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NASA airborne AVIRIS and DCS remote sensing of coral reefs

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Abstract. To adequately image through a water column and delineate variation in coral reef ecosystem benthic cover types, sensors having high spatial resolution, high spectral 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 cover 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 Airborne Visible Infrared Imaging Spectrometer (AVIRIS) and Cirrus digital camera system (DCS) on a NASA ER-2 over Puerto Rico. Also, in December 2005, we flew AVIRIS on a Twin Otter over priority sites for Puerto Rico 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 are being used to classify different benthic cover types present within the AVIRIS imagery. An overview of the airborne missions and coincident field data collection for calibration and validation of the airborne remote sensing data are presented along with preliminary image and field-collected spectral data products.

Key words: Coral reefs, hyperspectral, AVIRIS, airborne remote sensing.

Introduction

The photosynthetic pigments in the symbiotic algae (zooxanthellae) of corals and the general establishment of corals in shallow well-lit waters enables the detection of spectral information from corals through a clear shallow water column with a remote sensing instrument. Corals display distinct reflectance features between 550 and 650 nm 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., relative health and 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 cover types, there is a unique requirement for not only high spatial- but high spectral-resolution remote sensing data to adequately discriminate benthic cover types, variations due to disturbance, and changes in reef ecosystems in an optically complex environment. Recently, remote sensing of coral reef communities has evolved from purely multispectral (e.g., Landsat) to improved mapping using higher spatial resolution multispectral (e.g., Ikonos) (Mumby and Edwards 2002; Purkis, 2005) to advanced hyperspectral (e.g., AVIRIS) techniques (Goodman and Ustin 2007).

Hyperspectral sensors provide a greater range of fidelity when discriminating between bottom types, because details of spectral shape and pattern are better revealed using numerous narrow bands rather than fewer broad multispectral bands (Holden and LeDrew 1999; Zimmerman and Wittlinger 2000; Butler and Hopkins 1970). As the water depth increases, light in longer wavelengths (>600 nm) is attenuated more readily than in green to blue wavelengths (shorter wavelengths), leaving 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 high number of channels and narrow bandwidths of NASA's airborne hyperspectral remote sensor, AVIRIS, to provide a more comprehensive assessment and mapping of shallow coastal resources (Guild et al. 2007).

The objectives of the coincident AVIRIS and field data collection missions included 1) mapping coral reef benthic type and degradation and 2) interpretation of reef biodiversity and variability.

Materials and Methods

Study Site. Our field site is the La Parguera shelf, southwestern Puerto Rico (17º 57' N, 67º 02' W: Fig. 1). La Parguera has numerous bank reefs that protect the shore from intense wave action, resulting in extensive seagrass meadows and a coastline dominated by mangroves with algal plains, sandy lagoons and two bioluminescent bays. This area has minimal input of suspended sediments or dissolved organic matter from land sources due to low precipitation and absence of riverine input. Annual precipitation ranges from 500 to 1,200 mm with a dry period from December through April.

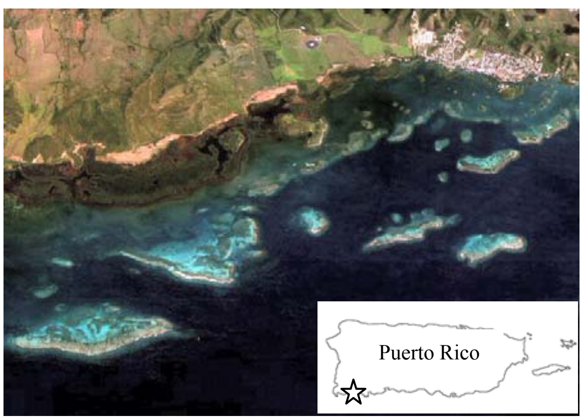

Figure 1: The study site, designated by a star, is La Parguera in Southwestern Puerto Rico. This AVIRIS image was acquired during the 2004 AVIRIS mission. This RGB composite image displays channels 31, 21, and 10 at wavelengths of 655, 559, and 453 nm, respectively.

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

In mid-December 2005, in response to the most devastating regional-scale coral bleaching event on record in the Caribbean (Wilkinson and Souter 2008), AVIRIS/DCS was again flown over sites in Puerto Rico, as well as the US Virgin Islands, to investigate areas of coral bleaching. AVIRIS and DCS were flown onboard the NASA Twin Otter platform at an altitude of approximately 3.5 km for sensor spatial resolutions of 3.5 m and 0.7 m, respectively. Further, an additional DCS camera was flown on a low-altitude aircraft the week following the AVIRIS mission in Puerto Rico acquiring 15 and 30 cm spatial resolution data at 1 and 2 km altitudes, respectively.

AVIRIS has 224 contiguous spectral channels with wavelengths from 380 to 2500 nm and a 10 nm nominal bandwidth. AVIRIS has a high signal-to-noise ratio and has 32 channels in the visible wavelength range (400-700 nm), which are valuable for 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 also exhibits reduced signal-to-noise in atmospheric absorption wells (e.g., water vapor) in bands located at or very close to wavelengths where atmospheric absorption appears (e.g., reduced reflectance in AVIRIS bands 62-64 corresponding to 929.0, 945.1, and 954.5 nm due to water vapor absorption around 945 nm).

