ACQUISITION OF UNDERWATER REFLECTANCE MEASUREMENTS AS GROUND TRUTH

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1. INTRODUCTION

Work is being performed to establish effective quantitative methods for the mapping, monitoring and assessment of coral reef ecosystems using hyperspectral remote sensing. Specifically, imagery acquired over the Hawaiian Islands by NASA's Airborne Visible InfraRed Imaging Spectrometer (AVIRIS) is being used to develop, apply and evaluate algorithms for analyzing coral reefs using airborne hyperspectral data. The imagery was obtained during two separate AVIRIS deployments to Hawaii, one in April 2000 and another in October 2001. The coral ecosystems covered in these deployments exhibit conditions ranging from significantly human impacted reefs in the Main Hawaiian Islands to the relatively pristine coral environments of the Northwestern Islands. In addition to this significant spatial coverage, the deployments also provide temporal coverage through repeat acquisition of select study areas. Of these locations, the primary study area being used for this research is Kaneohe Bay on the windward shore of Oahu (Figure 1). This area provides many advantages as a model system for developing algorithms, including ease of accessibility for fieldwork, a wealth of supporting research literature and limited species diversity. The bay also exhibits a significant range in habitat health, from coral-dominated to algae-dominated, thereby allowing evaluations of algorithm effectiveness in identifying such differences.

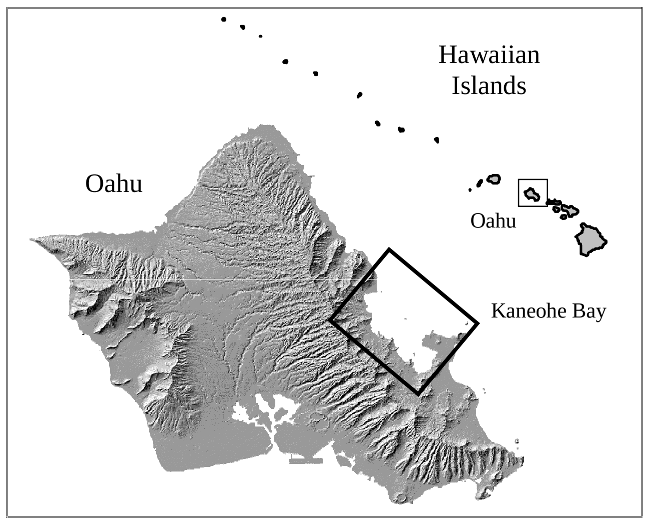

Figure 1. Kaneohe Bay, Oahu, Hawaii.

As an evolving field in remote sensing, hyperspectral analysis of benthic environments still requires many technical developments prior to reaching a comprehensive level of image classification and analysis. The confounding influences of varying water column properties and the complex mosaics of coral species create many technical challenges and physical limitations for applications of remote sensing in benthic habitats (Dustan et al., 2000; Holden and LeDrew, 1998; Lubin et al., 2001). Furthermore, there is an observed deficiency in accepted standard methods for acquiring field spectral measurements. As such, an early focus of this research project has been to examine traditional terrestrial hyperspectral techniques, particularly acquisition of field reflectance measurements, and adapt those methods for application in an underwater environment. Presented below is a description of the field instrument selected for this task, a summary of the field methods developed using a set of control experiments, and an illustration of reflectance results obtained in Kaneohe Bay for coral, algae and benthic calibration targets.

2. METHODS

As support for hyperspectral analysis, field spectroscopy plays an important role in characterizing the reflectance properties of the individual components comprising an image. The *in situ* data supplied by these field measurements provide valuable information with which to compare, calibrate, and analyze data obtained by the sensor. Field-portable spectroradiometers are commonly used in terrestrial hyperspectral analysis to measure the reflectance of target areas for use in image calibration, develop spectral libraries for image analysis, and identify suitable endmembers for use in classification algorithms (Milton, 1987; Salisbury, 1998). Similar methods are being used in the underwater environment; however, as of yet, no standard has been developed.

