Determination of bottom-type and bathymetry using WorldView-2

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ABSTRACT

Observations taken from DigitalGlobe's WorldView-2 (WV-2) sensor were analyzed for bottom-type and bathymetry for data taken at Guam, Tinian, and Pagan in late February and early March of 2010. Classification of bottom type was done using supervised and unsupervised classification techniques. All eight of the multispectral bands were used. The supervised classification worked well based on ground truth collected on site. Bathymetric analysis was done using LiDAR-derived bathymetry in comparison with the multispectral imagery (MSI) data. The Red Edge (705-745 nm) band was used to correct for glint and general surface reflectance in the Blue (450-510 nm), Green (510-580 nm), and Yellow (585-625 nm) bands. For the Guam beach analyzed here, it was determined that the Green and Yellow bands were most effective for determining depth between 2.5 and 20 m. The Blue band was less effective. Shallow water with coral could also be identified.

Keywords: WorldView-2, shallow water bathymetry, multispectral sensor

1. INTRODUCTION

The ability to accurately determine the landscape of underwater regions is of great importance to civilian and military organizations alike. Whether mapping bottom type with the intention of monitoring marine habitats, modeling coastlines, or navigating through aquatic areas, the study of bathymetry is a critical field.

When remotely sensing the ocean floor, it is generally assumed that the bottom is homogeneous. However, what if this is not always the case? We are examining this question utilizing two test sites in Guam, three test sites in Tinian, and three test sites in Pagan where a variety of bottom-types (corals of different colors, sand with different colored grains, rock, sea grass, etc.) are found at various depths. WV-2 data ought to provide improved bathymetric mapping and bottom-type determination over 4-band sensors.

The goal of this research was to determine how WV-2's eight bands provide improved bottom mapping capabilities and more accurate bathymetric measurements. The WV-2 data used for this research were provided by DigitalGlobe.

2. BACKGROUND

2.1 Determination of bottom type and bathymetry using multispectral data

There are several benefits to using WV-2 for this type of research, including the capability of providing imagery for remote places. Using these data will allow analysts to create navigational charts for areas that do not have accurate surveys. Fast revisit times will also allow for rapidly conducted change analyses[1].

Bathymetry has been analyzed using spectral data by a number of authors. Stuffle (1996) used HYDICE hyperspectral data to map Lake Tahoe with high accuracy and spatial resolution. The additional dimensionality provided by the many bands allowed for distinguishing bottom type and reflectance[2]. Fisher (1999) and Stumpf (2003) address the problem of surface reflectance[3, 4]. Stuffle and Fisher's work followed the work by Bierwirth (1993)[5] and Mobley (1994)[6]. Camacho (2006) followed this model with analysis at Midway Island[7].

Loomis (2009) modeled WV-2 starting with hyperspectral imagery (HSI)[8]. He found that band combinations that use WV-2's Yellow band should be superior for looking at water at medium depths, even more so than combinations with

Blue and Green alone. Puetz et al. (2009) conducted a similar simulation of WV-2's spectral response and found that use of the Coastal and Red Edge bands lead to a significant improvement in classification when looking at water – ranging from deep to shallow water with particulate matter within the water column[9].

2.2 WorldView-2

Built by Ball Aerospace & Technologies Corporation, WorldView-2 is DigitalGlobe's third operational satellite. It is capable of capturing 46 cm panchromatic imagery and 1.84 m resolution 8-band multispectral imagery. At an operating altitude of 770 km, WV-2 can collect nearly 1 million km^2 of imagery per day, and offers an average revisit time of 1.1 days around the globe[10].

WorldView-2 is the first commercial high-resolution satellite to provide eight spectral sensors, and has bands that range from the visible to near-infrared (400-1040 nm) (Figure 1). Each sensor is focused to a particular part of the electromagnetic spectrum to be sensitive to a specific type of feature on the ground or property of the atmosphere[10].

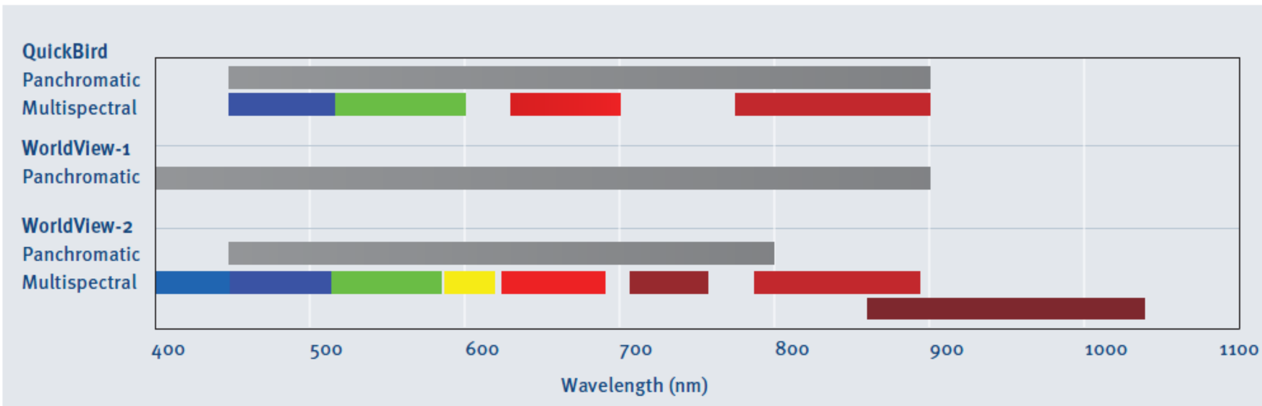

Figure 1. Spectral bands of DigitalGlobe's three satellites[10]

2.3 Study sites

The Mariana Archipelago encompasses 14 islands of the U.S. Commonwealth of the Northern Mariana Islands (CNMI) and the U.S. Territory of Guam (Figure 2). The Marianas can be divided into two groups based on geology – the older southern island arc that includes Guam, Rota, Tinian, Saipan, Farallon de Mendinilla, and Aguijan, and the younger, volcanic northern islands that include Anatahan, Sarigan, Guguan, Alamagan, Pagan, Agrihan, Asuncion, Maug, and Farallon de Pajaros[11].

