Hyperspectral Imaging of River Systems

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Award Number: N000141010448

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 15 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 take avantage of the Hyperspectral Imager for the Coastal Ocean (HICO) currently flying on the International Space Station (ISS). As HICO Project Scientist I work to enhance community awareness of the need for and utility of hyperspectral imaging of the coastal ocean. Our work includes advancing methods of on-orbit calibration and product validation, and processing and analyzing hyperspectral data of the coastal ocean. In particular in this study we are using HICO data to characterize the properties of river systems. Conventional ocean color sensors have 1 km pixels and a few spectral channels; these have not proven adequate to resolve the complexity of river systems. HICO was designed to sample the coastal ocean and has 90 m GSD and 90 spectral channels suitable to resolve river systems. To make the best use of this data we are developing algorithms and approaches for resolving the constituents of river plumes and other complex systems.

APPROACH

Two tasks are planned for the two year period of this grant (FY2010-2011):

1. Develop, test and evaluate algorithms for deriving optical properties, chlorophyll, suspended sediments and CDOM for coastal systems including river systems. We will work with MERIS and HICO^{TM} data and use the Columbia River system and adjacent coastal waters as a test area for this work.

Report Documentation Page

Form Approved
OMB No. 0704-0188

1. REPORT DATE	2. REPORT TYPE	3. DATES COVERED
APR 2011	**N/A**	**-**

4. TITLE AND SUBTITLE	
Hyperspectral Imaging of River Systems	5a. CONTRACT NUMBER
	5b. GRANT NUMBER
	5c. PROGRAM ELEMENT NUMBER
6. AUTHOR(S)	5d. PROJECT NUMBER
	5e. TASK NUMBER
	5f. WORK UNIT NUMBER
7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES) **College of Oceanic and Atmospheric Sciences 104 COAS Admin, Bldg. Corvallis, OR 97331**	8. PERFORMING ORGANIZATION REPORT NUMBER
9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)	10. SPONSOR/MONITOR'S ACRONYM(S)
	11. SPONSOR/MONITOR'S REPORT NUMBER(S)

12. DISTRIBUTION/AVAILABILITY STATEMENT
Approved for public release, distribution unlimited

13. SUPPLEMENTARY NOTES
FY2010 Annual Reports of S & T efforts sponsored by the Ocean Battlespace Sensing S & T Department of the Office of Naval Research., The original document contains color images.

14. ABSTRACT

15. SUBJECT TERMS

16. SECURITY CLASSIFICATION OF:			17. LIMITATION OF ABSTRACT	18. NUMBER OF PAGES	19a. NAME OF RESPONSIBLE PERSON
a. REPORT **unclassified**	b. ABSTRACT **unclassified**	c. THIS PAGE **unclassified**	**SAR**	**10**	

Standard Form 298 (Rev. 8-98)
Prescribed by ANSI Std Z39-18

2. As soon as it is available we will collect HICO™ data for the Yangtze River and adjacent coastal regions in China. Once we have developed the algorithms and approaches that work for the Columbia River we will test and evaluate those algorithms for the Yangtze and other river systems. The goal is to validate our algorithms and to further our understanding of this important river and the East China Sea which are rapidly changing due to the development of the Three Gorges Dam and continued urbanization of China.

WORK COMPLETED

This is the first year of this two year project. 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. For example the standard MODIS and MERIS products give false high chlorophyll values for the Columbia River Plume (**Fig. 1**). The MERIS neural network (algal 2) algorithms are designed for European coastal waters and do a better job of separating chlorophyll and suspended sediments. We are working to modify them for Oregon coastal waters and eventually for use with HICO™ data. Note also that the 1 km MODIS data does not sample the Columbia River mouth including the mixing zone that is order 50 km from the coast. MERIS 300 m data does a better job of imaging the estuary but HICO has 90 m GSD and full spectral data (400 – 900 nm at 10 nm resolution) is closer to ideal for this example river system.

