Hyperspectral Imaging of the Coastal Ocean

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LONG-TERM GOALS

The Navy has a requirement to rapidly and covertly characterize the coastal environment in support of Joint Strike Initiatives. Over the past 12 years we have demonstrated that spaceborne hyperspectral remote sensing is the best approach to covertly acquire data on shallow water bathymetry, bottom types, hazards to navigation, water clarity and beach and shore trafficability to meet those requirements. The long term goal of this work is to put a hyperspectral imager capable of making the appropriate measurements in space to demonstrate this capability.

OBJECTIVES

The objective of this work is to put a hyperspectral imager in space to demonstrate the ability to covertly acquire data on shallow water bathymetry, bottom types, hazards to navigation, water clarity and beach and shore trafficability. The proposed activities are designed to move us closer to flying either the Hyperspectral Imager for the Coastal Ocean (HICO) or the Coastal Ocean Imaging Spectrometer (COIS) or both to demonstrate the spaceborne capability, to advance methods of processing and analyzing hyperspectral data of the coastal ocean and to enhance community awareness of the need for hyperspectral imaging of the coastal ocean.

APPROACH

I proposed two tasks over the two year period (FY 08-09):

1. Complete publications on three topics using the in situ and PHILLS airborne hyperspectral data from the LEO-15, New Jersey, Mobile Bay, Alabama and Monterey Bay, California experiments. The first is on the in situ optical data form all three sites, the second is on scaling of hyperspectral data to resolve coastal features using the LEO-15 data and the third is a comparison of the three sites using the PHILLS data.

2. I will continue my active support for flying HICO on the International Space Station (ISS) and COIS on a spacecraft of opportunity. It is critical to get this technology in space to demonstrate its full utility for naval applications. At the request of Mike Corson (Naval Research Laboratory) the Principal Investigator for HICO and COIS I continue to be the Project Scientist for both HICO and COIS.

Report Documentation Page

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WORK COMPLETED

Our work is focused on the coastal ocean and a major issue for the coastal ocean is that the standard case 1 algorithms used to calculate chlorophyll and other water properties assume that phytoplankton with an associated level of Colored Dissolved Organic Matter (CDOM) and water itself are the only optically active components. In coastal waters high levels of CDOM from rivers and coastal runoff, large phytoplankton blooms, sediments from rivers, or resuspension from the bottom are all significant optical components that need to be considered as part of the optical signature. As a consequence many researchers are moving away from the case 1 waters assumptions and directly calculating Inherent Optical Properties (IOPs) from remote sensing data (IOCCG, 2006). To develop and validate IOP algorithms for coastal waters it is essential to collect profiles of IOPs and simultaneous water samples for further analysis for phytoplankton, suspended particulates and CDOM. To accomplish this we developed the Profiling Optics and Water Return (POWR) system (Rhea et al., 2007). POWR is used to measure temperature, salinity and a suite of IOPs of the upper 100 m and collect up to 8 water samples at selected depths. Data is displayed in real-time on the ship and that data can be used to select the depth for water samples. We are using the data collected with POWR to characterize a diversity of coastal environments. In Snyder, et al. (2008) we reported a study of optical scattering and backscattering of particulates for three coastal sites that represent a wide range of the optical properties found in U.S. coastal waters. The 6000 scattering and backscattering spectra collected for this study can be well approximated by a power-law function of wavelength. The power-law exponent for particulate scattering changes dramatically from site to site (and within each site) compared to particulate backscattering where all of the spectra - except possibly the very clearest waters - cluster around a single wavelength power-law exponent of -0.94. Simultaneous Particulate Organic Matter (POM) and Particulate Inorganic Matter (PIM) measurements from the water samples are available for some of our optical measurements and s*ite-averaged* POM and PIM mass-specific cross sections for scattering and backscattering were derived. Cross sections for organic and inorganic material are different at each site and the relative contribution of organic and inorganic material to scattering and backscattering depends on the relative amount of material that is present at each site.

Current ocean color sensors, for example SeaWiFS and MODIS, are well suited for sampling the open ocean. However, coastal environments are spatially and optically more complex and their characterization require higher spatial resolution sensors equipped with additional spectral channels. In an earlier study (Davis, et al, 2007) we analyzed the spectral characteristics and spatial scales of variability in airborne hyperspectral data of a harmful algal bloom in Monterey Bay, CA using semivariogram analysis. The results indicated the need for a channel near 709 nm (as found on MERIS) for the detection of these large surface blooms. Also, we found a continuum of spatial scales with the dominant scales being 150 to 300 m depending on the image analyzed. Now we are applying the same approach to look at optically shallow environments including coastal waters at the LEO-15 site at Tuckerton, NJ, the Bahamas Bank near Lee Stocking Island and Looe, Key, FL and comparing those results with the results for optically deep waters.

