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A framework for a seamless depiction of merged bathymetry and topography along U.S. coasts

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Abstract

A seamless depiction of merged bathymetry and topography in the coastal zone supports multiple uses, such as hazard mitigation, spatial planning, habitat research, coastal change studies, and Earth visualization. Developing a robust, extensible depiction of elevation in the coastal zone requires an overarching framework of common specifications, procedures, and guidelines, so that multiple groups can contribute well-described lidar and sonar elevation data and integrated digital elevation models (DEMs) in a consistent way. The NOAA National Geophysical Data Center and the USGS Earth Resources Observation & Science Center have collaboratively developed such a framework for the creation of an accurate, consistent, and seamless national depiction of merged bathymetry and topography in the U.S. coastal zone. This framework, specific to square-cell "raster" models, enables shared development of coastal DEMs that are then made freely available for public use, such that users can seamlessly integrate public coastal DEMs built by different Federal agencies, academia, and the private sector. The square-cell, coastal DEM framework described herein is being tested by developing integrated bathymetric-topographic DEM tiles of the New Jersey coast and Delaware Bay that are consistent with and align with the USGS National Elevation Dataset.

Lead author biography

Dr. Eakins is a marine geophysicist at the University of Colorado, Boulder. He served 6 years in the U.S. Navy before obtaining his B.A. in Geology from the University of Colorado and his Ph.D. in Earth Sciences from Scripps Institution of Oceanography, University of California, San Diego.

Introduction

The National Geophysical Data Center (NGDC), an agency of the National Oceanic and Atmospheric Administration (NOAA), and the Earth Resources Observation & Science (EROS) Center, an agency of the U.S. Geological Survey (USGS), have collaboratively developed a sustainable framework, described herein, for the creation of accurate, consistent and seamless topographic-bathymetric digital elevation models (DEMs) of the U.S. coastal zone that will be freely available for public use. This framework is specific to square-cell "raster" models, which are the most commonly used, not triangular irregular networks (TINs) or other types of DEMs, though some of the requirements and recommendations described herein may also be applicable to those DEM types. This framework will be tested and improved upon by building a suite of square-cell coastal DEMs of the New York-New Jersey shoreline that were impacted by storm-surge from Hurricane Sandy in 2012.

Square-cell, coastal DEMs support a wide variety of uses, including modeling of coastal flooding, coastal change analysis, habitat mapping, spatial planning, and Earth visualization [e.g., *Eakins and Taylor*, 2010]. In order to support the seamless merging of coastal DEMs built by multiple government agencies, academia and the commercial sector, such DEMs need to be developed within a well-defined framework, which includes key DEM requirements and recommendations, as well as consistent documentation to support discovery, access, and use. This framework needs to be robust and capable of being implemented by multiple groups (i.e., be agnostic with respect to software being utilized in DEM development).

The square-cell, coastal DEM framework described herein will be tested, reviewed, and improved as part of NGDC's Sandy Supplemental work. The goal is to create a sustainable framework for the Nation that enables shared development of seamless, mergeable and public topo-bathy elevation models of U.S. coastal areas as called for in the President's National Ocean Policy [*National Ocean Council*, 2013]. The framework needs to:

- define key coastal DEM specifications necessary to support seamless merging of DEMs.
- provide recommendations and best practices for data processing, DEM development, and DEM assessment.
- describe techniques for efficiently updating coastal DEMs as new, public elevation data are released.
- determine documentation requirements to capture important data processing and DEM development steps (e.g., in standards-compliant metadata records and spatial metadata).
- identify areas for future improvement, such as gaps in data acquisition and processing, improvements in data delivery, and coastal areas where collaborations and synergies can improve DEM accuracy and coverage.

Coastal DEM Specifications

There are several key coastal DEM specifications (Table 1) that square-cell, public models of U.S. coasts need to adhere to in order to ensure that coastal DEMs built by different groups or agencies will consistently align on a cell-by-cell basis. DEMs that do not align will not be capable of being merged as part of a national, seamless depiction of coastal and bathymetric elevation.

