Developing Coastal Inundation Digital Elevation Models to support NOAA's Tsunami Program

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Abstract

NOAA's National Geophysical Data Center (NGDC) is building high-resolution digital elevation models (DEMs) for select U.S. coastal regions. These combined bathymetric–topographic DEMs are used to support tsunami forecasting and modeling efforts at the NOAA Center for Tsunami Research, Pacific Marine Environmental Laboratory (PMEL) in Seattle, Washington. The DEMs are part of the tsunami forecast system SIFT (Short-term Inundation Forecasting for Tsunamis) currently being developed by PMEL for the NOAA Tsunami Warning Centers, and are used in the MOST (Method of Splitting Tsunami) model developed by PMEL to simulate tsunami generation, propagation, and inundation.

Myrtle Beach, South Carolina

Two spatially coincident DEMs—a 1/3 arc-second (~10 meter) DEM and a 1 arc-second (~30 meter) DEM—were developed for the Myrtle Beach, South Carolina region (see Table 1). The 1/3 arc-second DEM was generated from numerous, diverse digital datasets in the region (see Data sources below). This DEM was then resampled with ESRI ArcGIS (http://www.esri.com/) to generate the 1 arc-second DEM.

Table 1. PMEL specifications for the Myrtle Beach DEMs.

DEM Area	Myrtle Beach, South Carolina
Coverage Area	78.4° to 79.2° W; 33.25° to 33.95° N
Coordinate System	Geographic decimal degrees
Horizontal Datum	World Geodetic System 1984 (WGS84)
Vertical Datum	Mean High Water (MHW)
Vertical Units	Meters
DEM Spacing	1 arc-second and 1/3 arc-seconds
DEM Format	ESRI ArcGIS ASCII grid

Building the DEM

- Evaluate data received from multiple sources in different formats and measured in different terrestrial environments
- Convert data to common format and common horizontal and vertical datums (reference frames)
- Reassess data to ensure consistency
- Generate DEM by averaging data values
- Evaluate DEM by comparing with source data
- DEM is posted on-line for public access

Establishing common datums

One of the most important steps in developing the coastal inundation DEMs is converting the various datasets to common horizontal and vertical datums. PMEL requires a horizontal datum of WGS84, for consistency with other ocean-spanning DEMs, and a vertical datum of Mean High Water (MHW) for modeling of "worst-case scenario" flooding. The equations transforming datasets from one horizontal datum to another are generally well known, and, except for Alaska, are straightforward to accomplish; NGDC uses the software package FME (http://www.safe.com/).

Vertical datums are a different problem altogether. Bathymetric data are typically tied to tidal datums (Figure 2), which are measured at local tide stations (http://tidesandcurrents.noaa.gov/); NOS hydrographic surveys are referenced to Mean Lower Low Water (MLLW) to provide mariners with the shoalest depths they can expect to encounter. Topographic data are typically referenced to NAVD88, the U.S. geodetic standard. To convert data from NAVD88 requires leveling of local tide stations to the geodetic standard (e.g., Figure 2). *Note that for DEMs with large cell-size (i.e., 3 arc-seconds or greater) the differences between vertical datums, which are typically a meter or two, are less than the error introduced by averaging scattered elevation values over that cell-size.*

For Myrtle Beach, PMEL supplied three ASCII grids relating MHW to Mean Sea Level, NAVD88 and MLLW over the bathymetric portion of the gridding region; a constant of 0.047 meters was used to first convert Mean Low Water data to MLLW. Topographic data, submitted in NAVD88 vertical datum, were shifted to MHW using the average difference between the two datums, which was derived from local tide station values.