We originally used the semivariogram technique to analyze a time series of images of the northeast corner of Monterey Bay off the coast of central California. The statistics reported here are the lagged distance and semivariance values using “Queen’s move” pixel pairs (calculated with the software package, ENVI, ITT Visual Information Solutions, Boulder, CO). Queen’s move calculates the squared difference over all pairs of pixels in the image in all eight directions. For a given wavelength, the nugget, sill, and range was determined by plotting the semivariance $\gamma(h)$, over distance between pixel pairs, h. For the commonly used spherical model of saturating semivariance, γ(h), with increased distance, h, the equation for a theoretical semivariogram is as follows:

$$\gamma(h) = c_0 + c_1[(3h/2a) - 0.5(h/a)^3]$$

The non-zero intercept or nugget of the variogram, c_0, determines the degree of unresolved variability; for sensor comparison it can represent the degree to which the particular pixel size captures the underlying phenomenon. The range, a, of a semivariogram determines how quickly the underlying variability reaches a global maximum, essentially the distance to which the structure of a variable is spatially dependent. The sill, c_1, determines the total variance resolved in the image or region of interest. Equations based on real data may exhibit much more complex behavior than the theoretical spherical model with multiple nodes often apparent at distances less than the sill.

For the optically deep waters of Monterey Bay better than 90% of the variance is resolved in the 10 m data. This is not the case when the data are binned to 100 or 300 m (Fig.1). One hundred meters does a reasonable job resolving 60 to 80% of the variance. However, when binned to 300 m we only resolve 60% to as little as 30% of the variance. In particular, only 30% of the variance is resolved at 300 m for the data from the 15th. This well mixed case is more typical for many coastal regions.

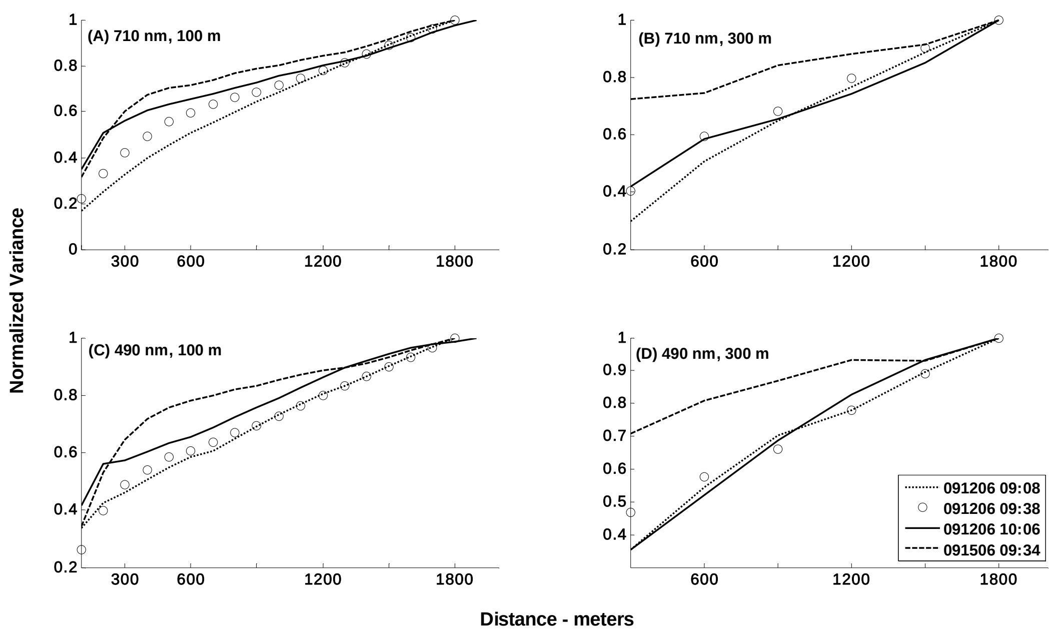

Fig. 1. Airborne hyperspectral data for Monterey Bay binned to 100 m (a, c) and 300 m (b, d). For these optically deep waters 100 m data was adequate to resolve 60 to 80% of the variability in the scene (nugget (c_0) is 0.2 to 0.4). The 300 m data only resolved 60% to as little as 30% of the variability.

