HOLES IN THE OCEAN: FILLING DATA VOIDS IN BATHYMETRIC LIDAR, A CASE STUDY IN DRY TORTUGAS NATIONAL PARK, FLORIDA

by

JOHN BENJAMIN COLEMAN

(Under the Direction of Xiaobai Yao)

ABSTRACT

The mapping of coral reefs may be efficiently accomplished by the use of airborne laser bathymetry. However, there are often data holes within the bathymetry data which must be filled in order to produce a complete representation of the coral habitat. This study presents a method to fill these data holes through data merging and interpolation. We first merge ancillary digital sounding data with airborne laser bathymetry data of Dry Tortugas National Park, Florida. What follows is to generate an elevation surface of topography under the sea by spatial interpolation based on the dataset obtained in the first step. Four interpolation techniques, including Kriging, natural neighbor, spline and inverse distance weighted, are implemented and evaluated on their ability to accurately and realistically represent the shallow-water bathymetry of the study area. The natural neighbor technique is found to be the most effective qualitatively with a root mean square error of 3.8 meters. This enhanced digital elevation model is used in conjunction with Ikonos imagery to produce a complete, three-dimensional visualization of the study area.

INDEX WORDS: Airborne laser bathymetry, Digital elevation model, Dry Tortugas, Interpolation, Kriging, Coral reef

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CHAPTER 1

INTRODUCTION

The Earth's coral reefs are an invaluable ecological resource. Coral reefs serve as habitat for hundreds of thousands of species of marine life and are among the biologically diverse places on the Earth. Coral reefs provide socio-economic stability to millions of people around the world.

However, the Earth's coral reefs are in peril. Wilkinson (2004) has classified 20% of coral reefs in the world as destroyed, while 24% are considered in imminent danger and 26% are threatened to collapse in the long term. Threats to coral ecosystems include coral bleaching due to climate change, increased incidence of coral diseases, and direct anthropogenic sources such as pollution from urban and industrial developments and damaging fishing techniques (Goldberg & Wilkinson, 2004).

Mapping of coral reefs using remote sensing is a rapidly growing field of research which can contribute to better understanding and management of coral reefs, and contributes to a very detailed understanding of the spatial attributes of reefs (Knudby, 2007). This kind of information improves managers' ability to study and protect coral reefs. This study focuses on combining several remote sensing techniques (including airborne lidar bathymetry, digital soundings, and satellite imagery) to create a complete, three-dimensional representation of an area of coral reefs in Dry Tortugas National Park, Florida.

There are many substrate and coral types associated with the underwater landscape of the Florida Keys. This particular region has a variety of benthic habitats, including patch reefs, platform margin reefs, bare sand and sea grass. The Florida Fish and Wildlife Commission's

Fish and Wildlife Research Institute, in conjunction with the NOAA's National Ocean Service, has developed a collapsible classification scheme of shallow-water coral ecosystems for the entire Florida Keys. Four basic classes of benthic habitat—coral, seagrasses, hardbottom, and bare substrate—were expanded to classify all bottom-types within the Florida Keys (CCMA, 2008). Table 1.1 gives a partial listing of several distinct coral and bottom-types found in the study area. Figures 1.1 and 1.2 are sample images of habitat types found within the study area.

Table 1.1: Reef classifications found in Dry Tortugas National Park (Source: CCMA)

Class	Description
Platform margin reef—Remnant (low profile)	Coral/hardbottom features not exhibiting distinctive signature of spur and groove reefs. Usually parallel to line of reef tract, but may form transverse features perpendicular to the reef tract. Relief from less than 0.5m - 1 or 2m.
Platform margin reef—Reef rubble	Zone landward of bank reefs and other high energy reef tract areas where unstable rubble exists with little or no visible colonization. In relatively shallow water (1 - 6m) often in association with Thallassia or Syringodium. Signature on the aerial photographs is distinctive from other coral/hardbottom communities. May form transverse features perpendicular to line of reef tract.
Patch reefs—Individual	Discrete coral communities, typically dome-shaped, usually outside of Hawk Channel, with a few inshore. Can be linear features where several or a series occurs. Discrete coral communities, typically dome-shaped, usually outside of Hawk Channel, with a few inshore. Can be linear features where several or a series occurs. (See fig. 1.1.)
Patch reefs—Coral or rock patches with bare sand	Very sparse features that are similar in nature to patch reefs, but are on the outer reef tract. These areas are dominantly sand or a veneer of sand over low relief rock.
Patchy seagrass	Predominantly sand and/or mud with small, scattered seagrass patches. (See fig. 1.2.)
Bare substrate—carbonate sand	Sand-size carbonate sediments, usually in areas exposed to current and wind energy that continually sort out and remove finer sediment fractions.

The preservation of these coral habitats is a vital part of the larger goals of biological preservation. This research outlines a method for incorporating different geographic data types in a geographic information system in order to form a more complete spatial understanding of coral reef habitats. Detailed spatial information of underwater habitats can help coral reef managers around the world develop better preservation strategies for this precious natural resource.

Figure 1.1: Individual patch reef

Figure 1.2: Seagrass

CHAPTER 2

HOLES IN THE OCEAN: FILLING DATA VOIDS IN BATHYMETRIC LIDAR, A CASE STUDY IN DRY TORTUGAS NATIONAL PARK, FLORIDA[1]

[1] Coleman, J.B., Jordan, T.R., Yao, X., and M. Madden. To be submitted to *Computers and Geoscience*.

Introduction

Coral reefs are a major source of the Earth's ecological biodiversity and some are considered among the most biologically diverse places in the world (Wilkinson, 2004). Their contributions to global and local ecological systems are invaluable. Unfortunately, coral reefs around the world are under increased environmental pressures for a variety of reasons—from various pollution sources to warming ocean temperatures to damaging fishing techniques and negligence (Goldberg & Wilkinson, 2004). Most coral reefs in the United States are under the management of national or state parks. Management agencies could function with greater efficiency and efficacy when more detailed and complete data about benthic and coral reef habitats are available. Digital satellite imagery and digital elevation models (DEMs) of coral reef and benthic habitats assume complementary roles as information sources for managers. They have many uses, from identifying geomorphologic zones to assessing the state and developmental direction of biodiversity within the habitat (Knudby, 2007). Additionally, near-shore bathymetric information is very useful for a variety of applications involving seafloor morphology which include navigation and coastal engineering (Su, 2008).

However, there are often areas of missing data in the coverage, also called holes or data holidays. Airborne laser bathymetry (ALB) is an accurate (often < 1 m) and efficient means of collecting shallow water bathymetric data, but often the laser signal gives no return signal or data quality is corrupted in the postprocessing phase. The method described in this paper suggests combining freely available bathymetric lidar data with ancillary depth sounding data to produce a complete, enhanced DEM of an area inside a Research Natural Area in Dry Tortugas National Park, Florida.

Once holes in the bathymetric data have been filled, the data may then be combined with high resolution digital imagery in order to facilitate both automated classification of substrate type and calculation of volumetric measurements related to each class. This type of information would be useful for comparing a reef system's morphological state across different time slices, particularly a reef system which is under threat, protected or in danger of damage. These types of data may also be combined to create a three-dimensional visualization of the reef. This step provides a more intuitive understanding of reef geomorphology for both analytic and educational purposes.

This study presents a method for filling the data holes without additional data collection in order to minimize both monetary costs and environmental impact. We present and evaluate the method with a case study of the Dry Tortugas National Park area. The proposed method is an efficient means of producing a complete DEM which may be used for management and conservation purposes in an area with only two bathymetric data sets of widely differing spatial densities to choose from. The objectives of this research are:

- to resolve vertical datum difference between NAVD88 and mean lower low water (MLLW) within the study area.
- to integrate incomplete bathymetric lidar with digital sounding data in order to create a seamless, enhanced DEM representation of the ocean floor in a protected Research Natural Area in Dry Tortugas National Park.
- to evaluate the performance of various interpolation techniques in marrying these two data sets of vastly different spatial distribution.
- to develop a three-dimensional visualization of benthic habitat for the area based on the enhanced DEM combined with Ikonos satellite imagery.

Literature Review

A variety of studies have focused on merging bathymetric and topographic data. But these studies have mainly considered areas in which there are known vertical datum transformations between the datasets (as computed using the National Oceanic and Atmospheric Association's (NOAA) Vdatum tool). Such areas are usually found in large commercial ports of the continental United States. The method presented in this study focuses on a more universal application of merging the data sets.

A variety of studies have focused on merging bathymetric and topographic data. But these studies have mainly considered areas in which there are known vertical datum transformations between the datasets (as computed using the National Oceanic and Atmospheric Association's (NOAA) Vdatum tool). Such areas are usually found in large commercial ports of the continental United States. The method presented in this study focuses on a more universal application of merging the data sets.

ALB is an increasingly popular and useful tool for obtaining detailed information about sub-aqueous terrain and coral reef habitats on the meter to sub-meter scale (Knuby, 2007). It has been shown to be a more cost-effective technique than field-survey methods for coastal habitats (Mumby & Green, 1999). A low-flying aircraft equipped with a light detection and ranging (lidar) device emits optical laser pulses whose return times are measured and geometries computed by triangulation with the aircraft's precisely known global positional coordinates (Guenther, 2007). Each data point the lidar device records is inherently georeferenced. The resulting lidar point cloud can then be transformed into other forms of geographic data which very precisely describe the shape of a surface, even a surface under water. Lidar is most typically applied in situations above water, such as forestry applications, but the use of lidar for obtaining information about sub-aquatic environments is a budding facet of geographic research and application. Some of the main benefits of using ALB as opposed to more traditional bathymetric methods such as sonar or digital soundings are the speed, efficiency and accuracy with which the area can be surveyed (Guenther, 2007). This fact enables surveys of the same areas to be completed in close temporal proximity and therefore provide multi-temporal views of dynamic habitats at less expense than traditional surveys.

There is increasing interest in lidar applications involving the description and measure of marine geomorphology (Knudby, 2007). Coral reefs and other submerged features have been effectively mapped using lidar in ALB applications (Finkl, Benedet & Andrews, 2005; Brock *et al.*, 2006; Wedding *et al.*, 2008). Bathymetric lidar has also been used to quantitatively determine rugosity, a measure of roughness or surface variability, of areas of coral reef (Brock *et al.*, 2006). ALB applications also include the measurement of temporal morphodynamics and the derivation of metrics of sandbars and barrier islands in marine environments (Brock, Krabill & Sallenger, 2004). The ability to represent three dimensions of bathymetric features in great detail provides the cartographer or geographic information manager with additional insight for classification and discrimination purposes. ALB also has the distinct advantage of virtually eliminating the possibility of damage to fragile biological assets at or near the surface (Guenther *et al.* 1994).

