TOPOGRAPHIC AND BATHYMETRIC DATA CONSIDERATIONS:

Datums, Datum Conversion Techniques, and Data Integration

Part II of *A Roadmap to a Seamless Topobathy Surface*

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NOAA Coastal Services Center
LINKING PEOPLE, INFORMATION, AND TECHNOLOGY

NOAA CONTRIBUTORS

LYNNE M. DINGERSON
NOAA COASTAL SERVICES CENTER
CHARLESTON, SOUTH CAROLINA
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Coastal Services Center	H. Jamieson Carter Brian C. Hadley Darcee Killpack Doug C. Marcy Steven C. Raber Keil A. Schmid Adam K. Stein Kirk J. Waters, Ph.D
National Geodetic Survey	David R. Doyle Jason W. Woolard
National Geophysical Data Center	Lisa A. Taylor
Office of Coast Survey	Frank Aikman III, Ph.D Mary C. Erickson Jesse C. Feyen, Ph.D Maureen R. Kenny Edward P. Myers, Ph.D
Pacific Marine Environmental Laboratory	Chris D. Chamberlin Nazila Merati

U.S. DEPARTMENT OF COMMERCE
CARLOS M. GUTIERREZ, SECRETARY

NATIONAL OCEANIC AND ATMOSPHERIC ADMINISTRATION
CONRAD C. LAUTENBACHER, JR., VADM USN (RET.), UNDER SECRETARY

NATIONAL OCEAN SERVICE
JOHN H. DUNNIGAN, ASSISTANT ADMINISTRATOR

COASTAL SERVICES CENTER
MARGARET A. DAVIDSON, DIRECTOR

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ABOUT THE SERIES: *A Roadmap to a Seamless Topobathy Surface*

A topobathy digital elevation model (DEM) is a single surface combining the land elevation with the seafloor surface—and which can be used to examine processes that occur across the coastal and nearshore areas. *A Roadmap to a Seamless Topobathy Surface* (*Roadmap*) is a series of documents and maps that seek to improve and streamline the process of creating a topobathy DEM. The series aims to make topographic and bathymetric data and reference information accessible and make connections between data set quality and DEM application (such as coastal inundation modeling). Understanding the links between input data quality and application can help users create a DEM surface designed for a particular purpose, can help data collectors provide data sets that meet needs, and can assist technical users in defining their data requirements more explicitly.

The *Roadmap* examines resources and processes associated with DEM creation, including the following: (1) available data resources, (2) processes to generate high-resolution DEMs that minimize error, and (3) examples of topobathy applications. The target audience for this suite of information includes technical users of surface data within coastal management groups, scientists, federal and state agencies, and local offices using topographic and bathymetric data for technical applications. The *Roadmap* may also be useful to managers who are involved in activities such as planning a data collection. This series of products will help detail the steps required to create seamless coastal maps—a task that has been highlighted as an important national need by the National Research Council.

The first part of the *Roadmap* series is an inventory of available topographic and bathymetric data resources for the Gulf of Mexico: *Topographic and Bathymetric Data Inventory: Gulf of Mexico (Gulf Inventory)*. The Gulf of Mexico coastal area was chosen for this project to assist data coordination efforts and to enhance geospatial capacity across the Gulf states. The *Gulf Inventory* is meant to increase awareness and use of existing topographic and bathymetric data sets, decrease duplication of effort, and strategically target data collections to fill gaps. It is a “snapshot” of data availability as of November 15, 2007, and it identifies location, collection date, and sources of available data sets. This resource is currently available on the National Oceanic and Atmospheric Administration (NOAA) Coastal Services Center’s website (*www.csc.noaa.gov/topobathy/*). The next *Topographic and Bathymetric Data Inventory* will be for the Southeast portion of the U.S., from Florida to Maryland.

This document, *Topographic and Bathymetric Data Considerations: Datums, Datum Conversion Techniques, and Data Integration (Data Considerations)*, is the second part of the *Roadmap*, and it strives to improve and streamline the process of creating DEMs by providing a review of available datum conversion and integration techniques. It describes the importance of establishing a uniform reference for multiple data sets and techniques for manipulating and joining data sets. This document provides information on vertical and horizontal references (datums) for data sets and addresses the need for and the importance of datum conversion. It also introduces available datum conversion techniques, details the resources necessary to use each technique, and discusses limitations and error for each technique. Once data sets have a uniform reference, many data integration techniques are available to create a topobathy surface that suits the final DEM application, and many common data integration techniques are addressed in this document.

The third part of the *Roadmap* will highlight some common coastal applications that can benefit from a highly accurate, high-resolution DEM. This reference, which is not yet completed, will describe applications of topographic, bathymetric, and topobathy DEMs and address standards for input data and the resulting DEM for an application. This information will help guide users on the practical and potential need for, and uses of, coastal elevation data and also provide technical users of elevation data with information to create a DEM specific to the needs of their application. Some examples of applications that may be addressed are shoreline delineation, wetland mapping, and inundation modeling. This reference is now in development and will be available in online.

ABOUT THIS PAPER: *Topographic and Bathymetric Data Considerations*

To understand the effects of a change in coastal water level or the impacts of inundation, a seamless surface that represents both the topography of the land and the bathymetry of the seafloor is necessary. Such a seamless topobathy surface can require high-resolution data and is an important factor when modeling processes (such as storm surge) that occur across the land-water interface. The need for accurate seamless coastal elevation maps was highlighted in the recommendations of the National Research Council report on "National Needs of Coastal Mapping and Charting," specifically with respect to the coastal management community.

