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The Coastal Zone Color Scanner (CZCS) on NASA's Nimbus-7 satellite (1978-1986) demonstrated the utility of ocean color measurements for studying the dynamics of the ocean. The CZCS worked well for the continental shelf and open ocean regions. However, it did not have the spectral and spatial resolution needed to deal with the complexity of the coastal ocean. With the goal of developing tools suitable for the coastal ocean we initiated studies using the Airborne Visible-InfraRed Imaging Spectrometer (AVIRIS) in 1989. This paper reviews the progress from those initial studies to the current state of imaging spectrometry for the coastal ocean.

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The Development of Imaging Spectrometry of the Coastal Ocean

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Abstract - **The Coastal Zone Color Scanner (CZCS) on NASA's Nimbus-7 satellite (1978-1986) demonstrated the utility of ocean color measurements for studying the dynamics of the ocean. The CZCS worked well for the continental shelf and open ocean regions. However, it did not have the spectral and spatial resolution needed to deal with the complexity of the coastal ocean. With the goal of developing tools suitable for the coastal ocean we initiated studies using the Airborne Visible-InfraRed Imaging Spectrometer (AVIRIS) in 1989. This paper reviews the progress from those initial studies to the current state of imaging spectrometry for the coastal ocean.**

Keywords; imaging spectrometry, hyperspectral, coastal, ocean

EARLY WORK WITH AVIRIS

The Airborne Visible-InfraRed Imaging Spectrometer (AVIRIS) [1] is a NASA facility instrument built and operated by the Jet Propulsion Laboratory (JPL). AVIRIS has 220 10 nm wide spectral channels covering the 0.4 to 2.5 μm spectral range. It typically flies on an ER-2 at ~20 km producing 20 m pixels and an 11 km wide swath. Initial ocean studies uncovered problems in the early AVIRIS data including patterned noise and a Signal-to-Noise Ratio (SNR) that was insufficient for dark ocean scenes. We showed these problems to the AVIRIS team and they quickly eliminated the patterned noise and improved the SNR. By 1990 the data were usable but recalibration and binning or low-pass filtering were required to enhance the SNR for ocean scenes [2,3]. However, these studies clearly showed the utility of the high spatial and spectral resolution of AVIRIS data for coastal ocean applications leading to further studies with AVIRIS and other systems. Over the years many upgrades have been made to AVIRIS, so that it now produces outstanding-quality, very-high SNR data that are excellent for ocean and land applications.

This work supported by NASA and the U.S. Office of Naval Research.

Obtaining quality imaging spectrometry data for the coastal ocean was one issue. The second issue was to calibrate and atmospherically correct the data for ocean scenes. The third issue was to collect the sea truth data and use it to develop and validate ocean product algorithms. AVIRIS is well calibrated using an integrating sphere in the calibration facility at JPL. Unfortunately, as is typical for laboratory calibration sources, the sphere produces very little blue light. So for the spectral range of 400 to 440 nm the ocean scene is brighter than the brightest setting for the sphere and the calibration is done by extrapolation rather than interpolation. The calibrated values are low for this spectral region, which results in negative water leaving radiances when the at-sensor signal is corrected for the large Raleigh component from the atmosphere. To correct for this we collect extensive sea truth data including water-leaving radiance and above-water remote-sensing reflectance data that are used to vicariously calibrate the AVIRIS data in the blue region e.g. [2].