The effectiveness and accuracy of various remote imaging sensors for detecting and mapping underwater areas has been extensively studied recently (Mumby & Edwards, 2002; Andréfouët *et al.*, 2003; Palandro *et al.*, 2003; Benfield *et al.*, 2007). These studies found high spatial resolution, multispectral satellites such as Ikonos and Quickbird to be most effective for mapping smaller (< 500 km^2) underwater environments where independent classifications are available and attention to detail is necessary. Researchers have also studied the spectral reflectance of different coral reef habitat bottom types from both *in situ* observations and data collected from remote sensing satellites (Lubin *et al.*, 2001; Holden & LeDrew, 2001, 2002; Hochberg, Atkinson & Andréfouët 2002; Hochberg & Atkinson, 2002).

The combination of lidar data and high resolution digital imagery is a proven tool leading to the interpretation, classification and quantification of reef habitat (Kundby, 2007). Increasingly, lidar devices are equipped with red-green-blue (RGB) and color-infrared (CIR) digital cameras, or other imaging equipment such as digital video, which capture georeferenced aerial images simultaneously with the collection of the lidar data points (Su, 2008; USGS, 2008). This technique facilitates the combination of the two data types into a more informative and complete synthesized data product.

Detection of bottom features in ALB applications depends upon water depth, turbidity and atmospheric condition. These factors generally limit the regions which can be effectively mapped using ALB to shallow, clear and calm waters (Guenther, 2007). Despite the high demand for bathymetric lidar data, the high cost of data production and other factors conspire to keep worldwide coverage minimal and spatially limited (Su, 2008). Even within areas which are surveyed, there are often holes, sometimes called data holidays, in the data. Areas of various sizes and shapes may be void of lidar data because of selective survey coverage, water depth which is too great for the lidar sensor to perceive a return signal, or the removal of lidar processing artifacts (USGS, 2008). Such holes prevent a complete analysis and visualization of the data.

Hensley, Munjy and Rosen (2007) suggest three primary ways to fill data holes in DEMs: 1) Specially obtain data pertaining to the holes, 2) Use data from previous data collections or ancillary data sources, or 3) Employ interpolation techniques such as surface fitting, kriging or polynomial interpolators. Each of these methods has its tradeoffs between data quality and ease of obtaining the data. Obtaining omitted data with the same survey technique via subsequent surveys is best from a quality perspective, but usually consumes the most resources. Data collected and integrated from other sources is most likely held to different quality standards, but can be relatively easy to collect, especially if no additional surveying is required. Spatial interpolation techniques alone are acceptable in many situations, but not all surfaces reflect the mathematical trends used to define the interpolations, especially surfaces with high topographic variability.

Research Design

Study Area

The Dry Tortugas are a collection of small, low-lying islands and reefs located approximately 70 miles west of Key West, Florida. Their relative remoteness from a large population center has for hundreds of years provided some degree of protection from damaging anthropogenic forces. The Dry Tortugas National Park has existed as such since 1992 (NPS, 2009a). As of January 19, 2007, a large portion of the park, including the study area, is now designated a Research Natural Area (RNA) by the U.S. Federal Government. RNAs are considered “no-take” zones in which fishing and anchoring are prohibited due to loss of habitat and species degradation. In short, the keys and surrounding reefs, once thought to be pristine, are not immune to the ill effects of tourism and sport fishing. Staghorn coral (*Acropora cervicornis*) species alone have declined 99% since 1977 (NPS, 2009b).

The particular study area within the Dry Tortugas National Park is 36 km^2 and rectangular in shape (fig. 2.1). It is centered roughly around Loggerhead Key. The region extends from 302,000 m East (NAD83 UTM Zone 17N) along the western boundary to 308,000 m East on the eastern boundary. The northern boundary extends along 2,728,000 m North and the southern boundary is located along the 2,722,000 m North gridline.

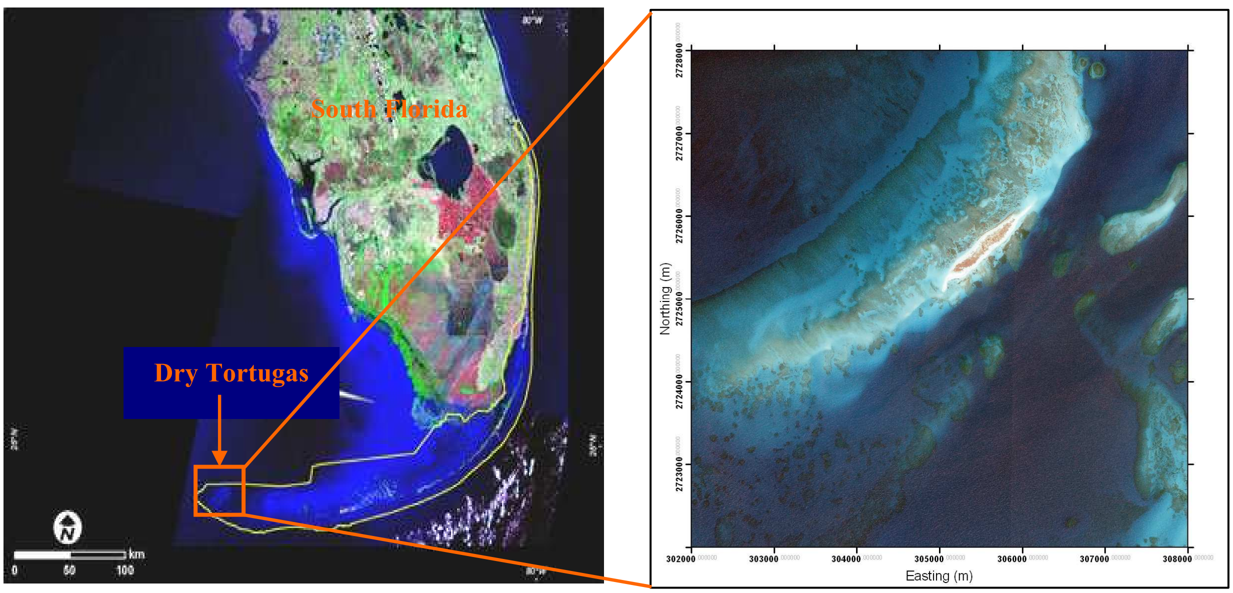


Figure 2.1: Regional map of the Dry Tortugas (left), and Ikonos image of the study area (right)

In addition to the coastal habitat characteristics and important locational role as part of an protected national park, this study area was also chosen because it has freely available, incomplete bathymetric lidar coverage, at least one freely available source of ancillary bathymetric data, and freely available, cloudless Ikonos imagery all collected within a reasonably short time span. These factors allow for the synthesis of data types to produce an enhanced bathymetric DEM and subsequent visualization. Dry Tortugas National Park managers could benefit from all aspects of data acquisition related to the local marine bathymetry. The protected status of the park is an additional compelling reason for compiling detailed bathymetric information for the area.

Data Sets

ALB-derived data provides the backbone for this analysis. NASA has developed the Experimental Advanced Airborne Research Lidar (EAARL) device, a lidar specifically designed for collecting bathymetric data (USGS, 2008). In optically clear waters, the laser can penetrate to depths of up to 1.5 Secchi disc depths (approx. 25 m in ideal conditions). The laser footprint is roughly 20 cm in diameter. The USGS, in a partnership with NASA and the National Park Service (NPS) has produced quality-controlled raster grids which are interpolated from the raw EAARL multipoint data. The grids have approximately 1m horizontal accuracy (NAD83) and 20 cm vertical accuracy (NAVD88). The EAARL data were collected during summer of 2004. Figure 2.2 illustrates the extent of EAARL survey coverage over the study region.

In order to complement the EAARL bathymetric data, sounding point data from the National Oceanic Service's (NOS) Office of Coast Survey (OCS) Electronic Nautical Charts (ENCs). ENC depth soundings adhere to the International Hydrologic Organization's (IHO) S-44 International Hydrologic Survey Standards and are a primary source for navigation data distributed by OCS. Total vertical uncertainty is no more than 50 cm at the 95% confidence level for this survey. Total horizontal uncertainty is no more than 5 m plus 5% of depth at the 95% confidence level (IHO, 2009).

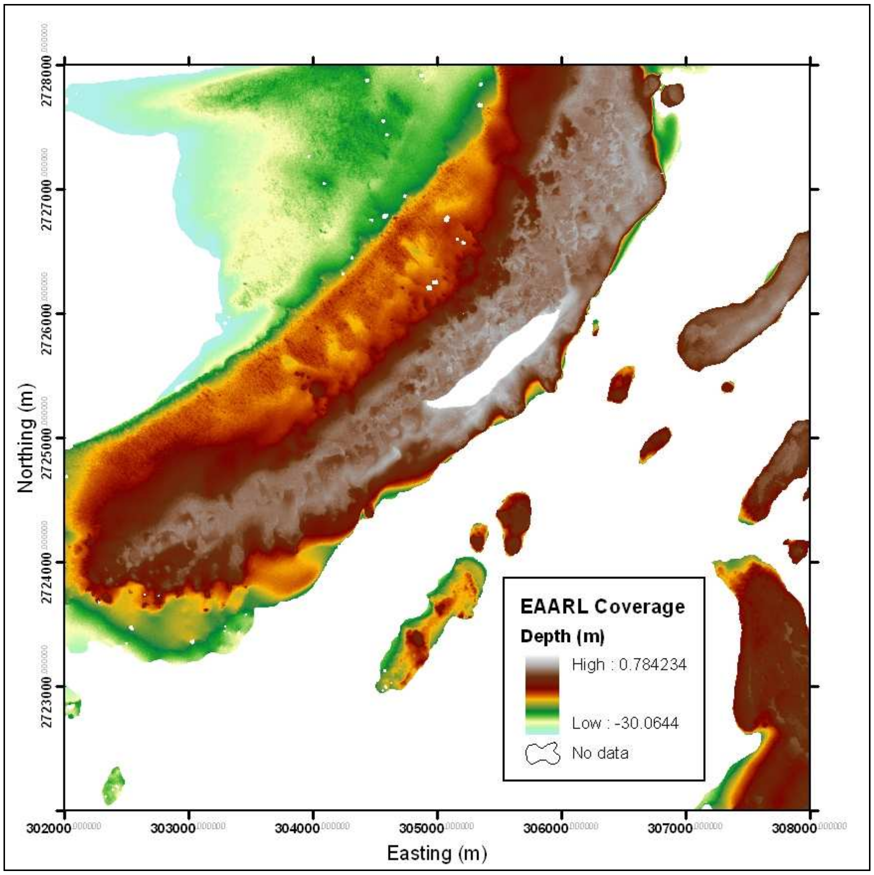


Figure 2.2: EAARL data coverage over the study region

The raw soundings are referenced in accord with the WGS84 ellipsoidal datum (horizontal) and mean lower low water (MLLW) vertical tidal datum. The MLLW tidal datum for this region is an average of lowest daily tidal levels referenced to a series of tidal gages in Garden Key, Dry Tortugas, Florida taken over a 19-year National Tidal Datum Epoch (1983-2001) (National Oceanic and Atmospheric Administration, 2008). No geodetic relationship between the fixed orthometric NAVD88 and MLLW has been determined for this region.

