            :=  -DREAL8 -DLINUX -DCSCA
  DP            :=  -DREAL8 -DLINUX -DCSCA -DCMPI
  DPRE          :=  -DREAL8 -DLINUX
  DPRE2     :=  -DREAL8 -DLINUX -DCMPI
  IMODS        :=  -I
  CC            := icc
  CFLAGS        := -I. -O2 -DLINUX
  CLIBS         :=
  LIBS         :=  -L ../metis  -lmetis
  MSGLIBS      :=
#endif
```

Figure F.4. Intel-Linux compiler flags for ADCIRC as tested on ESRL’s HPCS.

```
#!/bin/csh -f
#
#$ -N runname
#$ -A mmap-emd
#$ -pe queuename 36  !!!NOTE: use queuename = ncomp for IJET, ecomp for EJET
#$ -cwd
#$ -r y
#$ -p 0
#$ -m b
#$ -m e
#$ -M first.last@noaa.gov
#$ -l h_rt=08:00:00
set WRKDIR="/misc/p50/mmap-emd/username/run_dir/"
echo "********************************************" >> $WRKDIR/run_name.out
echo "Starting job script at:" >> $WRKDIR/run_name.out
date >> $WRKDIR/run_name.out
echo "Configuring MPI..." >> $WRKDIR/run_name.out
source /usr/local/bin/setup-mpi.csh
set np=36
echo "Starting PADCIRC....." >> $WRKDIR/run_name.out
echo "********************************************" >> $WRKDIR/run_name.out
echo $np >> $WRKDIR/run_name.out
mpirun -np $np --gm-v  $WRKDIR/padcirc >> $WRKDIR/run_name.out
```

Figure F.5. SGE job submission script for ESRL’s HPCS.

F.3. RUNNING ADCIRC

The first step is to create the model input files. A sample of the fort.15 files is shown in Figures F.2 and F.3.

Even if great care is taken in setting up the initial model grid and input files, the first runs often experience stability problems. The follow are some suggestions on how to deal with commonly seen problems with each of the models used.

Often the instabilities manifested with the ADCIRC model are due to bathymetry or grid configuration problems. The first step should be to carefully examine the grid for areas of “missing” elements, disjoint nodes, etc. Also, elements that transition too quickly for a small to large element can cause problems. SMS can help look for these areas.

The model time series results can be examined too look for the exact location where the instabilities begin. Sometimes there is not enough resolution in areas where high velocities occur; more resolution can be added. If the bathymetry has not been carefully checked this should be done to make sure there aren’t steep (and unnatural) changes from one node to the next. This will have to be done by careful visual inspection; possibly a computer program to evaluate the percent depth change within an element could be written.

F.4. MODEL OUTPUT FILES

ADCIRC places output into several files. The file fort.61 contains water levels at selected nodes and fort.62 contains u- and v-components of water velocity at selected nodes, while fort.63 and fort.64 contain the respective quantities at all nodes. The files fort.51 and fort.52 contain harmonic constants analyzed from the time series of water levels and velocities, respectively, at selected nodes, and fort.53 and fort.54 contain corresponding data for all nodes. Files fort.67 and fort.68 contain values that can be used for a ‘hot start’.

After model stability has been established, the model results should be compared to the station data. As the models are only simulating astronomical events (disregarding the meteorological effects that are included in the tidal datum measurements at the NOS water level stations), it is useful to look first at the comparison of the tidal constituents from the analyzed model time series data with the tidal constituents at the NOS water level stations.

The shelf-scale models provide the most accurate open boundary forcing available, but they are not without problems themselves. After several model runs of the regional tidal datum model, the user may find that adjusting the amplitude of the larger constituents along the open boundary may provide more accurate results in the interior of the domain. Adjusting the boundary conditions should be a last resort, of sorts, and every attempt should be made to correct errors in the regional model by accurately representing the bathymetry, providing sufficient resolution and appropriately choosing lateral eddy viscosity and bottom friction parameters before changing the constituents along the open boundary.