The first optically shallow environment was analyzed using a Portable Hyperspectral Imager for Low-Light Spectroscopy (PHILLS, Davis et al. 2002) image from the Coastal Benthic Optical Properties (CoBOP) experiment at Lee Stocking Island. The area of the image analyzed includes seagrass beds, coral reefs and sandy bottom (Fig. 2). The longer wavelength channels (680 and 710 nm) do not penetrate the water to image the bottom, and therefore they do not resolve the full range of features in the image. The wavelengths that do image the bottom (440, 490 and 560 nm) show a continuum of space scales down to the sampling scale of 1.9 m.

Figure 3 shows the PHILLS image of the Mullica River Estuary mud flats which are at a depth of 1 to 5 m. In this very shallow environment all of the channels image the bottom at least in the shallower parts of the image. All of the channels show the same semivariogram with a continuum of spatial scales down to the sampling scale of 1.8 m.

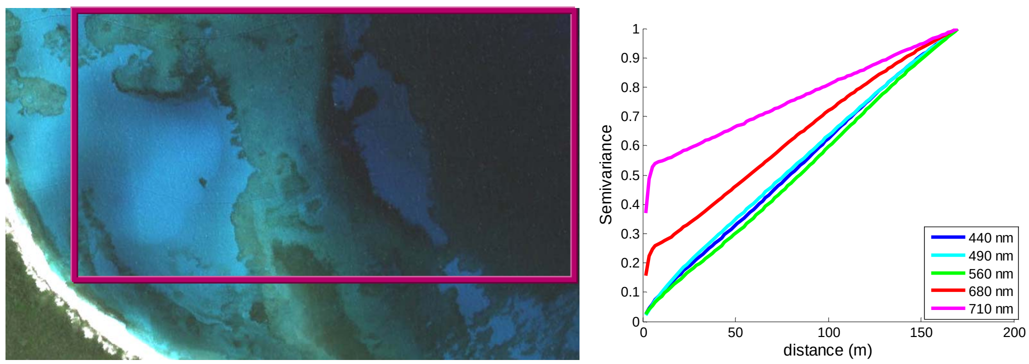

Fig. 2. Left, the PHILLS image of Horseshoe Reef near Lee Stocking Island in the Bahamas with a box indicating the area used for this analysis. Right, the Semivariogram results. PHILLS data, 1.9 m GSD, 400 – 800 nm at 3.7 nm spectral sampling.

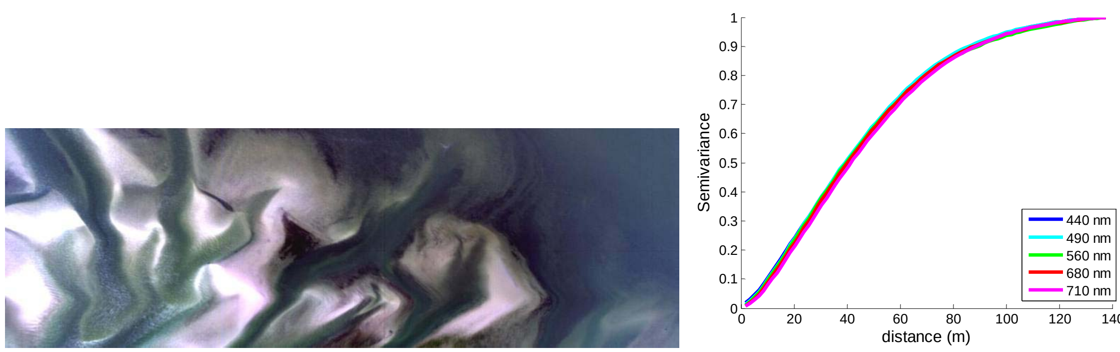

Fig. 3. Left, the PHILLS image of mud flats in the Mullica River Estuary, NJ. Right the Semivariogram results which are identical for all channels showing a continuum of space scales down to the 1.8 m sampling scale.