For a typical ocean scene the atmosphere and reflections off the sea surface contribute ~80-100% of the at-sensor radiance for wavelengths from blue to infrared. Because of this, accurate atmospheric correction is essential for ocean scenes. The ATmospheric REMoval algorithm (ATREM) [4] was developed for atmospherically correcting AVIRIS land data. However, it did not correct for reflections off of the sea surface. Ocean color atmospheric correction algorithms have been developed for CZCS, SeaWiFS and other ocean color sensors by Howard Gordon and collaborators e.g. [5,6] but they only work for a sensor in space and are designed to work specifically for each sensor. Initially this was addressed by assuming that the atmosphere was the same

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over a small AVIRIS scene, and using LOWTRAN/MODTRAN to carefully provide an atmospheric correction for the center of the scene e.g. [2,3]. However, a more general approach was needed for larger scenes, and in anticipation of spaceborne imaging spectrometer data. The special challenges of atmospheric correction over the ocean required a new approach using a full vector radiative transfer model and designed specifically to deal with skylight reflecting off of the sea surface. This atmospheric correction algorithm was initially published in 2000 [7] and versions have been developed for imaging spectrometers flying at any altitude including space.

OCEAN PRODUCT ALGORITHMS

To develop ocean products field experiments have been conducted in a variety of coastal environments. The experiments include collecting all of the in situ data essential for ocean product algorithm development coincident with the overflight of AVIRIS or other imaging spectrometer system. Band ratio algorithms, such as those used for SeaWiFS and MODIS data e.g. [3] were initially used with imaging spectrometer data. However when the bottom is imaged the scene is more complex (Fig. 1) and algorithms that use the full spectral information in the imaging spectrometer data are needed to solve the three variable problem and provide information on bathymetry, bottom type and water column optical properties [8].

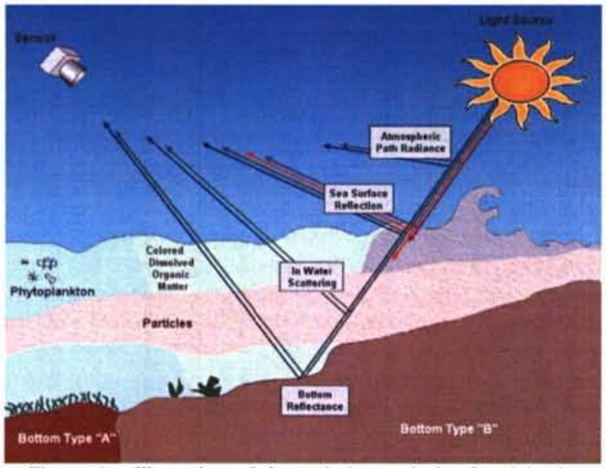

Figure 1. Illustration of the optical complexity found in the coastal ocean, particularly when imaging the bottom. Imaging spectrometer data are required to resolve bathymetry, bottom type and water column optical properties at the same time.

Three approaches have been developed that utilize the entire spectrum. Lee et al. [9] used a semi-analytic model for remote sensing reflectance as a function of absorption, scattering, bottom albedo and depth. Then they used a predictor - corrector approach and optimized the result by minimizing an error function [10]. They have successfully demonstrated this approach using AVIRIS data for Tampa Bay (Fig. 2) [11]. A second approach is to use neural networks to invert the remote sensing data to obtain bathymetry and bottom type.

