MAPPING CORAL REEF BATHYMETRY WITH HIGH-RESOLUTION, MULTISPECTRAL SATELLITE IMAGERY*

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ABSTRACT

A potentially efficient method to map coral reef environments is provided by the availability of high resolution, multispectral, commercial satellite imagery. For benthic mapping and management, spatially detailed bathymetry is needed. We have developed an alternative to the standard linear algorithm. This new algorithm, based on ratios has fewer parameters, simpler tuning and retrievals at greater depth, although apparently somewhat noisier.

1. INTRODUCTION

The Northwest Hawaiian islands include 10 islands, atolls, and reefs extending over 1800 km of the Pacific including over 7000 square kilometers of potential coral habitat. This remote region is currently under national and state management and is being considered for designation as a US National Marine Sanctuary, indicating a need for habitat information. A potentially efficient method of mapping coral reef environments is provided by the availability of high resolution, multispectral, commercial satellite imagery. For benthic mapping and management, spatially-detailed bathymetry is needed. Effective mapping of these regions with passive remote sensing instruments requires knowledge of the water depth, but depth information with the spatial resolution and coverage of the satellite imagery is difficult to obtain for such large areas by conventional means, such as shipboard surveys and airborne lidar, particularly in remote areas. We employ an alternative approach, which is to estimate bathymetry directly from the multispectral satellite imagery, predominately IKONOS imagery, using only a limited amount of ground-truth information to empirically tune the results.

Well-known algorithms based on Lyzenga (1978, 1985) have been used to determine water depth from passive multispectral satellite imagery. We have found several complications in applying these algorithms to extensive mapping of benthic coral reef habitat owing to tuning and depth limitations, and have examined an alternative algorithm.

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2. PROCESSING

The analysis uses IKONOS data to derive the bathymetry and a set of lidar bathymetry from the LADS (lidar airborne depth system). The LADS lidar was operated with a 4-m spot spacing and 200 m swath. The survey met International Hydrographic Survey standards for accuracy of order 1. Positional accuracy of the LADS was under 4 m, vertical reproducibility was 5 cm at cross-overs. Residual errors from the lidar positioning and the tide model are < 15 cm.

The IKONOS satellite was launched in September 1999 by the commercial vendor, Space Imaging. It has two sensors: one panchromatic with a 1-m nominal field-of-view, and one multispectral with a 4-m nominal field-of-view when viewing at nadir. The instrument is a pushbroom sensor that collects an 11 km swath that can be up to 1000 km long. Multiple (shorter) swaths can be collected of an area on the same orbit, since the satellite has a pointing capability. The panchromatic sensor observes light from the green to the near-infrared and provides information over bright sand to a depth of approximately 6 m. The multispectral sensor has four 70-nm bands, nominally centered at 480 nm (blue), 550 nm (green), 665 nm (red), 805 nm (near-infrared), and 11-bit digitization in each band. Instrument nominal sensitivity is about 4-fold greater than the Landsat-7 enhanced thematic mapper. The IKONOS imagery was positioned to with 15 m using standard orbital information. A subsequent survey by the National Geodetic Survey permits positioning to <4 m. The imagery was processed to water reflectance using the current calibrations provided by Space Imaging and a correction for atmosphere and surface effects based on Stumpf and Pennock (1989).

In the linear relationship, presented in Lyzenga (1978, 1985), depth, Z, is determined from

$$Z = a_i X_i + a_j X_j + Z_0 \qquad \textbf{(1)}$$

with

$$X_i = \ln\, [R(\lambda_i) - R_\infty(\lambda_i)] \qquad \textbf{(2)}$$

and R_∞ is the reflectance of appropriate optically deep water, R_w is the water reflectance at wavelength λ and a_i, a_j and Z_0 are coefficients that are a function of the optical characteristics of the water. The use of two bands of differing absorption (blue and green) provides the correction for bottom albedo. The linear method has five parameters that must be tuned: a_i, a_j , Z_0, $R_\infty(\lambda_1)$, and $R_\infty(\lambda_2)$, all of which are affected by the water clarity and backscattering. In addition, while a low bottom albedo will always limit the depth penetration, the algorithm will fail once either band can no longer resolve the difference between the water reflectance and optically deep water.

In a ratio of bands of different water absorptions, one band shows arithmetically lower values than the other. As the depth increases, the ratio of the band with lower absorption to that of higher absorption also increases. A solution for depth can be described as:

$$z' = m_1\ [\ln(n R_w(\lambda_i))/\ln(n R_w(\lambda_j)) - m_0]] \qquad \textbf{(3)}$$

$$Z = z' \ln z' \qquad \textbf{(4)}$$

where n is a constant, m_1 is a conversion coefficient, m_0 is the offset coefficient for a depth of zero meters (z =0). In contrast to the linear method the ratio method has only two tuned parameters: m_1 and m_0.

