Derivation of Near-shore Bathymetry from Multispectral Satellite Imagery used in a Coastal Terrain Model for the Topographic Analysis of Human Influence on Coral Reefs

by
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AN ABSTRACT OF THE THESIS OF

Kyle Richard Hogrefe for the degree of Master of Science in Geography presented on June 5, 2008.

Title: Derivation of Near-shore Bathymetry from Multispectral Satellite Imagery used in a Coastal Terrain Model for the Topographic Analysis of Human Influence on Coral Reefs

Abstract approved:

Dawn J. Wright

The analysis of material and energy exchange between the marine and terrestrial components of island ecosystems enables research into the impact of human population and land use on the health of coral reef habitat. Satellite and acoustic remote sensing technologies enable the collection of data to produce high resolution bathymetry for integration with terrestrial digital elevation models (DEMs) into coastal terrain models. An integrated terrain surface that incorporates the land-sea interface, grounded by a geographic information system, is a powerful analytical tool for geomorphic studies of watersheds and coastal processes. The island of Tutuila, American Samoa is an ideal case study due to its high relief terrain, data availability and local interest in impacts to coral reef resources. The Tutuila model integrates a USGS DEM, multibeam bathymetry from 15 to 500 m and near shore bathymetric data from 0 to 15 m derived from IKONOS satellite imagery. The high spatial resolution of IKONOS imagery is suitable for detection of features with subtle relief and intricate structure. Shallow water bathymetry is derived by quantifying the relative attenuation of blue and green spectral band radiance as a function of depth. The procedure used to derive bathymetry, Lyzenga (1985), is identified as the most effective of several proposed in the recent literature. The product is error-checked using control points extracted from multibeam sonar data and collected during recent field surveys, as well as terrain profiles. The coastal terrain model provides morphological detail of fine resolution and high accuracy for terrain and land use analysis to enhance the study of ecosystem interconnectivity and the effects of anthropogenic inputs to coral reef habitats. Subsequent topographic analyses of the Tutuila model use drainage patterns to identify contiguous marine/terrestrial basins within which the marine environment is most directly impacted by land use through freshwater inputs from affiliated catchments. Human population density serves as an indicator of intensified land use and urbanization, which has been shown to increase pathogen and sediment loads in runoff, while percent coral cover, coral colony density and coral genera diversity are used as indicators of reef health. Spatiotemporal correlation analyses of population density against the three reef health indices within each of the marine/terrestrial basins reveal a decline in reef health associated with increased population density. This paper integrates and builds upon established methods of satellite imagery analysis and terrain modeling to create the Tutuila coastal terrain model and uses it to refine the scale of other studies linking human terrestrial activities to the physical condition of coral reefs.

Master of Science thesis of Kyle Richard Hogrefe
presented on June 5, 2008.

APPROVED:

Major Professor, representing Geography

Chair of the Department of Geosciences

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I understand that my thesis will become part of the permanent collection of Oregon State University libraries. My signature below authorized release of my thesis to any reader upon request.

Kyle Richard Hogrefe, Author

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I also want to acknowledge the data contributions that made these investigations possible. Thanks to NOAA's Pacific Islands Benthic Habitat Mapping Center for providing the multi-beam sonar bathymetry and contacts to acquire IKONOS satellite imagery; to NOAA's Pacific Island Fisheries Science Center, Coral Reef Ecosystem Division for providing coral species distribution data and for collecting field control points during a busy deployment schedule on the 2008 American Samoa Research and Management Program research cruise aboard the NOAA Vessel *Hi'ialakai*; and to NOAA's Center for Coastal Monitoring and Assessment, Biogeography Team and NOAA's Coastal Services Center for providing the at-sensor IKONOS imagery needed for deriving bathymetry.

Finally, I want to convey deep gratitude to my fiancé and soon to be wife, Jeanette Hawkins, for her patience and unwavering support and to my family for providing the foundation of who I am and for their part in my growth over the last 39 years.

CONTRIBUTION OF AUTHORS

Dr. Wright, as my major advisor, provided technical advice regarding GIS techniques, data sources and scientific method in the completion of both chapters 2 and 3, as well as editorial advice in the design and writing of this entire thesis.

Dr. Hochberg provided essential technical advice in identifying and then pursuing the most accurate procedure for deriving depth from multispectral satellite imagery as detailed in chapter 2. He also provided editorial comment concerning the design and focus of chapter 2.

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Chapter 1. Derivation of Near-shore Bathymetry from Multispectral Satellite Imagery used in a Coastal Terrain Model for the Topographic Analysis of Human Influence on Coral Reefs

Introduction

The research goal of this thesis is the derivation of shallow water bathymetry to enable the completion of a terrain model and its subsequent use in a topographic analysis to compare human land use with the health of nearby coral reefs. The research question is how does terrain influence the impact of human land use intensification to the physical condition of coral reefs? The logical sequence through two manuscripts establishes the validity of using multispectral satellite imagery to deduce bathymetry and describes the technical steps for deriving accurate depth data and integrating it into a seamless terrain surface. The resulting coastal terrain model (CTM) is then used to determine combined marine/terrestrial units (MTUs) in which human activity would be most likely to influence the near shore environment. Subsequent analyses indicate spatiotemporal correlations between human population density and three criteria commonly used to assess the condition of coral reefs.

In Chapter 2, the research goal is the identification of the most accurate method to derive bathymetry from multispectral satellite imagery and its use to provide near-shore data for the creation of a CTM. The research question is what errors are associated with derived bathymetry and its use in a CTM? Though several methods have been developed to calculate depth from multispectral data by gauging the relative attenuation rate of different wavelengths of light as the pass through water, research using this derived bathymetry in any capacity is scarce. This paper identifies Lyzenga (1985) as the most accurate of several published methods, relying on a multiple linear regression analysis to establish the statistical relationship between the differential attenuation rate of the blue and green spectral bands as they pass through water. This multivariate linear relationship is then used to derive depths to fill a data gap between terrestrial and deeper seafloor data, in order to complete a CTM of Tutuila Island, American Samoa. The errors associated with interim products and the final model are assessed through regression analyses and terrain profiles.

In Chapter 3, the research goal is to conduct a terrain analysis using the Tutuila CTM to answer the question how does island terrain influences the impact of increased human land use intensity on the physical condition of coral reefs? The Tutuila CTM is analyzed to determine MTUs, defined as areas of contiguous terrestrial and marine terrain as identified by drainage patterns that would occur if the whole area were dry land. This classification distinguished terrain units in which nutrients, sediment and pathogens contained in freshwater inputs are most likely to impact the physical condition of coral reefs. The comparison of population density to percent coral cover, coral colony density and coral generic diversity within each MTU reveals correlations between increased human population density and the health of coral reefs. Strong negative correlations between population density and the percent change of both colony density and generic diversity between 2004 and 2006 indicate that increased population density leads to an increased rate of decline of these two indices. A positive correlation between population density and percent change in coral cover poses a less definitive relationship, but the island wide decrease of this criterion still implies an impact as population has increased.

The synthesis of these two manuscripts (one submitted for publication to the journal *Marine Geodesy*, and the other in submission to a journal to be determined) contributes to the advancement of scientific knowledge by integrating two established analytical approaches to create an original product and using this product to refine the scale of previous research. The identification of the most accurate of multiple published methods of bathymetric derivation, the integration of bathymetry derived by this method, and the error analyses conducted on the product establish an accurate and cost effective data source for coastal terrain modeling in remote areas. The division of Tutuila's terrain into MTU allows for the refinement of previous island scale analyses of correlations between population density and coral community diversity to a smaller, drainage basin scale. In doing so, the MTU approach demonstrates the influence of terrain on land use and how this ultimately impacts coral reefs.