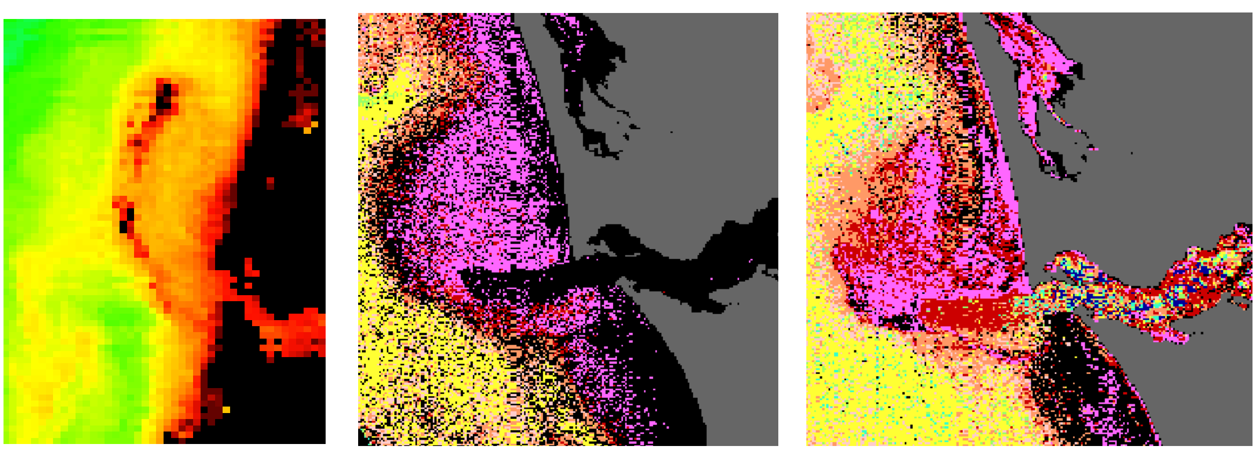
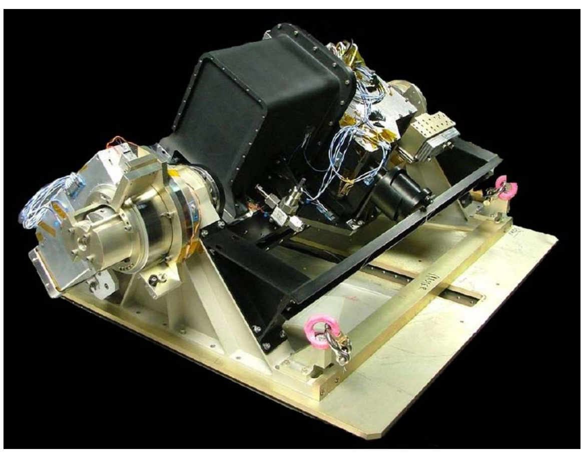


Figure 1. Satellite ocean color images of the Columbia River estuary and plume on September 10, 2009. Left, is the MODIS standard 1000 m chlorophyll product. This algorithm gives false high values for the river system (red in this color scale) due to the high suspended sediments in the river water. The large pixels do not image the river mouth effectively. Center is the MERIS 300 m standard chlorophyll product (algal 1). The river mouth and near shore plume are black indicating the algorithm does not give a valid product for these waters and the results are masked out. Right is the MERIS neural network coastal chlorophyll product (algal 2) which shows reasonable chlorophyll values for the river mouth and nearshore plume. The 300 m MERIS pixels do a much better job of imaging the river mouth.