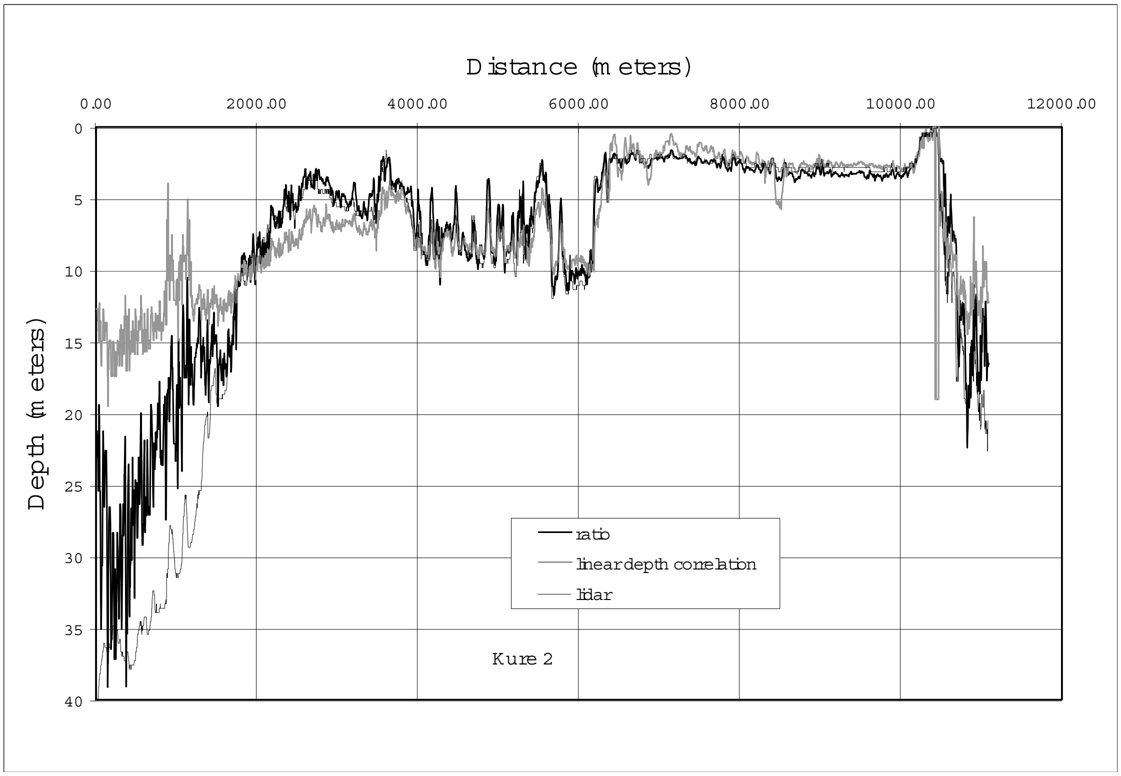

Figure 1 Profile across Kure atoll from forereef at left into the lagoon with patch reefs (2000-6000 m), sand flat from 7000-10000 m, and across the reef crest and back to forereef.