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2.1 Instrument

The fundamental starting point for acquiring underwater spectral measurements was to select a suitable instrument for the task. Although subsurface spectra are acquired for a variety of scientific purposes and appropriate instruments have been developed for these investigations, diver-portable spectroradiometers are less common. In the interest of cost and instrument availability, it was decided to modify a field-portable GER-1500 spectroradiometer for use in the underwater environment. Selecting this instrument, as opposed to a specifically designed underwater unit, has the advantage of maintaining the ability to use the instrument outside of its housing for acquiring measurements of terrestrial targets. While one option is to leave the instrument on the surface (typically in a small boat) and simply utilize the fiber optic cable underwater (Hochberg and Atkinson, 2000; Holden and LeDrew, 1998; Holden and LeDrew, 2001), this method has the disadvantages of a limited range and depth in which spectra can be acquired, as well as difficulties in communication between the diver and the instrument operator located on the surface. Thus, the design selection used here was to completely enclose the GER-1500 in a custom underwater housing with external controls allowing full operation of the instrument by a diver (Figure 2).

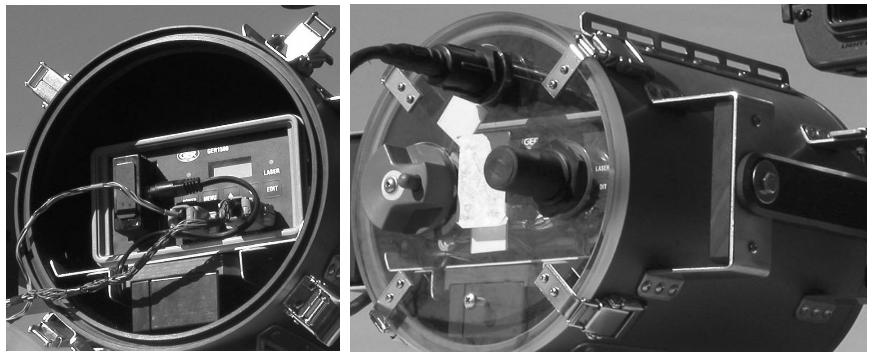

Figure 2. GER-1500 in underwater housing.

The GER-1500 is a reasonably small field instrument with the ability to function in a stand-alone mode of operation. This mode allows full access to the instrument controls, as well as an internal memory capacity for storing field data. It has a silicon diode array measuring 512 spectral bands in the region from 350 to 1050 nm with a resolution of approximately 1.5 nm. Aside from the underwater housing itself, modifications included a larger capacity battery for extended life between charging and instrument adjustments to allow operation from external controls on the underwater housing. In addition to the GER-1500, a 10 inch Spectralon® 99% diffuse reflectance panel was carried underwater with the diver for use as a reference standard.

2.2 Control Experiments

The issues involved in underwater spectroscopy have many similarities to already established terrestrial methods, but there are a few important differences. Unlike terrestrial conditions, the presence of a water column, which separates both the airborne sensor and field instrument from the features being measured, introduces significant variations in the light field that must be brought into consideration. Of most importance was the effect of wave-focusing (Figure 3), which is a function of the sea surface state and manifests itself as a rapidly fluctuating underwater light field. Surface waves also inherently exhibit differing heights and orientations, which result in changing path lengths for downwelling irradiance as well as varying illumination angles due to refraction. Thus, the presence of surface waves, which occurs on all but the rarest of windless days in the field, greatly complicates the ability to achieve uniform illumination conditions for both reference and target measurements. A set of control experiments were performed using the above described underwater field spectroradiometer to develop a field methodology to account for these illumination issues and thereby minimize errors introduced by environmental fluctuations (Goodman and Ustin, 2002). Different lighting conditions and instrument settings were used to establish the reliability of obtaining field spectra under variable situations. Experiments were performed in a controlled pool environment at the Bodega Marine Laboratory of the University of California, Davis. Results from these experiments indicated the utility of acquiring field reflectance

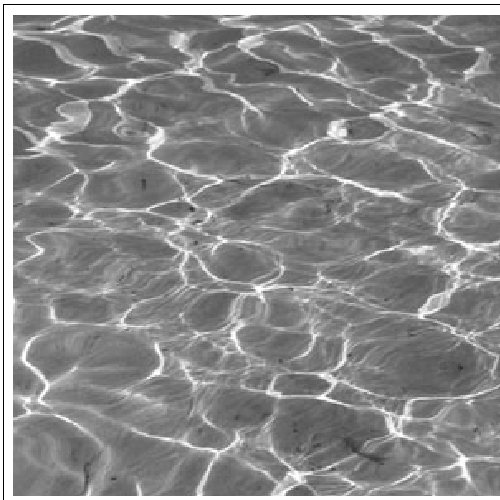

Figure 3. Wave-focusing.

measurements by creating diffuse lighting conditions (achieved by shading the target of interest) during both measurement of the reference standard and the target surface.