The CNMI is about as far away from the United States West Coast as Washington, D.C. is from Cairo, Egypt. The International Date Line, situated between the Mariana Islands and Hawai'i puts the CNMI ahead of the conterminous U.S. by several time zones (four time zones west of Honolulu, six zones west of California, and nine zones west of Washington, D.C.)[12].

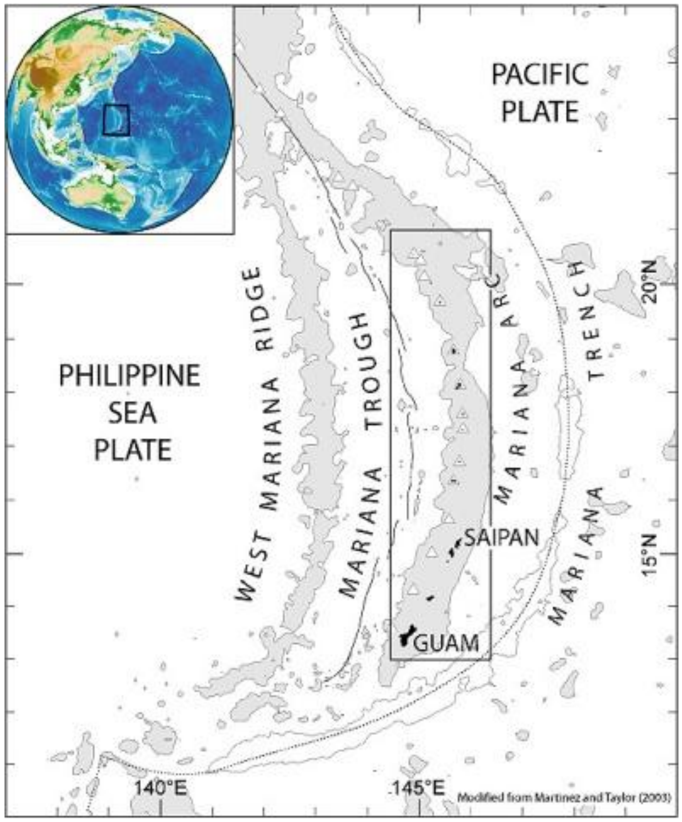

Figure 2. Guam and the Commonwealth of the Northern Mariana Islands (CNMI)[11]

2.3.1 Guam

Guam is the largest island in Micronesia and has a total land mass of 550 km^2, excluding reef formations[12] (Figure 3). The southernmost island of the Mariana Archipelago, Guam is part of the Mariana frontal arc and has been repeatedly elevated and submerged over time. The peak of a submerged mountain, Guam rises approximately 11,500 meters above the floor of the Mariana Trench, the greatest ocean depth in the world. Guam also straddles the subduction zone where the Pacific Plate is submerging below the Philippine Plate, which makes the Mariana Islands volcanically active[13].

The island is geologically unique in that the southern part is composed mostly of volcanic features, while the northern part is mostly made up of uplifted coral limestone[13]. The oldest formations on Guam have been dated as mid- to late-Eocene (48-33 Ma). The northern limestone plateau is surrounded by cliffs and, due to deforestation, has no running water. The southern half is mountainous and composed mostly of basalt that has erupted through the uplifted coral limestone. The numerous bays, canyons, and valleys on the flanks of this volcanic region are covered by grasslands[11].

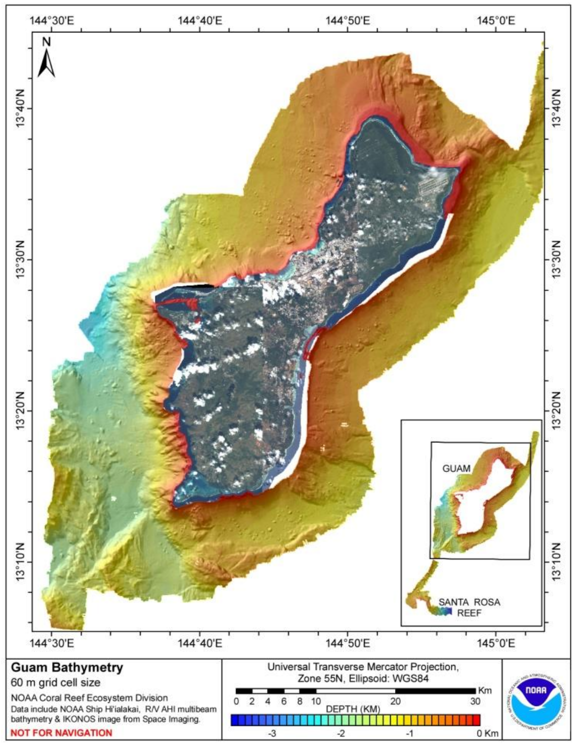

Figure 3. The island of Guam with surrounding bathymetry data (red represents shallow water and blue represents deeper water)[14]

2.3.2 Tinian

Tinian is approximately 185 km north of Guam. It is 17 km long by 8 km at its widest point, and has a total area of 101 km^2 and a coastline that is about 61 km in length[12] (Figure 4). Tinian and the nearby island of Aguijan form the Tinian Municipality. The island is perhaps best known as the launching place of U.S. planes for attacks on Japan during WWII[11].