Table 1. Coastal DEM specifications.

Projection	Local UTM Zone		Geographic				
Cell size	1 m	3 m	1/9 arc-sec	1/3 arc-sec	1 arc-sec	3 arc-sec	9 arc-sec
Offshore coverage	1 nm	3 nm	3 nm	24 nm	500-m depth	200 nm	ECS, LMEs
Grid registration	Pixel						
Horizontal datum	NAD 83						
Vertical datum	NAVD 88				Sea level		
Edge precision	3 m		0.01 degrees (36 arc-sec)				
Elevation precision	0.01 m	0.1 m				1 m	
Multi-temporal	yes		No				
Surface type	Bare earth						
Restrictions	None/Public						

Projection: Square-cell coastal DEMs should be in either a local universal transverse Mercator (UTM) zone projection or geographic coordinates (i.e., unprojected; Table 1). Local UTM zone projections are most appropriate for the highest resolution, meter-scale models at the shoreline. Geographic coordinates are most appropriate for lower-resolution DEMs that extend farther offshore. Because transforming square-cell rasters between the two introduces distortion—square cells in one are not square in the other—such transformations should be minimized.

Cell size: UTM Zone DEMs should have cell sizes of either 1 meter or 3 meters (Table 1). Geographic coastal DEMs will range in cell size from 1/9 arc-second to 9 arc-seconds (Table 1). The factor of three steps will help ensure consistent nesting between coastal DEMs of different cell sizes but same coordinate system (i.e., 9 cells at one cell size will have exactly the same geographic footprint as one cell at the next coarser cell size).