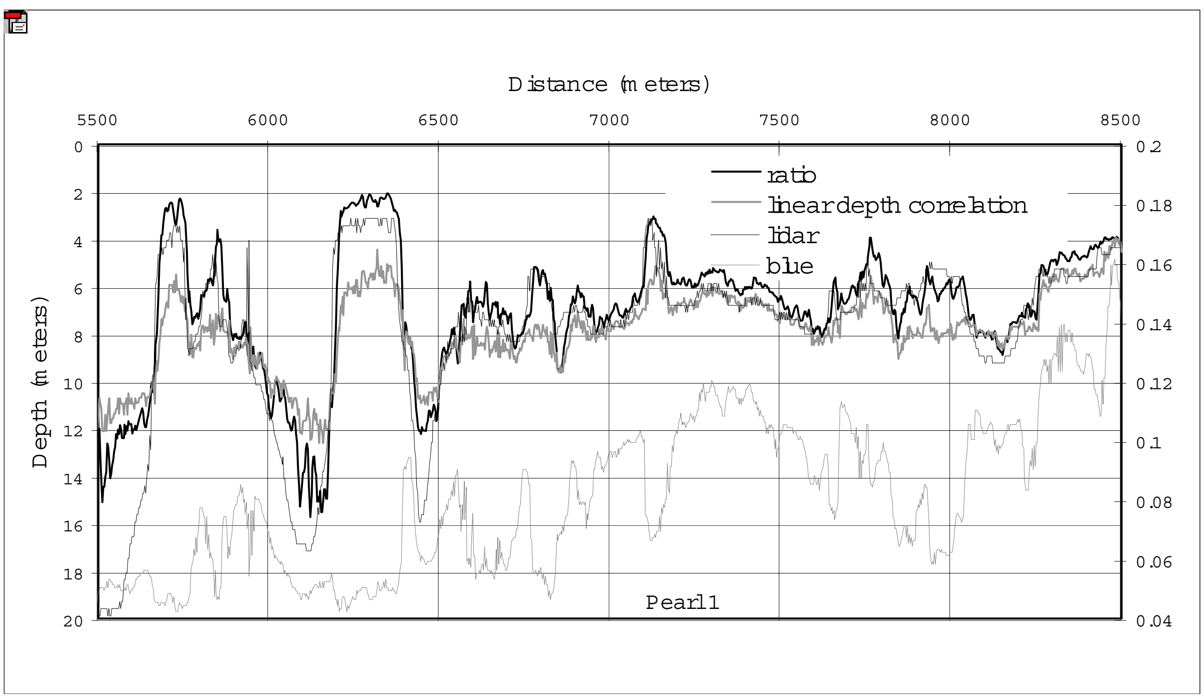

Figure 2 Profile in Pearl and Hermes. Blue water reflectance is also plotted. Kure calibration was applied here. Shallow pinnacles are covered in coral, encrusting coralline algae, and some other algaes.

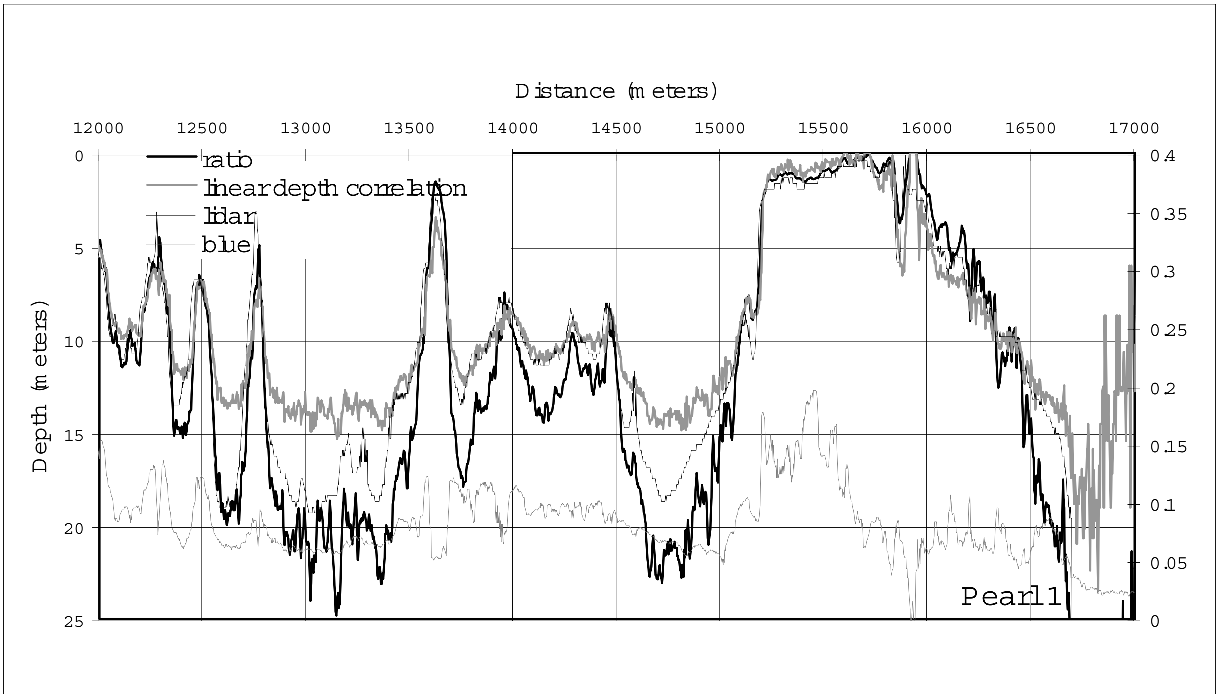

Figure 3 Second profile in Pearl and Hermes extending across reticulated reef, onto the reef crest, and down the forereef at right.