The Hyperspectral Imager for the Coastal Ocean (HICO; Corson et al. 2008) is an imaging spectrometer based on the PHILLS airborne imaging spectrometers (Davis et al. 2002). HICO is the first spaceborne imaging spectrometer designed to sample the coastal ocean. HICO will sample selected coastal regions at 90 m with full spectral coverage (400 to 900 nm sampled at 5.7 nm) and a high signal-to-noise ratio to resolve the complexity of the coastal ocean. HICO is sponsored by the Office of Naval Research as an Innovative Naval Prototype (INP), to demonstrate coastal products including water clarity, bottom types, bathymetry and on-shore vegetation maps. As an INP, HICO also demonstrates innovative ways to reduce the cost and schedule of this space mission by 80% by adapting proven PHILLS aircraft imager architecture and using Commercial Off-The-Shelf (COTS) components where possible.

The HICO program was initiated in February 2006. In January 2007 HICO was selected to fly on the Japanese Experiment Module Exposed Facility (JEM-EF) on the International Space Station. Construction began following the Critical Design Review on November 15, 2007. HICO was completed in July 2008 (**Fig. 2**) and it was integrated into the HICO and RAIDS Experimental Payload (HREP) in August 2008. HICO is integrated into HREP and flown with support and direction from DOD's Space Test Program. HREP has completed environmental testing at NRL and NASA's Marshall Space Flight Center and was shipped to Japan on April 9, 2009. HREP was launched on the H-2 Transfer Vehicle (HTV) September 10, 2009. The HTV rendezvoused with the ISS on September 17, 2009. HICO was installed on September 23 (**fig 2**) and collected its first images on September 24, 2009. The image quality looks excellent and the team is assessing the calibration and testing processing systems. Data should be available for distribution by the end of 2010.



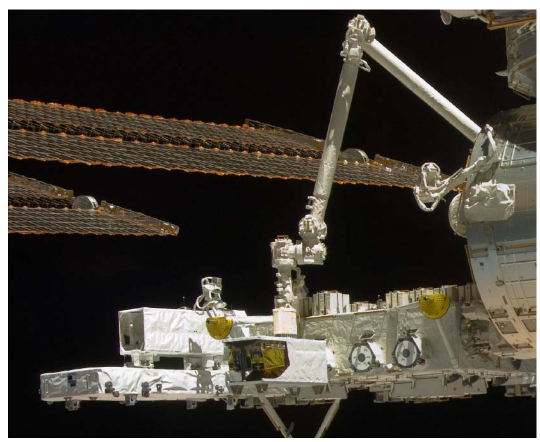


Figure 2. Left, The HICO Flight Hardware which was completed in July 2008. HICO was launched to the International Space Station on September 10, 2009. Right HREP is being installed on the ISS using the Japanese Arm on September 23, 2009. RAIDS is the gold covered instrument in the front of HREP and HICO is housed in the white section at the back of HREP.

For the past year we have been collecting HICO™ data for the Columbia (**Fig. 3**) and Yangtze Rivers (**Fig. 4**). There are many constraints on data collection with this demonstration instrument including being limited to one image per orbit for data transmission, gaps due to the ISS orbit and operations and clouds. However, we now have several good images for both rivers and are continuing to collect imagery at both locations. We are still working out automating the distribution and atmospheric correction processing, but the current products are reasonable and automated processing is expected by the end of the year.

Figure 3. Psudocolor image of the Columbia River mouth and adjacent coastal waters made with 3 channels of HICO data. The 90 m HICO^{TM} data shows many more details including shallow bars in the river, the bridge from Astoria Oregon across to Washington, breakwaters and the complex mixing patterns as the plume moves offshore.