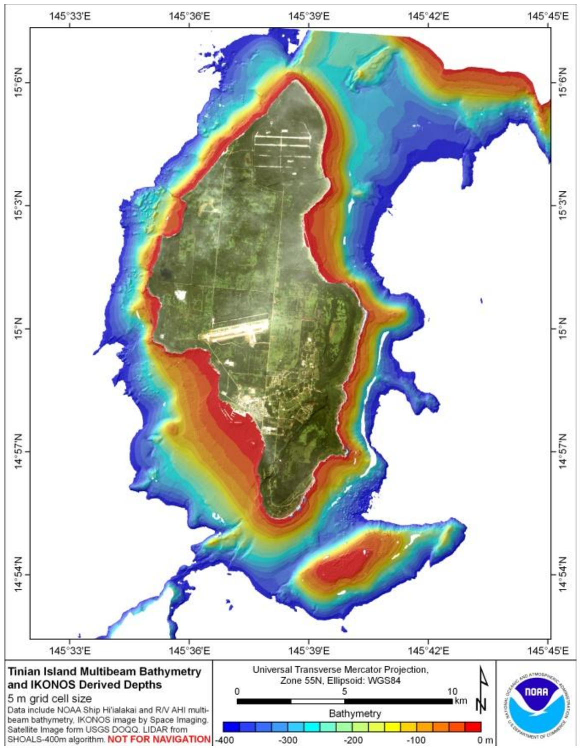

Figure 4. The island of Tinian with surrounding bathymetry data (red represents shallow water and blue represents deeper water)[15]

2.3.3 Pagan

Pagan is approximately 530 km north of Guam, and is 17 km long and 7 km wide at the widest point (Figure 5). Pagan is one of the most active and largest of the Mariana volcanoes, and is formed by two volcanoes connected by a narrow isthmus. Almost all eruptions dating back to the 1600's have originated from the northern volcano, Mount Pagan. In 1981, 53 residents were evacuated after a major eruption, and the island has been uninhabited since, due to volcanic threat[11]. Because of the presence of volcanism on the island, the beaches that were visited have black sand.

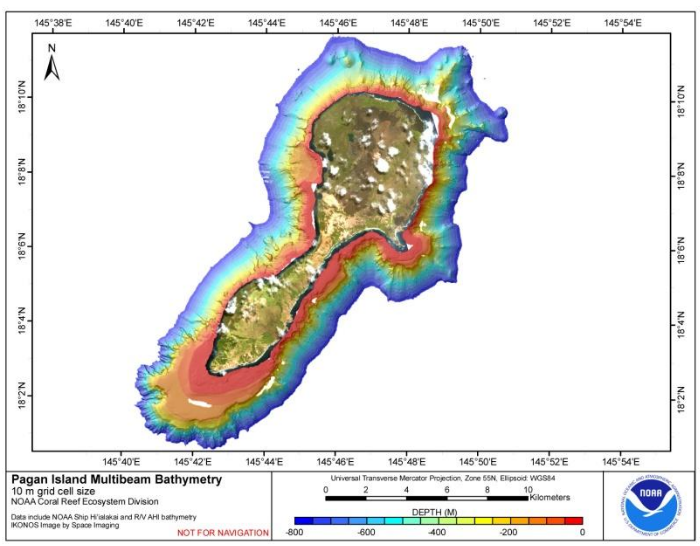

Figure 5. The island of Pagan with surrounding bathymetry data (red represents shallow water and blue represents deeper water)[16]

3. METHODS

3.1 Fieldwork

A number of beaches were visited on each of the islands and ground truth data were collected in late February and early March of 2010.

3.1.1 Beaches visited

A total of eight beaches were visited during the field campaign that took place between the end of February and beginning of March 2010. Beaches were chosen based on a variety of factors, including accessibility, beach sand grain size, and difference in bathymetry and bottom-type. The following figures are subsets of the WV-2 imagery centered on the particular beaches where field work was conducted. On Guam, two beaches were visited – Dadi and Tipalao (Figure 6).

Figure 6. From left to right, Dadi Beach and Tipalao Beach, Guam

Three beaches were visited on Tinian – Unai Lam Lam, Unai Babui, and Unai Dangkolo (Figure 7).

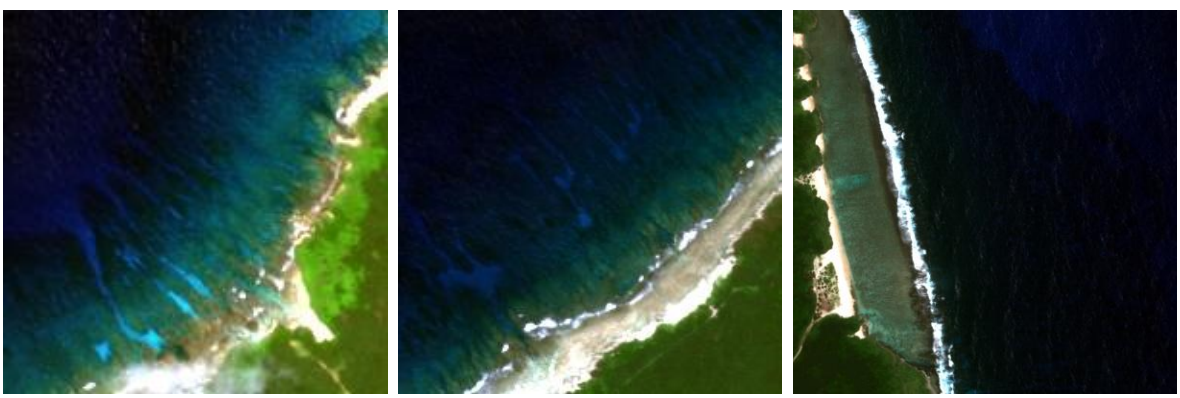

Figure 7. From left to right, Unai Lam Lam Beach, Unai Babui Beach, and Unai Dangkolo Beach, Tinian

On Pagan, three beaches were visited and named Beach 1, 2, and 4 by the field crew (Figure 8).