Reference

Lyzenga, D. R. 1985. Shallow-water bathymetry using combined LIDAR and passive multispectral scanner data. *International Journal of Remote Sensing* 6 (1):115-125.

Chapter 2. Derivation and Integration of Shallow-water Bathymetry: Implications for Coastal Terrain Modeling and Subsequent Analyses

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Abstract

Satellite and acoustic remote sensing enable the collection of high-resolution seafloor bathymetry data for integration with terrestrial elevations into coastal terrain models. A model of Tutuila Island, American Samoa is created using depths derived from IKONOS satellite imagery to provide data in the near-shore gap between sea level and the beginning of sonar data at 10-15 m depth. A derivation method gauging the relative attenuation of blue and green spectral radiation is proven the most effective of several proposed in recent literature. The resulting coastal terrain model is shown to be accurate through statistical analyses and topographic profiles.

2.1 Introduction

Coastal terrain models (CTM) incorporating both topography and bathymetry, grounded by a geographic information system (GIS), have proven to be powerful analytical tools for the modeling of watershed and coastal morphology. The integration of environmental and societal datasets into a CTM enable investigations into the relationships and interactions of island ecosystems and provide information about terrestrial influences to coral reefs from human activities (Mumby et al. 2004). The marine and terrestrial components of island ecosystems are linked by fresh water inputs that reach miles out to sea and provide for nutrient exchange and larval transport, but they also carry sediment and pollutants that diminish the species diversity of coral reef community structure (Andrefouet et al. 2002, Shapiro and Rohmann 2005). Other research links diminished reef species diversity to human development density through the increased turbidity that it causes at the island scale (Sealey 2004). A finer scale investigation, at the watershed level, may reveal more direct relationships between land use practices, freshwater plumes and coral reef health.

Satellite and acoustic remote sensing technologies produce readily accessible data to create coastal terrain models detailed enough to run oceanographic, hydrographic and atmospheric simulations (Mumby et al. 2004, Shapiro and Rohmann 2005). However, a challenge in the creation of a CTM is the acquisition of data from 0 to 15 m where surf conditions and shallow terrain features make the operation of bathymetric survey vessels hazardous (Figure 2.1). In clear water conditions, both LIDAR (light detection and ranging) surveys and processed satellite imagery show promise for filling this data gap. Though LIDAR data are more accurate, survey costs may be prohibitive and satellite imagery is more easily available and cost effective, particularly in remote locations or poor countries (Mumby et al. 1999). Recent work (Hochberg et al., unpublished) investigates the accuracy of several methods proposed to derive bathymetry and points to one process (Lyzenga 1985) as the most effective. Similar methods, coupled with processing steps to eliminate surface glint, are used to derive bathymetry from IKONOS satellite imagery. These data are used in creation of a CTM for the island of Tutuila and its surrounding bathymetry and are subjected to error analysis during CTM integration.

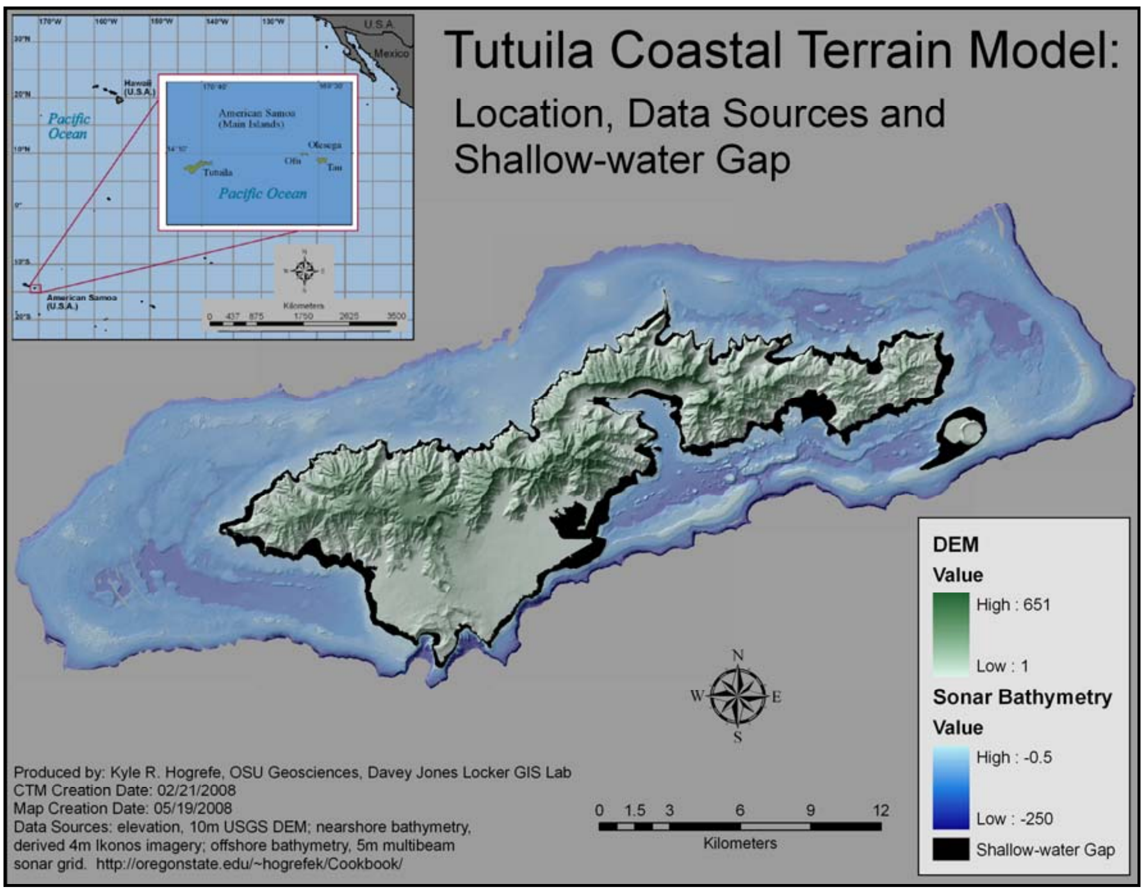

Figure 2.1: The island of Tutuila, American Samoa. Data sources include a 10-m USGS digital elevation model (DEM), near shore bathymetry derived from 4-m IKONOS imagery, and offshore bathymetry at 5-m resolution, (more information online at oregonstate.edu/~hogrefek/Cookbook). Projection and datum are Universal Transverse Mercator (UTM) Zone 2 South, World Geodetic System (WGS) 1984. Notice the gap in data between the island and the deepwater bathymetry.

