HYPERSPECTRAL IMAGE ANALYSIS OF CORAL REEFS IN THE HAWAIIAN ISLANDS

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1. INTRODUCTION

Concern over the health of coral reef communities has greatly intensified in recent years, particularly with regard to the complex dynamics of global change. The synoptic spatial and temporal monitoring capabilities of remote sensing provide a valuable avenue for evaluating the impacts of local, regional and global change on this important natural resource. Hyperspectral imagery acquired over the Hawaiian Islands in the spring of 2000 by NASA's Airborne Visible InfraRed Imaging Spectrometer (AVIRIS) will be used to develop, apply and evaluate algorithms for analyzing coral reefs using remote sensing data. In order to truly leverage the synoptic capabilities of remote sensing, algorithms developed in this research will be based on fundamental scientific principals that will allow methods to be used in diverse geographic locations. Primary algorithm development will be conducted in Kaneohe Bay, Oahu due to the extensive supporting resources available for evaluating algorithm accuracy. Subsequent to the Kaneohe Bay phase of the research, the resulting analysis tools will be applied to portions of the recently established Northwestern Hawaiian Islands Coral Reef Ecosystem Reserve. Work for this project is being conducted at the Center for Spatial Technologies and Remote Sensing at the University of California, Davis in collaboration with the Hawaii Institute of Marine Biology at the University of Hawaii.

An essential element of any program to preserve, protect and manage coral reefs is to identify a reliable means for quantitatively mapping and assessing the dynamics of community distribution, identifying stressor-response relationships, incorporating multiple levels of spatial analysis and efficiently monitoring the current and future health of the ecosystem. The ability to address such issues using remote sensing is made possible by recent advances in detector technologies, the acquisition of coral-specific spectral information, increases in the spatial and spectral resolution of sensors, as well as by improved computer capabilities and analysis methods. This research project will develop a set of analysis tools using the latest advances in hyperspectral remote sensing. Hyperspectral technology provides improved spectral resolution over more traditional remote sensing methods, and thus translates to greater usefulness in being able to distinguish between the varying spectral characteristics of different benthic habitat types. Specific objectives of the overall research project are 1) to develop algorithms for bathymetry and benthic habitat mapping, 2) create tools for the identification of large-scale coral community composition and 3) to examine causal relationships associated with environmental stress and global change. Presented here are results from the first phase of this analysis examining spectral separability of different species and different habitat types in Kaneohe Bay using both field spectra and imagery.

2. BACKGROUND

2.1 Corals

The overall interest of this research is to develop generalized algorithms for analyzing coral ecosystems that are readily observable from airborne and spaceborne remote sensing platforms. Hence, this research focuses on shallow-water, tropical, reef-building corals. Many factors affect the distribution, diversity and relative health of coral reef ecosystems. These factors exhibit temporal and spatial variations that fluctuate as a result of both natural processes and anthropogenic influences. Coral reefs have naturally adapted to a certain level of environmental stress, such as the seasonal rise and fall in water temperatures, climatic variations like El Niño and La Niña, and the occurrence of hurricanes and other destructive storms. Unfortunately, as with most other ecosystems, the addition of human influences to this system is rarely positive. This tends to result in an unstable equilibrium where the coral reefs become very sensitive to any additional stress.

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Coral bleaching is perhaps the most obvious visual indication of decline and has been attributed to a variety of stressors. Coral bleaching describes a situation whereby unfavorable conditions cause the corals to expel their symbiotic zooxanthellae, which contain the pigments producing the colorful coral exterior. The loss of these organisms results in exposure of the underlying, almost colorless, coral skeleton (hence the term "bleaching"). Corals can recover from a bleaching event, but are very vulnerable during the recovery process and additional disturbances can be fatal. Furthermore, the overall decline in health of coral communities is not always spatially contiguous. Not only are the affected areas patchy, but in many cases there is a transitory temporal dynamic, with some reef areas being unaffected, some areas recovering, some areas exhibiting lingering affects, and other areas dying. The exact mechanisms for these processes are not entirely clear, and although some corals do recover, the end result is greater stress and a less healthy coral environment.