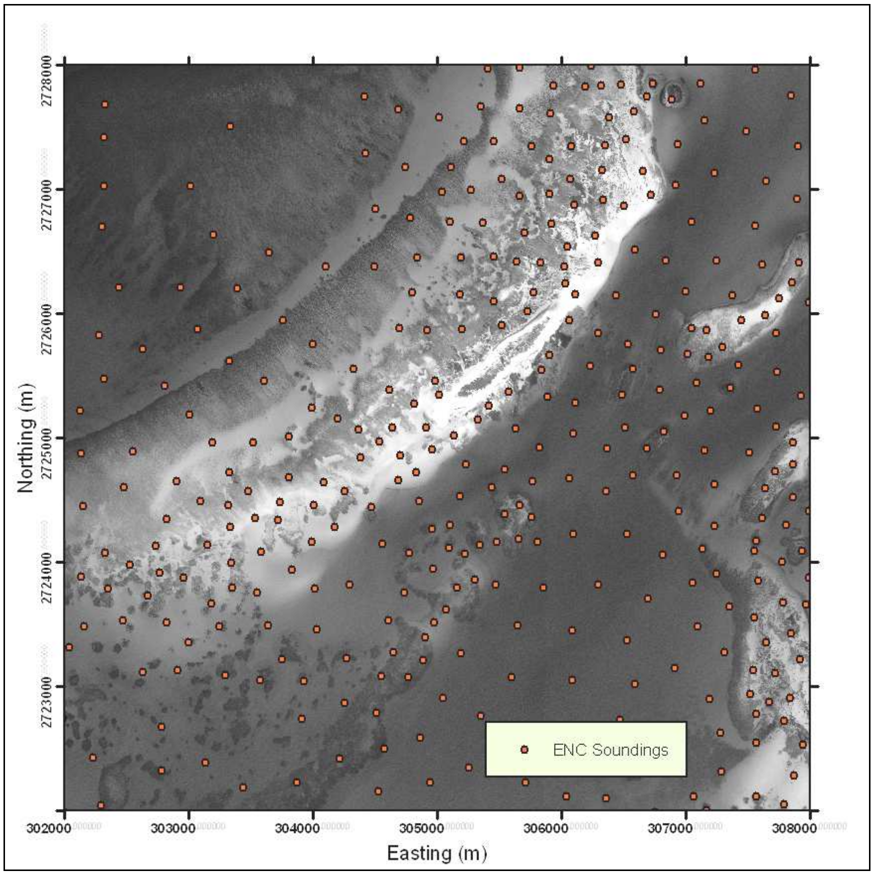


Figure 2.3: ENC depth soundings overlaid on single-band Ikonos image of the study area

Imagery for the study area is available from the Ikonos satellite operated by GeoEye (fig. 2.4). A combination of both the blue (0.45 – 0.52 μm) and green (0.51 – 0.60 μm) wavelength bands is optimal for viewing the bathymetric features in this scene due to the high amount of sun glint and noise in both the red and near-infrared bands. This particular swath of Ikonos imagery was acquired on February 21, 2006. There are no clouds apparent in the image and seas were calm—lending to a particularly good satellite image for interpretation. The image has been georectified to the UTM Zone 17N coordinate system (NAD83).

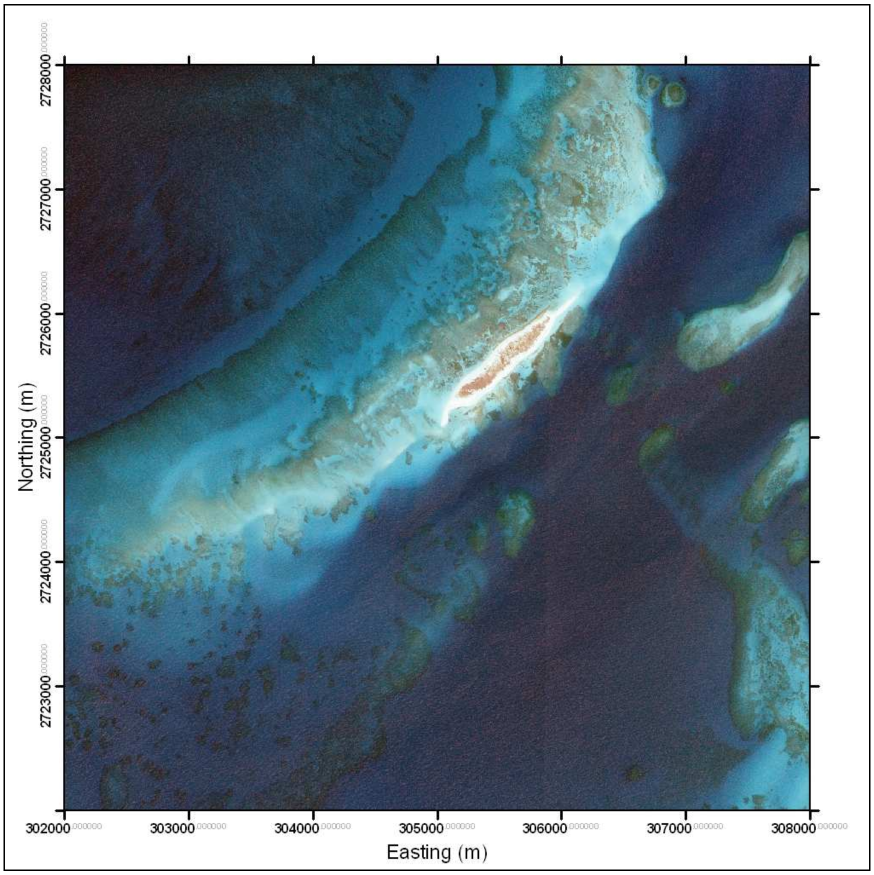


Figure 2.4: Ikonos multispectral imagery of study area. Note the sliver of Loggerhead Key near the center of the image, the only area of dry land in the image

Methods

There are four main steps involved in this method: 1) Merging the EAARL and ENC data sets; 2) Interpolating a representative bathymetric surface; 3) Accuracy assessment and result interpretation; and 4) Geovisualization. The workflow is illustrated in Figure 2.5.

Merging the two data sets involves converting both into the same horizontal and vertical datums. Without proper datum adjustment, large spatial errors may result in the method. This is accomplished through standard transformation of the horizontal datum as well as statistical and geostatistical analysis of the vertical datum shift between the two. Also in this step, the EAARL raster data is converted into a rectangular array of points which are merged with the point geography of the ENC soundings in order to provide smooth transitions between the two data types during the mosaicking portion of the interpolation step.

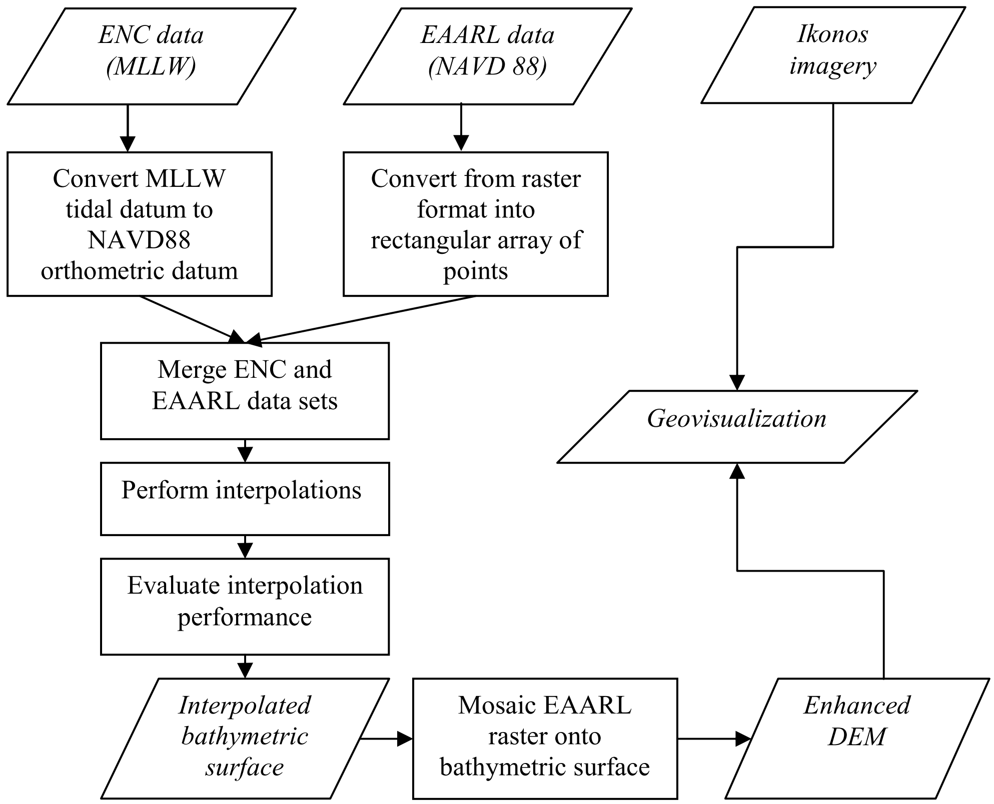


Figure 2.5: Work Flow of Method

In the next stage, four interpolation techniques are implemented and evaluated based on their ability to accurately represent the true bathymetric surface. Ordinary spherical Kriging, spline, inverse distance weighted (IDW), and natural neighbor interpolators are all used and subsequently compared to one another. Natural neighbor is an interpolation technique which weighs the influence of neighbors by constructing a Voronoi diagram between the target point and its nearest neighbors and then calculating proportional areas. Kriging is a geostatistical interpolation method which attempts to minimize errors by estimating error trends in the data and compensating for them. The spline interpolation method constructs a continuous and differentiable (i.e. smooth) surface of minimum curvature between all points. IDW conceptualizes neighbor influence as an inverse function of distance, mathematically mimicking Tobler's (1970) First Law of Geography.