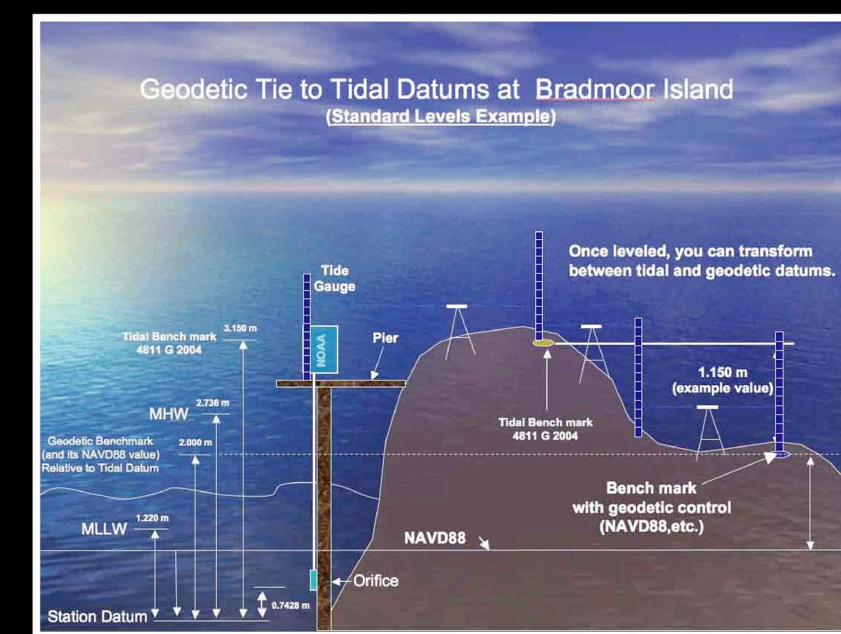


Figure 2. *Diagram illustrating how the relationship between tidal and geodetic datums is established. The tide gauge determines the tidal datums: its benchmarks are geodetically surveyed and tied to geodetic datums. [Image courtesy of Allison Allen, NOAA CO-OPS]*

Processing procedures

After conversion of the various datasets to WGS84 and MHW, extensive evaluation of potential mismatches between datasets is performed in ESRI ArcGIS (see Problems encountered below).

For Myrtle Beach, several of the datasets had data point spacings much greater than that required for the 1/3 arc-second (~10 m) DEM. The shoreline-crossing beach profiles have point spacings on the order of a meter, however, the profiles are spaced from roughly 80 meters up to a kilometer apart. These datasets were separately "surfaced" with Generic Mapping Tools software (http://gmt.soest.hawaii.edu/) to infill regions between the well-defined beach profiles with elevationally consistent data values. The resulting "pre-grids" were closely cropped to the spatial extent of the data coverage area to prevent extrapolation into areas covered by other datasets. USGS multibeam interferometric sonar survey data (~100-m spacing) and NOS open-ocean surveys (up to 1 km spacing) were also surfaced to infill areas between soundings. The NOS river surveys had point spacings of tens of meters: these surveys were gridded with ESRI ArcCatalog to a distance of 5 grid cells from the soundings so that the river channels and harbors were well defined prior to DEM creation.

DEM creation was accomplished using the shareware package MB-System (http://www.ldeo.columbia.edu/res/pi/MB-System/), an NSF-funded software designed for manipulating multibeam sonar data, including ASCII xyz data. The xyz data were extracted from the edited ESRI shape files and assigned a data "hierarchy" (Table 3) so that the best data had the largest impact on the values calculated for each grid cell.

Evaluating the DEMs

Several different methods are available for evaluating the DEMs: visual inspection, comparison with source datasets, and comparison with independent datasets.