2.3 Field Measurements

Results obtained from the control experiments were utilized to develop a measurement protocol for acquiring underwater field reflectance data. The diver making the spectral measurements floats over the bottom target or reference panel to produce shaded conditions during data acquisition (Figure 4). For consistency, all measurements are acquired from a distance of 30 cm from the subject. Additionally, the spectroradiometer is set to average three measurements per reading and each reference reading is quickly followed by five readings of the selected target. This protocol was applied during two separate visits to Kaneohe Bay to obtain *in situ* measurements of sand, rubble, coral and algae. Supporting data obtained in the field included time of measurement, water depth, photographic record and WAAS-corrected GPS location. The first visit corresponded with the October 2001 AVIRIS deployment to Hawaii and was undertaken with the express purpose of acquiring field data coincident with the AVIRIS overflight of Kaneohe Bay. The second visit was completed in April of 2002 in order to obtain field data at the same time of year as the earlier acquired AVIRIS imagery in 2000. This data is being used to investigate potential seasonal differences in the reflectance data (e.g., physical and physiological differences in the targets and as a function of seasonal differences in illumination characteristics), as well as expand on the spatial coverage of the field data.

Figure 4. Underwater measurement.

3. RESULTS

3.1 Coral and Algae

The methods employed in the field data collection were designed to minimize errors in underwater reflectance measurements resulting from the inherent variability of lighting conditions. Thus, it can be inferred that the resulting spectral characteristics of each target can be attributed primarily to its biological and physical properties and not to products of environmental variations. Accordingly, because individual measurements were acquired from numerous locations and depths, results are presented not just in terms of averages but also with an indication of species variation (e.g., through the standard deviation). Results from the 2001 data collection in Kaneohe Bay for two species (one coral and one algae) are presented in Figure 5.

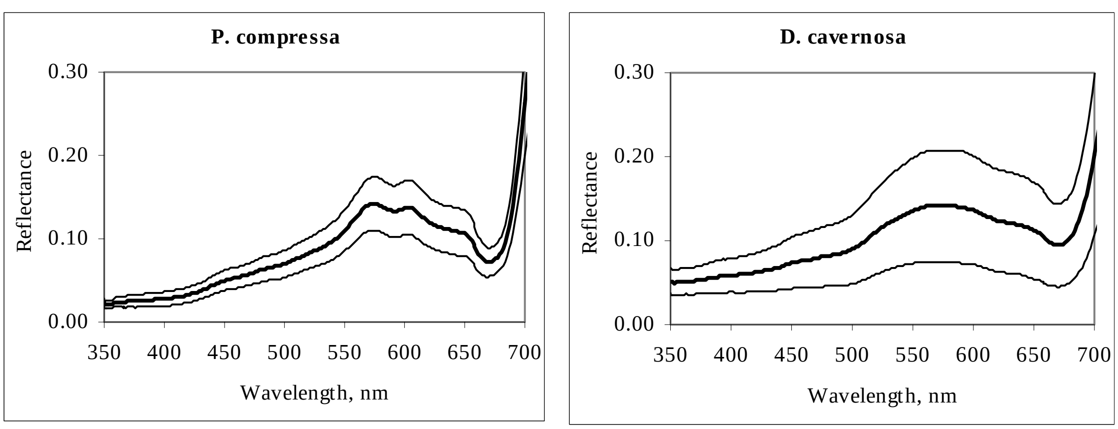

Figure 5. Reflectance of *Porites compressa* (coral, n = 51) and *Dictyosphaeria cavernosa* (algae, n = 34); average and +/- 1 standard deviation.

