NASA Airborne AVIRIS and DCS Remote Sensing of Coral Reefs

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Abstract – To adequately image through a water column and to delineate variation in coral reef ecosystem benthic types, sensors having high spatial, e.g., a Cirrus digital camera system (DCS), and spectral, e.g., the Airborne Visible Infrared Imaging Spectrometer (AVIRIS), resolution and high signal to noise are needed. Further, there is a need to better understand the optical properties of coral reefs, seagrass, other benthic types, and water column constituents from field-collected data so current and future remote sensing can be optimized for coastal zone ecosystem research and management. In August 2004, we flew the AVIRIS and DCS on a NASA ER-2 over the Florida Keys and Puerto Rico. In March 2005, we flew AVIRIS/DCS on the Twin Otter over Kaneohe Bay, Oahu. Also, in December 2005, we flew AVIRIS/DCS on the Twin Otter over Puerto Rico and the US Virgin Islands for assessment of the 2005 Caribbean coral reef bleaching event. For each of these deployments, we collected coincident spectral data from dominant bottom types and coral under various health conditions using a hand-held spectroradiometer. These spectral data will be used to classify the benthic types within the AVIRIS imagery. An overview of the airborne missions and coincident field data collection will be presented along with preliminary image and field-collected spectral data products.

Keywords: coral reefs, hyperspectral, AVIRIS, airborne remote sensing.

1. INTRODUCTION

The photosynthetic pigments of coral's symbiotic algae (zooxanthellae) and the general establishment of corals in shallow well-lit waters enables the detection of spectral information from coral through a clear shallow water column with a remote sensing instrument. Corals display distinct reflectance peaks between 550 and 650nm related to the densities of chlorophyll-*a* and accessory pigments in their tissue (Holdren and LeDrew, 1998; Myers et al., 1999; Hochberg and Atkinson, 2000; Hochberg et al., 2003). Research has shown that spectral distinction of reef bottom types (i.e., coral, algae, and carbonate sand) is possible using field spectroscopy (Clark et al, 2000; Hochberg and Atkinson, 2000; Andrefouet et al., 2001; Lubin et al., 2001; Hochberg et al., 2003; Wettle et al., 2003). Of further interest is the identification of spectral features indicative of degradation in reefs which could lead to better ecological assessment (e.g., biodiversity) and forecasting (Call et al., 2003; Hochberg et al., 2003).

Because only the visible range of the electromagnetic spectrum can penetrate deep enough into the water column to reach shallow-water benthic types, there is a unique requirement for not only high spatial- but high spectral-resolution remote sensing data to adequately discriminate benthic types, variations due to disturbance, and changes in reef ecosystems in an optically complex environment. Recently, remote imaging of coral reef communities has evolved from purely multispectral (i.e., Landsat) with improvements in mapping these communities using Ikonos with higher spatial resolution (Mumby and Edwards, 2002; Purkis, 2005) to include hyperspectral (e.g., AVIRIS) techniques. Hyperspectral sensors provide a greater range of fidelity when discriminating between similar bottom types, because the narrow bands can reveal small absorption features that are not resolved in broader multispectral bands (Holden and LeDrew, 1999; Zimmerman and Wittlinger 2000; Butler and Hopkins 1970). In deeper waters, the high number of bands becomes even more important as the total absorption in red wavelengths (>600 nm) at depth leaves only blue and green wavelengths (400-600 nm) with which to differentiate corals and other substrates (Green et al., 2000; Holden and LeDrew, 2002). We are leveraging the capabilities of NASA's airborne hyperspectral remote sensor, AVIRIS, to provide a more comprehensive assessment and mapping of shallow coastal resources.

The objectives of the AVIRIS missions included determination of 1) distribution patterns of live coral cover, *Palythoa* (colonial zooanthid), algae, and seagrass beds (Florida Keys and Puerto Rico); 2) evidence of herbivory on corals in sites protected by no fishing zones; 3) variability of the bio-optical properties in Mayaguez Bay (west coast of Puerto Rico); 4) AVIRIS' ability to spectrally discriminate the wide range of reef communities and biodiversity; 5) reef status in terms of the extent of bleached corals and coral mortality.