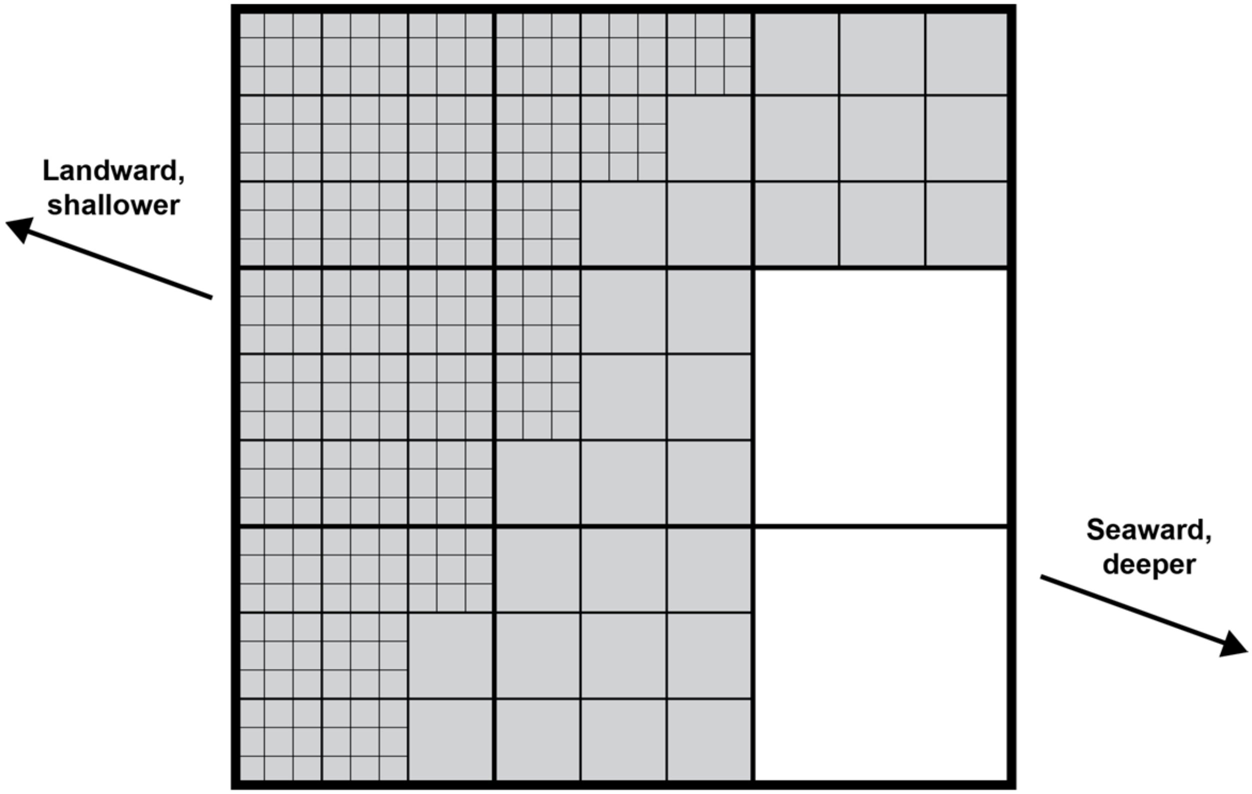

Figure 1. Example of DEM cell nesting. One, bold-outlined cell at the coarsest resolution, is comprised of 9 cells at the next higher resolution, which in turn has some cells comprised of 9 gray cells at the next higher resolution, and so on. In this conceptual schematic for square-cell DEMs, the coastline would be towards the top left.

Offshore coverage: Each successively coarser coastal DEM should extend farther offshore (Table 1; Figure 1), so that there is a rough correspondence between bathymetric data density and cell size (e.g., in deeper waters, soundings are farther apart). Table 2 lists the approximate offshore coverage of these “telescoping” geographic DEMs, shown in the Figure 2 schematic. The 1 arc-second geographic DEMs should extend out to approximately the 500-m depth contour, roughly corresponding to the edge of the continental shelf. The 3 arc-second DEMs should extend out to the 200 nm limit of the U.S. Exclusive Economic Zone (EEZ), while the 9 arc-second DEMs should encompass deeper water in farther offshore areas, such as large marine ecosystems (LMEs), small ocean basins (e.g., Gulf of Mexico), and the U.S. extended continental shelf (ECS).