The reflectance characteristics observed in Figure 5 are similar to averages presented in other coral reflectance investigations. The difference here is the inclusion of the standard deviation of measured spectra for each species. This provides a valuable indication of the variation within and between each species, which aside from a few limited publications (Andrefouet et al., 2001; Hochberg and Atkinson, 2000; Holden and LeDrew, 2001) is typically not reported. Such variation is a significant factor to consider in spectral analysis, particularly for investigations focused on examining the spectral separability between and among species (and between other bottom materials such as sand, rubble and mud). Furthermore, it is important that the measure of variation is indicative of actual differences between species and not to fluctuating environmental conditions. The field protocol used here has been shown to minimize such unwanted errors in underwater reflectance measurements (Goodman and Ustin, 2002). Therefore, by using this protocol, the measured differences and similarities in reflectance characteristics indicated by this data can be confidently attributed to the actual differences in reflectance properties of each individual species.

3.2 Calibration Targets

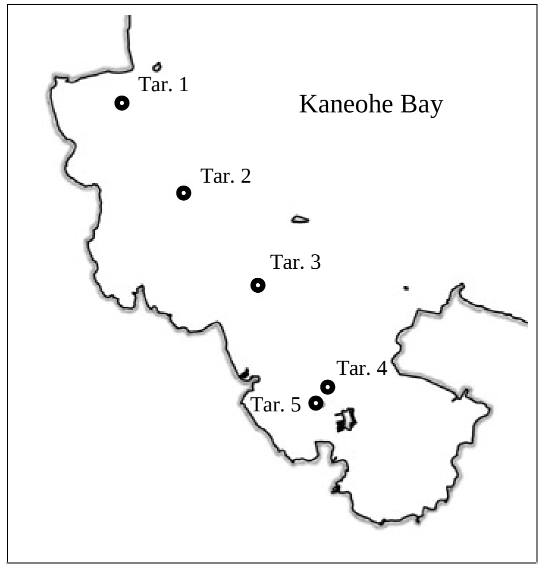

Figure 6. Calibration targets.

In addition to obtaining measurements of individual coral and algae species, reflectance characteristics of five natural calibration targets were also acquired during the two field visits. These targets are similar to terrestrial calibration areas whose spectral information is used to assist in calibrating hyperspectral imagery to reflectance. For image analysis of coral reef and other shallow benthic habitats, the calibration procedure necessitates both atmospheric and water column corrections. Accordingly, underwater calibration targets needed to be identified and measured for use in calibrating images. The targets selected for Kaneohe Bay (Figure 6) are distributed at different locations and at different water depths throughout the study area. Each individual target consists of a large homogeneous sand area of uniform depth and was characterized by collecting a random sampling of 40 to 60 individual reflectance measurements. Results for two of the areas acquired in 2001 are presented in Figure 7. It is apparent that these areas exhibit a much greater variation in reflectance than the individual coral and algae species. Also evident in these graphs (and for all the target areas measured within Kaneohe Bay) is the characteristic chlorophyll-a absorption feature around 680 nm. This feature has been reported in other investigations and results from the presence of benthic microalgae within the sand, which can contribute significantly to overall primary productivity (Roelfsema et al., 2002). As with the coral and algae measurements, the field method used in this research produces an indication of the natural differences between targets. Among other functionality, this allows the target measurements to more confidently serve as ground truth for use in evaluating the effectiveness of water column correction algorithms.