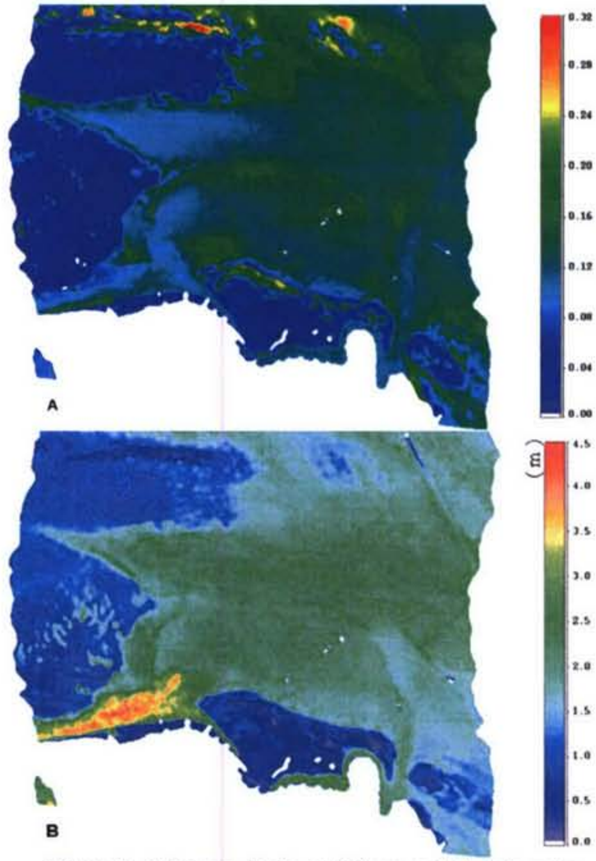

Figure 2. a) Bottom albedo at 550 nm and b) bathymetry derived from AVIRIS data for Tampa Bay, FL. Accurate values were retrieved in spite of the fact that water clarity varies greatly over the scene [11].

Neural networks require extensive training, but a well-trained network can process data very quickly and potentially makes a good operational algorithm [12]. The third approach is to use an ocean radiative transfer model to generate look-up tables for the expected range of ocean conditions. Then given the remote sensing reflectance value the table is searched for the combination of properties that minimizes the error in all spectral channels to give a simultaneous solution for water clarity, bottom type and bathymetry [13].

PHILLS, COBOP AND HYCODE

Success with AVIRIS data led to the desire for small, dedicated systems available for frequent ocean measurements. In the mid 1990s the Naval Research Laboratory (NRL) began a program to develop a small compact imaging spectrometer for naval applications. The fourth version of the Portable Hyperspectral Imager for Low-Light Spectroscopy (PHILLS) was specifically designed for ocean applications [14]. It combines an

Offner spectrometer with a thinned backside-illuminated CCD camera to provide excellent ocean imagery. Two PHILLS imagers have subsequently been used in a series of field experiments in costal waters of the Bahamas, Florida, California, New Jersey and Mississippi. The Office of Naval Research (ONR) funded two field programs addressing coastal optics; the Coastal Benthic Optical Properties (CoBOP) and the Hyperspectral Coastal Ocean Dynamics Experiment (HyCODE). CoBOP was conducted in optically shallow waters in the Bahamas, while HyCODE addressed the optical properties of a dynamic coastal area off the New Jersey coast. Both experiments involved PHILLS overflights and many of the results can be found in a special issue of Limnology and Oceanography (48(1)) including a number of papers using PHILLS data e.g. [15,16,17] This was followed by a special issue of Oceanography (17(2)) on Coastal Ocean Optics and Dynamics. The lead article by Chang, et al. [18] "the new age of hyperspectral oceanography" highlights how using in situ and remote sensing spectral data has opened up the use of spectroscopy techniques to study ocean processes and has changed the field of oceanography.

SPACEBORNE HYPERSPECTRAL IMAGING

Putting an imaging spectrometer in space for earth imaging has been an illusive goal. The initial effort was the High Resolution Imaging Spectrometer (HIRIS) [19] with Alex Goetz as the Principal Investigator. HIRIS was selected in 1989 as part of the NASA Earth Observing System (EOS) Program. Curt Davis and Ken Carder were the ocean team members and Curt was the HIRIS Project Scientist at JPL. HIRIS was subsequently dropped three years later as part of a major down sizing of the EOS Program. Alex Goetz provided a clear view of the developments that would be needed to make use of the HIRIS data, and Under Alex's leadership the HIRIS team developed ATREM [4] and developed the Spectral Image Processing System (SIPS) [20] the forerunner of ENVI (RSI, Boulder, CO) which is now the standard for analysis of imaging spectrometry data. Alex also saw the need for compact, well calibrated and reliable field spectrometers, and he founded Analytical Spectral Devices (ASD, Boulder, CO), which produces high-quality field spectrometers to meet this need.