Topographic and Bathymetric Data Considerations (Data Considerations), the second part of the *Roadmap* series, strives to improve and streamline the process of creating DEMs by providing a review of available datum conversion and integration techniques. When developing a topobathy surface, it can be critical to minimize error where possible, and some error occurs when combining data sets to create one surface. It is essential to (1) consider the original data reference (or datum, a surface to which the data collection is referenced), (2) understand issues with and options for converting among datum references, and (3) use data integration techniques that produce a useful surface for the application. *Data Considerations* is designed to inform a technical user about elevation data reference and to help identify areas where error can be minimized. As data collection technologies grow more precise, techniques used to manipulate data sets must maintain the integrity of the original data. When a high-resolution, high-accuracy digital elevation model (DEM) is necessary for an application, it is critical to establish a common reference and use appropriate data integration techniques when combining data sets. For applications that require lower resolution DEM surfaces, it may not always be necessary to establish a common reference.

For topobathy DEMs, which are composed of topographic and bathymetric data sets, datum conversion is usually necessary. Topography data sets are collected mainly for land-based applications (such as hydrology and habitat mapping), while bathymetric data sets are typically collected for applications relevant to the water level (such as navigation). Because of the difference in intended application, these data sets are collected using different datum references. The first step in creating a seamless topobathy surface that integrates these two data sets is to convert the data sets to a uniform reference. Tools and techniques, including VDatum, the Harmonic Constant Datum Method, and Interpolation, have been developed to approximate the differences between datum references. *Data Considerations* introduces each of these techniques, provides information on the data required and methods used, and describes the sources of error and limitations of each technique. In addition, it also describes the consequences for not taking datum reference for a DEM into account. This document is not a manual for execution of a specific technique; instead, it provides an overview of each technique, a description of the resources necessary to use the technique, and the relative accuracy of the transformation. In general, there is a trade-off between the necessary human or data resources necessary and the accuracy of the transformation. The choice of datum transformation mechanism should consider the quality of the existing data (input data and hydrodynamic data), available resources to enhance data, and the application for which the DEM is designed. Ultimately, all mechanisms are limited by the number and spatial distribution of points tied to multiple datums, such as surveyed tide stations; hence, the elimination of error is not possible.

Resolving the data reference issue will not eliminate all data mismatches; those stemming from differences in collection date, sensor, or impacts from a major event will persist in the data sets. Many can be resolved or generalized by using the appropriate data integration techniques. The keys to integrating data sets are selecting a grid that suits the application, knowing when to use interpolation and selection techniques, and knowing the cell-size and type appropriate for the application. Using data integration and datum conversion techniques appropriate for the final application will allow modelers to represent the surface with maximum accuracy and minimum cost.

INTRODUCTION

In recent years, topographic (land-surface) and bathymetric (seafloor-surface) data collection technology has grown more precise, and high-resolution data have become increasingly available. Yet creating high-resolution digital elevation models (DEMs) that use multiple data sets can be complicated by data set mismatches in reference, sensor, or collection date. Resolving these mismatches—by establishing a uniform reference and using data integration techniques—is essential when generating a seamless topobathy DEM for a specific application (such as shoreline delineation, coastal flood zone mapping, wave modeling, coastal engineering, habitat restoration, and modeling of storm surge, inundation, or tsunami). This document outlines many important considerations when building a high-resolution DEM. Specifically, this document reviews available datum conversion and integration techniques that are especially important for high-resolution topobathy DEMs.

A topobathy surface seamlessly represents the solid surface from the topography of the land to the bathymetry of the seafloor. This continuous surface is essential for modeling applications that span the land-water interface (such as inundation modeling). Unfortunately, while the names of the two surface types combine easily to form the blended topobathy name, the data collections for each type cannot be combined as easily because they use different reference surfaces (datums). The reference surfaces are chosen with the final application in mind, and topographic surfaces are used for different purposes than bathymetric surfaces. Topography is generally collected for land-based applications (such as hydrology and habitat mapping), and bathymetry is collected for applications that are relevant to the level of the water (such as navigation). When applications require a topobathy surface, it is critical to understand how to combine these data sets using datum conversion and integration techniques to minimize error in high-resolution DEMs.

Particularly for high-resolution applications, datum conversion techniques should be used (where possible) to establish a common reference system among data sets. Conversion techniques (such as VDatum, the Harmonic Constant Datum Method, and Linear Interpolation) can be used to transform data sets to a uniform reference. When selecting a method, it is important to consider the information necessary to apply the technique, advantages to the approach, error associated with the process, and limitations to its use. If the data set references are not resolved to a uniform reference, error is introduced into the final model. For low-resolution applications, converting data sets to a uniform reference is not always cost-effective because the error introduced by inconsistent data reference is outweighed by the generalization over a large grid cell size. Once data sets have a consistent reference, some data integration is usually still required to make the data sets seamless.

Differing reference surfaces are not the only reason for data set mismatches; mismatches can occur because of differing collection dates, seasons, or sensors. Data integration techniques can help resolve additional conflicts. Three such techniques, involving data subsets, point selection methods, and grid cell size and structure, are discussed in this document.

The goal of a topobathy DEM is to accurately represent the surface of the Earth, but the degree of accuracy that is necessary and achievable will vary depending on the application. High-resolution applications and applications where changes in slope are particularly important require a higher degree of accuracy than low-resolution applications. Several lower-resolution topobathy products are available (including the 5 arc-minute TerrainBase, 2 arc-minute ETOPO2, and 3 arc-second Coastal Relief Model), but they are too coarse for many applications in coastal management. These topobathy DEMs do not correct for vertical or horizontal reference, but the area over which the elevation is averaged is large enough that correcting for datum reference would not make a substantial difference in the application of the DEM. Minimizing sources of error by using datum conversion and data integration techniques (as described in this document) is critical when the final product is a high-resolution DEM.

One application of a high-resolution topobathy DEM is modeling inundation from storm surge. Storm surge modelers can use a highly accurate DEM to analyze areas of greatest vulnerability during a storm event. The data sets that comprise this DEM must have a uniform reference or the accuracy is compromised. For example, if reference is not taken into account and the offset between two adjacent data sets is two feet, the DEM will indicate the existence of a two-foot drop-off at the intersection. If this DEM were used for storm surge modeling, the water would behave differently because of this drop-off, and the prediction of inundated areas would be inaccurate.