2.2 Methods

2.2.1 Study Area

This research focuses on deriving bathymetry to complement pre-existing datasets for the creation of a CTM for the island of Tutuila, American Samoa (Appendix A) and testing its accuracy for the assessment of human population and land use practices on coral reefs. Tutuila is ideal for a case study of human driven terrestrial impacts. Its volcanic origin and the tropical climate of the South Seas have resulted in topography of well-defined ridgelines and valleys that extend beyond the shoreline to significant depth. These distinct marine/terrestrial units provide naturally defined topographic basins for comparing land use impacts to adjacent reefs. The population pattern of the island consists of valleys that contain human settlements ranging from cities such as Pago Pago (population ~ 4000) to small villages of populations less than 100, with some small valleys remaining uninhabited. Though most of the settlement is concentrated on relatively flat coastal terrain, population pressure pushes development up steeper valley slopes and traditional land use, such as such as small plot agriculture and the harvest of fruit and wood, occurs farther up in the valleys. Pago Pago Harbor supports industrial activities such as a fish cannery and port services to support an extensive fishing fleet and international commerce. Densely-populated areas spreading to the southwest of Pago Pago Harbor along the coast cross through several watersheds, support a large percentage of the island's population and have many impervious surfaces that probably enhance runoff and contribute to pollutant loads.

Personal experience with community leaders, resource managers and the general population on Tutuila as well as recent research (Wright 2002) indicate a strong desire to take action to protect marine resources. However, the mitigation of pollutants in terrestrial runoff is problematic because it requires changing social practices, which further requires either extensive outreach and education or passage of regulations to modify people's actions. These solutions demand scientific information to convince individuals of the necessity of change or to justify the implementation of new policies (Hoffman 2002b, Mumby et al. 1999).

2.2.2 Data

2.2.2.1 IKONOS Imagery

The IKONOS satellite is a high spatial resolution "push broom" sensor with a sun synchronous polar orbit operated by GeoEye, Inc. The instrument obtains multi-spectral data in four bands at 4 m nominal resolution and panchromatic data at 1 m nominal resolution (Table 2.1). IKONOS images were originally obtained by NOAA Coastal Services center in 2001 and used to create a mosaic covering the islands of Tutuila and Aunu'u for the Pacific Islands GIS project. NOAA's National Centers for Coastal Ocean Science, Center for Coastal Monitoring and Assessment (CCMA) provide original imagery for this research. The images were acquired on 11/07/2001, 12/02/2001 (two images) and 02/03/02 at approximately 21:44 hours and delivered as NTF files.

Table 2.1: IKONOS Spatial and Spectral Resolutions.

Band	Spectral Range (μm)	Color Range	Resolution (m at nadir)
1	0.45 – 0.52	Blue	4 x 4
2	0.52 – 0.60	Green	4 x 4
3	0.63 – 0.69	Red	4 x 4
4	0.76 – 0.90	Near-infrared	4 x 4
Pan	0.45 – 0.90	Panchromatic	1 x 1

2.2.2.2 Multibeam Sonar Data

The Coral Reef Ecosystem Division (CRED) of NOAA's Pacific Islands Fisheries Science Center (PIFSC) in conjunction with the University of Hawaii's Pacific Islands Benthic Habitat Mapping Center provides bathymetry at a depth range of 15 – 250 m. The data were collected from January to March, 2004 and February to March, 2006 using the 30 kHz Simrad EM300 and 300 kHz Simrad EM3002D sonar systems aboard the NOAA *R/V Hi'ialakai,* a 218' research ship, and the 240 kHz RESON 8101-ER sonar system aboard the *R/V AHI* (Acoustic Habitat Investigator), a 25' survey launch operated by the PIFSC. The effort supports the Coral Reef Conservation Program goal of mapping all coral reefs in less than 30 m depth, and select reefs in deeper water, by 2009. Sonar soundings were processed into a 5 m resolution raster grid and the data were provided as an ASCII file.

The projection and resolution of the deepwater bathymetry were chosen as project defaults so that, once the file was converted to an ESRI raster and defined in its projection, no further processing was required prior to CTM mosaicing. However, data gaps are apparent in the bathymetry in areas where sonar swaths did not overlap (Figure 1). An expression is employed using the ArcGrid command line window to close these data gaps using a moving average algorithm that assigns a mean value to "NoData" cell values without changing the original data.

2.2.2.3 Digital Elevation Model

The source of terrestrial data is a 10 m resolution mosaic of 1:24,000 scale USGS digital elevation models (DEMs) produced in April, 2001 for the American Samoa Land

Grant Extension program and provided to the American Samoa GIS User Group. Raster data grids derived from the original DEMs were mosaicked using ArcGIS to create the compilation. This product is the baseline dataset for terrain analysis on Tutuila and has previously been merged with bathymetric data around the island, but the shallow-water data gap prevents a seamless surface (Figure 2.1). To prepare the DEM for integration into the CTM, it is reprojected from the North American Datum of 1983, Geodetic Reference System (GRS) 1980 ellipsoid to World Geodetic System (WGS) 1984, Universal Transverse Mercator (UTM) 2S and resampled from a 10 m to a 5 m resolution.

2.2.2.4 Ground-Truth Data

Data points used to conduct error analysis on the derived bathymetry and the CTM are from two sources: recently collected control points and points created in ArcGIS with depth extracted from the PIBHMC multibeam sonar bathymetry. NOAA CRED's Oceanography Team collected most of the field survey control points during the 2008 American Samoa Research and Management Program research cruise. At each control point, position and depth data are collected either haphazardly or at specific waypoints; a small number of additional points are gleaned from oceanographic sampling records (CTD casts) from previous cruises. Each data point was collected using a Gramin76 GPS unit and an echosounder. The resulting 140 control points fall within all categories of bathymetric data used in the CTM. To more fully explore the range of error associated with the data, two additional sets of point features are used to extract sonar and derived depth values for comparison. The first set entails the same point features used to extract the linearized spectral values used in determining the depth/spectral decay relationship (next section). Using these same points to evaluate derived depths may be considered biased; however, given that they were chosen in areas where image conditions looked most favorable for a clean spectral signal, they are useful for an analysis focused on areas likely to have a reasonable result. For an error analysis with greater geographic coverage and less bias, features of over 800 points with haphazard distribution were created for each IKONOS image to extract derived values from depths shallower than 20 m as defined by the sonar bathymetry.

2.2.3 Bathymetric Derivations from IKONOS Satellite Imagery

Digital image processing techniques allow for the derivation of shallow water bathymetry by assessing the relative radiance of blue and green bands (Table 1) of the electromagnetic spectrum as they are attenuated as a function of depth. Bathymetric derivation procedures require starting with "at sensor" data, as provided by the CCMA, to assure accurate tracking of processing lineage and the validity of derived depth. The high spatial resolution of the IKONOS imagery makes the data suitable for detection of features with subtle relief and intricate structure (Stumpf et al. 2003, Mumby et al. 2004, Shapiro and Rohmann 2005). Depth derivation from spectral data is a multi-phase procedure using ArcGIS 9.2 (Environmental Systems Research Institute, Inc., Redlands, CA) ENVI 4.3 (ITT Industries, Inc., Boulder, CO) Microsoft Excel (Microsoft Corporation, Redmond, WA), and S-Plus (Insightful Corporation, Seattle, WA).

The four images required to provide spatial coverage of Tutuila and Aunu'u were georectified and then radiometrically calibrated (converted from digital number to radiance values), using standard processing techniques (Appendix B). Sea surface glint effects were corrected using methods first described in (Hochberg et al. 2003) and refined by (Hedley et al. 2005) using the equation $R'_i = R_i - b_i(R_{NIR} - Min_{NIR})$; where R_i = radiance of band *i*, b_i = regression line slope of band *i* (y axis) against the NIR band (x axis), R_{NIR} = NIR radiance, and Min_{NIR} = minimum NIR value. The variable b_i is determined using a spatial subset of image pixels over optically deep water (> 15 m) to obtain radiance values for the linear regression; Min_{NIR} may also be determined from this subset. The values R_i and R_{NIR} are drawn from the input image as it is processed. However, Tutuila CTM bathymetric derivations employ a modified version of this formula by not subtracting the Min_{NIR} value to correct for atmosphere in the same manner as a “dark pixel subtraction” (Chavez 1988). Therefore, corrections for both sea surface glint and atmospheric effects are conducted using the formula $R'_i = R_i - b_i(R_{NIR})$. The linear regression between band *i* radiance and NIR radiance is calculated using MS Excel, while ENVI 4.3 enables other processing steps.