The interpolated surfaces are judged based on 1) root mean square (RMS) error of the validation set, and 2) representative ability—a qualitative category which addresses spatial correlation with the Ikonos image, evidence of interpolation artifacts, and transitions between the two data set densities. A standard validation technique is used to evaluate the quantitative appropriateness of each interpolation method. Additionally, two representative transects are used to compare profiles of the interpolated surfaces in order to gain insight about method suitability. Once interpolation evaluation is complete, the original EAARL raster data is mosaicked back on top of the interpolated bathymetric surface to produce the final, enhanced DEM.

Finally, the enhanced DEM serves as a platform for producing a complete, realistic visualization of the benthic habitat. The three-dimensional visualization is a combination of cloud-free Ikonos imagery draped over the enhanced bathymetric DEM and displayed using ESRI's ArcScene 9.3 software. The DEM provides the base heights for the visualization while the Ikonos imagery provides valuable spectral information related to the underwater habitats. A swim-through highlights major reef characteristics and provides context for interpretation and future classification.

Case Study: Dry Tortugas National Park

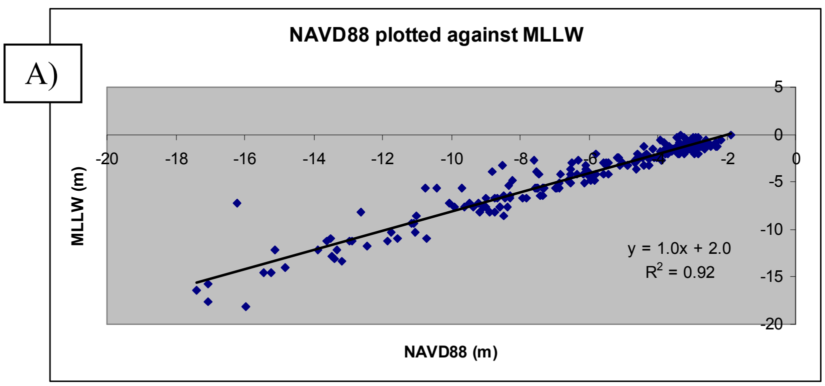
Conversion from MLLW to NAVD88

In order to accomplish the objective of integrating the EAARL data with the ENC soundings into an enhanced bathymetric DEM, it is necessary to first convert both data sets into a common horizontal and vertical datum. Spatial errors will result if the two data sets are based on mismatched datums. Horizontal datum transformations may be accomplished using standard industry software such as ESRI's ArcGIS and in this situation are assumed equivalent with ~1 m error between WGS84 and GRS80. The National Oceanic and Atmospheric Association (NOAA) published a vertical datum transformation tool called VDatum (http://vdatum.noaa.gov) which is able to convert between common local tidal datums (such as MLLW) and orthometric datums such as NAVD88. The VDatum tool has the advantage of incorporating models of local tidal variation into the conversion between various vertical datums (Myers *et al.*, 2007). However, this tool is only available for select coastal regions of North America, and does not include Dry Tortugas National Park. In the absence of such models for this region, differences between the measured MLLW values and EAARL data values are resolved using statistical techniques.

The primary idea for conversion from MLLW to NAVD88 for this application is to minimize the vertical datum measure difference between points found in both the ENC (MLLW) and EAARL (NAVD88) data sets. This was accomplished by removing statistical and geostatistical outliers from the ENC data set. The EAARL data, having been sourced by advanced ALB techniques, was assumed to be the more accurate and precise of the two data sets.

The first step consists of locating points in the ENC data set which are contained in the footprint of the EAARL raster data. The coinciding NAVD88 values can then be extracted into the attribute table of the coinciding ENC point soundings. In this case, there are 199 coinciding points. An ordinary least squares (OLS) regression analysis was performed with NAVD88 measures as the independent variable and MLLW measures as the dependent variable in order to check for potential depth bias in measurement difference between the two datums.

The mean difference in vertical data measurements for these two data sets was found to be 1.9 m with a standard error of 1.07 m. Figure 2.6 (A) shows the OLS regression analysis and regression line plot. The OLS linear regression model is an excellent predictor with an adjusted $R^2 = 0.92$. The coefficient of the predictive variable (NAVD88) is 1.0, suggesting that the two measures are not only directly proportional, but differ by a constant value regardless of depth.



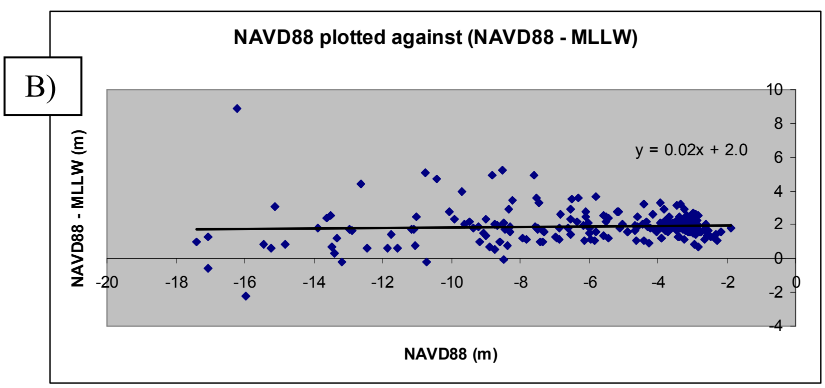


Figure 2.6: Results of OLS regression

Figure 2.6 (B) shows NAVD88 values plotted against the difference values for the two datums. The regression line for these two variables shows no significant depth trend in the difference between the two datums. Thus, it is shown that there is no significant variability away from a constant difference between the NAVD88 and MLLW vertical datums with depth.

The second consideration in modeling the difference between the two datums is spatial variability. Could there be spatial clusters of like difference values between the two? In order to address this question, Anselin's Local Moran's I analysis was implemented in order to detect both clusters of like difference values and spatial outliers. This technique is useful for identifying the spatial distribution of spatial autocorrelation effects. Several of the points were identified as statistically significant (fig. 2.7). For clarification, a point registered as "High next to high" would mean that the point indicated has a relatively large difference value compared to all points and is in a statistically significant cluster with similarly-valued points.

ENC sounding points which differed by more than 3 standard deviations (approx. 3 meters) from the EAARL data set are eliminated. This extraction process left a remaining data set of 180 points with a mean difference between the two datums (MLLW and NAVD88) of 1.8 m and standard deviation of 60 cm. An estimation of NAVD88 measures for all ENC points in the study area (excepting those which were considered outliers) was then calculated by eliminating the mean difference of 1.8 m from the ENC MLLW values. The resulting field had a mean difference of zero and standard deviation of 60 cm when compared with EAARL raster values (NAVD88) at the same location. This field is then used as the corrected NAVD88 heights for the ENC data set.

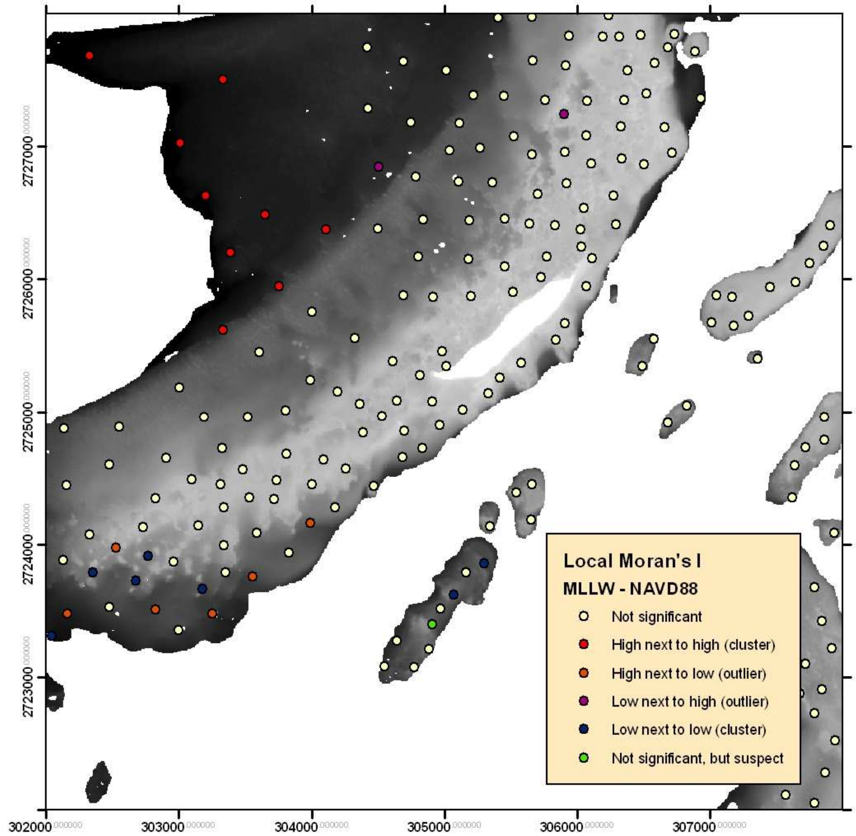


Figure 2.7: Results of Local Moran's I analysis

<u>Merging EAARL and ENC Data Sets</u>

Merging the two data sets may begin now that they are in the same vertical and horizontal datum. The first step in this process is to convert the EAARL raster into a vector-based point geography. In this case, conversion is accomplished by creating a raster grid with a 10 m by 10 m grid cell size which covers the study area and then converting this grid into a rectangular array of points spaced systematically every 10 m. The EAARL raster values are then extracted to this array of points. This step is only necessary if the ALB data for the project is no longer in point form as raw lidar data sets are usually in a multipoint or LAS data format. Points in the array which do not coincide with legitimate EAARL raster values are then eliminated from the array.

The remaining points in the array are subsequently merged with ENC sounding points which do not coincide with the EAARL raster data (fig. 2.8).

The resultant data set is therefore representative of both the area covered by the EAARL data and that covered only by ENC soundings, with the EAARL data taking precedence in areas where the two data sets coincide. The purpose of constructing the point data set in this fashion is to provide the basis for constructing an interpolated bathymetric surface with smooth transitions along the boundaries between areas covered by the densely-spaced EAARL data and the more sparsely-spaced ENC data. Smooth transitions in a natural setting provide a cleaner and more realistic visualization.