2.2 Project Rationale

It is becoming increasingly apparent that without adequate protection and preservation, coral reef ecosystems face an uncertain future (Dight and Scherl, 1997; Hoegh-Guldberg, 1999; Wilkinson, 2000). The global implications of this decline are significant because of the crucial role coral reefs play in overall marine ecosystem health and biodiversity. They also contribute numerous other economic and social benefits, as well as an inherent aesthetic appeal. Fortunately, the ecosystems themselves are incredibly resilient and have the ability to recover and thrive if adequate management and conservation measures are implemented. However, the complexity of both the natural system and the many factors involved does not lend itself to simple solutions, particularly when human factors are included in the equation (Hodgson, 1999).

This research is based on an understanding that establishing effective quantitative methods for rapidly monitoring and assessing coral reef ecosystems forms an essential component of resource management decisions and risk management evaluations. Such research has become more relevant recently because of the alarming rate of decline that has been observed in these communities (Hoegh-Guldberg, 1999; Sammarco, 1996; Wilkinson, 2000). The efforts to conserve and protect this valuable natural resource require quantitative information on characteristics of the stressors contributing to this decline, which exhibit local, regional and global variations (Hodgson, 1999; Hughes and Connell, 1999). Further requirements include consideration for the inherent spatial complexities of these ecosystems as well as their varying response to the associated environmental perturbations. A viable avenue for monitoring and assessing the complex dynamics of coral ecosystems is the synoptic spatial and temporal capabilities of remote sensing. Furthermore, advancements in the field of hyperspectral image acquisition and analysis are allowing a progression in the level of questions that can be addressed using remote sensing and an increase in the effectiveness of the resultant management tools. Imagery acquired in the spring of 2000 by AVIRIS affords a valuable opportunity for evaluating the applications of hyperspectral remote sensing to coral reefs. By linking this imagery with traditional methods of analysis, field data, and local knowledge of site conditions, a more robust management and analysis tool is created, one that encompasses site-specific information within a spatial and temporal monitoring context.

2.3 Coral Remote Sensing

Much of the past work on remote sensing of coral reefs has focused on the use of more traditional multispectral sensors (e.g., LANDSAT and SPOT) and reported results have been mixed (Dustan et al., 2000; Holden and LeDrew, 1998b; Mumby et al., 1998). Essentially, the limited spectral resolution of these sensors has restricted their applicability in such an environment. Nevertheless, remote sensing techniques have been identified as a valuable tool for scientists and resource managers working with these ecosystems. Recent investigations using hyperspectral imagery and field spectral data provide very promising indications of the utility of using this technology for coral reef investigations (Lubin et al., 2001; Mumby et al., 1998; Myers et al., 1999; Richardson and Kruse, 2000). Of particular interest are recent studies demonstrating that significant spectral resolution is required to differentiate among the varying coral species, between healthy and unhealthy coral colonies and between other associated benthic species (Hochberg and Atkinson, 2000a, 2000b; Holden and LeDrew, 1999, 1998a; Myers et al., 1999; Schalles et al., 2000). Hence, these analyses have indicated the utility of using hyperspectral instruments as tools for remotely analyzing coral communities.

3. STUDY AREA

3.1 Kaneohe Bay

The primary study area for this project is the coral reef ecosystem of Kaneohe Bay, located on the windward shore of Oahu, Hawaii (Figure 1). There are many benefits associated with working in this particular study area, most importantly because of the extensive amounts of field information and research that are available for evaluating and validating the calibration and classification results. Additionally, because the Hawaii Institute of Marine Biology (HIMB) is located within Kaneohe Bay, this study area also has the advantage of easy accessibility for fieldwork.