In recent work, bathymetric derivation procedures proposed since 1978 are tested using imagery from various sites across the pacific (Hochberg et al., unpublished). Figure 2.2 shows the results of an error analysis of the four most effective methods compared with SHOALS (Scanning Hydrographic Operational Airborne LIDAR Survey) data in Kaneohe Bay, Oahu, Hawaii. One method (Lyzenga 1985) far outperforms the others achieving an error range of ± 5 m, half the magnitude of other methods. Note the 5 m overestimate that occurs at a depth of 5 m and the 5 m underestimate that occurs at a depth of 20 m. Similar results are obtained when methods based on Lyzenga (1985) are used to derive shallow water bathymetry for inclusion in the Tutuila CTM.

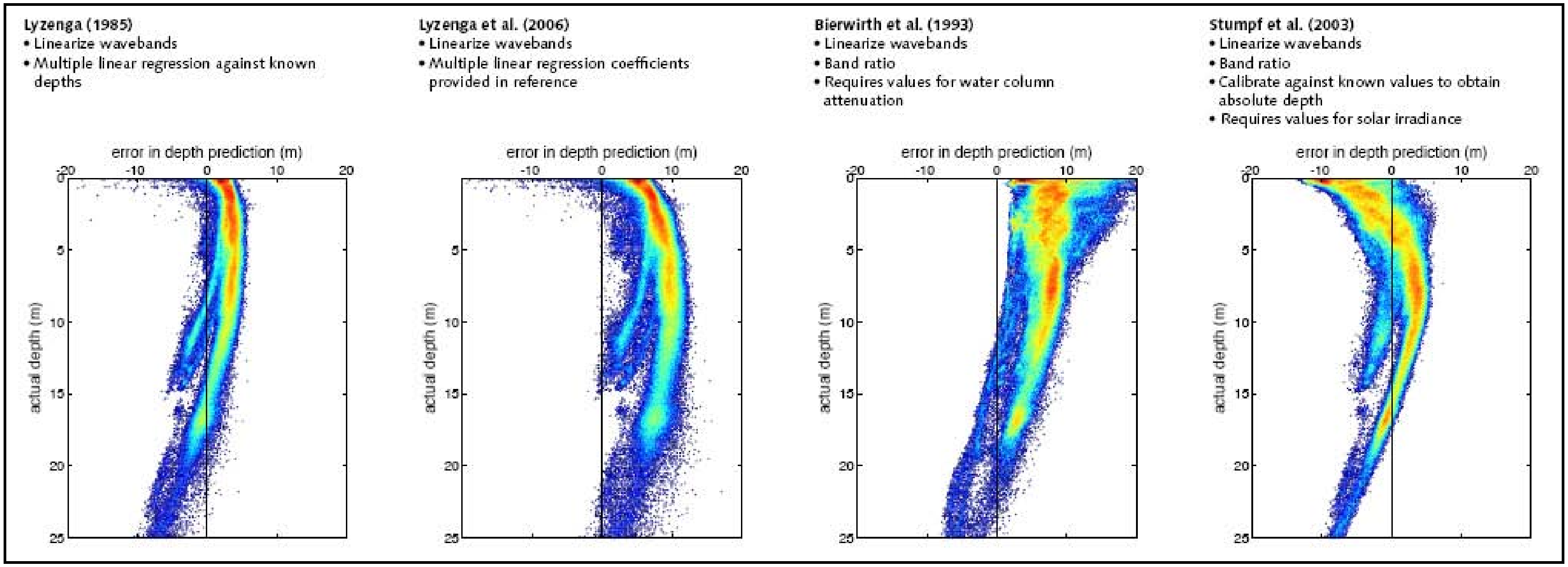

Figure 2.2: Error analyses for four published methods to derive bathymetry. Derived depths from an image of Kaneohe Bay, Hawaii are compared to SHOALS (Scanning Hydrographic Operational Airborne LIDAR Survey) data. The y-axis represents increasing depth while the x-axis shows the negative and positive error of the derived depth. Source: Hochberg (unpublished data, 2007).

Bathymetric data are derived by gauging the relative attenuation rates of blue (450-520 nm) and green (520-600 nm) spectral radiation as it passes through the water column. Spectral radiance values are first linearized using the formula $R_{Linear} = Ln(R_i - R_{imin})$; where R_i = radiance of band *i*, and R_{imin} = minimum radiance of band *i*. The variable R_i is drawn from the input image as it is processed while R_{imin} is determined using a spatial subset over optically deep water from the glint/atmosphere corrected image. With this step completed in ENVI 4.3, the linearized spectral data for the blue and green bands are exported to ArcGIS 9.2 for data extraction, a process greatly facilitated by the ENVI Reader for ArcGIS plug-in (http://www.ittvis.com/), to establish correlation with depth in a multiple linear regression using S-PLUS.

In ArcMap, features containing between 150 – 200 points are created for each IKONOS image extent in depths of less than 20 m and then used to extract sonar depth and linearized blue and green spectral values at each location. Multiple linear regression analysis is conducted with depth as the dependant variable and the linearized spectral radiance values as the independent variables. The outputs of interest are y-intercept, and the slope for each spectral band. Depth is then derived in ENVI 4.3 using the equation $D = a + (b_i)(x_i) + (b_j)(x_j)$; where a = y-intercept, b = slope, x = linearized spectral radiance and *i* and *j* indicate spectral band. The variables x_i and x_j are drawn from the input image as it is processed. The four ENVI raster files containing derived bathymetry are then opened in ArcGIS, converted to ESRI Grid files and mosaicked into a single raster grid. The derived bathymetry mosaic is then resampled to a resolution of 5 m and erroneous values from cells over optically deep water are trimmed in preparation for final integration into the CTM.

2.2.4 Dataset Integration

The CTM mosaic provides terrain data from the 650 m peak of the island to 250 m depth using the IKONOS derived bathymetry to fill the critical shallow water gap between 0-15 m (Appendix A). The integration of the CTM is accomplished using ArcGIS 9.2. Original datasets for the CTM are standardized to the geographic reference of the WGS94, UTM Zone 2 South.

The integration sequence entails merging the derived data from each image into a mosaic, combining the multibeam and derived bathymetry grids, and adding the DEM data. To assure that the most accurate data are retained during the mosaicking process, priority is first given to derived values from images that perform best in the error analysis described below, then to the sonar values so that they replace derived values in areas of overlap and finally to the DEM. After the derived / sonar data integration, a gap fill expression is then applied through a sequence of 46 iterations to completely fill all "NoData" values. Most of the smaller gaps, between swath widths, from terrain shadows and in surf zones, are filled after four iterations of the expression, but large voids remain from extensive areas of cloud cover. The last 42 iterations are required to provide information in these areas and result in far more dubious values; this issue is explored further below. The expression also adds values around the perimeter and into the center of the combined bathymetry grids, which are resolved by trimming the perimeter and by the DEM prioritization, described above.