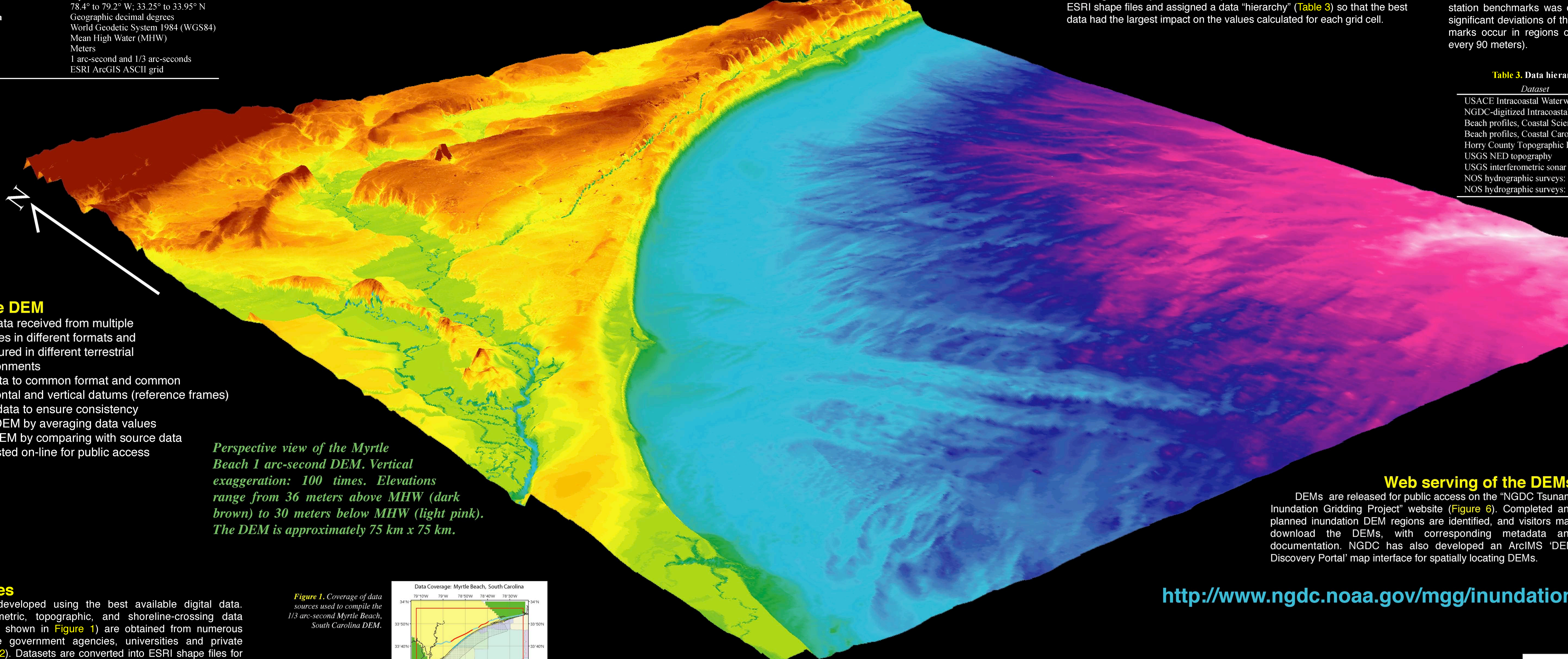
The 1/3 arc-second Myrtle Beach DEM was visually inspected for anomalous spikes and wells using ESRI ArcScene, which renders a 3-dimensional view of the DEM that can be rotated, colored and vertically exaggerated (e.g., central image). A "slope" map was also generated, which highlights changes in slope that should reflect natural morphology rather than artificial features at the edges of datasets. Close inspection revealed some artificial features that necessitated reevaluation of the data and regridding.

DEMs are also checked against select source data files used to build the DEM. Files are chosen based upon their contribution to grid-cell values (e.g., Table 3), and thus corresponding cells in the DEM should be consistent. Histograms of the difference between source data and the DEM may reveal discrepencies worthy of investigation.

A more exact evaluation method compares known elevation values for local tide stations and NGS geodetic monuments that are not used in building the DEM. Twenty tide stations in the Myrtle Beach regions, with measured benchmark elevations above MHW, were directly compared with the corresponding elevations extracted from the 1 arc-second DEM; comparison was made with the 1 arc-second DEM as the documented location of the tide station benchmarks was only accurate to within 6 arc-seconds. The most significant deviations of the DEM from the elevations recorded at the bench marks occur in regions covered by sparse NED topography (data points every 90 meters).

Table 3. Data hierarchy used to assign gridding weight in MB-System.

Dataset	*Relative Gridding Weight*
USACE Intracoastal Waterway surveys	100
NGDC-digitized Intracoastal Waterway dredged depths	100
Beach profiles, Coastal Science and Engineering, Inc.	100
Beach profiles, Coastal Carolina University	50
Horry County Topographic LiDAR	50
USGS NED topography	10
USGS interferometric sonar bathymetry data: pre-surfaced	5
NOS hydrographic surveys: gridded inland waterbodies	1
NOS hydrographic surveys: gridded open ocean	0.1



Perspective view of the Myrtle Beach 1 arc-second DEM. Vertical exaggeration: 100 times. Elevations range from 36 meters above MHW (dark brown) to 30 meters below MHW (light pink). The DEM is approximately 75 km x 75 km.