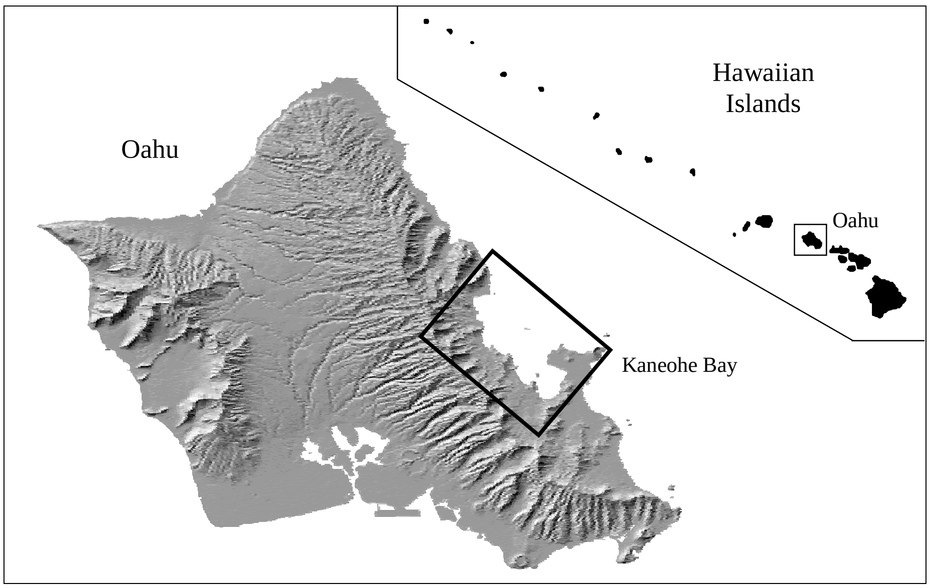


Figure 1. Study area, Kaneohe Bay, Oahu, Hawaii.

Kaneohe Bay is an extensive embayment, extending nearly 13-km along its northwest-to-southeast axis and 4-km in width. The hydrologic conditions within the bay are predominantly controlled by the exchange of seawater with the open ocean and by internal circulation patterns, which are in turn affected by tides, waves and wind. In addition to the oceanic influence, the hydrology of Kaneohe Bay is also affected by inflows from streams and directly through overland runoff. These inflows not only impart an influx of freshwater into the marine environment, but also sediments, nutrients and pollutants. The southeastern end of the bay is the most developed, containing both the town of Kaneohe and the Kaneohe Marine Corps Air Station. It is also mostly enclosed, resulting in limited circulation and poor water quality conditions. In contrast, the northwest portion of the bay experiences significant water exchange with the surrounding ocean and thus exhibits conditions resembling the oceanic environment. These differences have important implications with respect to the chemical and biological constituents in the water column, and ultimately to coral health.

3.2 Corals

Kaneohe Bay contains patch reefs, fringing reefs, and an extensive protecting barrier reef. Spatially, the corals tend to occur along the crests and slopes of these reef formations and are mostly absent from the lagoon bottom and reef flats. There are greater than 60 individual patch reefs within the bay, at locations that tend to be clustered near the two natural channels (Jokiel, 1991). These reefs have diameters ranging from 21 to 850-m and typically extend almost to the water surface. Fringing reefs are found along much of the shoreline, with natural breaks at stream outlets and artificial breaks where boat channels have been dredged. The barrier reef bounds the ocean side of the bay. It is more than 5-km long and has a width of approximately 2-km (Jokiel, 1991). The lagoon side of the barrier reef has an extensive reef flat, while the offshore side transitions into spur and groove formations.

Overall, the Hawaiian Islands tend to have a low coral diversity as a result of their isolated geographic location, and accordingly so too does Kaneohe Bay. Although less diverse than many other tropical reef systems, this simplicity is advantageous for developing the foundations of coral remote sensing. The most abundant coral in Kaneohe Bay is *Porites compressa*, which occurs mostly in low energy areas and comprises as much as 85% of the total coral in the bay (Jokiel, 1991). Other common coral species include *Montipora verrucosa*, *Montipora capitata*, *Pocillopora damicornis*, *Cyphastrea ocellina*, *Pavona varians*, *Fungia scutaria*, *Porites lobata* and *Pocillopora meandrina*. Figure 2 illustrates some of these species as well as a common algae species in Kaneohe Bay. What is important to note from a remote sensing perspective is the complexity of this environment, in terms of species composition, structural organization and variations in water depth.