Storm surge modelers commonly request the best currently available data sets that have a common datum reference. In many cases, this stated request is overly broad and does not identify the actual needs for data standards of the DEM. The question that should be asked is the following: What data are needed to represent the surface with sufficient accuracy for a specific application? To answer that question, modelers need to consider spacing and resolution, currency requirements, acceptable error, and delivery format for the final product. In some cases, the “best available” data set may not actually meet the needs of the final product. Much of the uncertainty in the answer to this question stems from uncertainty about model sensitivity. There is no general understanding of the impact on model results when topography or bathymetry is in error by a meter or 10 meters. The modeling community is beginning to address some of the questions associated with model sensitivity and evaluate the trade-offs involved with the answers. For example, storm surge and tsunami inundation modeling are generally similar, but each requires a unique evaluation of model sensitivity to various data parameters. This illustrates the need for experts in their fields to help define required data standards, as opposed to simply using the “best available.”

The final modeling application must be considered when making early design and data set decisions to streamline the process and make it cost-effective. This document will focus primarily on necessary considerations when integrating topographic and bathymetric data into a single, uniform topobathy DEM.

DATUMS

When integrating multiple data sets, it is important to ensure that all data sets are referenced to the same horizontal and vertical datum. Neglecting this step will introduce avoidable error into the final elevation surface. Each topographic or bathymetric data set is, or should be, referenced to a horizontal and a vertical datum.

- A *horizontal datum* is an established reference for location along a horizontal surface and is based on a geometric model.
- A *vertical datum* is an established surface that serves as a reference to measure or model heights and depths. Vertical datums are based on physical models, geometric/gravimetric models, or tidal models. Individual terrain (topography and bathymetry) data sets for topobathy surfaces will almost certainly be referenced to different vertical datums, including orthometric, tidal, and ellipsoidal datums. Each of these datums is best suited for particular applications, such as water flow, navigation, and satellite positioning, respectively.

Figure 1 depicts the relationship between the Earth's surface, the geoid, and the ellipsoid, and the figure is referred to throughout the following sections. The blue surface represents the surface of the Earth, and the green and red surfaces represent the geoid and ellipsoid reference surfaces, respectively. H is the distance (or height) between the Earth's surface and the geoid surface, and h is the distance (or height) between the Earth's surface and the ellipsoid. N is the distance (or height) between the geoid and the ellipsoid, which can be used to convert the reference of a data set. The height value for H, h, and N can be positive or negative depending on the spatial relationship of the surfaces. In the equation below, N is in brackets because the figure indicates that N is a negative number.

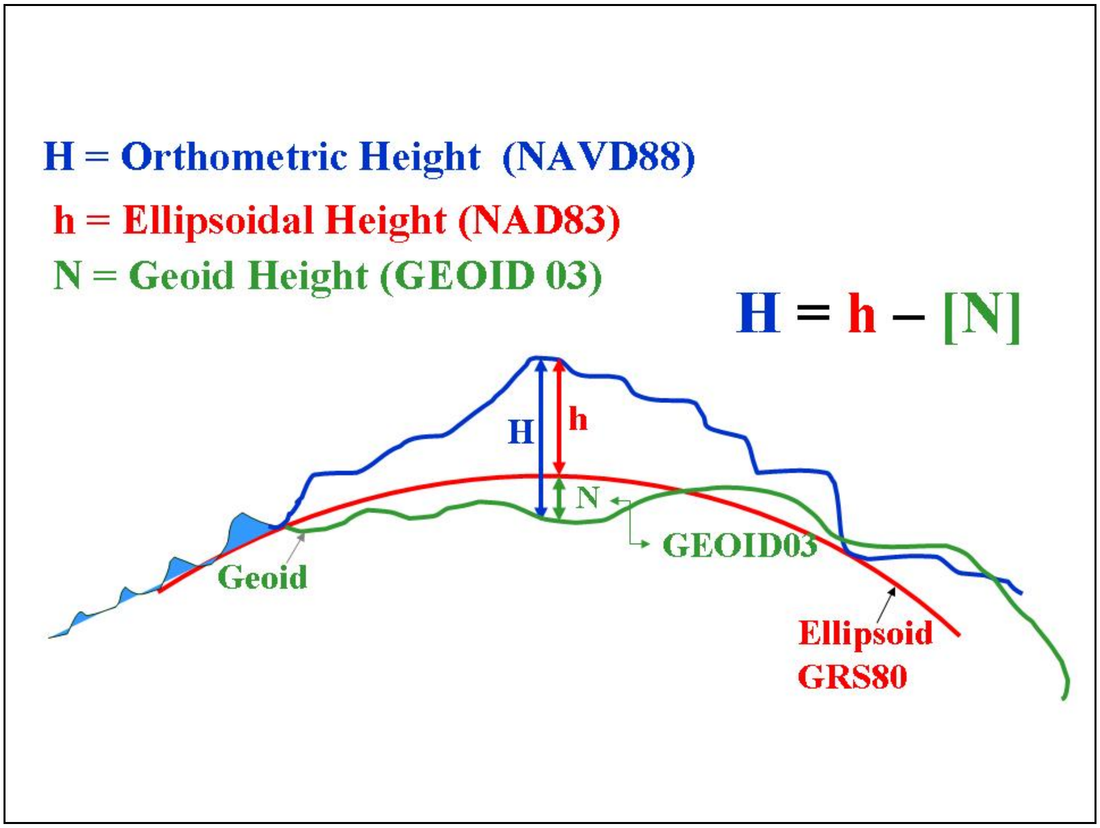

Figure 1: Relationship of orthometric and ellipsoidal surfaces to the surface of the Earth. The blue surface represents the Earth's surface and the red and green surfaces represent the ellipsoid and the geoid, respectively. (Source: NOAA National Geodetic Survey)

Orthometric Height Datums

Simply put, an orthometric height is the height of a point on a surface (such as the Earth) above or below a modeled surface (the geoid). The geoid is a physical and gravitational model that approximates the Earth’s equipotential surface—a modeled surface where the potential of gravity (geopotential) is the same everywhere. It is also meant to be a best fit to global mean sea level (MSL). The geoid surface is not a surface you can see or measure directly but is modeled from gravity, benchmark, and positioning data. The orthometric height reference is particularly useful when dealing with flow of water over land, since uniform gravity gives a clear indication of where water should flow.