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2. METHODOLOGY

A number of steps are required to complete the end-to-end processing of the AVIRIS hyperspectral, field spectroradiometer, and other ancillary data to generate the expected output data products. The analysis started with preprocessing, which included halo suppression, atmospheric correction and sun glint removal, and then utilizes a semi-analytical optimization model to retrieve bathymetry and water properties throughout the study area. Using field spectra data representing the dominant benthic components (e.g., spectral endmembers for sand, coral, algae, and seagrass), a constrained non-linear unmixing model will be utilized to classify the benthic substrate as a function of the fractional contribution from each endmember. The final step will be to utilize field observations to assess the accuracy of the resulting image products.

2.1 AVIRIS and DCS

AVIRIS has 224 contiguous spectral channels with wavelengths from 380 to 2500 nm and a 10-nm nominal bandwidth. AVIRIS uses a scanning mirror and performs “whisk broom” scanning. AVIRIS has a high signal to noise ratio and has 32 channels in the visible wavelength range (400-700 nm), of use in shallow water environments. The signal to noise ratio varies by wavelength from about 1000 in the visible region to about 500 in the infrared region and much reduced signal to noise in atmospheric absorption wells (e.g., water vapor).

The Cirrus DCS is a high resolution, medium format, color-infrared digital camera. The camera uses a Zeiss lens and provides 16-megapixel resolution. The camera can operate in visible (natural color) or color infrared mode. Visible mode was used for our deployments.

2.2 2004 Florida Keys and Puerto Rico AVIRIS and Cirrus DCS Mission

The NASA ER-2 was flown on August 17, 2004, over the upper Florida Keys between Plantation and Key Biscayne at 45,000 ft for 13-m AVIRIS and 3-m DCS pixel spatial resolution.

On August 19, 2004, AVIRIS and DCS were flown along the majority of coastal Puerto Rico, including Vieques Island. The altitude of the NASA ER-2 was approximately 20 km, resulting in 17-m AVIRIS pixel resolution and 7-m DCS pixel resolution.

2.3 2005 Hawaii AVIRIS and Cirrus DCS Mission

On March 1, 2005, AVIRIS was flown on the Twin Otter over Kaneohe Bay on the windward (East) coast of Oahu, Hawaii. AVIRIS and the DCS had 4 m and approximately 0.5 m pixel resolutions, respectively for this mission.

2.4 2005 Caribbean AVIRIS and Cirrus DCS Mission

In mid-December 2005, in response to the most devastating regional-scale coral bleaching events on record in the Caribbean, AVIRIS/DCS was flown over sites in Puerto Rico and the USVI to investigate the status of coral bleaching. AVIRIS and DCS was flown onboard the NASA Twin Otter platform at an altitude of ~3.5 km for sensor spatial resolutions of 3.5 m and 0.7 m, respectively.

2.5 *In Situ* Measurements

Underwater field sampling was conducted for the deployments for spectral library generation and to support the classification of the AVIRIS imagery based on benthic type. Surface reflectance measurements were also collected for validation of the AVIRIS atmospheric correction. A summary of the measurements are as follows: remote sensing reflectance (r_{rs}) of corals and other benthic communities, spectral water attenuation coefficients (K_d), chlorophyll, turbidity, surface reflectance (R_{rs}), flat field reflectance (R_{rs}) for calibration, and sunphotometer measurements of aerosol optical thickness (AOT) for atmospheric correction.

For water column characterization, water column light attenuation coefficients (K_d) were calculated from spectra of a spectralon panel at three depths using the GER 1500 (Spectra Vista Corporation). These spectra were collected during the AVIRIS overflights at the various patch reefs in the study area.

Spectra from flat panel bright and dark validation targets approximately 10m x 10m were also measured with the GER 1500 during the overflights. Aerosol optical depths were measured using two Microtops sunphotometers (Solar Light Co., Inc.) with calibrated filters for aerosols and ozone operated onboard boats at the various patch reefs during the overflights.

Spectral libraries of benthic types were collected to relate to the AVIRIS data for classifying benthic maps. Spectral measurements of dominant benthic types (including ecological variations) along 10-m transects were collected at reef sites for input into classification algorithms for delineation of benthic types and evaluation of variability within benthic types. The linear transects were positioned to sample an extent of a reef patch that was mostly continuous that would dominate even a 17-m AVIRIS pixel. Spectroradiometer (GER 1500 in underwater housing) measurements were taken at 1-m intervals on both sides of the metric tape along the 10-m transect. GPS positions were recorded at the transect endpoints. Further, additional spectral library measurements and GPS positions of other dominant bottom types were taken randomly around the transect tape to use in image classification. The perimeters of several large coral stands were also recorded as polygons of GPS points. Pictures were taken of each location of the GER spectra readings.