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 (e.g., red, green, blue channels only) was used for our deployments.

In Situ Measurements. Underwater field sampling of four patch reefs across La Parguera shelf and surface measurements were conducted during both airborne deployments to support the classification of AVIRIS imagery based on benthic type, and for validation of AVIRIS atmospheric and sunglint correction schemes. A summary of the measurements are as follows: *in situ* reflectance (R) of corals and other benthic communities, spectral water attenuation coefficients (K_d), chlorophyll, turbidity, surface remote sensing reflectance (R_{rs}) for calibration, and sunphotometer measurements of aerosol optical thickness (AOT) for atmospheric correction.

For water column characterization and correction of reflectance data, we use Hydrolight (Sequoia Scientific) radiative transfer algorithms. Water column light attenuation coefficients (K_d) were calculated from the average of three to five spectra of a spectralon panel at three depths using a GER 1500 (Spectra Vista Corp.) handheld spectroradiometer in an underwater housing. These K_d estimates serve as an independent verification of the range of appropriate K_d values used for Hydrolight. Only two depths are necessary for the calculation, but extra K_ds were collected to avoid sensor saturated data from wave focused light effects on the spectralon.

Spectra from bright and dark validation targets (10 m x 10 m) were measured with the GER 1500 during the 2005 overflights. Aerosol optical depths (AOT) were measured using two Microtops sunphotometers (Solar Light Co., Inc.) with calibrated filters for aerosols and ozone, both operated onboard boats at the patch reef study sites during the 2004 and 2005 overflights. These AOT estimates provide independent estimates for evaluating the range of appropriate AOT values used for the atmospheric correction algorithm (Lobitz et al. 2009; these proceedings).

Figure 2: Spectral measurements collected of elkhorn coral (*Acropora palmata*) using the GER 1500 spectroradiometer in underwater housing.

Spectral measurements of dominant benthic cover types (including ecological variation) along 10 m transects were collected at each reef site for calculation of reflectance of benthic types and for spectral library input into classification algorithms for delineation of benthic cover types and for evaluation of variability within and between benthic cover types. The distribution of these transects were randomly placed and stratified to represent example coral stands in forereef, reef crest, and back reef areas. The linear transects were positioned to sample an extent of a reef patch that was mostly homogeneous and would dominate even a 17 m AVIRIS pixel. Three to five spectra were taken each for the spectralon and benthic type (Fig. 2) at 1 m intervals on both sides of the metric tape along each 10 m transect. GPS positions were recorded at the transect endpoints and dGPS positions were established at a later date. Further, additional spectral library measurements and GPS positions of other dominant bottom types were taken around the transect tape to use in image classification. A photo record was taken of each GER spectral reading. The perimeters of several large coral stands were also recorded as polygons of GPS points to train/validate benthic classification.

Image Processing. We are employing new approaches for hyperspectral data analysis to study coral reef biology and optical properties and to evaluate the inherent spectral heterogeneity of cover types within pixels (Goodman 2004; Goodman and Ustin 2007; Roberts et al. 1998). *In situ* spectral libraries, collected specifically from sites in the study area, are being used in spectral mixture analysis algorithms for subpixel benthic classification and the assessment of changes in reef composition, particularly biodiversity.

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 (Fig. 3).

The analysis starts with three phases of image preprocessing, which includes stray light suppression, atmospheric correction and sun glint removal, and then image processing 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, and algae), a constrained non-linear unmixing model is utilized to classify the benthic substrate as a function of the fractional contribution from each endmember. The final step utilizes field observations to assess the accuracy of the resulting image products.

Preprocessing. The first step of the image preprocessing is suppression of the near-infrared glow (i.e., anomalously large values) in low-light AVIRIS 2004 and 2005 imagery. This glow was caused by stray-light leakage following an upgrade to the instrument prior to the 2004 flight season. It is suppressed by calculating a correction based on the glow's cross track profile and the difference between the central stripe of "good" data and the adjacent incorrect pixel values that include the contribution from the stray-light. Details of the stray light suppression can be found in Lobitz et al. (2009; these proceedings).

The second preprocessing 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 surface reflectance. Details of the atmospheric correction methods can be found in Lobitz et al. (2009; these proceedings).