The Earth's gravity field—determined using observations from terrestrial, airborne, and satellite gravimeters—can be used to determine the geoid because both gravity and the geoid shape are derived from the distribution of the Earth's masses. In general, land masses and density variations in the crust, mantle, and core account for much of the variation in the height of the geoid surface.

The North American Vertical Datum of 1988 (NAVD88) is the official orthometric vertical datum reference for most of the U.S. It is available for the contiguous U.S. and limited parts of Alaska; however, the remaining U.S. coastlines, such as the Pacific and Caribbean Islands, use separate orthometric references (such as the Puerto Rico Vertical Datum of 2002 (PRVD02) or the Guam Vertical Datum of 2002 (GUVD04)). In cases where there is no unified reference (such as Hawaii and the Virgin Islands), most data collections rely on local datums.

NAVD88, which is fixed to MSL at one tidal station in Quebec, Canada, superseded the National Geodetic Vertical Datum of 1929 (NGVD29), which is based on 26 tidal controls but which has substantial errors (because MSL does not follow the geoid). NAVD88 was affirmed as the official civilian vertical datum for the U.S. by a notice in the *Federal Register* on June 24, 1993, by the Federal Geodetic Control Subcommittee (FGCS). The notice stated any surveying or mapping activities performed or financed by the federal government be referenced to NAVD88. In addition, it required that all federal agencies using or producing vertical height information undertake an orderly transition to NAVD88. NAVD88 is a great improvement, since the difference between the two reference surfaces can be as much as 1.4 meters in the conterminous U.S. Converting between NGVD29 and NAVD88 can be accomplished in many ways, including using VERTCON (a conversion program that uses grids of the difference between the two datums to perform the conversion). The geoid is updated approximately every three years because of advancements in the ability to estimate the gravitational potential of an area, and the current geoid reference for the U.S. is GEOID03. (*www.ngs.noaa.gov/GEOID/*)

Tidal Datums

Tidal datums are water elevation averages over a given period, and there are a number of tidal reference surfaces from which to choose. MSL is the average of water levels recorded hourly at a single location, whereas mean high water (MHW) and mean low water (MLW) are the averages of daily high and low water marks at a location. Similarly, mean higher high water (MHHW) and mean lower low water (MLLW) are the averages of daily higher high and lower low waters recorded at a given location. Mean tide level (MTL) is the average of MHW and MLW, while mean diurnal tide level (MDTL) is the average of MHHW and MLLW. The tidal datum chosen for reference depends on the application of the data.

Tidal datums vary based on global tidal characteristics and local hydrodynamic influences. The tides are controlled primarily by the gravitational influences and interactions of the sun and moon on the rotating Earth. Local and regional aspects—such as the coastline, basin shape, latitude, subsidence, isostatic rebound, and other hydrodynamic characteristics—also have a strong influence on the resulting tidal datum. Typically, tidal datums are modeled rather than based on real-time tidal observations. These datums are computed to be representative of a given tidal epoch (18.6 years), which is approximately the amount of time required for the major astronomical influences to complete one cycle. Tidal models can be used to convert among datum references.

The tidal datum chosen for a reference usually depends on the application of the data. For instance, hydrographic data used to generate navigational charts is most often referenced to MLLW to portray navigational obstacles most effectively, whereas data used for modeling tsunami inundation is most often referenced to MHW in order to represent the worst-case scenario during a tsunami event.

Ellipsoidal Datums

Ellipsoidal datums, also known as three-dimensional (3-D) datums, are primarily used for horizontal reference and can also be used as a vertical reference. Each datum includes an origin for the coordinate system (such as Earth mass-center), an orientation, and a mathematical model for the size and shape of the Earth. This model is called an ellipsoid, and it is a simple geometric representation of the surface of the Earth that serves as a consistent reference surface—it is not, however, an accurate representation of the Earth's surface. One example of an application that benefits from ellipsoid reference is collecting Global Positioning System (GPS) reference locations in the field. Since satellites are used for positioning with GPS and for calculation of the mathematical model (the ellipsoid), this reference is well suited for the application.

The most commonly used ellipsoid in the world is the Geodetic Reference System 1980 (GRS80), which was adopted by the International Association of Geodesy in 1979. This ellipsoid is based on satellite tracking; therefore, it is consistent with the reference systems used by the various Global Navigation Satellite Systems (GNSS) —such as the World Geodetic System 1984 (WGS84) reference system used with the U.S. GPS. The Russian GLONASS and European Union Galileo also use similar systems. In North America, the North American Datum of 1983 (NAD83), which has been updated from the North American Datum of 1927 (NAD27), is the official horizontal reference system for the U.S. and Canada. Since the first publication of NAD83 coordinates in 1986, the system has been improved with the development of GPS High Accuracy Reference Networks (HARN) and a system of Continuously Operating Reference Stations (CORS), which increased the precision associated with representing the surface. NAD83 was affirmed as the official civilian horizontal datum for the U.S. by a notice in the *Federal Register* on June 14, 1989, by the Federal Geodetic Control Committee (FGCC), superseding NAD27.

In February 2007, the NOAA National Geodetic Survey (NGS) completed a readjustment of more than 60,000 GPS stations to create a consistent set of NAD83 values for the U.S., referenced as NAD83 (NSRS 2007). In other areas of the world, datums such as the European Terrestrial Reference System 1989 (ETRS89) and the Japanese Geodetic Datum 2000 (JGD00) are used. Heights defined in these datums are referred to as ellipsoid heights. Ellipsoid heights can differ from orthometric heights (as defined by NAVD88) by tens of meters.