Figure 4 is the AVIRIS (Vane, et al., 1993) image of the Mullica River Estuary which includes the same mud flats seen in Fig. 3, and adjacent areas with deeper waters. All channels indicate a dominant

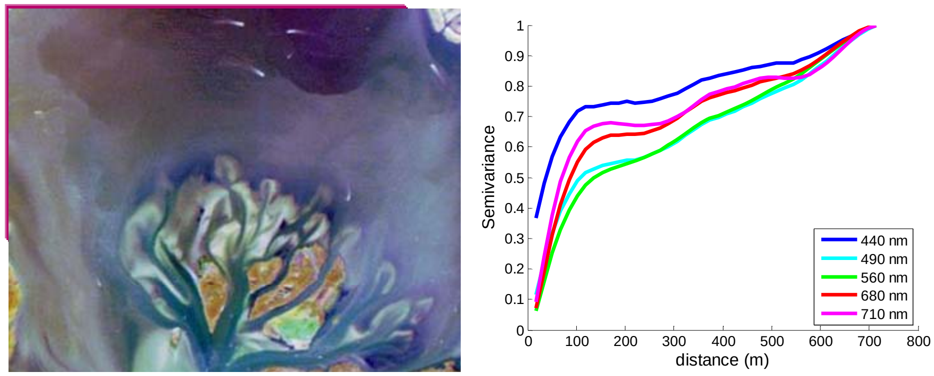

Fig. 4. Left, the AVIRIS image of mud flats in the Mullica River Estuary, NJ. The larger box indicates the part of the image including mud flats and deeper waters used in this analysis. For comparison the small box indicates the area of the PHILLS image in Fig 3. Right the Semivariogram results showing nodes at 120 and 400 m.

spatial scale at around 120 m, this is at the upper end of the distance scale analyzed in the PHILLS image and is seen as a leveling off of that data (Fig. 3). An additional node is seen at 400 m which is likely not associated with bottom features, but with the water column features in the upper part of the image.

Figure 5 shows the results of analysis of data from NASA's Hyperion on EO-1 (Ungar, et al, 2002) for a scene of Looe Key and surrounding coral reefs and deeper waters in the Florida Keys. The semivariograms for the 440, 680 and 710 nm channels show spikes reflecting the low signal-to-noise ratio of these channels which limits the ability to resolve ocean features. The 680 and 710 nm channels do not penetrate the water very far and thus do not resolve the bottom features which dominate the scales of variability. By contrast the 490 and 560 nm channels do penetrate deeply into the water and they show a continuum of scales associated with the bottom features similar to the results for Horseshoe Reef and the Mullica River Estuary.

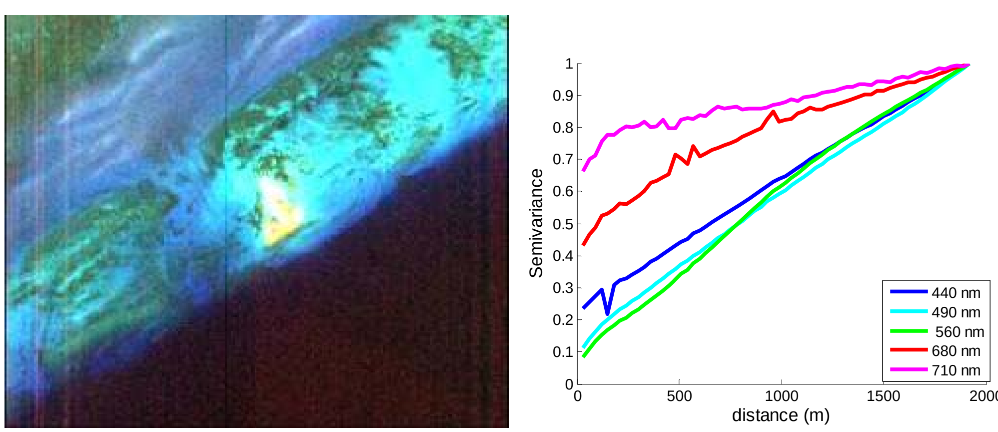

Fig. 5. Left, the section of the Hyperion image of Looe Key, FL used in this analysis. Right the Semivariogram results. Hyperion data), 30 m GSD, 426-2400 nm at 10 nm sampling. Processed according to Lee et al. (2007).

A comparison of the semivariograms for the four optically shallow environments shows similar patterns (Fig. 6). Because of issues with 440 nm and 710 nm channels in the Hyperion sensor the best comparison is made using the 490 nm channel. All of the benthic environments show a continuum of bottom features down to the scale of sampling. Sampling at 30 m GSD (vertical line in Fig. 6b) resolves 70% or more of the variance in these scenes. Clearly additional information can be gained with finer spatial sampling, however, this is extrememy costly interms of the size and cost of the instrument, the amount of data to process and the area that the sensor can cover. Thus 30 m GSD is a suitable compromise for a space sensor designed for sampling optically shallow ocean scenes.