Interpolation and Accuracy Assessment

Four interpolation techniques—natural neighbor, spline, IDW, and multiple manifestations of Kriging—were implemented in ESRI ArcMap using the merged data set. The vastly different spatial densities between the EAARL point data and ENC sounding data in this area offer unique challenges for spatial interpolation of a continuous, representative surface. The accuracy of the final data set is subject to error propagation from uncertainty in the vertical and horizontal planes of both the ENC and EAARL data sets. Vertical changes can be abrupt and unpredictable over small changes in horizontal position due to the discontinuous and abrupt nature of a relatively smooth sand ocean floor interrupted by coral protrusions. Also, differences are inherent between the interpolated portions of the bathymetric surface and the actual surface. There is a roughly 1 m horizontal discrepancy between the GRS80 ellipsoid and WGS84 spheroid, which for this project are considered equivalent datums

In order to assess accuracy in a quantitative manner, a randomly selected set of 16 ENC soundings which do not overlap EAARL data coverage were removed from the interpolation and the set is reserved as testing dataset. Predicted depth values at those 16 locations were then compared with measured values. RMS error was calculated and serves as a measure of interpolation method suitability. The validation set was returned to the ENC data set before final interpolated surfaces were rendered.

To complement the quantitative measures for accuracy evaluation, a qualitative evaluation is also performed by observing characteristics of the interpolation results. One such qualitative characteristic is the correlation between the visualization of each interpolation and the high resolution Ikonos imagery. This technique is used as surrogate of ground truth visual representation. , Another qualitative characteristic in use is the evidence of interpolation artifacts and transitions between areas covered by EAARL and ENC data were established to describe the ability of each technique to realistically represent the bathymetric surface. These artifacts appear as unnatural irregularities such as semicircles, jagged edges or abrupt breaklines which are visible in the interpolation visualization. All techniques were performed using interpolation tools in ESRI ArcMap 9.3. Table 1 summarizes the accuracy and qualitative assessment of the interpolation techniques.

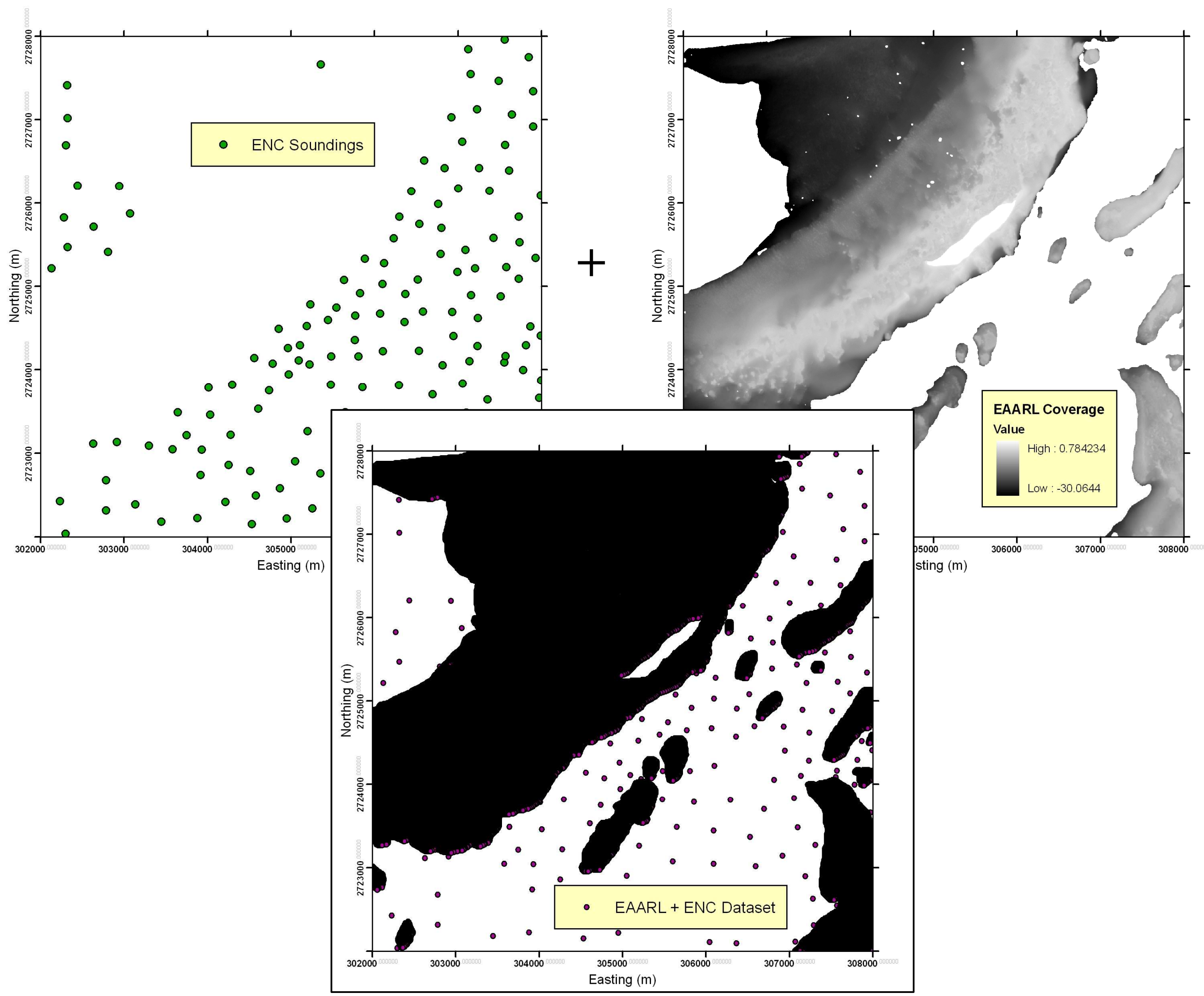


Figure 2.8: Merging EAARL and ENC data set

Kriging in this implementation was performed using the Geostatistical Wizard tool in ArcMap 9.3 with various combinations of parameters. Spatial lag was varied between 5 m and 500 m. The results in Table 1 are representative of the various Kriging interpolation results. The neighborhood search ellipse for the Kriging interpolations was also rotated in 30º increments to find the most desirable results. Rotation was found to have no significant effect on interpolation results.

Table 2.1: Analysis of interpolation validation results

Technique	Mean error (m)	RMS error (m)	Interpolation artifacts	Transitions	Image correlation
Natural neighbor	-0.5	3.8	Minimal	Smooth	Good
Spline	0.8	4.3	Obvious	Rough	Poor
IDW	2.3	5.5	Obvious	Rough	Poor
Krig 1 (lag 50)	-0.7	4.2	Apparent	Varied	Moderate
Krig 2 (lag 200)	-0.6	4.0	Obvious	Smooth	Good
Krig 3 (lag 15)	-0.3	3.3	Obvious	Varied	Moderate

As shown in Figure 2.9, the natural neighbor technique produces an interpolated surface virtually free of interpolation artifacts seen in Figures 2.10–14. Additionally, the natural neighbor technique is desirable in this setting because it does not create valleys, pits or peaks which are not explicitly represented by the data (Watson, 1992). For these qualitative reasons, as well as its relative low RMS error of 3.8 m, the natural neighbor technique prevailed as the most natural and accurate representation of the bathymetric surface

All interpolations suffer from edge effects in which the technique produces errant values toward the outer edges of the interpolated area. These errors are due to minimal and/or directionally biased neighbors. Users of the enhanced DEM should be aware that these effects are present.