Figure 8. From left to right, Beach 1, Beach 2, and Beach 4, Pagan

3.1.2 Fieldwork completed

At each beach location, a number of different experiments were performed using various tools at several data points along a sample transect (separated by some cm to tens of m). Tools included the following:
Dynamic Cone Penetrometer (DCP): The DCP measures substrate shear strength.
Lightweight Deflectometer (LWD): The LWD measures substrate bearing strength. It has a precise footprint with a diameter of 0.3 m. It sends three pulses into the ground, coming into contact with the substrate through a base plate with imbedded accelerometers to determine soil modulus.
Analytical Spectral Device (ASD): Spectra of several structures, features, and plants on land and the in water were measured with the ASD. While collecting over the water, the approximate depths at the time of measurement, as well as a basic description or guess of bottom-type were recorded.
Soil Corer: The top three inches of soil were collected at each data point. Samples were used to determine grain size distribution and moisture properties of substrates at regular intervals along transect locations. Each sample was weighed, dried (using a microwave), and weighed again to determine soil moisture content. Samples were then run through sieves to determine grain size distribution.

Actual depths or spectral measurements from fieldwork have not yet been applied to this research.

3.2 Preparation for classification

The Environment for Visualizing Images (ENVI) 4.8 software was used for this research.

A spatial subset was selected from each of the original WV-2 images of Tinian and Guam before performing any other necessary pre-processing. This was done to remove parts of the image that were not needed for analysis.

WorldView image data is typically distributed in relative radiance. ENVI 4.8 has a specific WorldView Radiance calibration utility to convert from relative radiance to absolute radiance (in units of [(μW)/(cm^2*nm*sr)]. This spectral tool uses the calibration factors in the WV-2 metadata file to perform the conversion[17].

A series of masks were created for each beach image to ensure that only specified locations would undergo the classification process (Figure 9).
(1) A mask was created to cover the land, with the exception of the beach pixels (in case field data are incorporated at a later time).
(2) A glint mask was created utilizing only the Red (630-690 nm) band. The glint shows brightly in this band and could be distinguished from other water pixels by means of a threshold.
(3) Because the glint mask would also classify some beach and shallow water pixels as something that should be masked, another mask was created to keep the glint mask from blocking these areas.
(4) Using band math, the masks from steps (2) and (3) were multiplied to create a mask that will cover glint, but not locations specified as something that should not be masked.

(5) The last step was to create the final mask by subtracting the mask created in step (4) from the original land mask from step (1).
(6) The final mask was then applied to the RGB image.

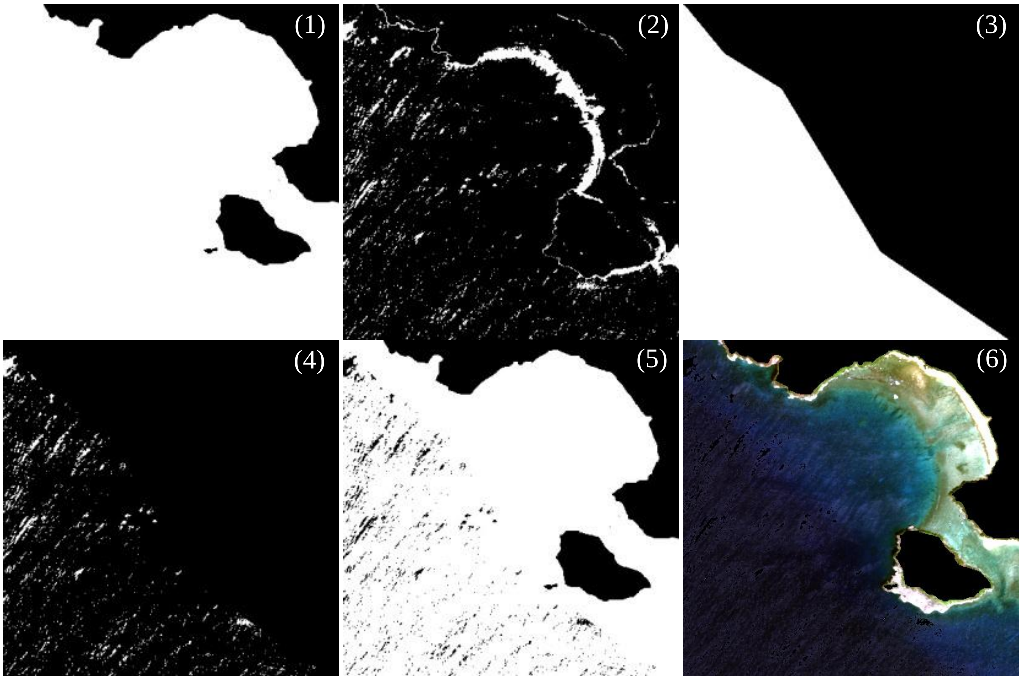

Figure 9. Examples of steps (1) through (6) on Tipalao Beach, Guam

This process was performed for each beach subset image.

3.3 Unsupervised classifications

After masks were created, unsupervised classifications were performed. Unsupervised classification is used to cluster pixels in a dataset based only on statistics, without any user-defined training classes[17]. Both the IsoData and K-Means methods were used in hopes of finding one that performed better for shallow water bathymetry.

Classifications were not only performed for all eight bands at once, but also individually. This was done in an effort to determine whether or not a specific band would play a role in correctly identifying a part of a beach or a certain water depth.

3.4 Supervised classifications

Supervised classification is used to cluster pixels in a dataset into classes corresponding to user-defined training classes. Training classes can consist of groups of pixels called Regions of Interest (ROIs) or individual spectra. ENVI also differentiates between masked pixels and unclassified pixels, and does not apply the algorithm to masked pixels[17]. ROIs were selected for specific classes based on visible changes in depth and bottom-type (Figure 10) and are shown in Table 1.