DATUM CONVERSION

The first critical step for preparing multiple data sets for a topobathy DEM is to establish a common horizontal and vertical reference for the data sets. A common reference reduces error in the final DEM by resolving any reference mismatches that occur between data sets. This is particularly important for applications requiring both a high spatial resolution and vertical accuracy. A common reference allows for combination and comparison of multiple data sets by removing one source of systematic bias.

When converting data sets to a common reference, the major issue is the lack of information on the relationship between datums. Orthometric and ellipsoidal heights are referenced to modeled surfaces (gravitational or mathematical) that are static, whereas tidal datums vary spatially and temporally. Topography is generally referenced to one or both static references. Orthometric reference is a static land-based reference system with many highly accurate benchmark reference stations, and ellipsoidal reference is a static satellite-positioning based reference. While individual geoids and ellipsoids are static, they can be updated to better represent the relationship between the Earth’s surface and the static surface. Tidal datums are relative references that vary spatially along a coastline and temporally with each new National Tidal Datum Epoch. The accuracy of a tidal datum reference is limited by the length of time observations have been collected; the longer a tidal benchmark has been recording, the more accurate the tidal datum determination will be. Bathymetry is generally collected with reference to a tidal datum, since many applications of these data sets are relevant to tidal conditions (such as navigation).

Trying to combine or compare data sets referenced to a combination of relative and static references can be problematic, and this is one of the major hurdles in creating an integrated or seamless topobathy DEM. The NOAA National Ocean Service (NOS) establishes the relationship between tidal and orthometric datums by surveying NGS benchmarks (which determine orthometric height) at NOS tide gauge stations (which determine local tide datums). To determine the spatial variability in the relationship between orthometric and tidal datums, it is essential to understand how the two relate. Generation of highly accurate hydrodynamic models for computing tidal datums can be costly; therefore, in many cases, alternative methods have been developed. Information about these methods—including necessary data resources and limitations—is contained in the following section.

The error introduced into a DEM surface because of the lack of a common reference can be substantial; however, the error is not constant due to the spatial variability of the difference between reference surfaces. Because each datum is an independent surface, rather than an offset surface, the distance between surfaces varies. NOS tidal benchmarks in the continental U.S. have a known height with reference to NAVD88. This height, in conjunction with observed MSL measurements, can be used to approximate the difference between datums. Table 1 shows selected tidal benchmarks to illustrate the regional variation in the difference between MSL and NAVD88.

NOS Benchmark Station Location	Benchmark Number	MSL		NAVD88		Difference	
		feet	meters	feet	meters	feet	meters
Portland, ME	8418150	13.49	4.113	13.81	4.208	0.32	0.095
St. Simons Island, GA	8677344	5.27	1.606	5.93	1.806	0.66	0.200
Key West, FL	8724580	5.45	1.662	6.32	1.928	0.87	0.266
Grand Isle, LA	8761724	6.39	1.947	5.31	1.617	-1.08	-0.330
San Diego, CA	9410170	6.73	2.052	4.22	1.287	-2.51	-0.765
Charleston, OR	9432780	7.84	2.390	4.26	1.298	-3.58	-1.092

Table 1: Difference between Mean Sea Level (MSL) and the North American Vertical Datum of 1988 (NAVD88) for selected National Ocean Service (NOS) tidal benchmark stations. Accessed from *www.co-ops.nos.noaa.gov/station_retrieve.shtml?type=Tide+Data* on February 26, 2007.

DATUM CONVERSION TECHNIQUES

Because there is no easy way to establish a common datum reference among tidal, ellipsoidal, and orthometric datums, methods have evolved to approximate the relationships between and among datums. Each method uses similar theory, but the resource requirements, complexity, accuracy, and sources of error are variable.

This section will focus mainly on the considerations when transforming data sets between tidal and orthometric datums. This is because the conversion between ellipsoidal and orthometric reference is a transformation between static reference surfaces, making this relationship relatively straightforward to model. This conversion relies on a grid of difference between the geoid model and the ellipsoid model to execute this transformation. The more difficult relationship to model is between tidal and orthometric datums.

In the following sections, four common methods of datum conversion are discussed. Significant constraints of each of these methods include the following:

- *Availability of high-quality input data for the hydrodynamic and geoid models* – including bathymetry, shoreline, benchmark data, tidal observations, and gravitational measurements.
- *Accuracy of geodetic and tidal benchmark information* – The location of benchmarks may change over time or because of a major event, making the reference inaccurate. The accuracy of the relationship between geodetic and tidal benchmarks can be seen as a limiting factor in each of these methods.
- *Density of tidal benchmarks* – The relationship between NAVD88 and MSL is only known at the benchmark; therefore, interpolation between benchmarks is necessary to approximate the relationship between benchmarks. Having closely spaced benchmarks allows greater accuracy in estimating this relationship.

VDatum: Vertical Datum Transformation Software

Overview

VDatum is a desktop software tool designed to convert among vertical datums with a high degree of accuracy. VDatum can transform a data set among 28 different reference datums in three major classes: orthometric, ellipsoidal, and tidal. This software uses a geoid model, a hydrodynamic model, and NOS tidal benchmarks to establish relationships among datums. VDatum is developed jointly by the National Oceanic and Atmospheric Administration (NOAA) Office of Coast Survey and National Geodetic Survey. Current availability is limited; however, if it is available for your area of interest, it can be downloaded at no cost from the following website, *nauticalcharts.noaa.gov/csdl/vdatum.htm*.

Methodology

VDatum uses two main pieces of information to convert between tidal and orthometric datums: a detailed hydrodynamic model of tides and a topography of the sea surface. The hydrodynamic model is used to determine the spatial variability of tidal datums within a region. It is created by simulation of the tidal response to sun and planetary influences, bathymetry, and local characteristics in an area to make grids that relate tidal datums to a local MSL. This tidal datum information is combined with tide gauge information to develop the topography of the sea surface, which can be used to describe the relationship between local MSL and NAVD88. These pieces of information provide the tools for translation between orthometric and tidal datums. Using the hydrodynamic model of a coastal region, data such as bathymetry, collected with reference to a tidal datum, such as MLLW, can be converted to local MSL. The topography of the sea surface can then be used to relate local MSL to an orthometric datum. If further conversion to an ellipsoidal datum is required at this point, a grid of difference between the geoid model and ellipsoid model is used to convert the data set.