The third preprocessing step, a spectral normalizing procedure based on Hedley et al.'s (2005) variation of Hochberg et al.'s (2003) method was 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 (750 nm) and each of the visible bands is

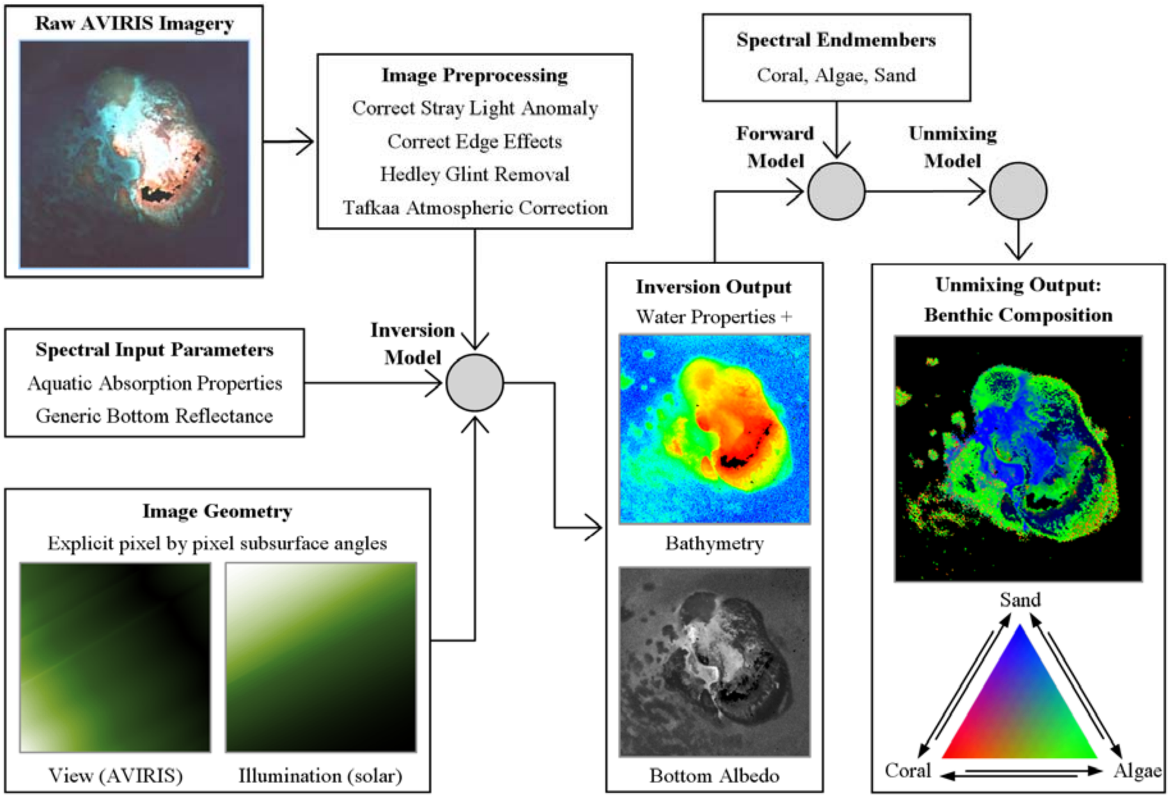

Figure 3: Overview of AVIRIS processing steps. On the left side are the inversion model processing inputs (corrected AVIRIS, spectral input parameters, and image geometry) and outputs (water properties, bathymetry, and bottom albedo) using a subset of the AVIRIS data for San Cristobal patch reef. On the right side are the forward model inputs (spectral endmembers, inversion output, spectral input parameters, and image geometry), integrated with the preprocessed AVIRIS imagery in the unmixing model to produce the benthic composition (sand, coral, and algae)

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-band value.

Inversion Model and Unmixing. Following image preprocessing corrections, a semi-analytical inversion model is used to retrieve estimates of bathymetry and water properties from measured surface remote sensing reflectance to correct for water column effects in the imagery (Fig. 3). Aquatic absorption properties are a combination of absorption properties of pure water and empirical spectra derived from field data and Hydrolight runs (Lee et al. 1998; 1999). The generic bottom reflectance used in the model is an average sand spectrum from the study area. Image geometry data indicate calculated variations in view and illumination angles within the AVIRIS image (Fig. 3). The Inversion Model is applied to derive water properties, bathymetry, and bottom albedo.

We then proceeded with defining spectral endmembers from measured field data and performed the benthic classification using unmixing techniques (Fig. 3) (Goodman and Ustin 2007; Goodman 2004).

Generic spectral endmembers of coral, sand, and algae (including a shade endmember) are used together with the inversion model outputs (water properties, bathymetry, bottom albedo) as well as the spectral input parameters and image geometry in the Forward Model. The next step is to take this information and run the Unmixing Model on the AVIRIS data to output a benthic composition image of coral, sand, and algae.

Results

The output benthic composition shows a predominance of algae and sand. The prevalence of algae in the reef areas is reasonable due to the pervasiveness of reef stands of rubble overgrown with algae. Since we have not delineated spectra for seagrass, seagrass in the back reef zone is classified as algae. We are currently evaluating the preliminary benthic composition image product and rerunning the unmixing model with additional spectral endmembers (including seagrass) to evaluate variation in the benthic composition output image (Fig. 3). The next step is to utilize field observations and DCS imagery to assess the accuracy of the resulting image products.

Discussion

Our research strategy includes refining the classification and evaluating our spectral transects with multiple endmember spectral unmixing as an additional approach to benthic classification.

A rich data set from the 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 about 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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