The supervised classification techniques explored included: Parallelepiped, Minimum Distance, Mahalanobis Distance, Maximum Likelihood, Spectral Angle Mapper (SAM), Spectral Information Divergence (SID), and Binary Encoding. The results of the Maximum Likelihood classifications, which often produced the best match to observations made in the field, are shown in Figure 11.

Imagery for Pagan was not used for this particular paper because of the amount of sun glint and clouds in the data. However, we will go back and use the same methodology with a different image dataset.

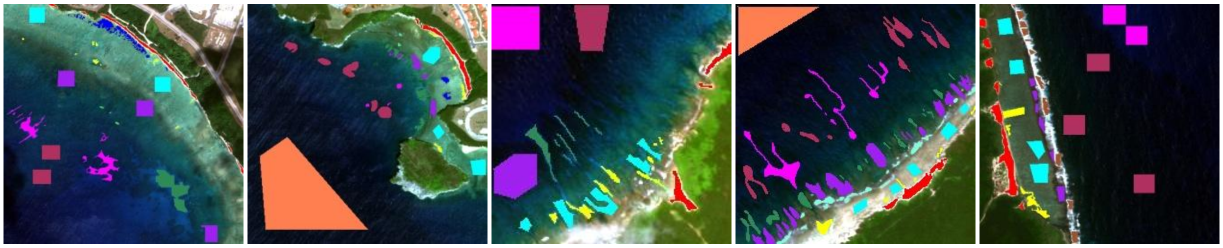

Figure 10. From left to right – ROIs for: Dadi Beach and Tipalao Beach (Guam), Unai Lam Lam Beach, Unai Babui Beach, and Unai Dangkolo Beach (Tinian) (refer to Table 1, below, for color meanings)

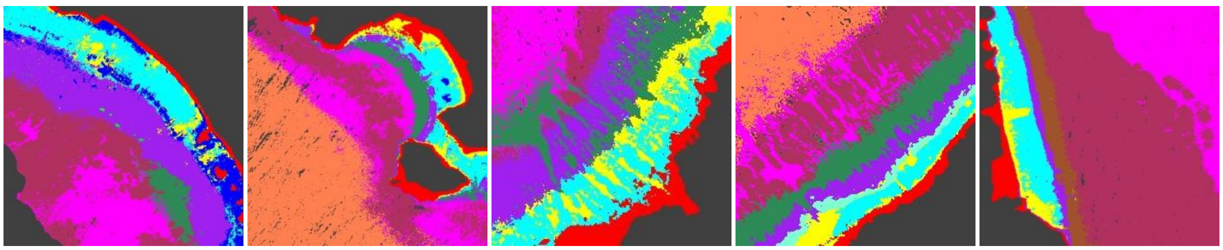

Figure 11. Maximum Likelihood classification of the above beaches for: Dadi Beach and Tipalao Beach (Guam), Unai Lam Lam Beach, Unai Babui Beach, and Unai Dangkolo Beach (Tinian) (refer to Table 1, below, for color meanings)

Beach Sand	Shallow Water (No Coral)	Deeper Water (With Coral)	Deep Water
Boats	Shallow Water (With Coral)	Mid-Range Water (No Coral)	Whitecaps
Sea Grass	Deeper Water (No Coral)	Mid-Range Water (With Coral)	

Table 1. ROIs used for supervised classification

3.5 Bathymetry

The bathymetry data used for this research came from the U.S. Army Corps of Engineers (USACE) National Coastal Mapping Program (NCMP). This program was designed to provide high-resolution elevation and imagery data along U.S. shorelines. The NCMP, executed by the Joint Airborne LiDAR Bathymetry Technical Center of Expertise (JALBTCX), uses its in-house survey capability called the Compact Hydrographic Airborne Rapid Total Survey (CHARTS) system. This sensor suite includes an Optech SHOALS-1000T and an Itres CASI-1500. The SHOALS-1000T contains a 1,000 pulse-per-second (pps) bathymetric laser, a 9,000 pps topographic laser, and a digital RGB camera that records one frame every second. The CASI-1500 is a programmable pushbroom hyperspectral imager that is capable of collecting between four and 288 spectral bands over the spectral range from 375-1050 nm, at pixel sizes ranging from 20 cm to 5 m (depending on system configuration).

Bathymetric data are collected from the shoreline to 1 km offshore at 5 m spacing. GIS products derived from these data include seamless bathymetric/topographic grids, bare earth bathymetric/topographic grids, building footprints, a shoreline vector, seafloor reflectance images, basic landcover classifications, and RGB and hyperspectral image mosaics[18] (Figure 12).

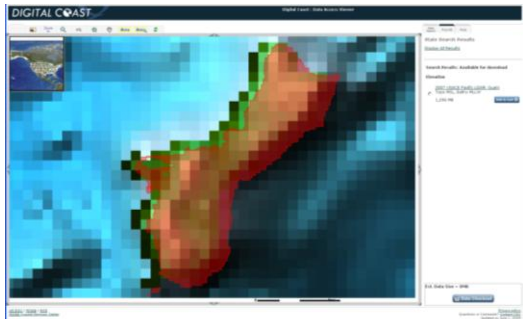

Figure 12. A screenshot of the JALBTCX window, focused on Guam[19]

The nominal ground spacing of the data is 2 m, and the vertical accuracy of the data is better than +/- 0.20 m at 1 sigma. The data were acquired in February and May of 2007 and were collected from the land/water interface seaward to a depth of 40 m or laser extinction, whichever came first[20].