In 1997 the Office of Naval Research (ONR) entered into a dual- use program with industry to fly the Naval EarthMap Observer (NEMO) [21]. NEMO progressed further than HIRIS and developed considerable flight hardware before the industry partner failed to come up with its part of the funding and the program was terminated in 2002. Canada and Australia also made serious attempts to fly an imaging spectrometer in the 1990s. In the end none of these spaceborne imaging spectrometers have been launched.

To date there has been only one imaging spectrometer in space for Earth observations; the Hyperion sensor on EO-1 satellite [22]. Hyperion is a hyperspectral imager flown by NASA as a technology demonstration. In spite of having very low SNR in the blue, Hyperion data have been used for a number of coastal environments with good success. Lee et al. [23] mapped bathymetry and bottom features in the Florida Keys with Hyperion data. Brando and Dekker [24] used a 5 x 5 low pass filter to enhance the SNR of Hyperion data for their study of Moreton Bay, Queensland, Australia. They calibrated the filtered data against in situ measurements of water- leaving radiance and were able to map suspended matter, colored dissolved organic matter and chlorophyll in Moreton Bay for a series of Hyperion images. The ability to use Hyperion data for coastal ocean studies in spite of its very low SNR for ocean scenes (10-50, compared to 300-1000 for multispectral ocean sensors) shows the power of imaging spectrometry for imaging the coastal ocean.

FUTURE DIRECTIONS

The future for coastal ocean imaging spectrometry is promising. Advanced compact airborne imaging spectrometers are being built by a number of companies. This will make quality airborne data more readily available for a variety of applications. Also airborne imaging spectrometer data is starting to be used more operationally. The Center for Integrative Coastal Observation, Research and Education (CICORE) was established in 2002 with funding from the National Oceanic and Atmospheric Administration in an effort to create a coastal monitoring and research observatory network for the entire 1200 miles of the California coast. As part of CICORE the Florida Environmental Research Institute (FERI; www.feriweb.org) has been using a PHILLS sensor to survey kelp beds and collect other environmental information for the California coast (Fig. 3). This has provided greatly improved data on the health

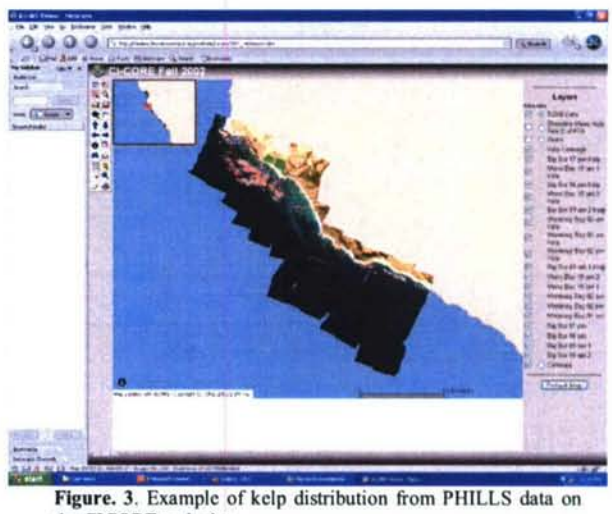

Figure. 3. Example of kelp distribution from PHILLS data on the CICORE web site.

and distribution of kelp, which is commercially harvested on the California coast. In turn this semi-operational use has led FERI to procure an advanced imaging spectrometer with integrated navigation system to speed the collection and processing of this data.

There continues to be a strong push to fly an imaging spectrometer for coastal imaging in space. The Coastal Ocean Imaging Spectrometer (COIS) developed for NEMO is now being considered for flight on one of the NPOESS spacecraft for launch in 2011. The Canadian government is again considering flying an imaging spectrometer for land and ocean applications. The great progress that has been made using airborne systems to develop algorithms for calibration, atmospheric correction, and ocean and land products means that when a system does fly, data can be rapidly processed and used for a wide variety of land and ocean applications.

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