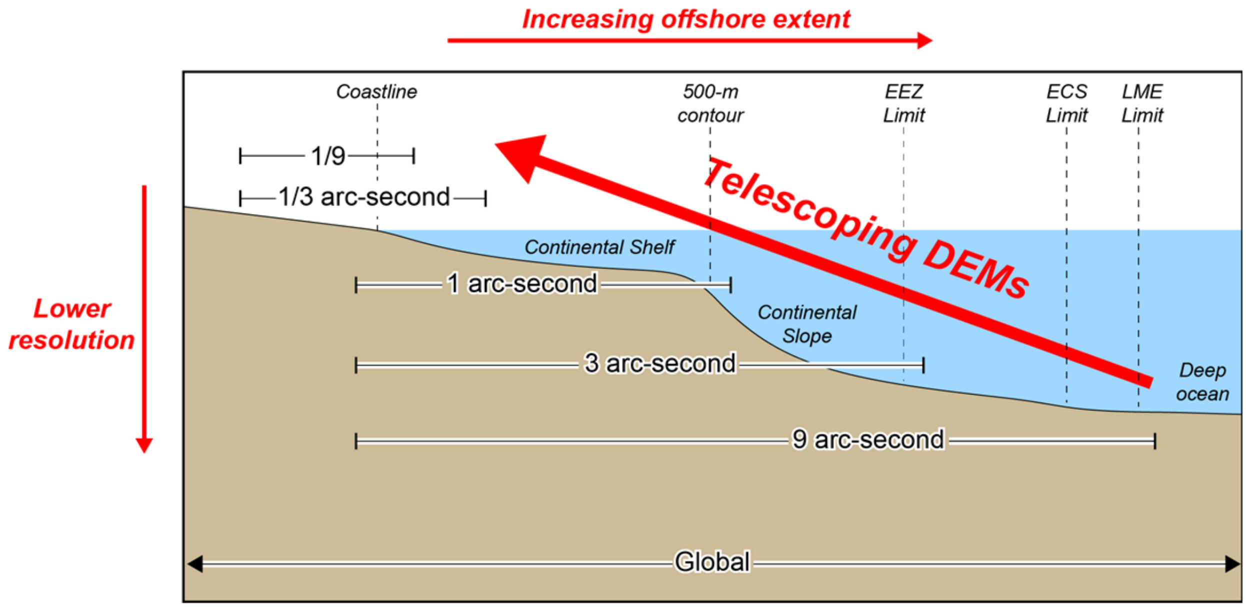

Figure 2. Example of DEMs extending farther offshore as cell size increases and resolution decreases.

Table 2. Approximate offshore coverage of geographic DEMs.

1/9 arc-sec	3 nm limit of State waters
1/3 arc-sec	24 nm limit of U.S. contiguous zone
1 arc-sec	500-m depth contour
3 arc-sec	200 nm limit of U.S. EEZ
9 arc-sec	Encompass ECS, LMEs and small ocean basins

Grid registration: UTM Zone and geographic coastal DEMs should be defined by the corners of the cells, also known as pixel- or cell-based registration (Table 1). This will help ensure that the coastal DEMs can be seamlessly merged with the USGS National Elevation Dataset (NED). NED topography is available in 1/9, 1/3 and 1 arc-second cell sizes, and NAD 83 and NAVD 88 horizontal and vertical datums, respectively. Pixel registration will also better enable Internet delivery of the coastal DEMs and corresponding color-relief images.

Horizontal datum: The horizontal datum of U.S. coastal DEMs will be the North American Datum of 1983 (NAD 83; Table 1). This datum is nearly identical with the global World Geodetic System of 1984 (WGS84) horizontal datum, and for the geographic DEMS, the two can be considered identical.

Vertical datum: The vertical datum of higher-resolution DEMs will be the North American Vertical Datum of 1988 (NAVD88; Table 1), as realized through the most recent geoid model developed by the National Geodetic Survey (at time of press Geoid12A). Lower-resolution models should be referenced to "sea level", as the elevation uncertainty at the cell level likely exceeds the magnitude of the offset between orthometric (i.e., NAVD88) and various tidal datums, obviating the need to establish a common vertical datum [*Eakins and Grothe*, 2014]

Edge precision: The precision of the edges/bounding extents of each UTM zone model, in meters, should be wholly divisible by three (i.e., result must be an integer, without remainder; Table 1) in order to enforce cell alignment and support DEM merging. To help ensure alignment between coastal DEMs built by different developers, the edge precision of each geographic model needs to be limited to two decimals of latitude and longitude (i.e., 0.01 degrees/36 arc-seconds; Table 1).

Elevation precision: The precision of elevation values within coastal DEMs should be appropriately limited to the resolution of the coastal DEM, to avoid implying greater accuracy in the DEM than is warranted (Table 1). For 1-meter cell-size UTM zone DEMs the elevation precision should be limited to 0.01 m. For the 3-m cell-size UTM Zone DEMs, and 1/9, 1/3 and 1 arc-second geographic DEMs, the elevation precision should be 0.1 m. For the 3 and 9 arc-second geographic DEMs, the elevation precision should be 1 m. Low-resolution global models (e.g., 30 arc-second cell size) should have a 10 m elevation precision.

Multi-temporal aspect: The UTM Zone coastal DEMs should include a multi-temporal aspect that will enable high-resolution coastal change analysis (Table 1). To support this, the survey dates and spatial footprints of the source data used to build each model need to be clearly documented, so that spatial-temporal differences between models can be quantified. The geographic coastal DEMs will not be expressly temporal, as they typically reflect "best available" source data, though older versions of coastal DEMs should be archived and publicly accessible.