Web serving of the DEMs

DEMs are released for public access on the "NGDC Tsunami Inundation Gridding Project" website (Figure 6). Completed and planned inundation DEM regions are identified, and visitors may download the DEMs, with corresponding metadata and documentation. NGDC has also developed an ArcIMS 'DEM Discovery Portal' map interface for spatially locating DEMs.

http://www.ngdc.noaa.gov/mgg/inundation

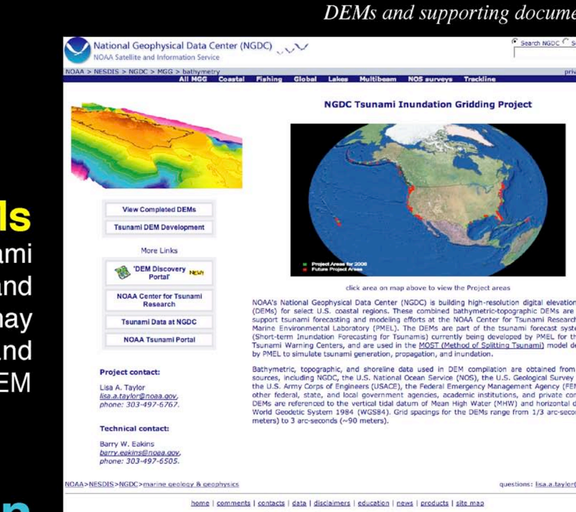


Figure 6. *Screen grab of "NGDC Tsunami Inundation Gridding Project" website, where visitors may download the coastal inundation DEMs and supporting documents.*

Data sources

The DEMs are developed using the best available digital data. Shoreline, bathymetric, topographic, and shoreline-crossing data (dataset coverage shown in Figure 1) are obtained from numerous federal and state government agencies, universities and private companies (Table 2). Datasets are converted into ESRI shape files for viewing, editing and evaluating with ArcMap. The data are collected by numerous methods, in different terrestrial environments, and at various scales and resolutions. Datasets are assessed for quality and accuracy both within each dataset, and between datasets to ensure consistency and gradual topographic transitioning along the edges of datasets. For some important bathymetric and topographic features there were no digital data, necessitating hand digitizing of these features for inclusion in the Myrtle Beach DEMs (see Problems encountered).

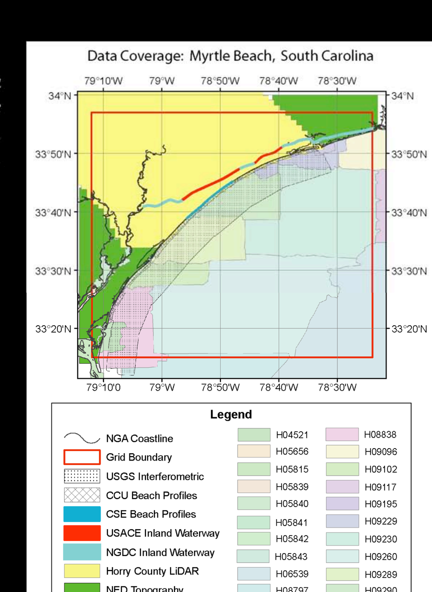


Figure 1. *Coverage of data sources used to compile the 1/3 arc-second Myrtle Beach, South Carolina DEM.*

Table 2. Datasets used in developing the Myrtle Beach DEMs.

Data type	*Source*	*Horizontal datum*	*Vertical datum*	*Year*
LiDAR topography	Horry County, South Carolina	South Carolina State Plane (feet)	NAVD88	2005
National Elevation Dataset topography	U.S. Geological Survey	NAD83 geographic	NAVD88	1970s–1980s
Mean High Water coastline	National Geospatial-Intelligence Agency	NAD83 geographic	Mean High Water	1998–2002
Shoreline-crossing beach profiles	Coastal Carolina University	South Carolina State Plane (feet)	NAVD88	2006
	Coastal Science & Engineering, Inc.	South Carolina State Plane (feet)	NGVD29	2005
Hydrographic surveys	National Ocean Service, NOAA	NAD83 geographic	Mean Low Water	1925–1972
	U.S. Army Corps of Engineers	South Carolina State Plane (feet)	Mean Low Water	2005–2006
Interferometric sonar surveys	U.S. Geological Survey	UTM Zone 17 (meters)	Mean Lower Low Water	1999–2003
Digitized soundings and features	National Geophysical Data Center, NOAA	WGS84 geographic	Mean High Water	

Problems encountered

Numerous problems were encountered during the data evaluation and gridding process. These included mismatches between datasets, morphologic changes to the region subsequent to data collection, and problems inherent to the data themselves.