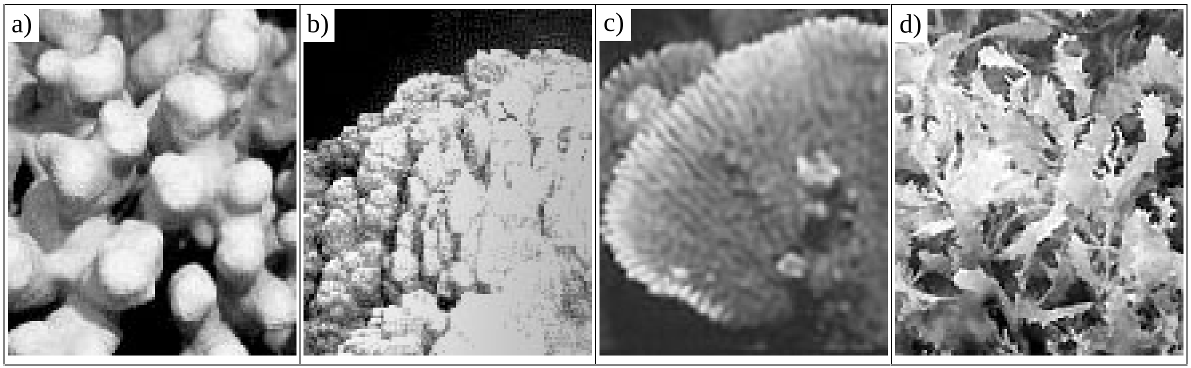


Figure 2. Three common corals and one algae present in Kaneohe Bay: a) *Porites compressa*; b) *Porites lobata*; c) *Montipora capitata*; d) algae, *Sargassum echniocarpum*.

3.3 Human Impacts

Kaneohe Bay has been the subject of numerous studies examining the characteristics and dynamics of its coral reef ecosystem over the last 30-years (Hunter and Evans, 1993; Jokiel, 1991). This is primarily attributed to scientific interest in the bay's ability to return to a coral-dominated system after excessive nutrient inputs caused a shift to an algae-dominated system in the 1970s (Hunter and Evans, 1993; Jokiel et al., 1993). The Kaneohe Marine Corps Air Station, located on the peninsula at the southeast end of the bay, began discharging untreated sewage directly into the bay starting in 1952. The city of Kaneohe further contributed to these sewage inputs when it began releasing secondarily treated sewage into the bay during 1963 (Jokiel, 1991). At the same time, other nutrient sources were also increasing due to changing land use and agricultural practices within the surrounding watershed. As a result, eutrophication in the southeast end of the bay began to produce a shift in species composition and a decrease in diversity. The effect on coral reefs was that large growths of algae began to smother and displace the corals as the dominant species. Eventually, in an effort to halt and reverse the effects of this phase-shift, both of the sewage outfalls were shifted to the deep ocean in 1978. The Kaneohe Bay ecosystem initially responded well to this change, but recovery has slowed in recent years and is still considered incomplete (Hunter and Evans, 1993). Other detrimental human influences on the Kaneohe Bay ecosystem include: increased pollutant loading due to urbanization; modification of much of the shoreline (e.g., native fishponds, seawalls, landfills, boat channels and the introduction of mangroves); overfishing; increased sediment influx due to changing land use and agricultural practices; and dredging and filling to accommodate larger ships within the main channels.

4. METHODS AND RESULTS

4.1 AVIRIS in Hawaii

One of the major AVIRIS missions during the 2000 flight season was a month-long assignment in April to the Hawaiian Islands. Over this time, AVIRIS was used to collect nearly 100 flightlines of data covering both the main Hawaiian Islands (Hawaii, Kahoolawe, Kauai, Maui, Molokai, Oahu and Niihau), as well as four regions of the remote Northwestern Hawaiian Islands (French Frigate Shoals, Gardner Pinnacles, Necker Island and Nihoa Island) (Figure 3). All of the data collected during this campaign utilized the high-altitude ER-2 platform, resulting in a pixel resolution of 20 by 20-m. Although many of these flightlines were acquired for a variety of research purposes, a significant number of the flightlines included imagery over coral reef habitats. Considering the amount of data that this campaign has made available for coral reef analysis, which includes both significantly human impacted ecosystems in the main Hawaiian Islands and the relatively pristine environments of the Northwestern Hawaiian Islands, this imagery represents a valuable resource for developing and validating coral reef specific hyperspectral analysis tools. Furthermore, the currently scheduled additional AVIRIS flightlines to be acquired in fall of 2001 will only serve to improve on the spatial extent of available data as well as providing repeat coverage for temporal change analysis.