By comparison 60 to 80% of the spatial information in the Monterey Bay scene is resolved at 100 m (Fig. 1). This is indicative of the spatial scales of water column features in coastal waters including fronts, algal blooms and slicks. Thus a system designed for sampling the water column only can be designed to sample at 100 m.

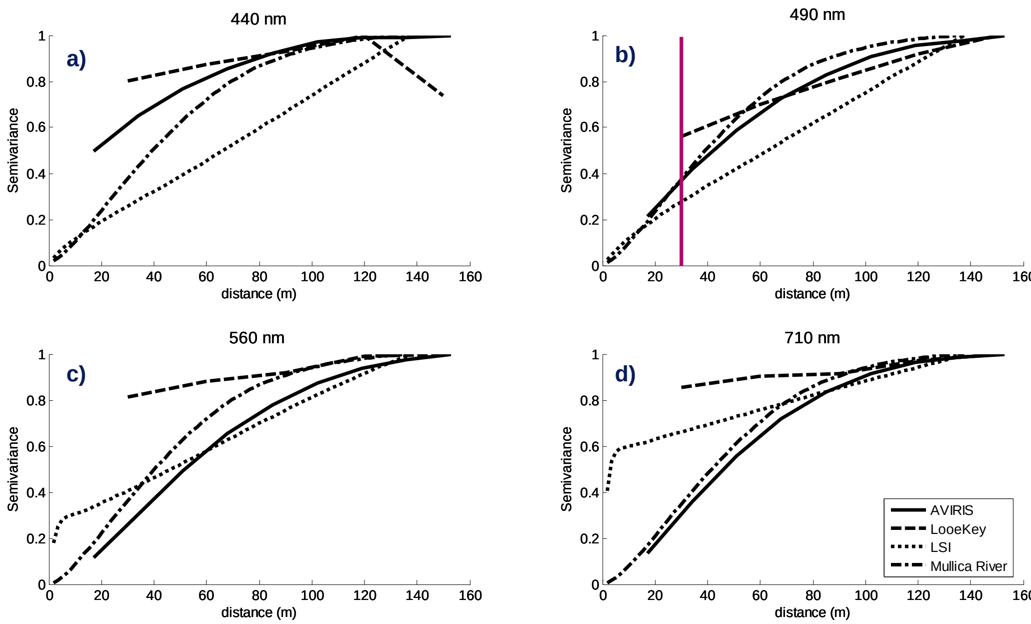

Fig. 6. Normalized semivariograms for four wavelengths a) 440 nm, b) 490 nm, c) 560 nm and d) 710 nm. The plots show the dominant spatial scales for the 4 visible wavelengths using the full resolution data. The four semivariograms in each plot are for the four optically shallow environments sampled in this study.

I continue to support the Naval Research Laboratory in the effort to fly COIS (Wilson and Davis, 1999) on a spacecraft of opportunity to provide high resolution hyperspectral data for the coastal ocean. Each year we have presented COIS to the Navy and DoD Space Experiment Review Boards (SERBs) and received high rankings. The current ranking for COIS is 4 out of 30 on the 2008 Navy SERB list and 10 out of 51 on the 2007 DoD SERB list. While HICO data will be 100 m GSD optimal for characterization of optically deep coastal waters, COIS would provide the 30 m GSD data optimal for optically shallow waters.