2.3 Results

The accuracy of both the derived bathymetry and integrated CTM data are assessed at multiple stages of data processing and integration using depth control points collected during field surveys and points features created to extract sonar depth data as controls. The ability of the derived data to detect terrain features, as well as the utility of the integrated CTM for providing seamless terrain across datasets, are evaluated using linear transects that cross both natural features and transition zones between the data sources.

2.3.1 Derived Bathymetry Error Analysis

Control points from both field surveys and sonar data extraction are used for linear regression analyses plotting the control depth (x) against the derived depth (y) to compare the accuracy of derivations from each image (Figure 2.3). The image specific datasets are then combined to extract values from the derived imagery mosaic after resampling (Figure 2.4). The four images needed to cover the extent of Tutuila are referred to as West Tutuila, West-central Tutuila, East-central Tutuila, and East Tutuila and they are presented in this geographic order across the columns of Figure 2.3. The indicators of quality and error in these graphs are the slope of the linear fit to the data and the r^2 value. The plotted control depths represent a “correct” linear relationship with a slope of 1. The further the value of the regression line’s slope is from 0 toward 1, the greater the sensitivity to spectral signal attenuation with depth in the derived bathymetry values. The closer the r^2 value it to 1, the more effective the derived values are at predicting the control values.

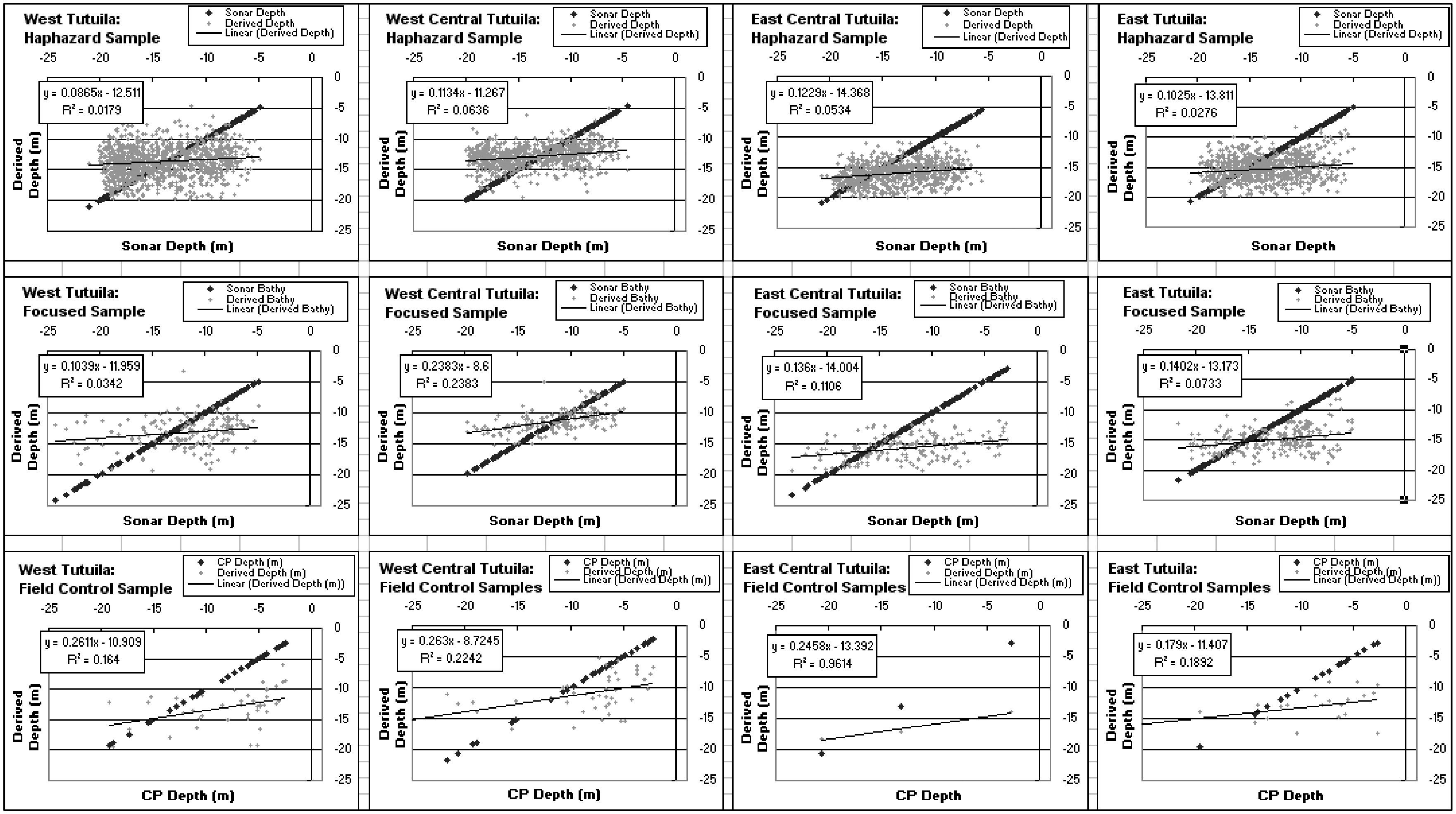

Figure 2.3: Derived bathymetry error analysis by linear regression. Notice that each column represents a satellite image and each row represents a point sample type.

Looking to the focused sample data for example, it is clear that the derived bathymetry from West-central image is the best product with a slope of 0.238 and an r^2 value of 0.238, followed by the East-central with a slope of 0.136 and an r^2 value of 0.110, East with a slope of 0.140 and an r^2 value of 0.073, and West Tutuila with a slope of 0.103 and an r^2 value of 0.034. Though the magnitude of these measures varies between the focused, haphazard and control point error analyses, this pattern of data quality is consistent between images. The fact that the most favorable results are exhibited by the control point data set, the most direct measurement of depth at location, has positive implications for the use of these data for terrain modeling. In a more immediate sense this information guided the prioritizing of image values during the mosaic process so that the best results were retained. However, the second best image, East-central, had such extensive data loss due to cloud cover that it made sense to prioritize the data from the third best image, East, in the derived bathymetry data mosaic. The only data available for western portion of the island was that with the most tenuous result.

The progression of derived depth quality across the images is explained by variable atmospheric and sea-state conditions at the time of data acquisition of each of the four images. The images were acquired on three dates over the course of three months and exhibit a range of ocean swell, wind wave (chop), sea spray conditions. More wave action causes a greater range of sea-glint values and frothy waves within a pixel's ground coverage area create erroneous spectral signals that result in less accurate sea glint corrections. Wind-blown sea spray, a particular problem in near shore areas close to breaking waves, increases the non-selective scattering of spectral energy and therefore increases the error in atmospheric correction for the effected pixels. These errors compound through processing and result in less accurate depth derivations as exemplified by the results in Figure 2.3, where the best results correlate with the best environmental conditions in the original imagery.