3.6 Combining spectral imagery and Digital Elevation Models (DEMs)

For this project, we used the LiDAR-derived bathymetry to map the radiance data to depth. The Digital Elevation Model (DEM) of Tipalao Beach, Guam was chosen as the data subset from which to model the following steps. The base process was to subtract the estimated surface reflectance derived from the Red Edge (705-745 nm) band from each band, and then take the log of that quantity, which should depend in a linear way on depth[2]. This was done iteratively by working within ENVI and the IDL programming languages to estimate the reflected component in the Coastal, Blue, Green, and Yellow bands. Figure 13 illustrates the resulting quantities plotted for the Blue, Green, and Yellow bands. In each figure, the horizontal axis is the LiDAR-derived depth, and the vertical axis is the log of the water leaving radiance. Zero depth is to the right in each figure, and radiance increases vertically. In such plots, we should see a linear relationship, as found for the Yellow and Green bands. Neither the Coastal nor Blue bands showed an obvious correlation, most likely because of the shallow water environment and relatively high surface glint.

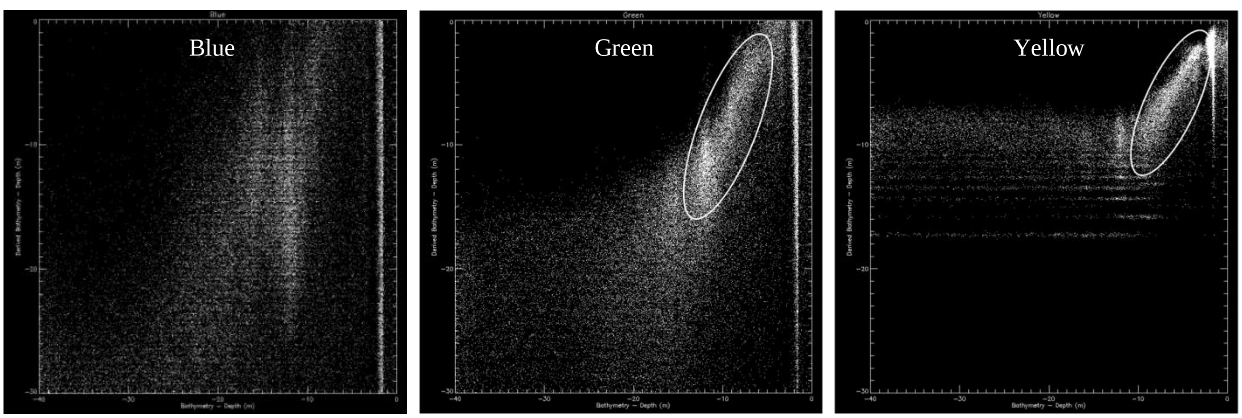

Figure 13. The reflected component in the Blue, Green, and Yellow bands
(horizontal axis: LiDAR-derived depth, where x ranges between -40 and 0 m; vertical axis: log of the water leaving radiance, where y is arbitrary units of log radiance)

A least-squares-fit was applied to each of the three bands illustrated and, from these, we can project the depth estimated from each channel. These depth estimates (in m) are illustrated in Figure 14, where the depth derived for the Green and Yellow bands are displayed.

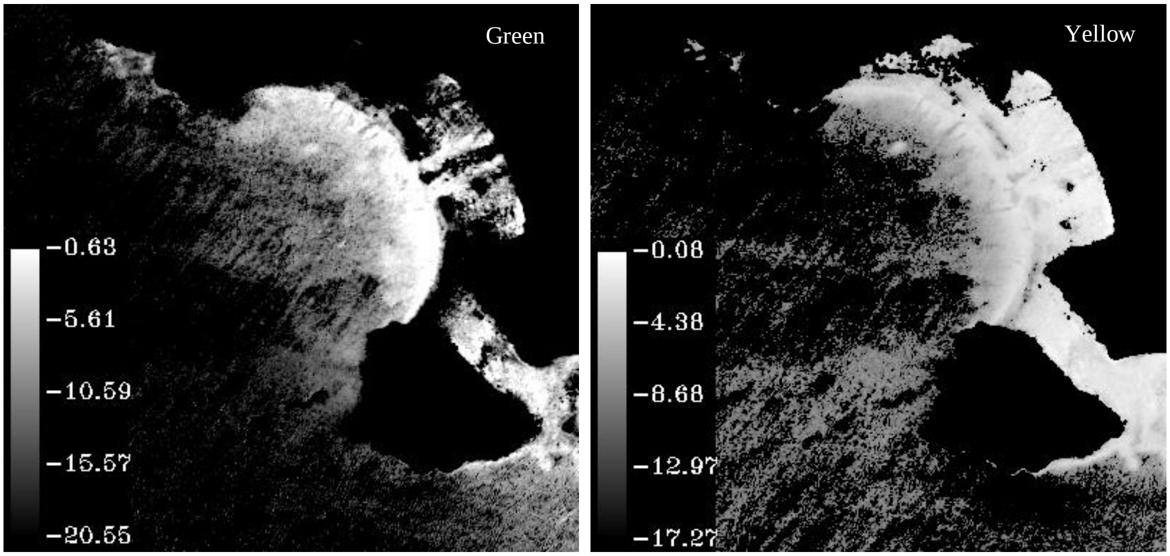

Figure 14. Derived depth (in m) of Tipalao Beach, Guam (left to right: Green, Yellow)

At this point, derived bathymetry depths were compared among individual bands. Using two dimensional scatterplotting and N-dimensional visualization (multidimensional scatterplotting), bands were compared to the DEM and one another. Several combinations were tried in an effort to create new ROIs that would accurately classify different depths between 2.5 and 20 m. One example and the resulting Maximum Likelihood classification image are seen below (Figure 15). These data show that it is possible to accurately classify bottom depths out to 20 m using this method.