Detailed methodology and documentation for use of VDatum can be found in NOS (2007, in preparation) and Milbert (2002).

Limitations and Error

VDatum uses the most accurate datum conversions available. However, generating the hydrodynamic models—on which the tidal datum conversions rely—is a time- and resource-intensive process. For this reason, VDatum conversions involving tidal datums are currently available only for select areas of the U.S. coastline. There is significant interest in developing VDatum for the entire U.S. coastline and associated coastal margins. One advantage to nationwide VDatum coverage is the availability of a uniform, accurate, and convenient mechanism for datum conversion. If this were the case, VDatum would likely be uniformly preferred over many other datum conversion techniques, regardless of whether the application required the most rigorous method of conversion.

Error from the datum conversion process stems from the methods for creation of the hydrodynamic model and the topography of the sea surface, but the total error of the process includes error from the constraints mentioned in the introduction. In general, this method has the least error when applied to areas of coastline with a well-defined geoid and steeply-sloping coastal topography. The hydrodynamic model is corrected to match datums computed from observations, and the VDatum team is currently assessing what errors may be present in the corrected model results between observation locations. The computation of the topography of the sea surface is also being analyzed for potential introduction of errors. Transformations that require conversion across several datums (such as MLLW to NAVD88 to NAD83) may compound errors, and that must be taken into account when evaluating the total error. The VDatum team is working to quantify all conversion-associated errors, and make that information available as metadata with the software tool. Ultimately, the team's goal is to have the expected error for the VDatum conversions reported for each transformation as total propagated error. Currently there is no established estimate of error for this method, but VDatum is widely accepted as the transformation method with the least error.

Harmonic Constant Datum Method

Overview

The Harmonic Constant Datum (HCD) method estimates tidal datums by relying on tidal constituents (or harmonics) to approximate the tidal curve. This process is particularly useful in areas where a detailed hydrodynamic model has not been created or where there are few long-term tide stations. This method requires development of a hydrodynamic model based on tidal constituents, and conversion is accomplished using a geoid model and NOS benchmark data. The hydrodynamic model constructed for the HDC method is similar to the hydrodynamic model constructed for VDatum, but it is an approximation of tidal datums and is less detailed than the VDatum hydrodynamic model. The HCD method was developed at the NOAA Center for Tsunami Research.

Methodology

The HCD method uses the signatures of major tidal influences to create a generalized hydrodynamic model. The main tidal influences are the moon, sun, and rotation of the Earth. The major model components (called harmonic constants) represent these influences. The HCD method uses a computation of the average tidal curve, rather than the actual or interpolated tidal curve, to translate between tidal datums. Using the harmonic constants, modelers can estimate tidal datums relative to MSL. This method is used only to compute tidal datums, but NOS tide gauge data can be used to translate between MSL and orthometric datums, as described in the VDatum section. Also similar to VDatum, the orthometric to ellipsoid conversion would use a grid of difference between the geoid and ellipsoid models. Detailed information on the use of the HCD method can be found in Mofjeld and others (2004) and Venturato (2005). In addition, the theory behind the methodology can be found in Harris (1894) and Coast and Geodetic Survey (1952).

Limitations and Error

This technique is especially useful in areas where tide records are available at only a few scattered primary tide stations. The HCD technique can help bridge the gap by providing modeled tidal heights. Researchers have compared tidal heights modeled using the HCD method to actual tidal heights in order to quantify error. In one case in the Puget Sound, modeled heights were generally less than the observed tidal heights across 48 tide stations. The greatest difference in MSL between modeled and observed tide heights for this instance was 12.8 centimeters. However, the large majority of differences were less than 5 centimeters. This error measurement only takes into account the error caused by the tidal modeling process, not error from the conversion using benchmarks. For additional information on error using this method, see table 5.4 in Mofjeld and others (2002).

The tidal regime is an important consideration when using the HCD method. This methodology is designed to work for semidiurnal tides (two high and two low tides of approximately equal amplitude per day), diurnal tides (one high and one low tide per day), and areas of mixed semidiurnal and diurnal tidal regimes. In areas with multiple types of tides, three approaches can be used to effectively represent tidal datum changes across a region, but there are some trade-offs. The approaches are as follows: (1) use separate algorithms for each area, which results in a discontinuity at the interface of the regions, (2) apply the mixed tidal algorithm for an entire region, which introduces some error, or (3) use a cubic polynomial that consistently defines the transition area.

Interpolation

Overview

When tidal benchmarks are located in the study area, the interpolation method can be used to convert data sets between tidal and geoidal/ellipsoidal datums. A tidal benchmark—which often combines tidal observations with corresponding information on the gauge's relationship to the geoid—can be used to represent tidal datums for the benchmark location. When multiple tidal benchmarks are available, the tidal surface can be created by interpolating the tidal surface between reference stations. The interpolation method can approximate the relationship between tidal datums and orthometric datums using one, few, or many benchmarks. Tidal benchmark data, including orthometric height, are readily available from the National Water Level Program and the National Water Level Observation Network (NWLON), *http://tidesandcurrents.noaa.gov/nwlon.html*.

Methodology

To use this method, at least one tidal benchmark must be in the region of interest. The benchmark(s) must have a known orthometric height and known tidal datums, such as MSL, MHW, and MLLW. The duration of observation at these tide gauge sites is critical to accurate determination of tidal datums. Generally, the longer an NOS tide gauge is in operation, the more precise the model of the tidal datum will be. Primary stations in the NWLON are often continuously observed for at least 19 years. In some cases where more detailed tidal information is necessary between reference stations, short-term reference stations (those operating for a year or more) can be used to assist in interpolation. If multiple tidal benchmarks are available, tidal datums relative to MSL can be estimated using tidal observation data from tide gauges and interpolating between benchmarks. If only one benchmark exists in the region of interest, the tidal observations at that gauge can be applied across the region to estimate the tidal datums. The orthometric heights of the benchmarks are used to relate MSL to orthometric datums. Using the same method as in VDatum and the HDC method, the grid of difference between the geoid model and ellipsoid model is used to convert to ellipsoidal reference.