The prioritization of datasets during mosaic integration and interpolations during the resampling of the mosaic grid from a 4 m to a 5 m resolution result in new values at many locations in the derived bathymetry mosaic. Therefore, the point features are aggregated and used to extract values from the mosaic for a final quality assessment previous to integration into the greater CTM (Figure2.4). The same pattern of increasing slope and r^2 values through the haphazard, focused and control point datasets apparent in the image specific analysis is also obvious in the mosaic data error analysis. Though this trend may be attributable to decreasing sample size, it has positive implications for the inclusion of the derived bathymetry in the CTM. The haphazard sample clearly shows the potential error in the derived bathymetry in the depth of the data cloud, but even this “broadest net” sample of derived values shows a weak correlation. The statistical results improved markedly using the data points from the focused sample, but these data are suspect for error analysis since the same points were used to extract the linearized spectral radiance values used in the depth derivation process. Herein lays the particular value of the CRED control point data, which were collected in a haphazard manner as the Oceanography Team completed other deployment duties around Tutuila. Where positions were provided to guide their efforts, they were chosen only on the presumption of shallow depths in the area and the only guiding criteria was that control point depths be less than 15 m. The control point slope value of 0.264 and r^2 value of 0.182 demonstrate a high degree of correlation between on site depth measurements and derived depth values using unbiased sample locations.

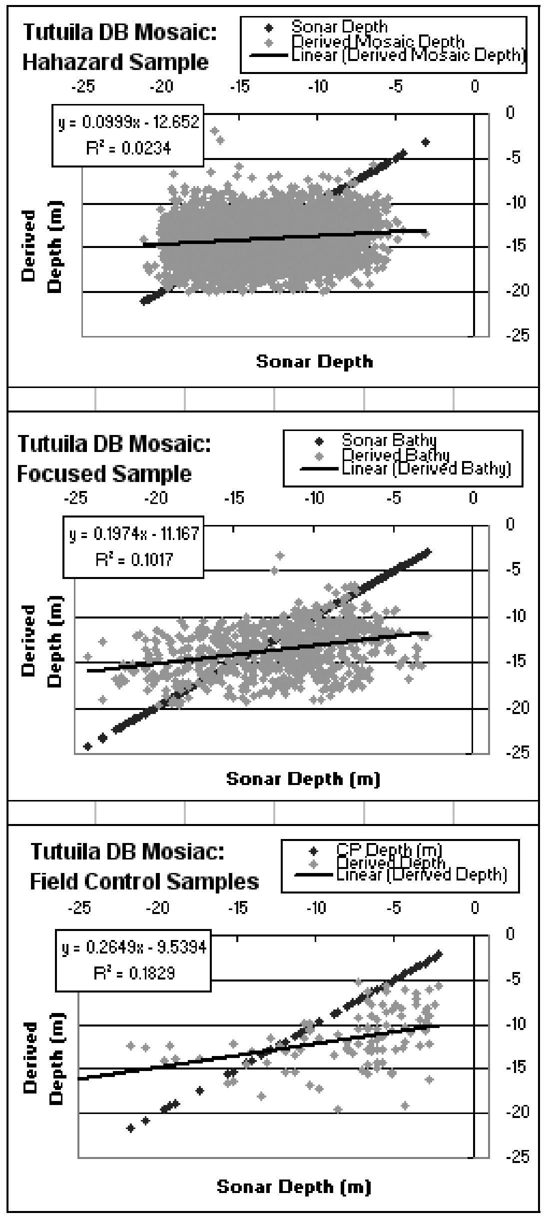

Figure 2.4: Error analysis by linear regression performed on integrated derived bathymetry.

2.3.2 CTM Error Analysis

With the derived bathymetry integrated into the full CTM mosaic, the CRED control points serve for two final error analyses. Of the original 140 control points, 103 fell within areas of derived bathymetry and have been used in the previous analysis (41 in West, 47 in West-central, 3 in East-central and 21 in East Tutuila – with overlap), 32 fell within areas of estimate depth and 5 fell in areas covered by multibeam sonar. The points within areas of estimated depth are used to assess the values calculated by the ArcGrid moving mean expression in areas void of data, while the full set of 140 points is used to extract values from the CTM for a final analysis of the fully integrated mosaic. Because of this control point spread, the final CTM error analysis can be considered inclusive of all data types with a focus on the derived bathymetry.

Cloud cover in the original IKONOS imagery necessitates that a significant area of the near shore bathymetry is estimated using the mean value of surrounding cells. Multiple iterations of the algorithm are needed to fill the larger gaps with the estimated surface error increasing with distance from the edge of valid data values. Figure 2.5 demonstrates the utility and relative accuracy of the estimated depths with a slope of 1.115 that is actually steeper than that of the control data and a high r^2 of 0.343, however, the large potential error in the data is illustrated by the outliers in the range of 30-35 m of estimated depth and 5-12 m control depth.

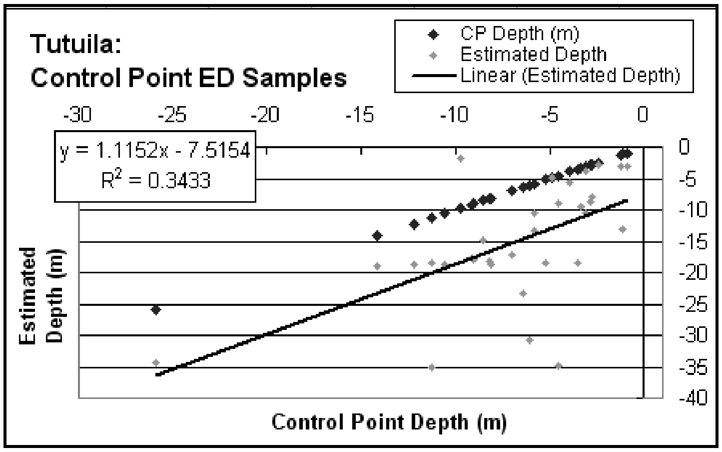

Figure 2.5: Error analysis by linear regression performed on estimated bathymetry.

With the derived and estimated bathymetry thus validated, and the DEM and multibeam sonar datasets presumed to be accurate on their own merits, a final error assessment of the integrated CTM is conducted using the 140 CRED control points to extract depth data from the CTM. Regression analyses of these data results in an initial slope of 0.585 and r^2 value of 0.285 which improve to a slope of 0.601 and r^2 value of 0.414 with the removal of 3 outliers (Figure 2.6) signifying a statistically valid representation.

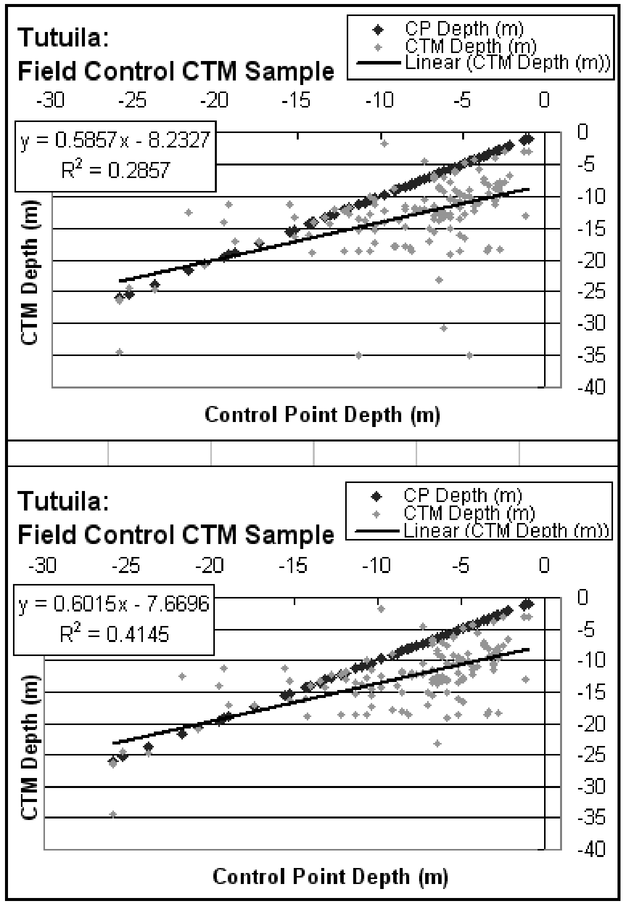

Figure 2.6: Error analysis by linear regression performed on complete CTM mosaic.