For the 2005 Hawaii mission, a University of Hawaii team conducted the field optical measurements concurrent to the AVIRIS overflights using two instrument packages. The first instrument was a diver-operated portable fiber optic spectrometer (Ocean Optics USB2000 in an underwater housing). Using this spectrometer, they measured spectral reflectance at the sea surface and sea floor. Measured over different albedos (i.e., bright and dark seafloor *plus* water column), sea surface reflectance can be used for empirical atmospheric radiative transfer effect corrections, effectively calibrating the AVIRIS imagery to Earth-surface reflectance. Seafloor reflectance measurements will be used to test the efficacy of water column radiative transfer corrections. The second instrument package consisted of a WETLabs ac-s (spectral beam absorption and attenuation meter) and a WETLabs ECO-VSF-3 (three angle, three wavelength backscattering sensor). This package was deployed concurrently with the AVIRIS overflight, thus measuring water column inherent optical properties occurring at the time of image acquisition. Given these data, coupled with water depth derived from SHOALS Lidar data (acquired 2000), we intend to remove water column radiative transfer effects from the AVIRIS imagery, thus generating an image of seafloor spectral reflectance. The Kaneohe Bay image will be classified using a library of ~30,000 reflectance spectra measured *in situ* on reefs throughout the world.

2.6 AVIRIS Data Processing

We will employ new approaches for hyperspectral data analyses for studies of coral reef biology and optical properties and inherent spectral heterogeneity of cover types associated with spectral dimensionality within pixels (Goodman, 2004; Goodman and Ustin, 2003; Roberts et al., 1998). *In situ* spectral libraries, collected specifically for sites, will be used in spectral mixture analysis algorithms for benthic classification and assessment of biodiversity and change in reef study sites in general.

Raw AVIRIS data are being processed utilizing a sequence of image processing steps to resolve the complex interaction of atmospheric conditions, bathymetry, sea surface state, water optical properties and bottom composition. For the purposes of this paper we will discuss our preprocessing techniques to date that include halo suppression, atmospheric correction and sun glint removal.

2.7 Image Preprocessing: Halo Suppression, Atmospheric Correction, and Sun Glint Removal

The preprocessing of the imagery involves three phases. The first step is suppression of the near-infrared halo around the central stripe contained in low-light AVIRIS 2004 and 2005 flight season imagery. This halo was caused by stray-light leakage following an upgrade to the instrument prior to the 2004 flight season and is suppressed by calculating the difference between the central stripe of "good" data and the halo pixel values, then reducing halo values based on this difference and the halo's cross-track profile.

The second step is atmospheric correction, performed using Tafkaa, an algorithm for atmospheric correction of imaging spectrometry data under development at the Naval Research Laboratory designed to address the confounding variables associated with shallow aquatic applications (Gao et al., 2000; Montes et al., 2003; Montes et al., 2001). The Tafkaa algorithm includes atmospheric gaseous absorption and aerosol corrections as well as pixel location-specific solar and viewing geometry to retrieve per-pixel water-leaving reflectances.

A spectral normalizing procedure based on Hedley et al.'s (2005) variation of Hochberg et al.'s (2003) method was then used to reduce the effects of sun glint (i.e., specular reflection from the water surface). In this method the slope of the regression line between pixel values from a NIR band (750nm) and each of the visible bands is computed over a sample containing sun glint. This slope is then used to reduce the values in each visible band, relative to the difference between the NIR-band minimum value within the training area and the location-specific NIR value.

3. RESULTS

An example of the halo suppression results for a St Croix (flight line f051216r03) can be seen in Figure 1. In this processing the central stripe data were not modified, the surrounding values were reduced to match the stripe. This flight line also included a calibration tarp at Buck Island from which atmospherically corrected reflectances could be extracted and compared to field data (Figure 2). The GER and AVIRIS measurements agreed well for the dark tarp, but the AVIRIS reflectances were somewhat high for the beach sand.