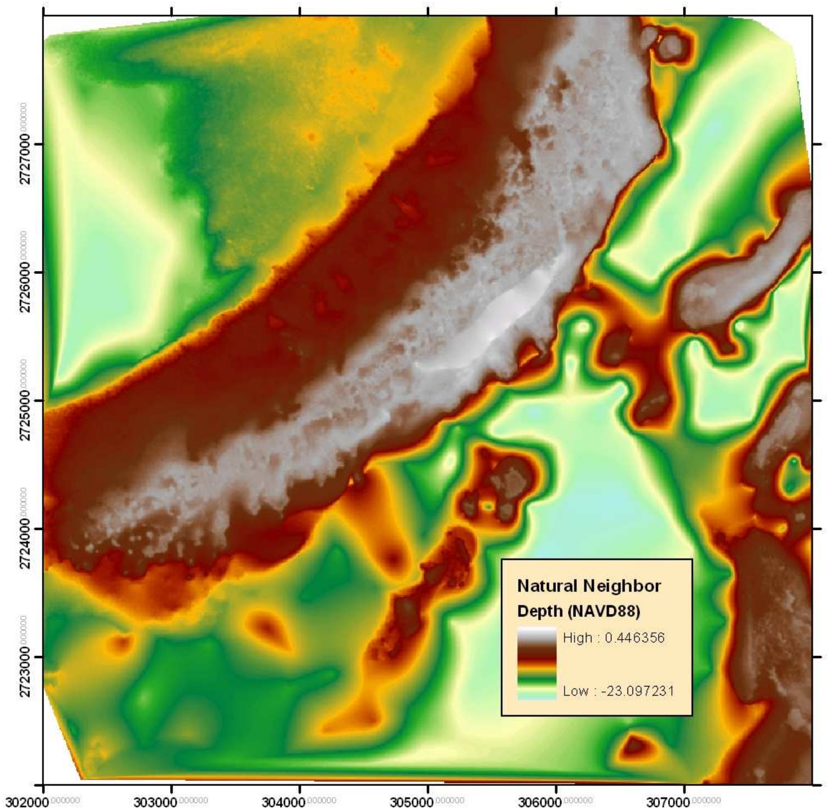


Figure 2.9: Natural neighbor interpolation results

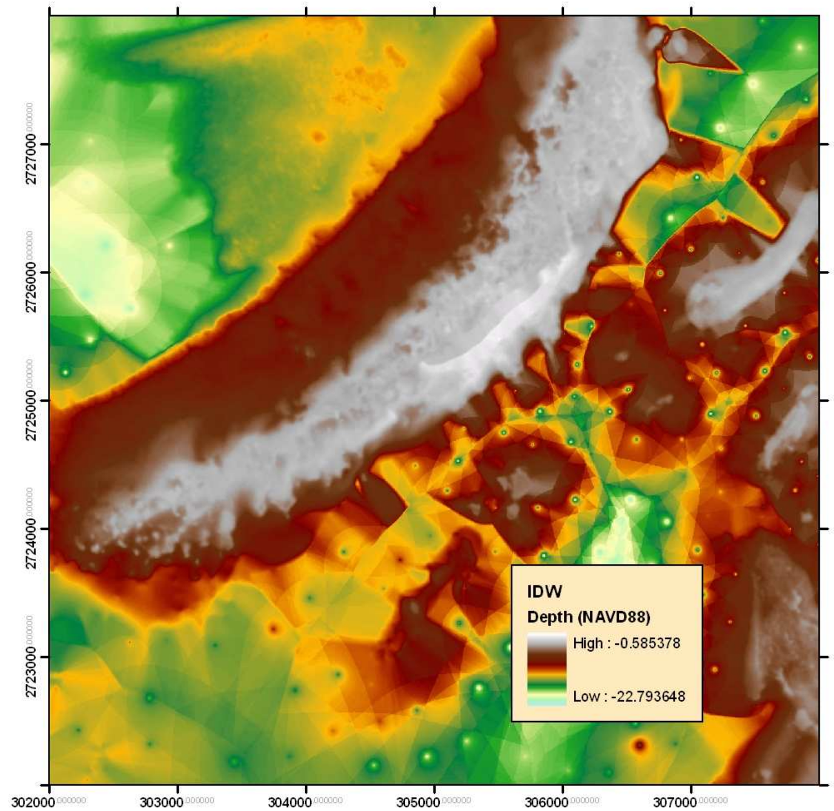


Figure 2.10: IDW interpolation results

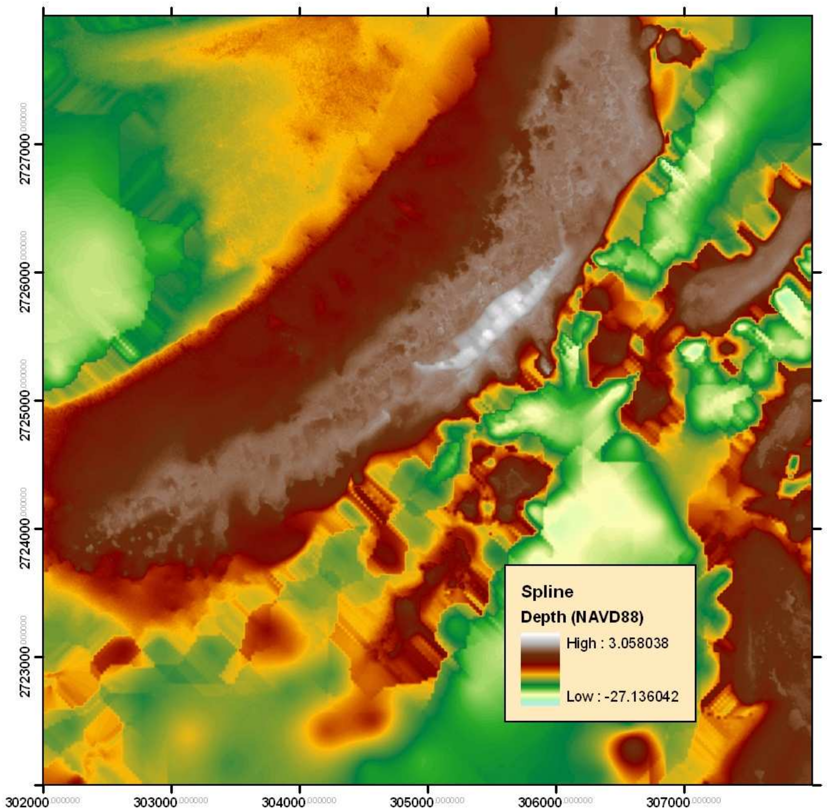


Figure 2.11: Spline interpolation results

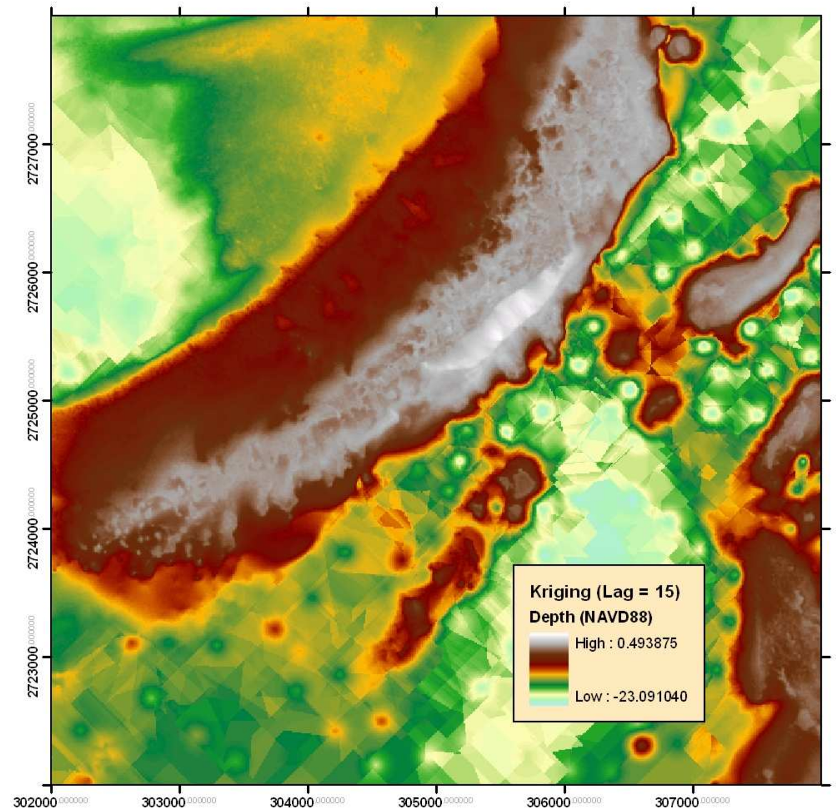


Figure 2.12: Kriging interpolation results (lag = 15 m)

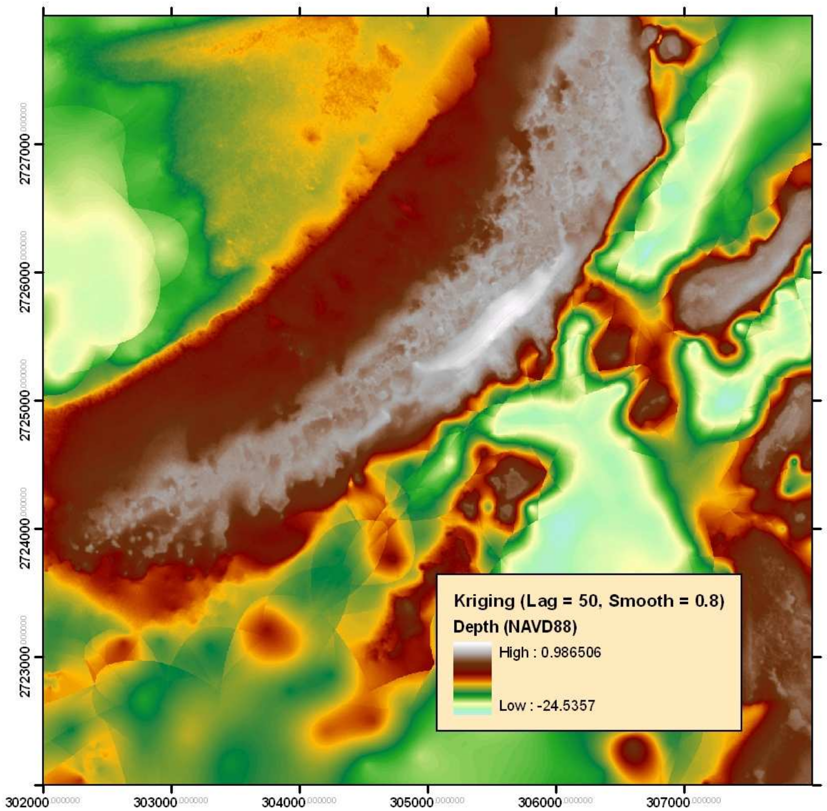


Figure 2.13: Kriging interpolation result (lag = 50)

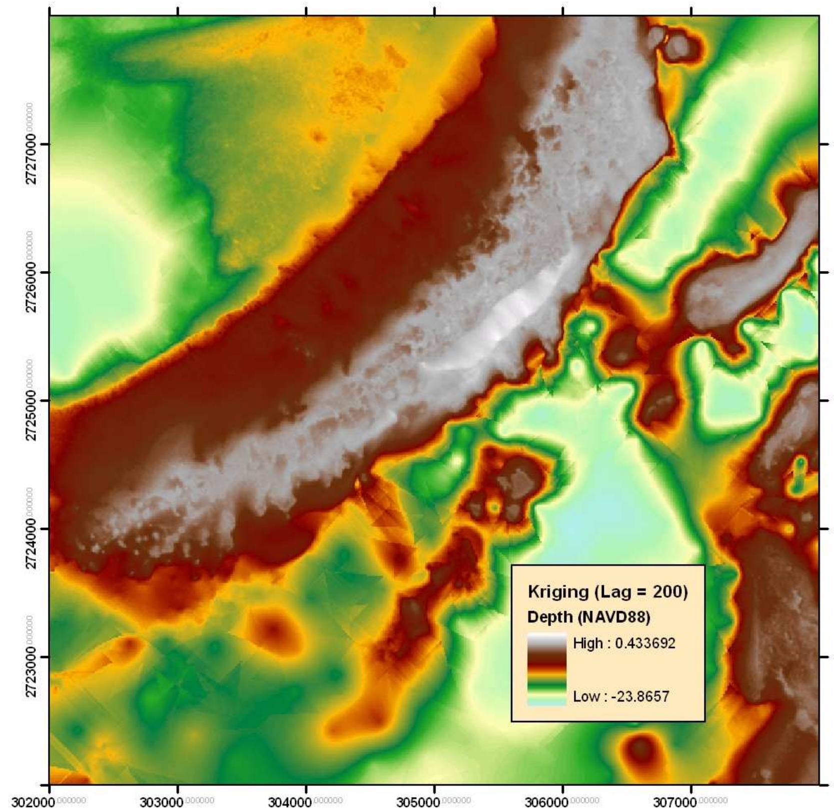


Figure 2.14: Kriging interpolation results (lag = 200 m)