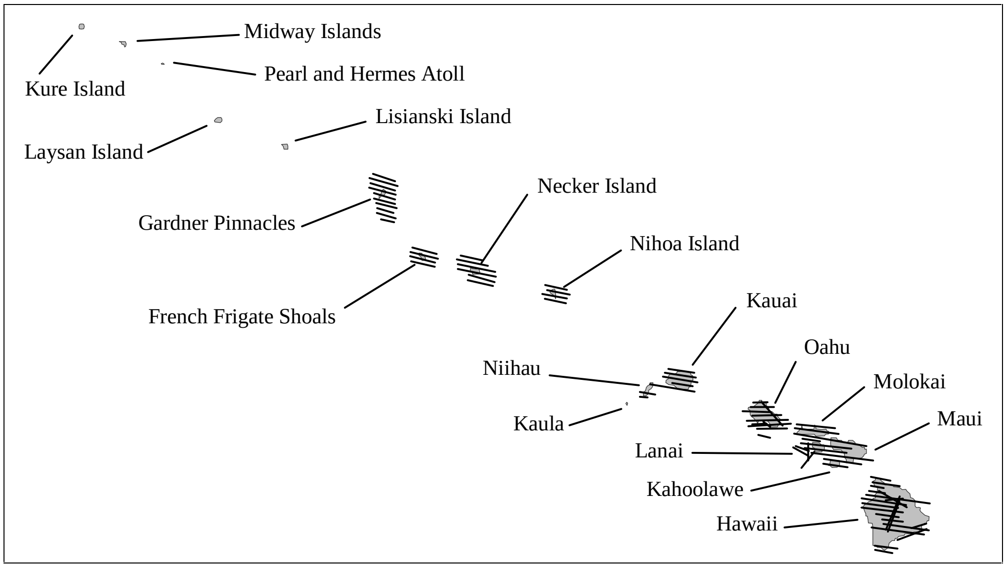


Figure 3. AVIRIS flightlines in the Hawaiian Islands, April 2000.

4.2 Kaneohe AVIRIS data

The flightline used for this project covers the coastal area of the windward shore of Oahu, including the entirety of Kaneohe Bay (AVIRIS flightline: f000412t01 p03_r08). Note that this flightline is predominantly cloud-free over the bay (Figure 4).