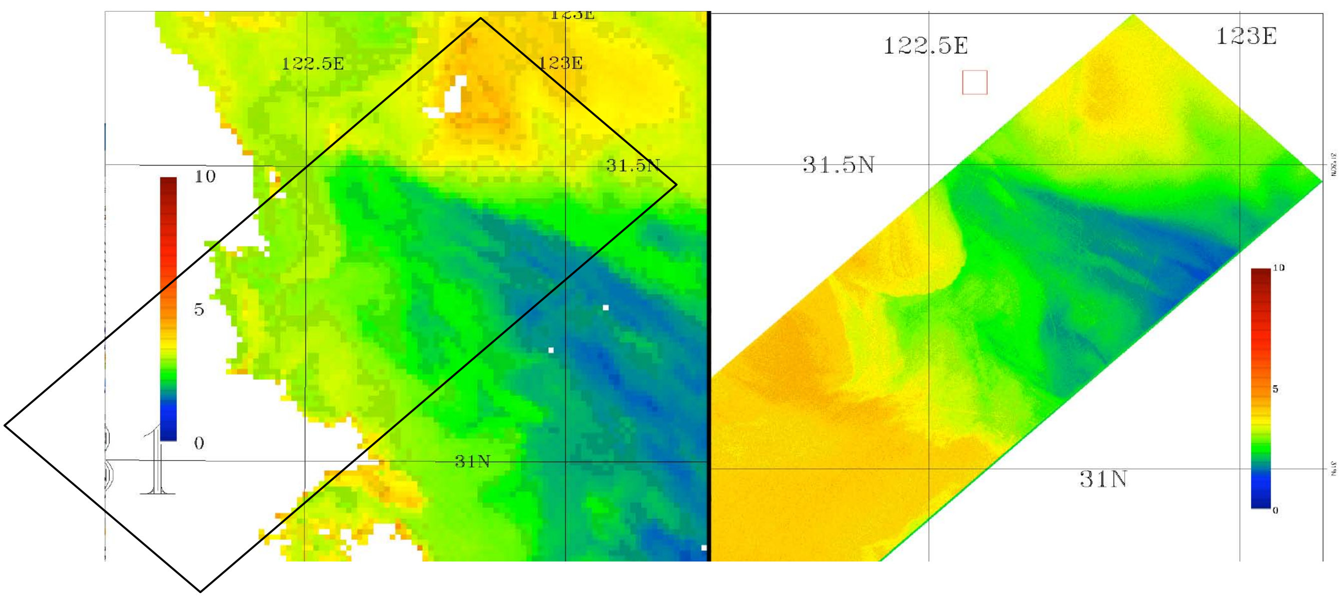


Figure 4. Nearly coincident MODIS and HICO^{TM} images of the Yangtze River, China taken on January 18, 2010. Left, MODIS image (0500 GMT) of Chlorophyll-a Concentration (mg/m^3) standard product from GSFC. The box indicates the location of the HICO^{TM} image relative to the MODIS image. Right, HICO^{TM} image (0440 GMT) of Chlorophyll-a Concentration (mg/m^3) from HICO^{TM} data using ATREM atmospheric correction and a standard chlorophyll algorithm. (Preliminary Results by R-R Li and B-C Gao.)

Yangtze River in China is a major source of sediments and nutrients to the China Sea and Straits of Taiwan. In a comparison of chlorophyll products from MODIS and HICO™ (**Fig. 4**) we see the big picture in the MODIS data, but far more detail in the HICO™ data. Also, note that the MODIS algorithms fail over waters with high sediments, but the HICO™ data is not saturated and the HICO™ algorithm returns useful data even in these high sediment waters. Were the MODIS data is not saturated the match of chlorophyll values is very good.

To validate MERIS and HICO™ data products we have been collecting profiles of downwelling irradiance and upwelling radiance using a Satlantic HyperPRO (**Fig. 5**). The HyperPRO is a free falling optical profiling system that collects profiles of spectral Lu and Ed and chl fluorescence, backscatter, T and salinity. The system is calibrated by Satlantic and we use the Satlantic software for processing including all of the latest corrections based on NIST calibrations. This system produces high quality measurements of spectral remote sensing reflectance (Rrs) for direct comparison to the HICO™ data after atmospheric correction. The HyperPRO data together with other data collected on each station including HPLC pigments, productivity, CDOM, suspended sediments are placed in the MILOCO data base with web access.