These final figures conclude the extended error analysis of multiple stages in the process of bathymetric derivation and CTM integration and provide support for the use of bathymetry derived from IKONOS imagery to provide shallow water depth data for coastal terrain modeling. Though the model is not perfect, analyses show that the derived depths represent a realistic measure of depth and that overall error decreased as the datasets are mosaicked into the CTM. Further analyses provide evidence that the derived data's range of error is small enough to provide realistic terrain through the sea-land transition and justifies additional steps to smooth seems between the datasets.

2.3.3 Dataset Seams and Morphological Detail

Having assessed the error associated with derivation of depth from spectral data and integration of the derived surface into the CTM, linear transects are used to extract elevation and depth data across the land-sea interface to visualize and quantify the vertical offset at the seams between the DEM, derived bathymetry, and multibeam sonar datasets. The transect profiles are also used to explore the CTM's representation of subtle topographic transitions and detection of specific terrain features. Four transects are created as point features in ArcGIS with a value extracted from each contiguous raster cell over distances of 800 m or 1200 m (Figure 2.7). The extracted data result in terrain profiles with a 5 m horizontal spacing and vertical reliefs of 50 m, 80 m, or 200 m over transitions between the DEM, derived bathymetry (DB), ArcGrid expression estimated bathymetry (EB) and sonar bathymetry (SB) data (Figures 2.8-2.11).

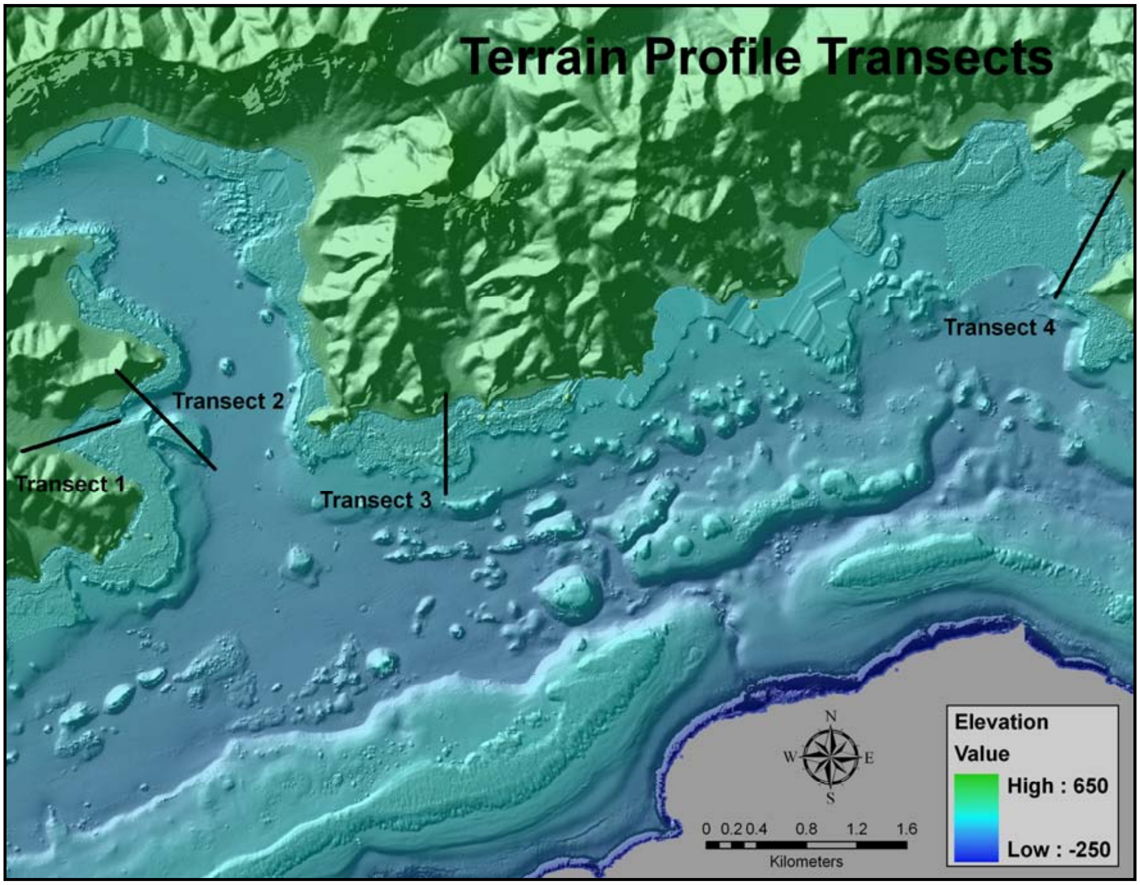

Figure 2.7: Tutuila CTM with terrain profile transects.

Transect 1 (Figure 2.8) begins on the floodplain of a small watershed and follows the hollow of the basin into an offshore submarine channel. The "stepping" on the left side of the profile is an artifact inherent on low slopes in data originating as an integer DEM. A vertical offset of 6.7 m is readily apparent at the transition between the DEM and EB. However, no offset exists at the transitions from EB to DB (at a distance of 510 m), which is as should be expected since the ArcGrid expression derived the EB values as the mean of nearby DB values, or from DB to SB (at a distance of 720 m), which simply shows excellent corroboration between the two sources of depth data.

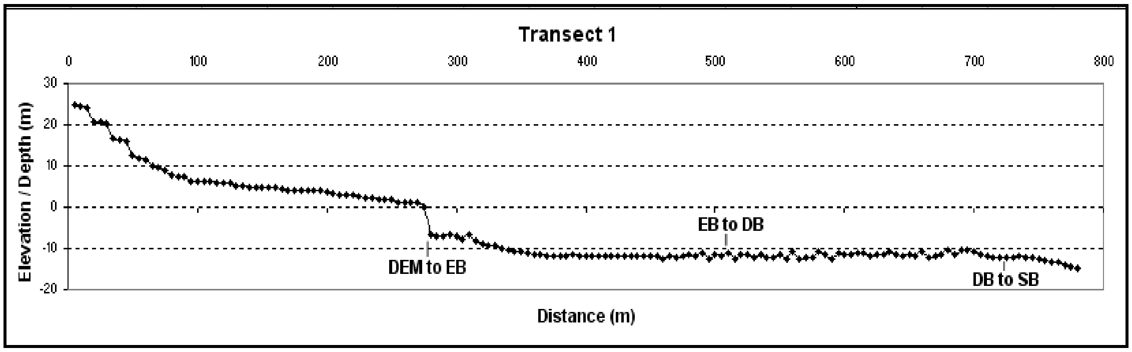

Figure 2.8: Terrain profile of Transect 1.