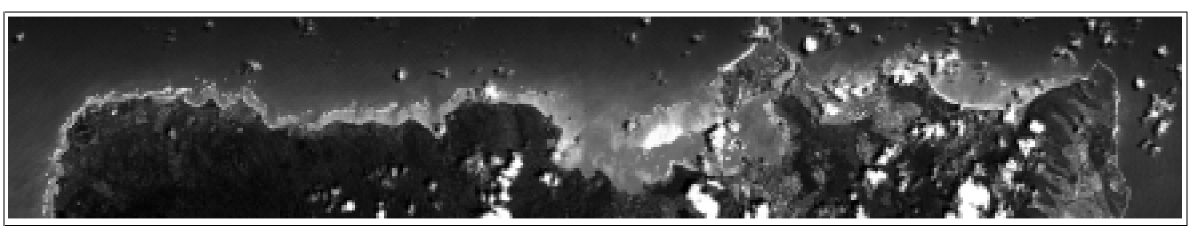


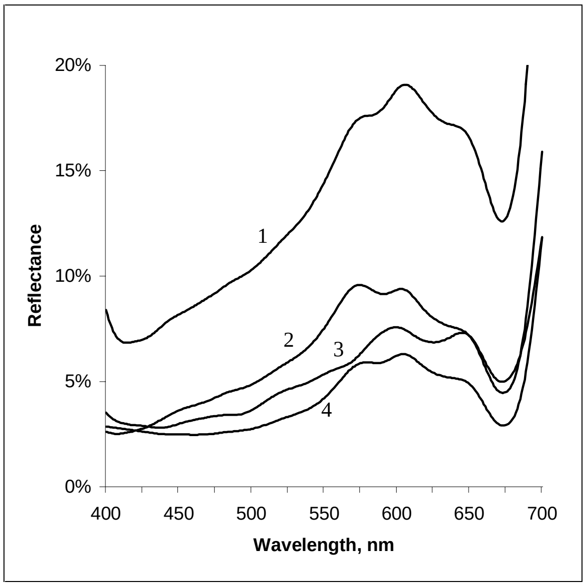
Figure 4. AVIRIS flightline, windward shore of Oahu, covering Kaneohe Bay.

4.3 Energy Interactions

In addition to the atmosphere interactions considered in terrestrial investigations, remote sensing of benthic habitats requires additional consideration for the water column and the air-water interface. At this interface, the majority of the energy is transmitted downward into the water column and a small portion is reflected back to the atmosphere (except at low sun angles, when significant amounts of energy can be reflected). Also at this interface, refraction alters the direction of incoming energy such that it is closer to vertical in the water column. Absorption and scattering in the water column then significantly attenuate the downwelling radiation. Absorption in the water column is similar to that in the atmosphere and is controlled by four main components (Kirk, 1996): the water itself, dissolved yellow pigments, photosynthetic biotic components, and abiotic particulate matter. Scattering in the water column is a function of both density fluctuation scattering (causing similar effects to Raleigh scattering at shorter wavelengths) and particle scattering. If it has not already been absorbed, the energy interacts with benthic features where it can be reflected, absorbed, or transmitted. Reflected energy, however, must pass back through the water column, the water-air interface, and the atmosphere before finally reaching the sensor. Ultimately, because the shorter wavelengths are strongly affected by Raleigh scattering and wavelengths in the near-infrared and longer are significantly absorbed in the water column, the remaining window for analyzing benthic reflectance is limited to approximately 400 to 800-nm.

4.4 Field Spectra

As with most terrestrial-based hyperspectral image analysis, field spectral measurements also constitute a valuable aspect of analyses in marine ecosystems. The measurements are used to identify characteristic spectra of the various habitat types, as well as providing an indication of the potential for distinguishing these different habitats in the hyperspectral imagery. Figure 5 illustrates average reflectance spectra of three major coral species, one algae species, rubble and sand in Kaneohe Bay. Each of the spectra in Figure 5 represents an average of numerous measurements made throughout Kaneohe Bay and thus does not depict the variability present within each species or habitat type. Instead, these spectra are used to illustrate that significant differences do exist between species and particularly between coral and algae (note the differences in inflection points at around 570-nm). Additionally, note the considerable variation in magnitude evident by the spectra of sand and rubble. Thus, these spectra provide a promising indication of the potential for classifying independent habitat types in the AVIRIS data.



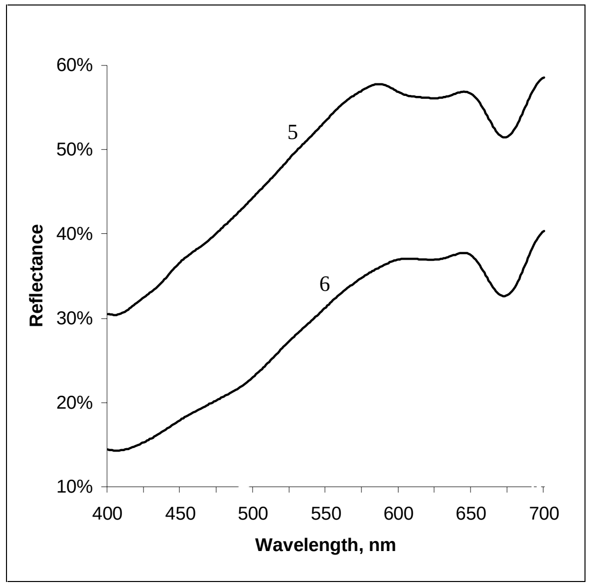


Figure 5. Example field spectra acquired in Kaneohe Bay (data courtesy of E. Hochberg, HIMB): 1) *Porites lobata*; 2) *Porites compressa*; 3) algae, *Sargassum echniocarpum*; 4) *Montipora capitata*; 5) sand; 6) rubble.