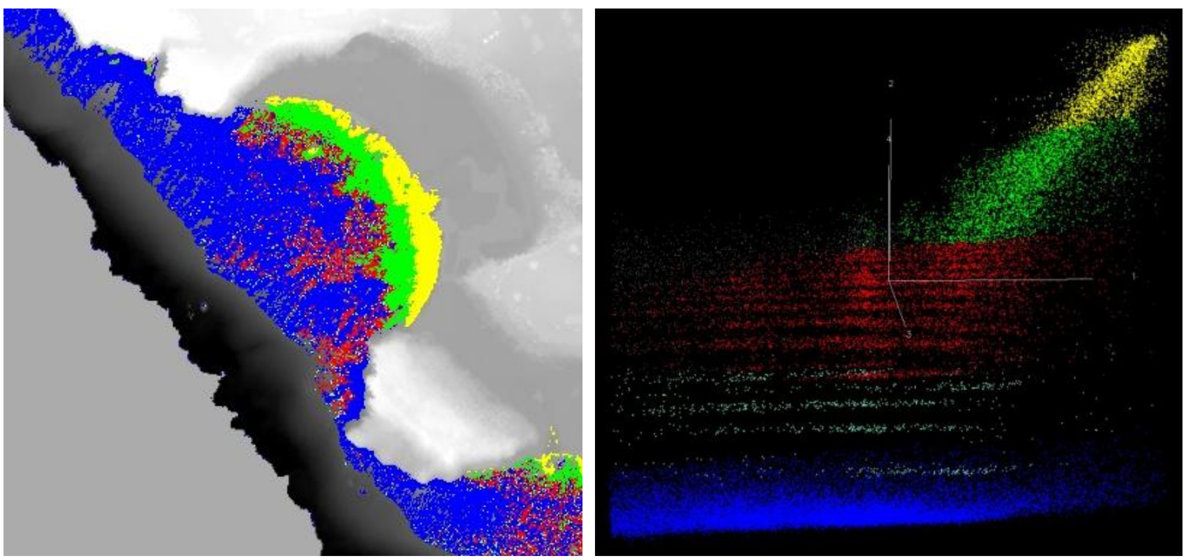
Figure 15. Left to right: bathymetric regions, n-dimensional scatterplot
(scatterplot has all four bands projected to two dimensions – DEM, Blue, Green, and Yellow – and colors represent changes in depth)

Based on the IDL output, the most informative bands are the Green (510-580 nm) and Yellow (585-625 nm). The regions where depths were derived from these two bands are given by the green and yellow ROIs displayed in Figure 15. These two ROIs were combined into a single region and exported to Microsoft Excel for further analysis. Excel made it possible to graphically visualize the degree of correlation between data.

4. RESULTS

4.1 Image analysis

The classified images displaying the Coastal and Blue bands appeared to have very accurate depictions of the shallow water regions in the original radiance images, based on visual comparisons. Along the same lines, the Green and Yellow bands looked to be the best individual bands to use for what we called "Mid-Range Water" classification. These individually classified bands also appeared to be better matches than the combined eight-band classification with 12 to 15 classes.

After comparing unsupervised classification techniques, a number of supervised classifications were tried. ROIs were created based on our own personal take on depth based on color, as well as some *a priori* knowledge from fieldwork performed in February and March of 2010. Between seven and eleven classes were used for every beach (refer back to Table 1). Each method had good and bad points, but there was no result as interesting as with the individually classified bands discussed in the previous paragraph.

Bathymetry maps acquired from JALBTCX were utilized to determine the accuracy of WV-2 depth estimates. The DEM for Tipalao Beach, Guam was used. An IDL program was then created to compare actual bathymetry and the bathymetry derived from the WV-2 imagery. Effects of surface reflectance were removed at this point in the process. Plots were created and a least-squares-fit was used to determine the bathymetry (in m).

The mean and standard deviation values of each were graphed. A diagonal line was entered to better show the result at a DEM depth of 0 and a derived depth up to 10 m (Figure 16). The next step we would like to take is to adjust fit coefficients to improve the result, as well as continue to test out different values and other bands and band combinations.