Limitations and Error

The more benchmarks available to represent the tidal datums, the more accurate this method is at representing the tidal surface and relating it to other datums. This method relies on interpolation and known information at one or more points to represent the tidal surface across a region. If one point is used, the difference between datums at one point is extrapolated to cover an extended area. If multiple points are available, interpolation is necessary to infer location of datums between reference stations. Neither of these methods precisely represents the differences in tidal datums across a region; however, this approximation is useful when minimal information is available. This methodology is most effective in an area with uniform shoreline, multiple benchmarks, consistent bathymetric characteristics, little tidal variation, and a small tidal range. Error associated with this method is highly individualized to the area the method is applied. The accuracy of this method reflects both the characteristics of the region and number of benchmarks used. This method will produce a transformation acceptable for some applications, but it is possible that it may not be sufficient for the highest resolution applications, such as shoreline delineation.

No Conversion to a Uniform Datum

Overview

Another option to consider is to simply not covert to a uniform datum; however, when a common reference is not established for multiple data sets, vertical accuracy of the elevation model is limited. A simple reason for not converting datums could be that no conversion options are available. If VDatum is not available, no HCD model has been developed, no benchmarks are in the study region, and no resources are available for data enhancement, then there are no options for establishing a common vertical datum.

In some cases, conversion methods are available but are not used because the DEM being created has a resolution coarse enough that differences caused by datum shifts do not significantly impact the quality of the resulting data set. This occurs when the variability within a grid cell of coarse resolution is larger than the adjustment between datums. Neglecting datum transformation is appropriate when the datum correction is well within the noise level of the data. For instance, the Coastal Relief Model is a nationwide data set that does not take into account vertical reference before generating the 3 arc-second (90 meter) topobathy grid. However, just because it doesn’t take into account datum reference, doesn’t mean it lacks utility. At this scale, the topobathy grid is useful for applications such as regional visualization of the coastal zone and watershed-scale analyses. In this case, the error from neglecting the vertical and horizontal reference is dwarfed by the error inherent in lower resolution grids. This error stems from selecting one elevation to represent a large area within a grid cell. More information about the Coastal Relief Model can be found at the following location, *www.ngdc.noaa.gov/mgg/coastal/coastal.html*.

Methodology

No relationship between datums is established; therefore, no datum conversion occurs. In this case, the researcher assumes that the datums are approximately equivalent.

Limitations and Error

This method limits the quality of a high-resolution DEM developed from these data sets. Without creating a common format, any high-resolution grid or surface created from these data sets will have substantial error. The amount of error introduced by not establishing a common datum reference is highly dependent on the area in which the grid is being generated and the size of the grid cell. Neglecting to correct for datum differences can cause discontinuity in heights within an elevation model, disconnected shoreline segments, and error in calculation of erosion rates and setback lines.

DATA INTEGRATION

Once data sets are referenced to a common vertical and horizontal datum, the next step in producing a high-quality topobathy DEM is data integration. Ideally, data sets would line up perfectly after the data sets were converted to a uniform reference, but that is rarely the case. Differences in data sets may be caused by different collection sensors, different seasons for data collection, or collecting data sets before or after a large event where surface change occurs. Data integration is the process of combining two or more data sets into a single, continuous surface. Several decisions must be made about how data sets are manipulated, and each decision affects the characteristics of the resulting DEM. Some of these decisions involve how to prepare raw point data, what type of grid is necessary, and what grid characteristics fit the application. Multiple techniques exist for each decision, and how they impact the final DEM will be addressed in the following section.

Preparation of Raw Points

Often DEM generation begins with preparation of raw point data. If raw points are used from multiple data sets, it is necessary to decide which points from each data set will be used.

For each data set, the decision must be made to include all points or use a subset of points to represent the surface. All points can be used to represent a surface for certain applications, but often a specific surface, such as bare-earth, is required and can be specified in some data sets. Some newer data collections, such as lidar with LAS classification, include elevation returns classified to represent features such as “water,” “vegetation,” “building,” and “ground.” A bare-earth surface can be created using only the points from the “ground” classification, and this data subset may represent the surface more accurately for certain applications. Alternately, it may be important to the application to keep the vegetation and buildings in the DEM, in which case, all points or key classified categories of points would be used.

In cases where there is an overlap of data sets, one data set may supersede another. For example, giving preference to a more recent collection or a collection with a more advanced sensor may represent the surface more accurately than a combination of points from both data sets. If data sets are of approximately equal quality and accuracy, all points may be used or data sets may be “feathered,” which means that alternating strips of data from each data set are woven together at the interface of data sets. Generally, new data should replace old data (where possible) to represent the surface using the most recent measurements and most accurate technology.

The result of preparing raw point data sets often leaves a surface of points that has dense elevation measurements in some areas and sparse elevation measurements in others. It will likely still have data mismatches, and there may be gaps where no data exist. Additionally, the size of the file will often limit its utility for an application. Because of these characteristics, often a grid is necessary to create a useful DEM to represent the topobathy surface.

Grid Design

Designing the grid to suit a particular application requires decisions about structure, cell size, and point selection mechanism. A gridding method may be chosen to reduce the size of the DEM file or processing time, to accommodate areas with lower-resolution data or sparse data sets, or to generally represent the surface from a dense data set when a highly detailed surface is not required for the application.