4.5 Image Analysis

Spectral separability refers to an ability to distinguish quantifiable differences in the reflectance characteristics between the categories selected for classification. Analysis conducted for this phase of the project was used to investigate spectral separability in the AVIRIS flightline covering Kaneohe Bay. This was accomplished using an unsupervised classification (Isodata clustering with 10 classes and 50 iterations applied to bands between 400 and 800-nm) to examine the potential for distinguishing different benthic habitat types in this flightline (Figure 6). It is important to note that this analysis was conducted directly on the radiance values, not reflectance, and did not incorporate atmospheric or water column corrections. Although no attempt was made to explicitly identify each of the resulting classes, observed patterns match those known to be present in the bay and illustrate clear spectral differences between habitat types. These results strongly support the validity of this approach and show promise for improved separability following atmospheric and water column corrections.

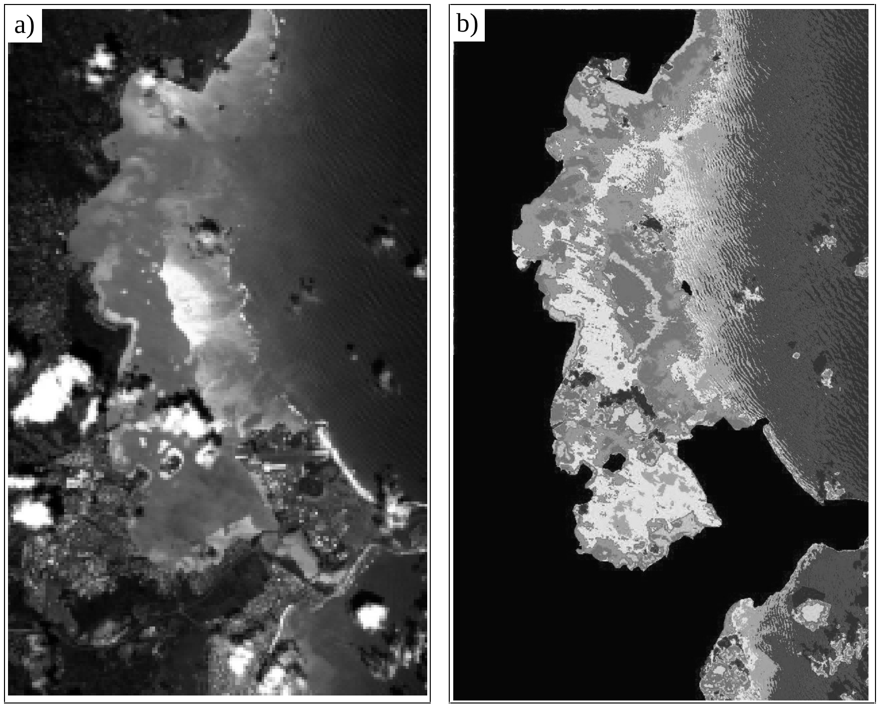


Figure 6. Unsupervised classification of Kaneohe Bay AVIRIS data: a) radiance image; b) classification output.

5. CONCLUSION

By taking advantage of the synoptic spatial and temporal monitoring capabilities of remote sensing as well as the spectral detail available from AVIRIS, the end product of this research will be an efficient tool for monitoring and assessing coral reefs. Adding this tool to the existing resources available to scientists and ecosystem managers will result in better preservation and protection strategies. Results from the first phase of this analysis have provided promising indications of the utility of the hyperspectral approach. Continued phases will address atmospheric and water column image corrections and identification of appropriate classification tools. Ultimately, a complete set of analysis tools will be developed that utilize the spectral resolution provided by AVIRIS and provide valuable products for coral management.

6. ACKOWLEDGEMENTS

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