Mismatches between datasets were most common with the NOS hydrographic surveys, many of which date from the 1930s. This was especially true where geomorphologic and anthropogenic change had modified the inland waterbodies: e.g., modern dredging of the Atlantic Intracoastal Waterway by the U.S. Army Corps of Engineers has significantly deepened that channel. As well, several river channels have experienced migration such that the recent topographic LiDAR data mismatches the older NOS surveys (e.g., Figure 3). Satellite imagery viewable with *Google Earth* was used to help assess the current morphology of suspect features before a determination was made as to which dataset to edit.

Figure 4 illustrates another problem encountered: namely, features without digital representation in any dataset. One significant tsunami-affecting feature is a new jetty at the entrance of Murrells Inlet. This feature is not represented in the NOS hydrographic surveys of the inlet, nor in the NED topography. NGDC chose to digitize this feature as two, 1-meter elevation lines, and excise NOS soundings in their immediate vicinity. *Google Earth* satellite imagery and a recent NOAA nautical chart were used to accurately locate the jetty.

Other problems included suspicious east–west lineated features within the Waccamaw river basin. This problem likely originated during topographic LiDAR data collection or initial processing and could not be rectified by NGDC. This LiDAR dataset also included numerous "wells" of anomalously deep elevations surrounded by "donuts" without data points, as well as returns from the surface of water bodies; these data points were excised prior to gridding. Also, some datasets, such as NED topography, contained "zero" values over rivers and the ocean, which were deleted by clipping to the coastline.

Recommendations for improving the Myrtle Beach DEMs include mapping of rivers that have undergone significant morphologic change since being surveyed by NOS.

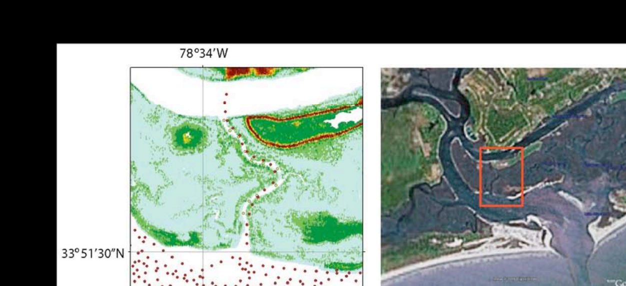


Figure 3. *Horse Ford Channel in the Little River Inlet. Figure on left shows original 1934 NOS sounding locations in red. The soundings were shifted horizontally (yellow circles) to lie within the current river channel location, as defined by the topographic LiDAR data and corresponding Google Earth satellite image (right).*

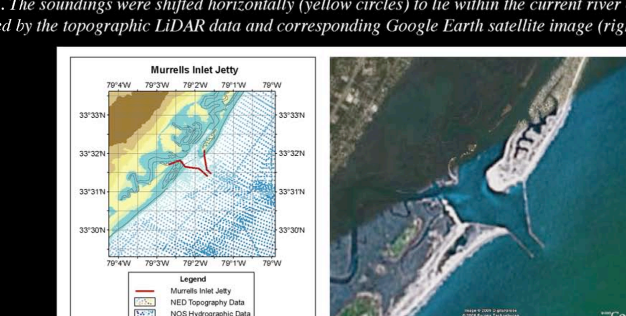


Figure 4. *Murrells Inlet jetty. The digitized jetty is shown on the left with surrounding NOS soundings and NED topographic data; neither dataset includes the jetty. The Google Earth satellite image on the right, in conjunction with NOAA Nautical Chart #11534, was used to digitize the jetty as a 1 meter elevation feature for gridding.*