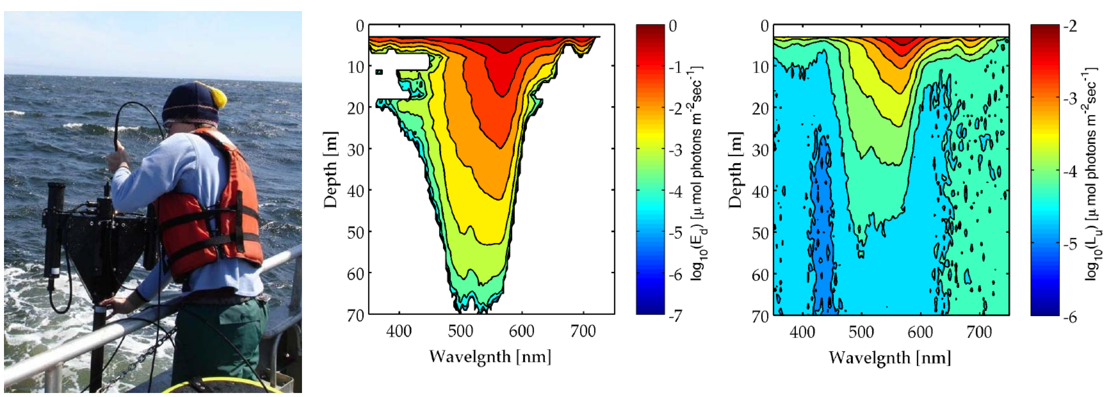


Figure 5. Collecting HyperPRO data and an example data set from the MILOCO cruise off the Oregon coast taken June 4, 2009. (Left side of the side of the figure shows a research associate lowering the HyperPRO instrument over the side of a small research vessel. The center panel shows the depth profile of the spectra of downwelling irradiance. The right panel shows the depth profile of the spectra of the upwelling radiance collected with the HyperPRO instrument.)

A key focus of our effort is to differentiate the river plume from the background signal and to find a rapid way of processing the data to produce a river plume product. The initial focus is to use techniques that do not need atmospheric correction but directly use the calibrated at sensor radiances. Nick Tufillaro is leading this effort and testing several approaches.

The starting point for atmospheric correction of a sensor above water radiance is the decomposition,

$$L_{\mathcal{T}}(\lambda) = L_a(\lambda) + \mathcal{T}(\lambda) L_w(\lambda), \qquad (1)$$

where L_a accounts for atmospheric and sea-surface reflection, L_w picks up contributions below the water surface, and T denotes the transmittance from the water surface to sensor. In developing 'indicator maps,' we will consider a slightly different decomposition. Namely, we start by imagining, at every pixel, the at-sensor radiance we would see if the water was clear, a so-called dark water pixel. This is an 'idealized' quantity, but the difference between this ideal radiance signal, and the observed signal at sensor, provides information about what is in the water, which is relatively independent of what is in the atmosphere. Thus it is a good starting point for creating an 'indicator' function for what is in the water.

In our approach a dark water pixel will be defined 'empirically,' based on an image, or collection of images, of a region of interest, and choosing pixels, or patches of pixels, which determine 'dark water,' or water free of river plume materials, or other features of interest, for that region. So in practice, the dark water pixel could contain some background material in the water column that we will consider as 'clear water,' or a 'dark pixel,' which is typical for the region. We could call this type of pixel, which contains some below water signal, a regional dark pixel, but in the following discussion we will just call it a dark pixel. It is the background signal from which we start any further signal processing.