3. RESULTS

The ratio method was tuned using three depths from a nautical chart (nominally 3 m, 6 m and 15 m near the Kure 2 profile in Figure 1). For the linear method, R_∞ was fixed to the offshore value. The coefficients a_i, a_j and Z_0, were determined using multiple linear correlation against the lidar data at < 12 m for the Kure 2 profile (Figure 1). These tunings were applied to all IKONOS for Kure and Pearl and Hermes.

Example profiles appear in Figures 1, 2, and 3. The ratio method retrieves changes in depth to 25-30 m, while the linear depth does not retrieve depths > 15 m. Both show the patch reef structures between 4000-6000 m. The plots for Pearl and Hermes also show the water reflectance in the blue band. The reflectance is quite variable, even at similar water depths. The lagoon at Pearl is fairly turbid, by open ocean standards, causing both algorithms to fail there at depths much over 12 m (evident at 5500 m on the far left of Figure 2). The ratio method generally follows the actual depths well, with discrepancies more common in the linear method. The depth image for Kure can be found in Figure 4.

Systematic biases in any method are likely when water clarity changes. The ratio method, however, is stable, and easily tuned with minimal data. It is somewhat noisier, although filtering the imagery with a 3x3 or 5x5 median filter can significantly reduce this.

4. REFERENCES

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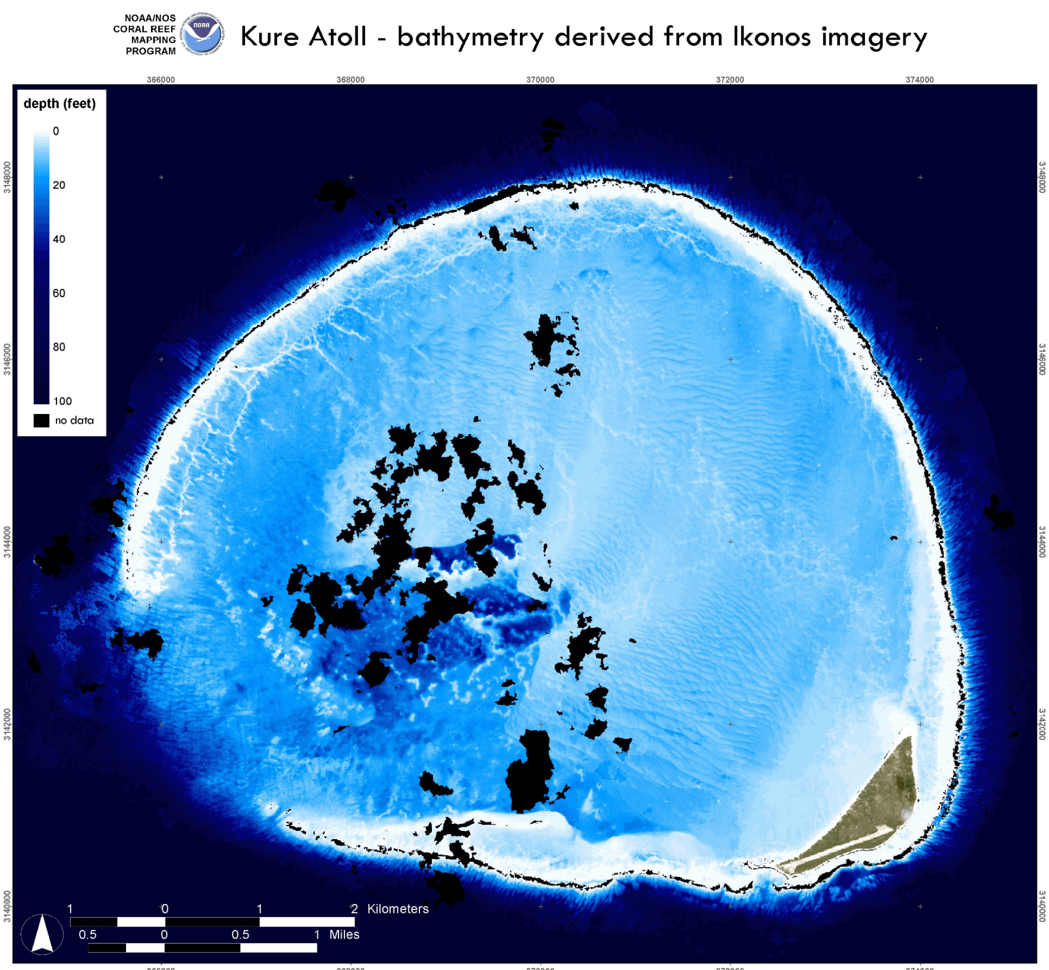

Figure 4. Bathymetry from IKONOS for Kure Atoll in northwest Hawaiian islands derived from ratio method.