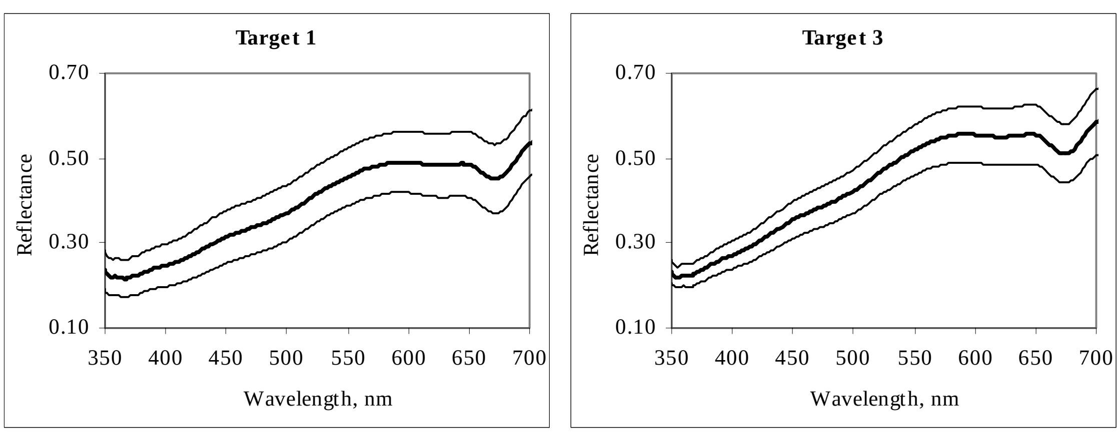

Figure 7. Reflectance of targets 1 (n = 50) and 3 (n = 45); average and +/- 1 standard deviation.

4. CONCLUSION

The physical limitations and technical difficulties associated with the water column present a challenging environment for remote sensing investigations. The energy interactions occurring at the air-water interface and within the water column alter many of the basic assumptions used in traditional terrestrial investigations. This is particularly evident when making *in situ* underwater reflectance measurements. Surface waves produce wave-focusing, changing wave height and varying refraction geometries. Absorption and scattering properties are also affected by varying constituents within the water column. Together, these factors result in highly variable underwater illumination conditions, both spatially and temporally. Control experiments were employed to address these issues and produce a field methodology that minimizes errors associated with environmental fluctuations. The methodology was then used to acquire reflectance measurements of coral, algae and sand within Kaneohe Bay. Data acquired from these field investigations is an important component of the ongoing research to develop hyperspectral image analysis techniques for coral reefs. Specifically, this includes utilizing the natural underwater calibration targets for empirical image calibration, applying a semi-analytical model for water column correction, developing algorithms for benthic habitat mapping, identifying large-scale coral community composition and examining causal relationships associated with environmental stress and global change.

5. ACKNOWLEDGEMENTS

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6. REFERENCES

Andrefouet, S, F.E. Muller-Karger, E.J. Hochberg, C. Hu and K.L. Carder, 2001, "Change Detection in Shallow Coral Reef Environments Using Landsat 7 ETM+ Data," Remote Sensing of Environment, vol. 79, pp. 1-13.

Dustan, P., S. Chakrabarti and A. Alling, 2000, "Mapping and Monitoring the Health and Vitality of Coral Reefs From Satellite: A Biospheric Approach," Life Support & Biosphere Science, vol. 7, pp. 149-159.

Goodman, J. and S. Ustin, 2002, "Underwater Spectroscopy: Methods and Applications in a Coral Reef Environment," 7th International Conference on Remote Sensing for Marine and Coastal Environments, Miami, Florida, May 19 – 22.

Hochberg, E.J. and M.J. Atkinson, 2000, "Spectral Discrimination of Coral Reef Benthic Communities," Coral Reefs, vol. 19, pp. 164-171.

Holden, H. and E. LeDrew, 1998, "Spectral Discrimination of Healthy and Non-Healthy Corals Based on Cluster Analysis, Principal Components Analysis, and Derivative Spectroscopy," Remote Sensing of the Environment, vol. 65, pp. 217-224.

Holden, H. and E. LeDrew, 2001, "Hyperspectral Discrimination of Healthy Versus Stressed Corals Using In Situ Reflectance," Journal of Coastal Research, vol. 17, no. 4, pp. 850-858.

Lubin, D., W. Li, P. Dustan, C.H. Mazel and K. Stamnes, 2001, "Spectral Signatures of Coral Reefs Features From Space," Remote Sensing of Environment, vol. 75, no. 1, pp. 127-137.

Milton, E.J., 1987, "Principles of Field Spectroscopy," International Journal of Remote Sensing, vol. 8, no. 12, pp. 1807-1827.

Roelfsema, C.M., S.R. Phinn and W.C. Dennison, 2002, "Spatial Distribution of Benthic Microalgae on Coral Reefs Determined by Remote Sensing," Coral Reefs, vol. 21, pp. 264-274.

Salisbury, J.W., 1998, "Spectral Measurements Field Guide," Defense Technology Information Center, Report No. ADA362372.