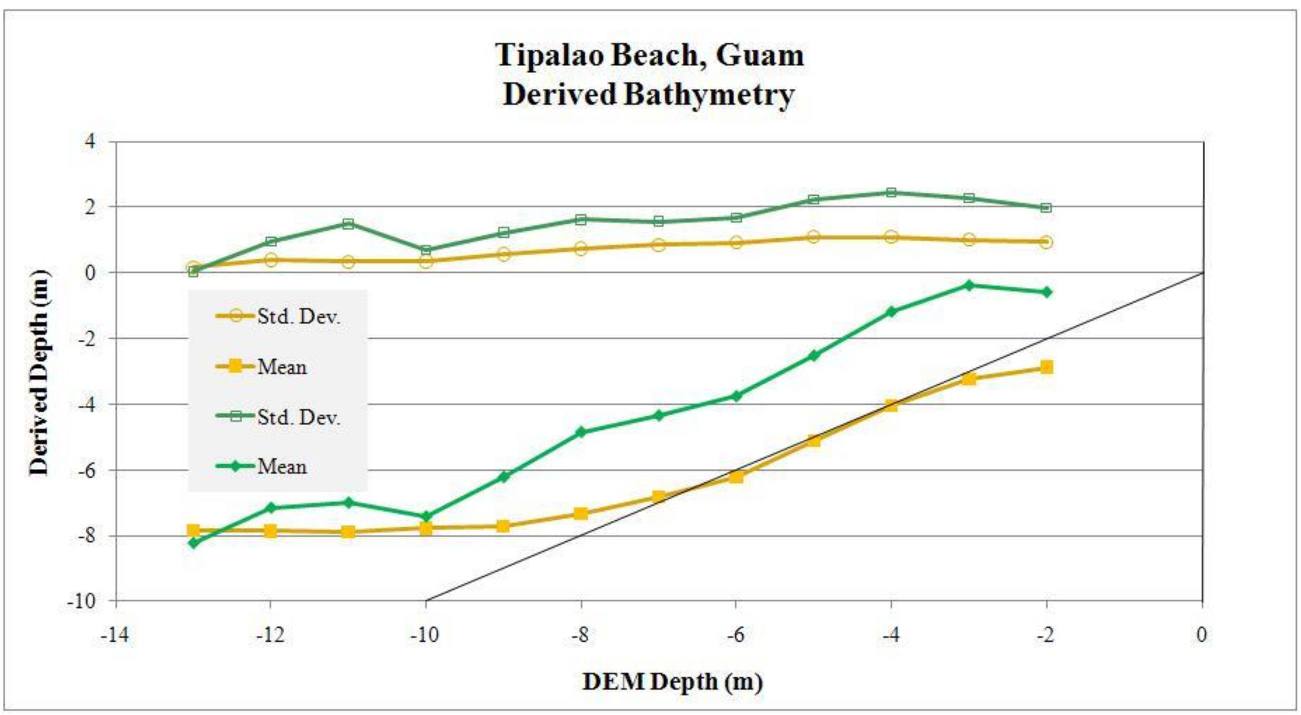

Figure 16. The mean and standard deviation values for the Green and Yellow bands

Based on these results, it was determined that the Green and Yellow bands were the best for determination of ocean water depths between 2.5 and 20 m (Figure 17).

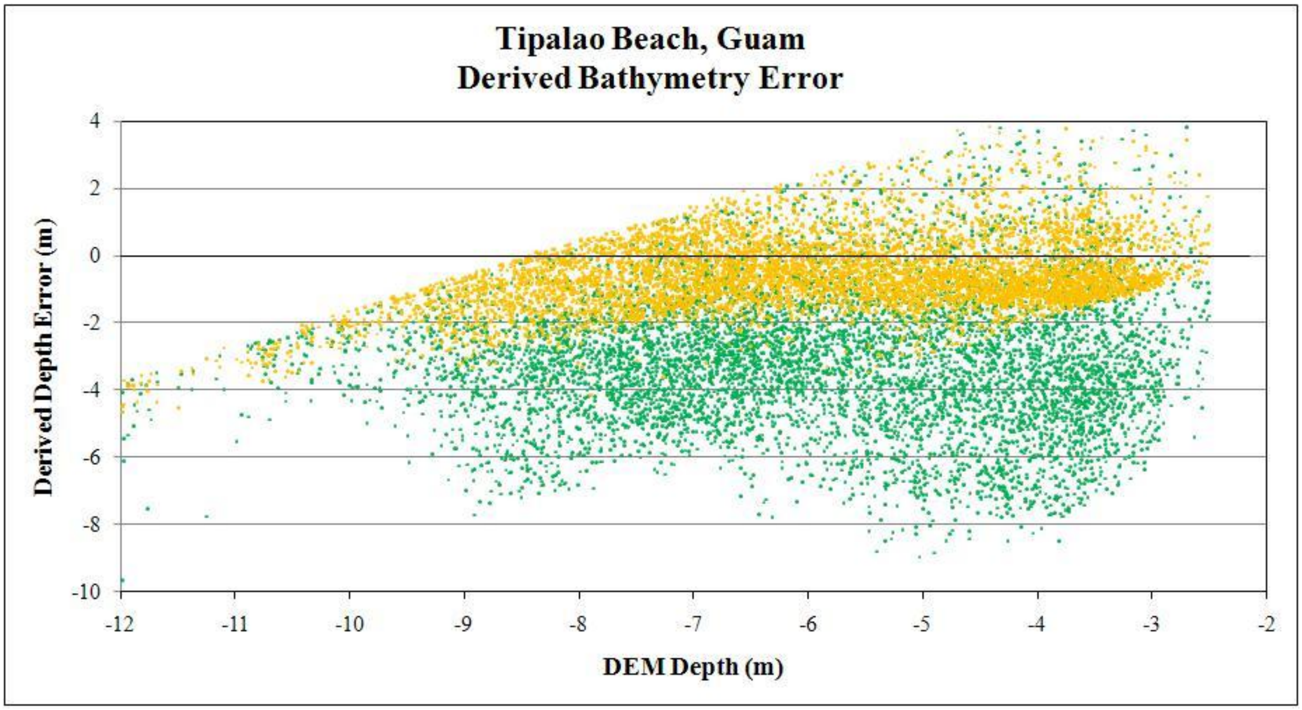

Figure 17. Derived depth error (in m) compared to the DEM depth (in m) for the Green and Yellow bands

5. CONCLUSIONS

In an effort to determine whether or not WV-2's four extra bands result in improved bottom-type identification and depth determination, a series of methods were used. Following the processes outlined by authors like Stuffle (1996)[2], Fisher (1999)[3], Stumpf (2003)[4], and Camacho (2006)[7], the Coastal, Blue, Green, and Yellow bands were compared to the Red Edge band. A linear relationship was found in the Green and Yellow bands after removing the effects of surface reflectance. A least-squares-fit was applied and depth was derived (in m).

For depths between 2.5 and 20 m, WV-2's Green and Yellow bands are the most useful for determining shallow water bathymetry. These bands are also able to pick out shallow areas with coral. This conclusion helps validate the research performed by Loomis (2009)[8].

It must be kept in mind that the bathymetry data used were collected in 2007, while the WV-2 data are from 2010. Ocean bottoms, especially in littoral zones, change very frequently. Errors are inevitable after three years between DEM and image acquisition.

Future work on this project will include further depth derivation and bottom-type identification of the other seven beaches. Comparisons to other types of multispectral and hyperspectral imagery will also be made. Part of the original proposal for this research was to incorporate HyVista Corporation's HyMap data. Although this was not accomplished in time for this particular project, the data will still be utilized and compared to the WorldView-2 data.

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