Surface type: The coastal DEMs need to represent the bare ground surface, or "bare earth" to support modeling of water flow. Buildings, trees, and other above- or below-ground surfaces should not be represented in the models, and need to be removed from source elevation data sets. Exceptions could be large, solid structures, such as jetties and dams, that are impervious barriers to water flow. The documentation should identify any structures that are represented in the DEM.

Restrictions on public access and use: No restrictions, other than "not to be used for navigation" should be placed on public access to and/or use of the square-cell coastal DEMs that are part of this framework (Table 1). Proprietary data that imposes restrictions on use and public dissemination of derived products (i.e., DEMs) should not be used in coastal DEM development, unless the data owner provides written consent that the DEM can be fully released to the public without restrictions. Such consent needs to be documented.

Documentation Requirements

The goal of DEM documentation is to provide all necessary information to users as to its limitations and appropriate use. This could include such things as coastal DEM specifications (see Table 1) and source data sets used in coastal DEM development, as well as processing, gridding and assessment techniques used. Other important factors, such as identifying manmade structures represented in the coastal DEM or consent to public release of a DEM built using restricted data, also need to be clearly documented. This DEM documentation will also enable online discovery in text and GIS search tools.

XML metadata: High-level descriptions of source elevation data, DEM development methods, and assessment results for each coastal DEM should be documented in standards-compliant XML metadata that is compatible with the ISO 19115 standard, and translatable to FGDC's metadata standard. Published, maintained XML metadata records can be provided to search portals, such as Data.gov and the Global Change Master Directory, for broader coastal DEM discovery.

Spatial metadata: Spatial metadata that contain the footprints and descriptions of source data sets will enable online visual display of the spatial relationships between source data and coastal DEM morphology. Such metadata will also support the UTM zone coastal DEMs as the multi-temporal aspect of these DEMs is dependent upon the overlapping footprints and dates of the source data, not the coverage of the DEMs, which are an amalgamation of a wide variety of surveys over years to decades. Web-based tools may also enable linking from a coastal DEM to source data ("provenance") to better support source data discovery.

Metadata grids: Each coastal DEM should also include cell-level distinction between measured elevations, gridding interpolation, and cells without an elevation value, which could be expanded to include source data set identifiers. The bathymetric attributed grid (BAG) and other multiband raster formats might accommodate this, though the BAG format is not yet in wide-spread use. Alternatively, this information could be included in a separate, companion grid that would accompany the coastal DEM.

Cell-level uncertainty: Quantifying DEM accuracy at the cell level will be of great benefit to many DEM users, especially those modeling coastal processes, such as tsunamis, storm surge, or morphologic change. The BAG file format also supports cell-level uncertainty, though quantifying the various sources of uncertainty (e.g., source data, interpolation, morphologic change) at the cell level is a topic of active research [e.g., *Amante and Eakins*, in press 2015].

Coastal DEM Recommendations

Publicly available data: Publicly available elevation data should be gathered from as many sources as possible, including NOAA, USGS, State and local government offices, academia, and the commercial sector. Academic journals, technical reports, development projects, and local associations may provide contacts for accessing offline elevation data [*Eakins and Grothe*, 2014].

Transformations: Source elevation data need to be transformed from their original horizontal and vertical datums to the datums of the final coastal DEM (Table 1). This may also include conversions to common file formats to support data visualization, editing, and DEM development. Where available, the NOAA *Vertical Datum* (*VDatum*) tool [*Parker et al*., 2003] should be used to convert bathymetric data in tidal datums to NAVD 88 as necessary, depending upon DEM cell size (see Table 1). In its absence, vertical datum conversions should be done following one of the methods outlined in *Eakins and Grothe* [2014] and needs to be clearly documented.