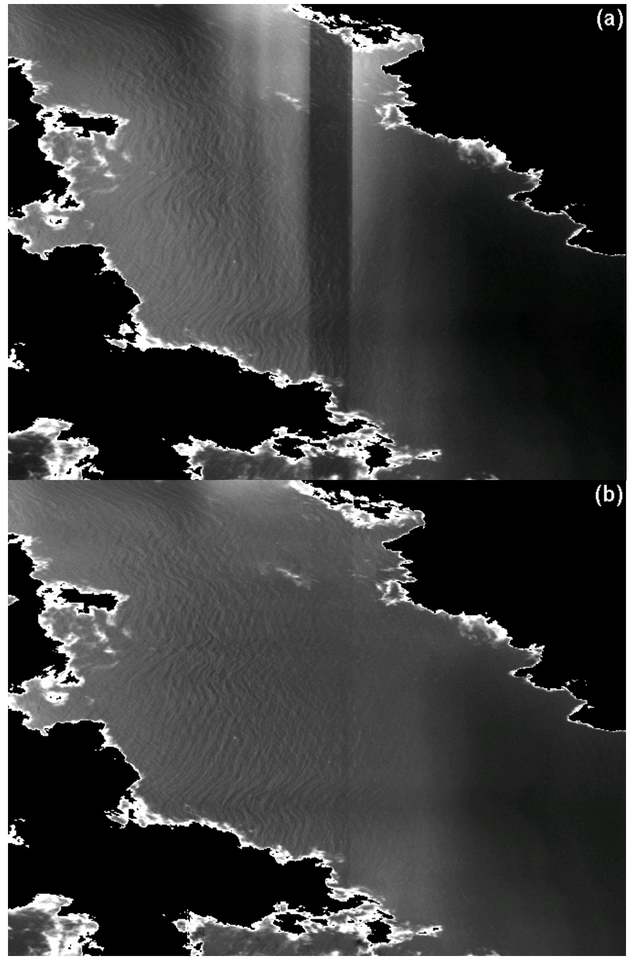

Figure 1. Subset of flight line f051216r03: a) original image showing central dark stripe of "good" data and b) halo suppression result. Black areas are clouds or land areas that have been masked out.

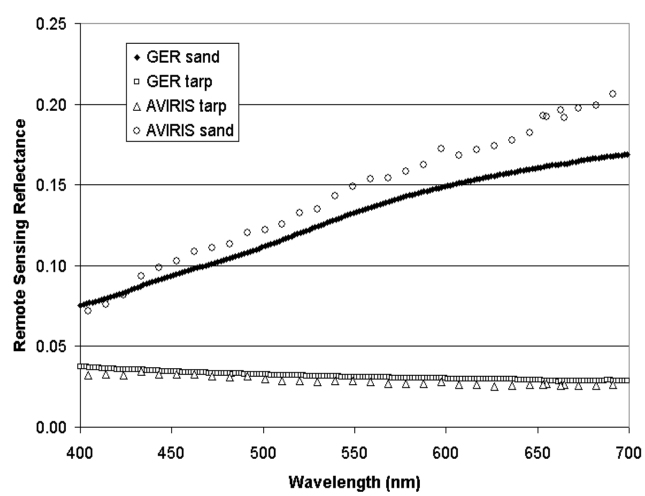

Figure 2. Field-measured and atmospherically corrected AVIRIS reflectances.

4. DISCUSSION

To date, significant progress has been made in processing the AVIRIS imagery. Further refinements to the preprocessing may lead to improvements in the validation of the atmospherically corrected data against the field data. Additional processing of these data is necessary before spectral endmembers can be determined and the imagery can be classified into benthic substrates. The next step is to use a semi-analytical inversion model to retrieve estimates of bathymetry and water properties from measured surface remote sensing reflectance to correct for water column effects. We will then proceed with defining spectral endmembers and perform the benthic classification using unmixing techniques.

5. CONCLUSIONS

A rich data set from the 2004 and 2005 AVIRIS airborne and field deployments provide a unique opportunity to advance studies in changes in coral reef ecological structure and biodiversity. The magnitude of field studies ongoing in our study sites, as well as data collected specifically to support the airborne deployments, provide a strong baseline of information for thorough analysis of the reef ecology and biodiversity in these regions. The lessons learned in terms of the investigation into which spatial resolutions are most appropriate for sensing coral reef benthic communities will provide specification requirements for future hyperspectral sensors onboard conventional aircraft, unmanned aircraft systems (UASs), and spaceborne platforms.

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