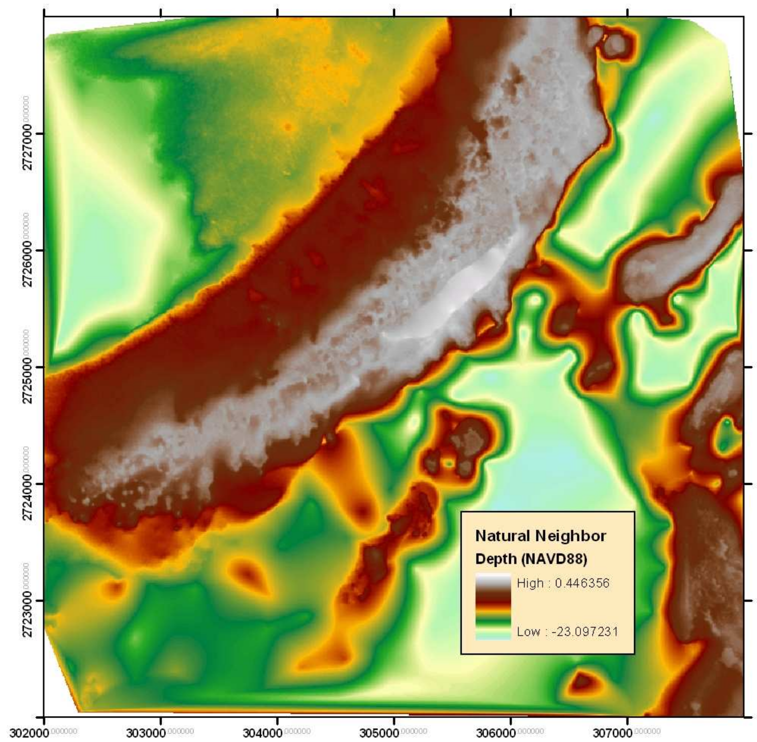


Figure 2.15: Representation of enhanced DEM created from EAARL and ENC data sets using natural neighbor interpolation technique

<u>Visualization</u>

The enhanced DEM serves as a platform for producing a complete, realistic visualization of the benthic habitat. The three-dimensional visualization (fig 2.16) is a combination of cloud-free Ikonos imagery draped over the enhanced bathymetric DEM and displayed using ESRI's ArcScene 9.3 software. The DEM provides the base heights for the visualization while the Ikonos imagery provides valuable spectral information related to the underwater habitats. An animated swim-through highlights major reef characteristics and provides context for interpretation and future classification.

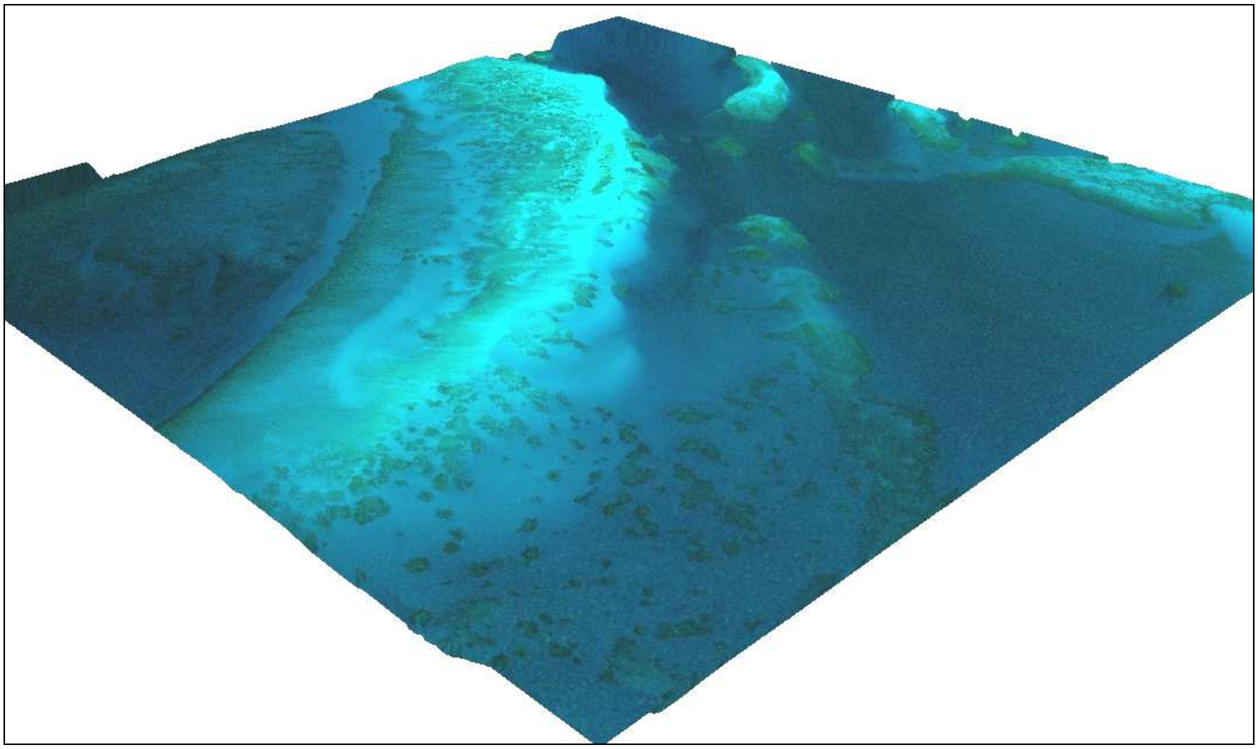


Figure 2.16: Full extent view looking northeast of complete visualization displayed in ArcScene

The visualization clearly benefits from the incorporation of both data types. Perspective shots from the visualization may be viewed in figures 2.17 and 2.18. Transitions between areas of EAARL and ENC data coverage appear natural and the visualization imparts the effect of swimming through the area. The visualization assists in clearly delineating the boundaries between coral structures and surrounding sandy areas.

Note in figure 2.17 the visualization illuminates the broad shelf of the platform margin reef A) as well as patch reefs jutting out from the smooth sand surroundings. Also, morphological differences between smaller, protruding patch reefs B) and broader, more gently sloped platform margin reefs are readily apparent when observed in three dimensions. The visualization, however, does not communicate the totality of bathymetric features. The field of patch and pyramid reefs (lower portion of fig. 2.16) in the southwestern section of the study area are at too large a scale for detection by ENC soundings and were not covered by the EAARL survey.

Areas of high spatial detail (those within the EAARL data coverage) remain high in detail. This visualization provides an intuitive understanding of local bathymetry which is useful for interpretation of reef features, communication of morphological characteristics, and education of the public.

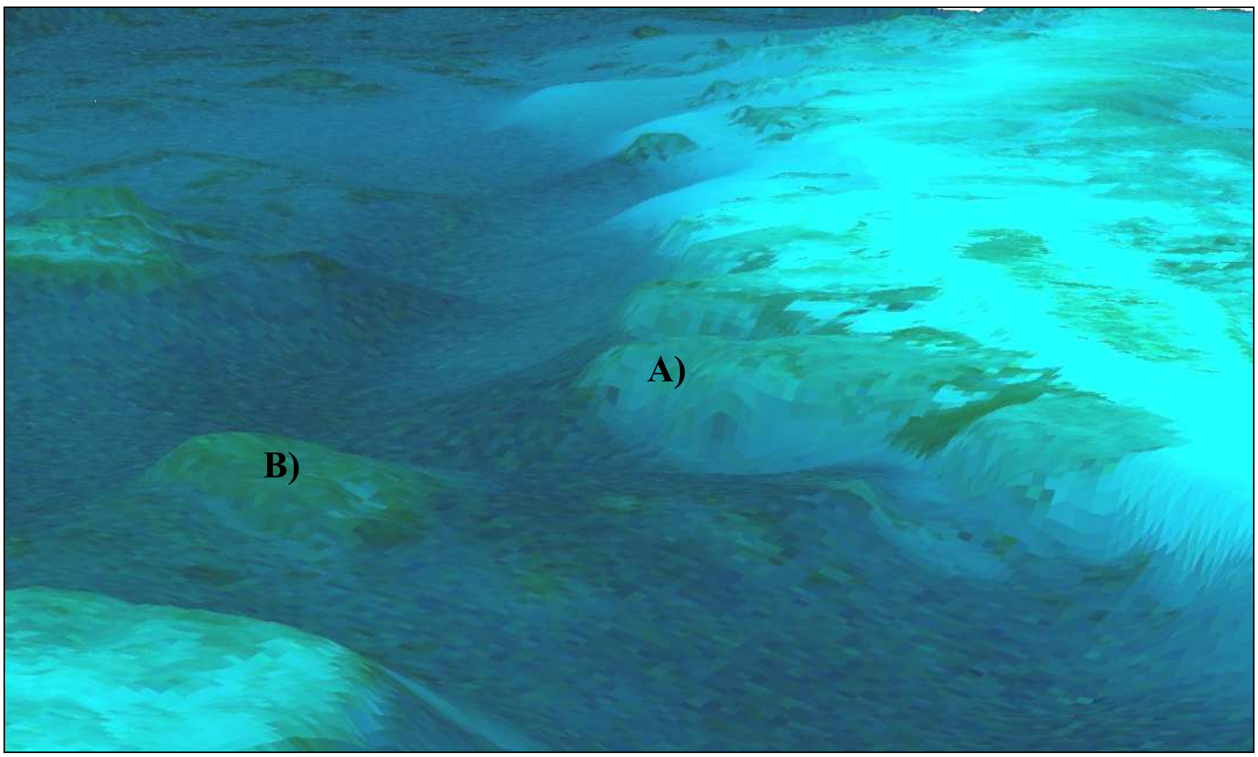


Figure 2.17: Perspective snapshot of 3-D visualization showing edge of platform margin reef (A) and protruding individual patch reef (B)

Figure 2.18: Perspective view of patch reef cluster

Conclusions

We resolved the NAVD88 and MLLW vertical datums in this area through a combination of statistical and geostatistical analysis with a resulting RMS error of 3.8 m. The method for resolving the datum difference could be used in other situations in which there are only two sources of bathymetric information. The resulting enhanced DEM covers the entire study area and adequately fills in holes in the bathymetric lidar data. We evaluated several interpolation techniques and found natural neighbor to be the most suitable for this application in which there are data sets of varying spatial densities. The enhanced DEM served to produce a realistic three-dimensional visualization for the entire study area, thus completing the objectives of this paper.

The method presented in this research for filling holes in the EAARL data set proves useful for a number of reasons. Primarily, there is no cost for additional data acquisition and no additional environmental impact for this protected area in Dry Tortugas National Park and this RNA in particular. Additionally, the combination of a natural neighbor interpolation mosaicked with the original EAARL raster data fills the holes in a reasonably realistic fashion which neither adds nor takes away information from the original data sources. The resulting visualization is an efficient and effective means for communicating complex seafloor morphology with a broadly varying bathymetry.

The comparison of interpolation techniques for these two combined data sets shows that natural neighbor is the most effective interpolation method for representing a surface interpolated from a combination of the two data sets with different spatial densities.