Mathematically we can write this decomposition as:

$$L_T(\lambda) = L_a(\lambda) + \mathcal{T}(\lambda)(L_d(\lambda) + L_b(\lambda)), \quad (2)$$

$$= L_M(\lambda) + L_I(\lambda), \quad (3)$$

where L_M is the modeled spectrum, and L_I is the 'indicator' spectrum, it is simply the residual between the at sensor radiance minus any modeling we do for the spectrum. If L_M is simply chosen as a dark pixel in the scene than it is what is normally referred to as 'dark pixel subtraction', a very simple but often effective scheme for atmospheric correction. The terms $L_d(\lambda)$ and $L_b(\lambda)$ are called the 'dark water' and 'bright water' contributions to $L_w(\lambda)$ respectively. The trick to this approach is finding (a probably empirical) model of dark pixel spectra that allow us to create a data based decomposition of L_T (λ) to identify one or more dynamic water constituents of interest. To find such a model we start by examining an image from HICO^{TM} of the at-sensor radiance (L1B) for a typical dark water scene, in this case the waters around Midway Atoll (**Fig. 6**).

To create an empirical model to fit the 'dark water' pixels shown by the circles in **Fig. 6** we take a guess at the following functional form:

$$L_m(\lambda) = (a + b(\lambda - \lambda_1))^{-4} \quad (4)$$

where a and b are model parameters which are to be estimated from the spectral data λ_n and $L_m(\lambda_n)$ and λ_1 is the first value of the wavelength in data set being modeled, a constant. In HICO L1B data sets, each at-sensor pixel consists 90 radiance values between about 400 nm to 900 nm. The typical swath size covers approximately 42 km by 190 km, and 500 by 2000 pixels. To 'model' the data we limit our data sets to wavelengths between 450 nm to 900 nm, so in our data sets λ_1 = 450 nm and λ_N = 900 nm. As expected the model works well for the Midway Image which is in clear waters. We have subsequently applied it to the Columbia River and Yangtze River HICO images to use it to differentiate the plume features. Those results are shown in the results section below.