The Hyperspectral Imager for the Coastal Ocean (HICO; Corson et al., 2007) program is the first demonstration of environmental characterization of the coastal zone using a spaceborne maritime hyperspectral imager. HICO is sponsored by the Office of Naval Research as an Innovative Naval Prototype (INP), and will demonstrate coastal products including water clarity, bottom types, bathymetry and on-shore vegetation maps. As an INP, HICO will also demonstrate innovative ways to reduce the cost and schedule of this space mission by adapting proven aircraft imager architecture and using Commercial Off-The-Shelf (COTS) components where possible. In January 2007 HICO was selected for flight on the International Space Station (ISS). HICO is an imaging spectrometer based on the PHILLS airborne imaging spectrometers (Davis, et al., 2002) with 100 m Ground Sample Distance (GSD) and a spectral range is 0.4 to 1.0 microns sampled at high resolution and then binned to 5 nm. The ISS orbital inclination is 52 degrees which is not sun synchronous and thus we will be able to observe target areas at all times of the day for understanding diurnal changes and to prepare for possible future ocean color sensors in geostationary orbit. HICO is being integrated and flown under the direction of DoD's Space Test Program. HICO will be combined with another NRL instrument RIADS as the HICO/RAIDS Experiment Payload (HREP). HREP is manifested on the Japanese Experiment Module-Exposed Facility (JEM-EF) on the ISS. HICO flight hardware (Fig. 1) was assembled and tested and calibrated at NRL over the past year. The flight hardware passed its acceptance test and was delivered for integration into the HREP package in July 2008. It is currently scheduled for launch in September 2009.

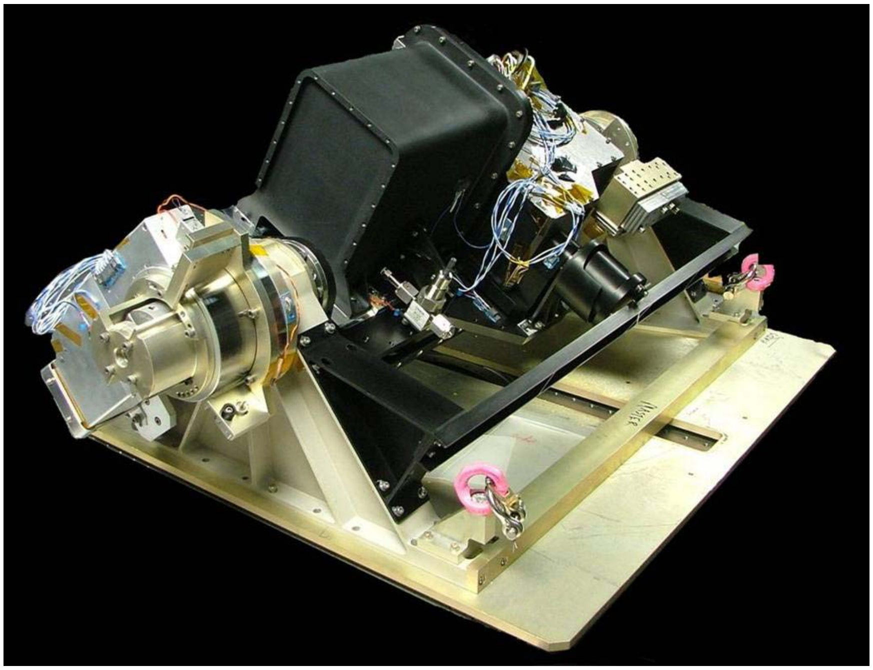

Fig. 7. The HICO Flight Hardware Completed in July 2008. HICO is manifested for a September 2009 launch to the International Space Station.

RESULTS

The focus of this effort is on the processing and analysis of existing data sets and the publication of results and new algorithms based on that data and on papers that explain the value and importance of hyperspectral imaging of the coastal ocean. We developed and published (Rhea, et al., 2007) a description of an IOP profiling system that provides real-time IOP data and the ability to collect water at selected depths based on that data. Then we published a paper (Snyder, et al., 2008) on the optical measurements collected with that system describing a diversity of US coastal waters. Another paper (Lee et al., 2007) describes the development of a new method for atmospheric correction and processing of Hyperion data from the Florida Keys. We continue to do analysis of data from CoBOP, HyCODE and other experiments to address the issues of algorithm development and spectral and spatial sampling in the coastal ocean. Also, the HICO flight hardware has been completed and is being integrated for flight on the ISS in 2009. HICO will be the first imaging spectrometer designed for coastal ocean imaging to be flown in space.

IMPACT/APPLICATIONS

The long term goal of this work is to put a hyperspectral imager capable of making the appropriate measurements in space to demonstrate the capability of this technology for the rapid and covert characterization of the coastal ocean to support naval operations around the world. We will use data from HICO on the ISS to demonstrate that capability beginning in the fall of 2009. The work completed this year is another incremental step towards that goal.

RELATED PROJECTS

I continue to collaborate regularly with colleagues at the NRL Remote Sensing Division (Code 7200; Mike Corson and others) and the NRL Oceanography Division (Code 7300; Bob Arnone and others) and with Zhong-Ping Lee at Mississippi State University.

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