Data processing: Available elevation data should be processed to bare earth—to remove docks, piers, trees, buildings, etc. Lidar data may need to be classified to support this requirement. The spatial footprints of all source data sets should be generated to support accurate coastal DEM documentation. Where data sets overlap, less accurate data—typically older and sparser—should be removed prior to DEM development. Visual inspection of source data in a GIS environment is necessary to ensure that data artifacts, anomalies, or non-Earth-surface detections are removed. A detailed, bare-earth NAVD 88 shoreline may also need to be developed to support seamless integration of bathymetric and topographic data at the coast. This coastline could be made available to other coastal DEM developers to help ensure consistency between coastal DEMs built by different DEM developers.

Gridding: Geographic coastal DEMs require every cell to have an elevation value, in order to support modeling of surface processes such as tsunamis or storm surge. If most DEM cells are constrained by measured data, and data gaps are therefore at most a few cells across, the choice of gridding technique (e.g., spline, inverse distance weighting, triangulation, kriging) can be left to the DEM developer [*Amante and Eakins*, in press 2015]. In regions where data are sparse at the resolution of the geographic DEM, requiring interpolation over a large number of cells, use of spline or kriging is recommended [*Amante and Eakins*, in press 2015]. In UTM Zone DEMs, cells without a number (i.e., "not a number"; NaN) are acceptable—to indicate data gaps—and choice of gridding technique, for infilling of small gaps, can be left to the DEM developer. The gridding technique used in coastal DEM development should be clearly documented. A spatial buffer of elevation data surrounding each coastal DEM should also be used, in order to minimize gridding artifacts along DEM edges. The buffer's width should be approximately 10% that of the DEM.

Tiling scheme: In order to support efficient coastal DEM development, updating, and delivery, the DEMs should be built in tiles. Geographic 1/9 and 1/3 arc-second tiles should have extents bounded by 1/4th of a degree, or 15 arc-minutes. Geographic 1, 3, and 9 arc-second tiles should cover 1 degree squares. Tiles should overlap neighboring tiles by at least 6 cells to minimize seams along tile edges when merging DEMs.

Hydro-enforcement of topography: The topography of the UTM zone coastal DEMs should be hydro-enforced to ensure proper modeling of surface water flow. USGS EROS is developing techniques to address this issue.

DEM assessment: The coastal DEM should be statistically compared to select source and independent data sets, with the root mean square error (RMSE) documented in the accompanying XML metadata. Investigation of histogram outliers may reveal problems that can be corrected [*Eakins and Grothe*, 2014]. The DEM should also be visually inspected in a GIS environment for significant anomalies and artifacts. This may include inspection of derived slope and curvature grids. Coastal DEMs could also be peer-reviewed by other parties, initially NOAA NGDC and USGS EROS, to ensure that accuracy is properly documented and that the DEMs are consistent with other, published DEMs.

DEM updating: Ideally, coastal DEMs would be routinely updated as new elevation data are acquired and made publicly available. This could be accomplished by retaining all processed source data and integrating with the new, processed data. It could also be accomplished by gridding the new, processed data to the specifications of the coastal DEM to be updated, and then assessing the accuracy of the new grid compared to the existing coastal DEM. Differencing of the new grid with the coastal DEM will highlight significant changes that need to be evaluated. If warranted, the grid of new data can then be merged or blended with the existing DEM. This second technique shall be investigated more thoroughly during the development of the coastal DEMs of the NY-NJ shoreline.

Future Considerations

VDatum expansion: VDatum currently has limited extent up rivers and offshore. Expanding the spatial coverage of *VDatum* to go farther inland/up river and to go farther offshore, as well as to other U.S. coastal areas (such as Alaska and Hawaii) will increase the accuracy of vertical datum transformations of elevation data in tidal datums in these regions, as well as resultant coastal DEMs.

Acknowledgements

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