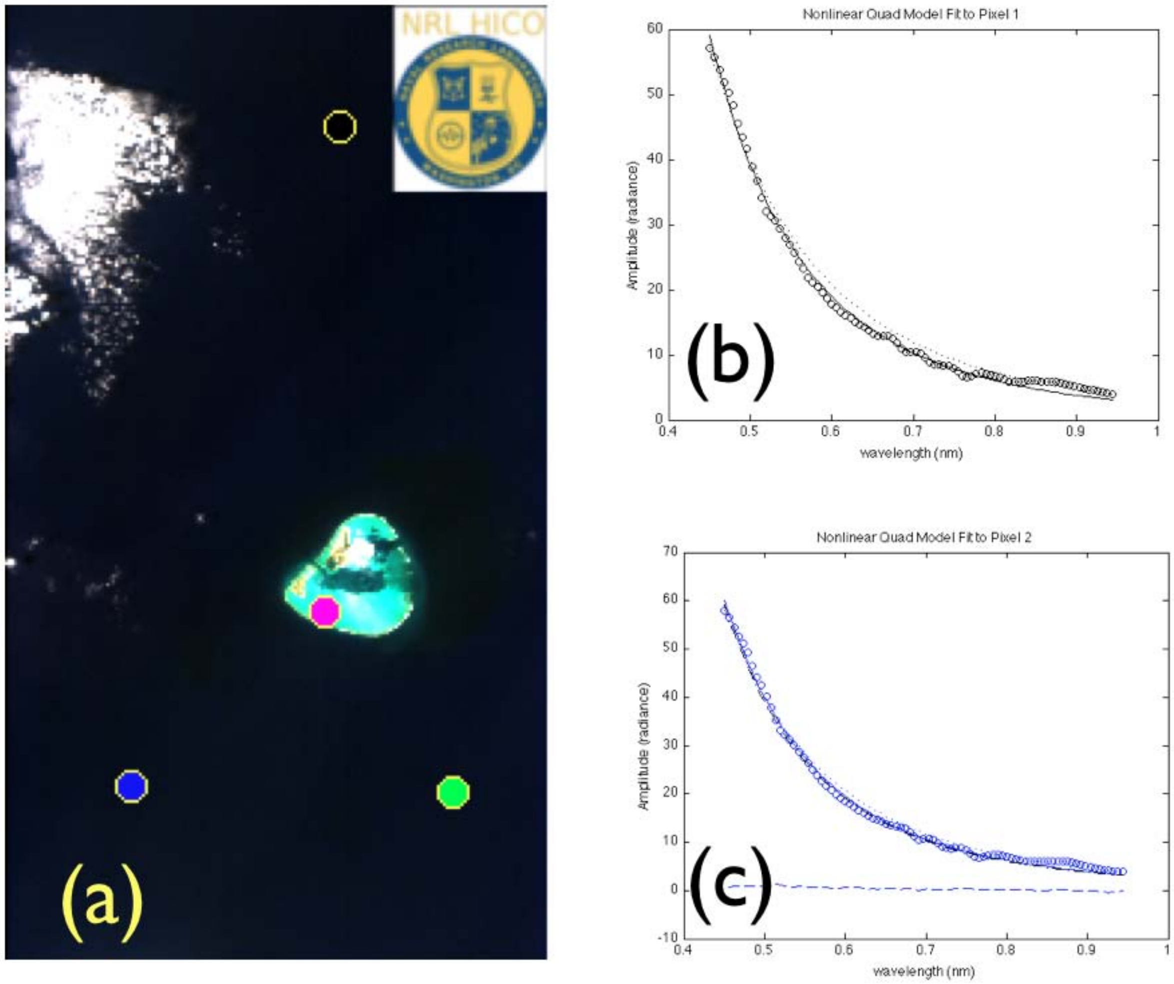


Figure 6. Image of Midway Atoll and selected spectra at indicated points. (a) HICO™ RGB image from 25 March 2010. Bright circles indicate regions for the spectra shown in Fig. 1 (b). The black, blue, and green dots indicate regions we expect to see 'typical' dark pixel spectra — i.e. clear water spectrum's. The magenta dot indicates an example of a (very) bright spectrum. The image is composed from at-sensor radiances, L1B data is supplied by NRL's HICO™ team [Corson 2010]. (b) At-sensor radiance for black pixel in Fig. 1 (a). The raw data is indicated by circles. The initialization for the nonlinear fit is shown by the dashed line. The final nonlinear fit to the dark pixel empirical model is shown by the solid line. (c) At-sensor radiance for blue pixel in Fig. 1 (a). The lower line shows the difference with the black pixel in Fig. 1 (b) which is essentially zero.

As HICO project scientist, I am funded by NRL to continue to work with the engineers and scientists at NRL and partner institutions to prepare for the processing and analysis of HICO™ data. The NRL team will process the HICO™ data to standard products. At OSU we will have an identical copy of the HICO processing system and will process and distribute data for academic users and international partners.

While HICO is now flying on the ISS 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 higher 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 5 out of 62 on the 2008 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 producing products like bathymetry and bottom types.

RESULTS

The focus of this effort is on the processing and analysis of HICO™ data to demonstrate the utility of hyperspectral imaging for characterization of coastal waters. Our efforts are particularly focused on river systems and we have conducted initial analysis of HICO™ data for the Columbia and Yangtze Rivers. During this first year we have processed an extensive set of MERIS data for the Columbia River and Oregon Coastal Waters. We have also collected an extensive set of in situ data for validation of products off the Oregon Coast.

We have also processed the available HICO™ images testing a variety of algorithms to evaluate their use for river systems. We have applied the Plume Indicator approach described above to 4 images of the Columbia River (**Fig. 7**). The results are very encouraging.