The structure of the grid, either structured or unstructured, depends on the requirements of the application. A structured grid has a uniform grid cell shape—a rectangle—with elevation values at each of the cell's four nodes or at the center of the cell. It does not require a uniform cell size, but it typically does not have an extremely broad range of cell sizes. An unstructured grid (such as a Triangulated Irregular Network) has grid cells with a triangular shape so that elevation values are at each of the three nodes. Cell size can be highly variable in an unstructured grid, and therefore it can show more detail in areas of a DEM where elevation change may be more meaningful, such as at the shoreline, and less detail in areas of uniform elevation. Also, unstructured grids are able to accommodate input data with variable resolutions. If the requirements for a DEM vary spatially, an unstructured grid could be advantageous. Selection of grid type also depends on the requirements of the model or software application that will be using the DEM. For instance, the Advanced Circulation (ADCIRC) model and the Sea, Lake, and Overland Surges from Hurricanes (SLOSH) model both simulate processes such as tides and storm surge. ADCIRC requires an unstructured grid input, whereas SLOSH requires a structured grid input.

The grid cell size chosen for a DEM depends on the density of available elevation data and model limitations in terms of processing time and stability. The ultimate goal of a grid is to be representative of the elevation surface; therefore, the grid size should be small enough to adequately represent the surface for a specific application. In addition, the cell should be small enough that the area covered by the cell is reasonably represented by one elevation value and that the resulting DEM captures the details of the relief. The grid cell should also be large enough so that the point data can support the grid size and the density of data points within each grid cell is representative of the elevation surface. Even in areas of sparse elevation measurements, the grid cell has to contain adequate measurements to represent the surface. An additional consideration when selecting grid size is ensuring the DEM will be cost- and time-effective to build and run in the selected model. Ideally, there is range among these considerations to satisfy requirements.

The point selection technique chosen to determine an elevation value for a grid cell or node is critical to the utility of the resulting grid. With the bounds of the cell delineating the grid area, all points inside must be represented using some mathematical function. For areas where data density is high, gridding allows the choice of (1) the largest value in the grid area (maximum), (2) the smallest value in the grid area (minimum), or (3) the average of the elevation values within the grid cell (average). Where data density is low, multiple grid interpolation methods are available, including inverse distance weighting (IDW), nearest neighbor, or more complex methods such as kriging. Each of these methods uses interpolation and values of neighboring data points to generate values in sparse areas.

CONCLUSION

Production of a high-resolution topobathy DEM involving multiple data sets requires conversion to a common reference. When selecting the datum transformation mechanism, the availability of data resources and the application for which the DEM is designed should be considered. For example, the existence of tide gauges or a hydrodynamic model can dictate which methods can be used for datum transformation. If a hydrodynamic model exists and is tied to NAVD88 at many tide gauges, it is an easy choice to use the information available for a highly accurate conversion using VDatum. However, if no hydrodynamic model and few or no tide gauges are available, decisions must be made about the time, monetary, and human resources that can or should be invested to satisfy the needs of the application. This situation is not uncommon; many remote areas have few tide gauges and poor tidal and geodetic information.

The quality of the input data can also dictate which method is appropriate for datum conversion. For instance, if data are sparse or collected with an instrument that is associated with large error, using a less rigorous transformation method may not significantly affect the quality of the resulting DEM because of the other sources of error in the elevation surface. Matching the transformation method to the DEM application is important and can save time and money. For example, if the elevation surface for a particular application requires a very small cell size and a high-detail DEM, the most rigorous method available should be used. Those applications requiring a moderate cell size may not be significantly affected by a less accurate (and potentially less costly) transformation. Using the appropriate method will ensure that error in the final DEM is reduced, where possible, and time and effort are minimized. The key to datum conversion is to choose the method that works best with available information for the region of interest.

Additionally, some limitations that apply to all these datum conversion methods should be considered as well. Ultimately, all these processes are limited by the geodetic and tidal benchmark height accuracy and the accuracy of the link to the geoid. If there has been subsidence around the benchmark since the last calibration, this error will have an impact regardless of the transformation method used. Another limitation for all methods is the need for interpolation between tide gauges. The relationship between MSL and NAVD88 is established at the tide gauges, and between tide gauges the relationship between the two surfaces is interpolated. This interpolation introduces error, because the geoid and tidal surfaces are not simply shifted—they are independent surfaces.

Although using the best possible conversion technique will accurately convert the reference of a data set, it will not completely resolve data steps and mismatches because these issues are also caused by other factors. Differences between data sets can stem from the collection sensor, the season of collection, and major events that occurred between collections. Many of these issues can be partially (or fully) resolved using data preparation and gridding techniques that correspond with the application. Considerations such as point selection, grid structure, and grid cell size will impact the utility of the resulting DEM surface. DEM applications range from shoreline delineation—where small changes in water level can impact the resulting shoreline—to storm surge modeling—where the region of interest may be large and the impacts must be considered from a regional perspective. The DEM required for each of these applications will have different characteristics, and the conversion and integration techniques chosen early on in the DEM development process must be based on the requirements of the end application. In general, a single DEM is unlikely to meet the needs of all applications.

To fully address the issues and considerations necessary to produce a high-quality DEM that is suited to the application, the modeling community needs to coordinate efforts and address difficult issues. Unresolved issues that persist in topobathy DEM generation include establishing methods to properly represent sub-grid scale features, finding solutions to fill gaps in data sets, and establishing standards by which accuracy of a DEM can be calculated. Some initial progress has been made by a small working group within NOAA. This group has dedicated its efforts to tackling difficult questions specific to topobathy, such as data collection needs, sensitivity analyses, compound error, and the spectrum of uses for a topobathy DEM.

Accuracy measurement for topobathy DEMs is another area that requires attention from the modeling community. Error in a topobathy surface comes from many different sources, and often all sources of error are not considered when evaluating an integrated DEM product. Common error sources include those from vertical reference, data collection, data processing, elevation change since collection, datum conversion, and data integration. The compound error of the end product could be substantial. Error is specific to each DEM created and may vary widely depending on location of the study, data collection mechanism(s), datum conversion techniques, and data integration methods.

These activities and broadening participation in working groups are critical to improving efficiency and understanding within the topobathy modeling community.

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