There are drawbacks to this method which stem chiefly from differences between the source data. Without a complete spatial examination of local tidal variability and empirical relationships between local MLLW and NAVD88, the transformation between the datums outlined in this research cannot be assumed with a high degree of certainty. However, this method has the advantage of circumventing expensive and time-consuming data collection. Differences in spatial density between EAARL data and the ENC sounding data obstruct a uniform level of detail throughout the DEM. This problem, as with all DEMs, could lead viewers to misinterpret features or assume an inappropriate degree of accuracy.

However, this method is shown to be an efficient means of integrating bathymetric data sets in both MLLW and NAVD88 vertical datums and with widely varying spatial densities. This integration is useful for most coral reef locations in the world, as the global coverage of ALB is limited and there is likely to be at most one additional source of bathymetric survey data available, particularly in remote locations.

Future work should focus on improving statistical and geostatistical methods to translate between the two vertical datums apart from empirical studies as well as further exploration of interpolation techniques for data sets of disparate spatial point densities. This method could lead to quantification of spatial attributes of coral reef habitat such as volume, carbon content, and more detailed classification of coral types.

CHAPTER 3

CONCLUSIONS

The method presented in this research describes an efficient means of integrating bathymetric data sets in both MLLW and NAVD88 vertical datums and with widely varying spatial densities. A combination of statistical and geostatistical methods was used to conclude that a uniform datum shift of 1.8 m could be applied to all MLLW datum measurements throughout the study area. This datum transformation method is useful for many areas where bathymetric data are in differing datums and no geodetic relationship has previously been determined. Also, it was found that the natural neighbor interpolation technique combined with the original bathymetric lidar data produced the best results in creating an enhanced DEM of the study area. This technique proved to be adept in terms of accuracy (3.8 m RMS error) qualitative characteristics at simultaneously handling point data at very different spatial densities.

This method may be used in areas with coral reef habitat and incomplete bathymetric lidar coverage in order to create a complete three-dimensional representation of the bathymetric surface. Such information is potentially helpful to coral reef managers in that it is a tool for a more detailed understanding of reef structure, spatial distribution and benthic properties. The visualization is an effective communication tool for informing the public and other scientists about the morphology of the coral reef environment. Increased knowledge about the coral reef environment could lead to an enhanced ability to conserve and protect these extremely valuable natural resources.

BIBLIOGRAPHY

Andréfouët, S., Kramer, P., Torres-Pulliza, D., Joyce, K.E., Hochberg, E.J., Garza-Perez, R., Mumby, P.J., Riegl, B., Yamano, H., White, W.H., Zubia, M., Brock, J.C., Phinn, S.R., Naseer, A., Hatcher, B.G., & Muller-Karger, F.E. (2003) Multi-site evaluation of Ikonos data for classification of tropical coral reef environments. *Remote Sensing of Environment, 88*, 128–143

Benfield, S.L., Guzman, H.M., Mair, J.M. and Young, J.A.T. (2007) Mapping the distribution of coral reefs and associated sublittoral habitats in Pacific Panama: a comparison of optical satellite sensors and classification methodologies. *International Journal of Remote Sensing*, 28 (22), 5047-70

Brock, J.C., Krabill, W.B. and Sallenger, A.H. (2004) Barrier island morphodynamic classification based on lidar metrics for North Assateague Island, Maryland. *Journal of Coastal Research*. 20 (2), 498-509

Brock, J.C., Wright, C.W., Kuffner, I.B., Hernandez, R., and Thompson, P. (2006) Airborne lidar sensing of massive stony coral colonies on patch reefs in the northern Florida reef tract. *Remote Sensing of Environment*, 104, 31-42

Call, K.A., Hardy, J.T. and Wallin, D.O. (2003) Coral reef habitat discrimination using multivariate spectral analysis and satellite remote sensing. *International Journal of Remote Sensing,* 24 (13), 2627-2639

Center for Coastal Monitoring and Assessment (2008) CCMA: Biogeography: Benthic Habitat Mapping of Florida Coral Reef Ecosystems. Retrieved May 19, 2009 from http://ccma.nos.noaa.gov/ecosystems/coralreef/fl_mapping.html

Cuevas-Jiminez, A., Ardisson, P.L., and Condal, A.R. (2002) Mapping of shallow coral reefs by colour aerial photography. *International Journal of Remote Sensing,* 23 (18), 3697-3712

Finkl, C.W., Benedet, L. and Andrews, J.L. (2005) Submarine geomorphology of the continental shelf off southeast Florida based on interpretation of airborne laser bathymetry. *Journal of Coastal Research,* 21 (6), 1178-1190

Goldberg, J. and Wilkinson, C. (2004) Global Threats to Coral Reefs: Coral Bleaching, Global Climate Change, Diseasee, Predator Plagues, and Invasive Species. In C. Wilkinson (Ed.) *Status of the Coral Reefs of the World: 2004* (pp. 67-92) Townsville, Queensland, Australia: Australian Institute of Marine Science

Guenther, G.C. (2007) Airborne Lidar Bathymetry. In D. Maune (Ed.), *Digital Elevation Model Technologies and Applications: The DEM Users Manual, 2nd Edition* (pp. 253-307). Bethseda, MD: American Society for Photogrammetry and Remote Sensing.

Guenther, G.C., LaRocque, P.E., & Lillycrop, W.J. (1994) Multiple surface channels in SHOALS airborne lidar. *Proc. SPIE Ocean Optics XII,* Vol. 2258, 422-30

Hensley, S., Munjy, R., and Rosen, P. (2008) Interferometric Synthetic Aperture Radar (IFSAR). In D. Maune (Ed.), *Digital Elevation Model Technologies and Applications: The DEM Users Manual, 2nd Edition* (pp. 253-307). Bethseda, MD: American Society for Photogrammetry and Remote Sensing.

Hochberg, E.J., Atkinson, M.J. and Andréfouët, S. (2002) Spectral reflectance of coral reef bottom types worldwide and implications for coral reef remote sensing. *Remote Sensing of Environment*, 85, 159-173

Hochberg, E.J. and Atkinson, M.J. (2002) Capabilities of remote sensors to classify coral, algae and sand as pure and mixed spectra. *Remote Sensing of Environment,* 85, 174-189

Holden, H. and LeDrew, E. (2001) Hyperspectral discrimination of healthy versus stressed corals using in situ reflectance. *Journal of Coastal Research,* 17 (4), 850-858

Holden, H. and LeDrew, E. (2002) Measuring and modeling water column effects on hyperspectral reflectance in a coral reef environment. *Remote Sensing of Environment,* 81, 300-308

International Hydrographic Organization (2008) IHO Special Publication No. 44: Standards for Hydrographic Surveys, 5th Edition. *International Hydrographic Bureau*: Monaco.

Knudby, A., LeDrew, E. and Newman, C. (2007) Progress in the use of remote sensing for coral reef biodiversity studies. *Progress in Physical Geography,* 31 (4), 421-434

Lubin, D., Li, W., Dustan, P., Mazel, C.H. and Stamnes, K. (2001) Spectral signatures of coral reefs: features from space. *Remote Sensing of Environment,* 75, 127-137

Maune, D.F., Ed. (2007) Digital elevation model technologies and applications: The DEM users Manual. 2nd ed. *American Society of Photogrammetry and Remote Sensing*

Mumby, P.J. and Green, E.P. (1999) The cost-effectiveness of remote sensing for tropical coastal resources assessment and management. *Journal of Environmental Management,* 55 (3), 157-67

Mumby, P.J. and Edwards, A.J. (2002) Mapping marine environments with Ikonos imagery: enhanced spatial resolution can deliver greater thematic accuracy. *Remote Sensing of Environment*, 82, 248-257

Myers, E., Hess, K., Yang, Z., Xu, J., Wong, A., Doyle, D., Woolard, J., White, S., Le, B., Gill, S., & Hovis, G. (2007). VDatum and Strategies for National Coverage. Retrieved May 15, 2009 from http://vdatum.noaa.gov/download/publications/2007_myers_Oceans.pdf

National Oceanic and Atmospheric Administration (2008) Tidal Datums. Retrieved June 3, 2009 from: http://tidesandcurrents.noaa.gov/datum_options.html

National Park Service (2009a) Dry Tortugas National Park – History & Culture. Retrieved May 15, 2009 from http://www.nps.gov/drto/historyculture/index.htm

National Park Service (2009b) Dry Tortugas – What is the Research Natural Area? Retrieved May 15, 2009 from http://www.nps.gov/drto/upload/What%27s%20a%20RNA%20-%20edit%205.pdf

Palandro, D., Andréfouët, S., Dustan, P. and Muller-Karger, F.E. (2003) Change detection in coral reef communities using Ikonos satellite sensor imagery and historic aerial photographs. *International Journal of Remote Sensing,* 24 (4), 873-878

Su, H., Liu, H., and Heyman, W.D. (2008) Automated derivation of bathymetric information from multi-spectral satellite imagery using a non-linear inversion model. *Marine Geodesy*, 31 (4), 281-298

Tobler, W.R. (1970) A computer movie simulating urban growth in the Detroit region. *Economic Geography* 46, 234-240

United States Geological Survey (2008) EAARL: Experimental Advanced Airborne Research Lidar. Retrieved December 2008 from:
http://coastal.er.usgs.gov/remote-sensing/advancedmethods/eaarl.html
http://pubs.usgs.gov/of/2006/1244/Metadata/lidar_drto_faq.htm
http://coastal.er.usgs.gov/remote-sensing/advancedmethods/lidar.html

Walker, B.K., Riegl, B. and Dodge, R.E. (2008) Mapping coral reef habitats in southeast Florida using a combined technique approach. *Journal of Coastal Research,* 24 (5), 1138-1150

Watson, D. (1992) Contouring: A Guide to the Analysis and Display of Spatial Data. *Pergamon Press,* London.

Wedding, L.M., Friedlander, A.M., McGranaghan, M., Yost, R.S., and Monaco, M.E. (2008) Using bathymetric lidar to define nearshore benthic habitat complexity: Implications for management of reef fish assemblages in Hawaii. *Remote Sensing of Environment,* 112, 4159-4165

Wilkinson, C. (2004) Executive Summary. In C. Wilkinson (Ed.) *Status of the Coral Reefs of the World: 2004* (pp. 7-50) Townsville, Queensland, Australia: Australian Institute of Marine Science

Yamano, H. and Masayuki, T. (2004) Detection limits of coral reef bleaching by satellite remote sensing: Simulation and data analysis. *Remote Sensing of Environment,* 90, 86-103