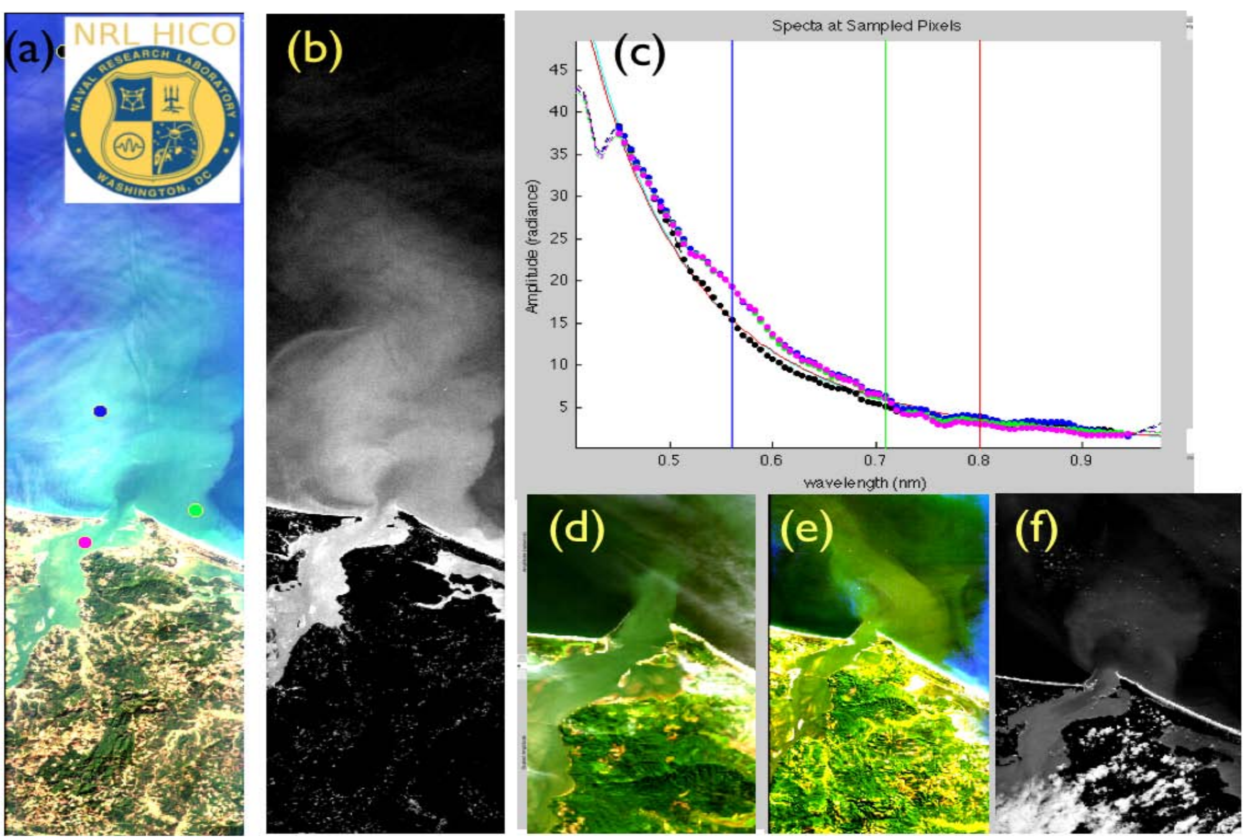


Figure 7: Images of Columbia River with indicator map highlighting sediments: (a) L1B HICO™ image of Columbia River mouth 19 March 2010. (b) An indicator for sediments in the Columbia River based on the dark pixel spectral separation for the image presented in Fig. 7(a). (c-f) Typical spectra and sediment indicator maps for three HICO images from July 2010.

We are extending this approach by using more realistic models for removing the underlying spectral trends from the solar spectrum and the Rayleigh scattering in the atmosphere. Further we are then using derivative spectra to identify the constituents in the plumes to track and quantify them.

HICO has been on the ISS for one year. Over 1700 images have been collected for sights around the world. HICO is operating as planned and the initial data products look very good. HICO operations have been extended to three years. We continue to work with the NRL team on the on-orbit calibration and validation of HICO. As Project Scientist it is my goal to work with the scientific community to make the best possible use of this unique data set.

IMPACT/APPLICATIONS

The long term goal of this work is demonstrate the value of 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 are using data from HICO on the ISS to demonstrate that capability. 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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