Transect 2 (Figure 2.9) starts at the top of a ridge, descends quickly before crossing a narrow reef flat, proceeds across a channel with two small ridges and then crosses a large coral plateau. At the land-sea transition, the first DB value has a large vertical offset of 19.2 m, but subsequent DB values are much more realistic and provide for good terrain representation across the reef flat to a seam without vertical offset between DB and SB at a distance of 215 m. From this point to a distance of 435 m ridges in the bottom of the channel are clearly indicated by SB data, then there are two transitions from SB to DB and back at 440 m and 665 m with vertical offsets of only 2.5 m and 2.3 m as the transect crosses the coral plateau.

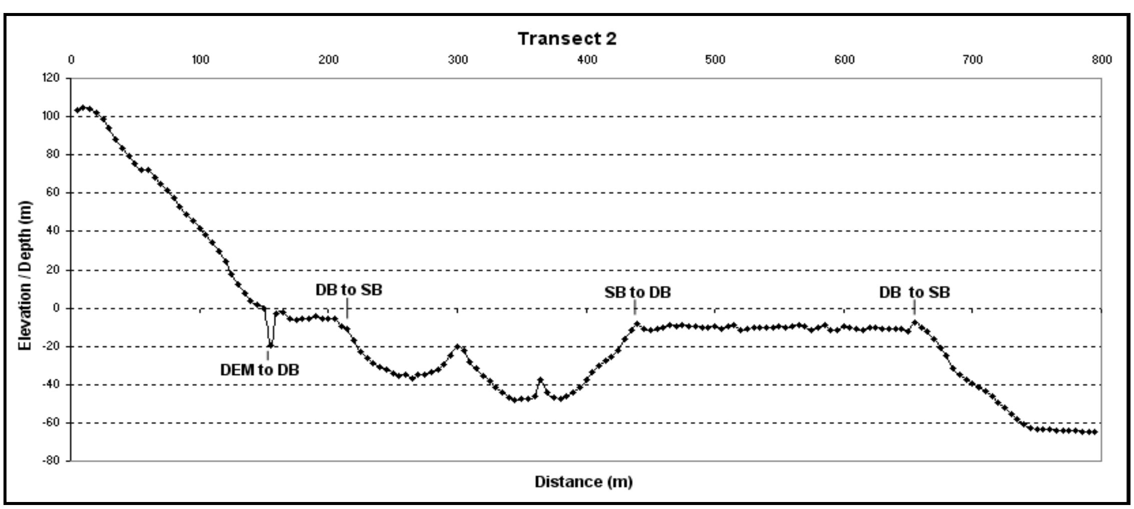

Figure 2.9: Terrain profile of Transect 2.

Transect 3 (Figure 2.10) initiates at the base of a ridge crossing a steep grade to the shoreline, proceeds across a broad back reef and reef crest before ending on the fore reef slope. There is a vertical offset of 5.67 m between the DEM and the DB at the land-sea interface. From this transition to a distance of 400 m, the profile exhibits typical back reef terrain with moderate rugosity and variable depth that increases until a sudden decrease at the reef flat, which causes a notable data issue. At a distance of 330 m the DB values began to thin out (in the derived bathymetry mosaic) due to surf conditions and breaking waves on the reef flat, and the depth values become "more estimated" to the right. The other side of this surf zone data gap is at a distance of 675 m in the SB data where the depth values become "more estimated" to the left on the profile. The drastic vertical offset of 19.5 m between distances of 575 m and 590 m is the transition between EB calculated from original DB and SB data during several iterations of the ArcGrid expression run to fill the data gap. The large error at this seam is a result of the EB data failing to capture the real change in depth from the shallows at the edge of the DB values to the deeper reef slope SB values.

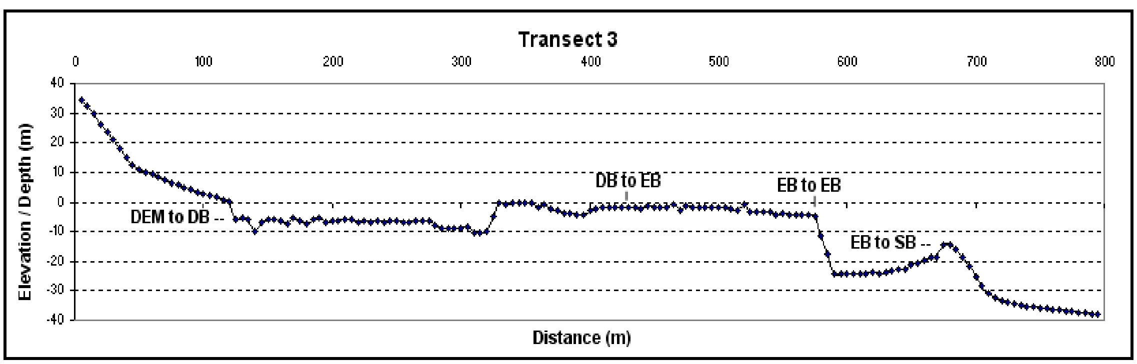

Figure 2.10: Terrain profile of Transect 3.

Transect 4 (Figure 2.11) runs from the base of a ridge across a moderately sloped coastal plain to the shoreline, proceeds across a narrow back reef and then continues along the fore reef while crossing a channel and then finally descends the reef slope. There is a vertical offset of 6.74 m between the DEM and the DB at the land-sea interface. From this point to a distance of 640 m the DB profile again indicates typical back reef / fore reef morphology and closer inspection of the terrain that transect 4 crosses reveals that the DB data provide a high degree of detail allowing for the detection of potholes in the variable terrain of the shallows and the channel in the fore-reef at a distance of about 400 m. One of the limitations of the bathymetric derivation method is evident between the distances of 665 m and 1000 m. The derived depth data bottoms out at the lower range of the derivation procedure's effective limit of around 15 m (in this case) until the transect crosses the tip of a fore reef outcrop that is in range from of 835 m to 875 m distance. The vertical offset of 9.1 m at distance of 1005 m is the transition between this "false floor" artifact and the SB data. This data artifact is also apparent in Figure 7, in the middle of the bay to the west of transect 4, where most of the data in the central bay is false floor with a vertical offset of up to 35 m at the seam. Fortunately for the model, this is the only area around the island with such a large gap between the effective range of the derived bathymetry and the extent of the sonar bathymetry dataset.

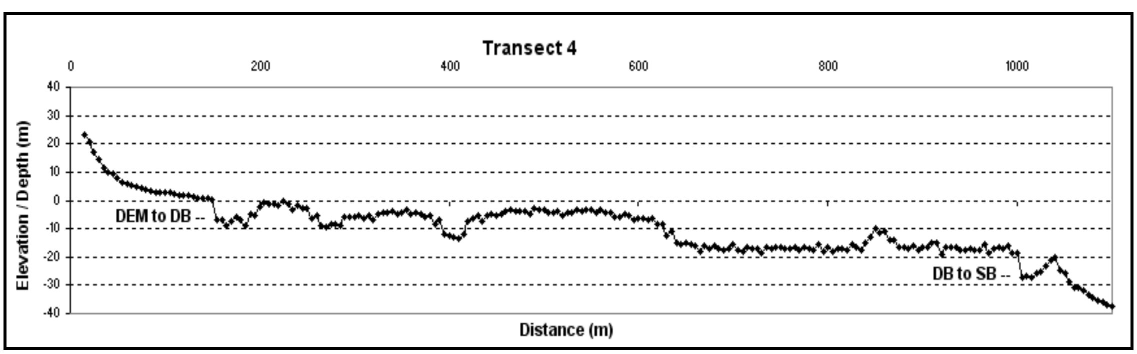

Figure 2.11: Terrain profile of Transect 4.