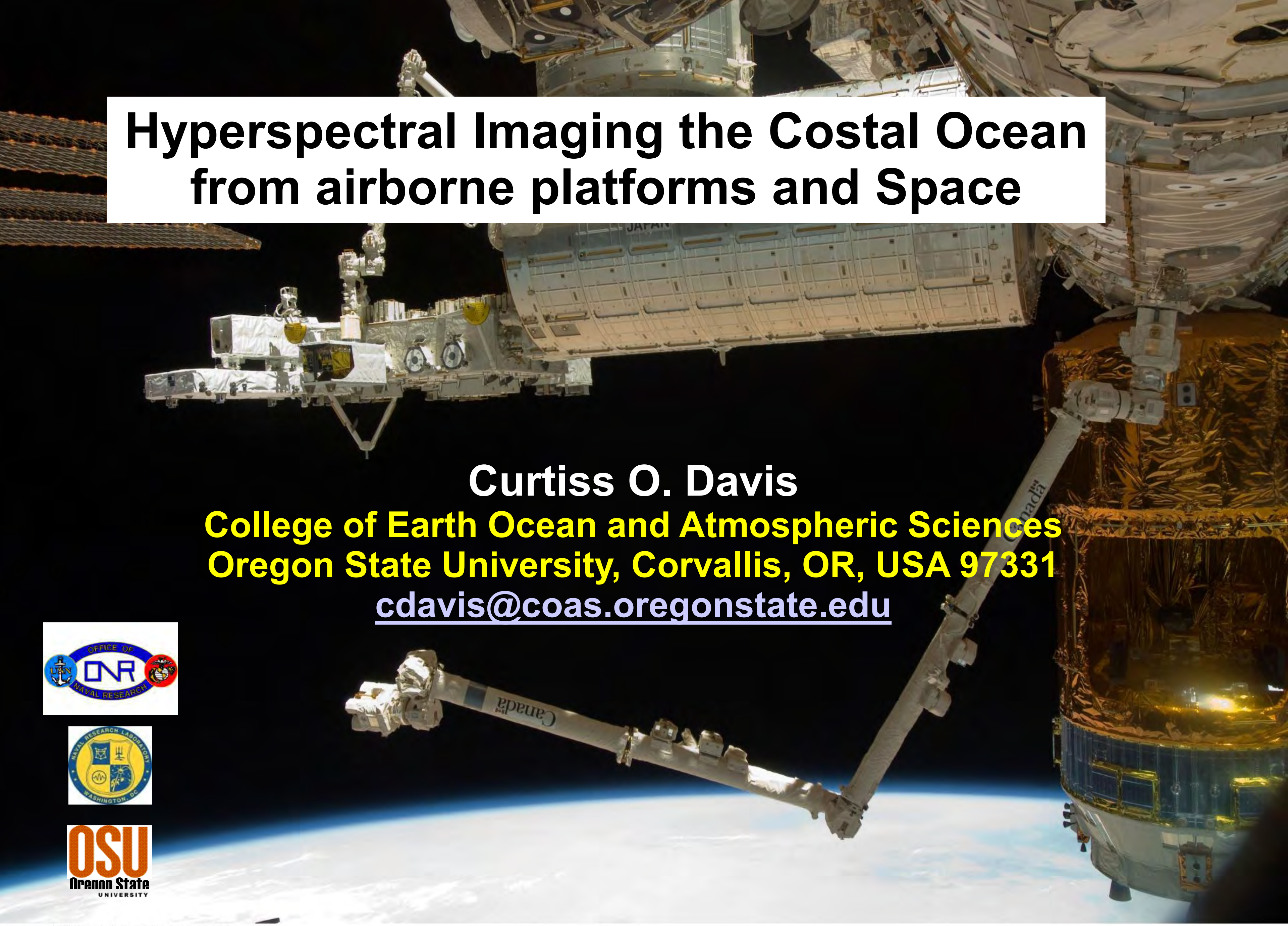


Hyperspectral Imaging the Costal Ocean from airborne platforms and Space

Curtiss O. Davis

College of Earth Ocean and Atmospheric Sciences

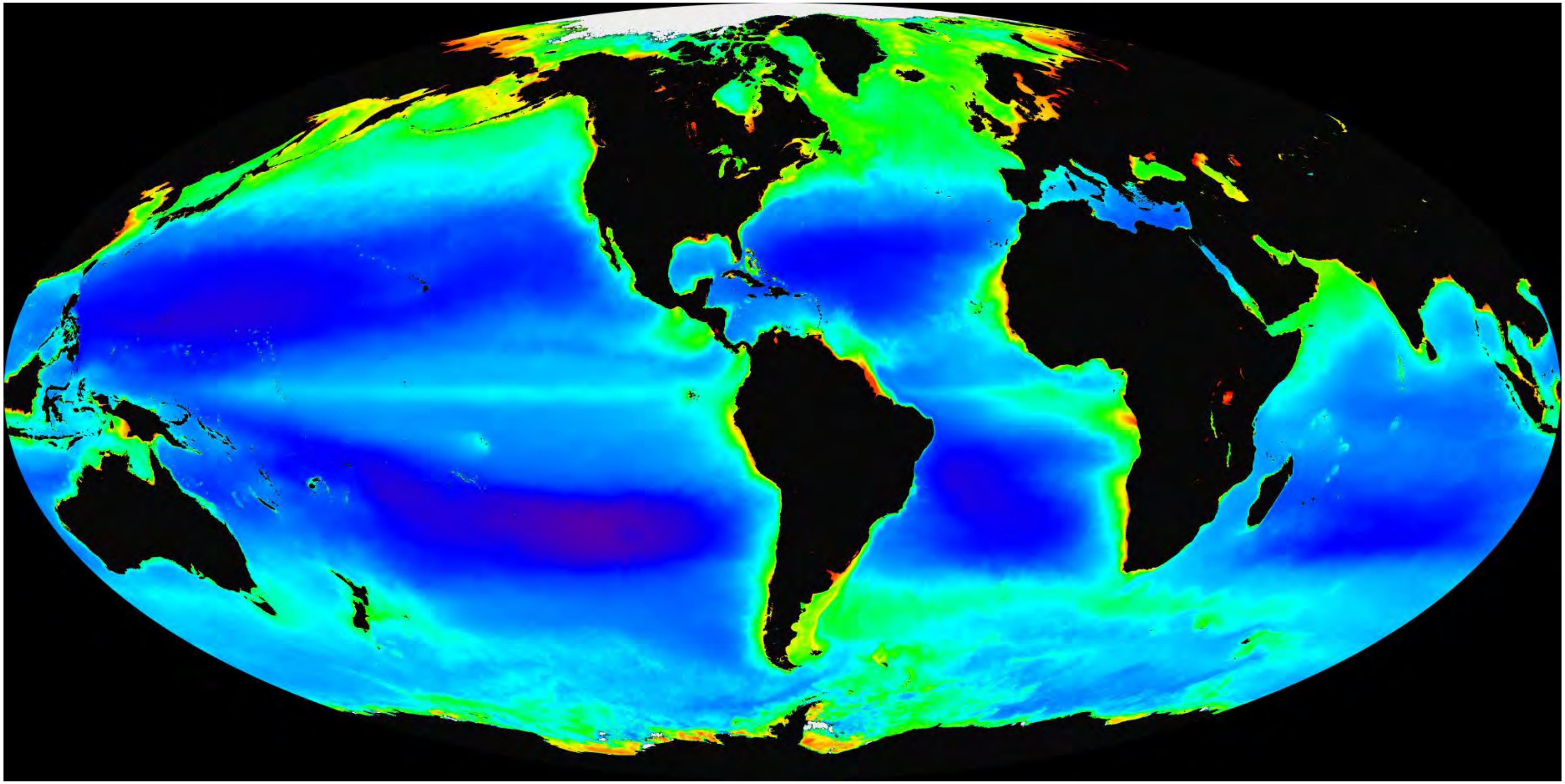
Oregon State University, Corvallis, OR, USA 97331

cdavis@coas.oregonstate.edu

Introduction and Outline

- Why use hyperspectral imaging for the coastal ocean?
- Airborne systems, Hyperion on EO-1
- The Hyperspectral Imager for the Coastal Ocean (HICO)
  - How it came to be
  - The challenge of operating on the International Space Station (ISS)
- What we can see with HICO?
- Access to HICO data via. COAS HICO website
- Vision for the future

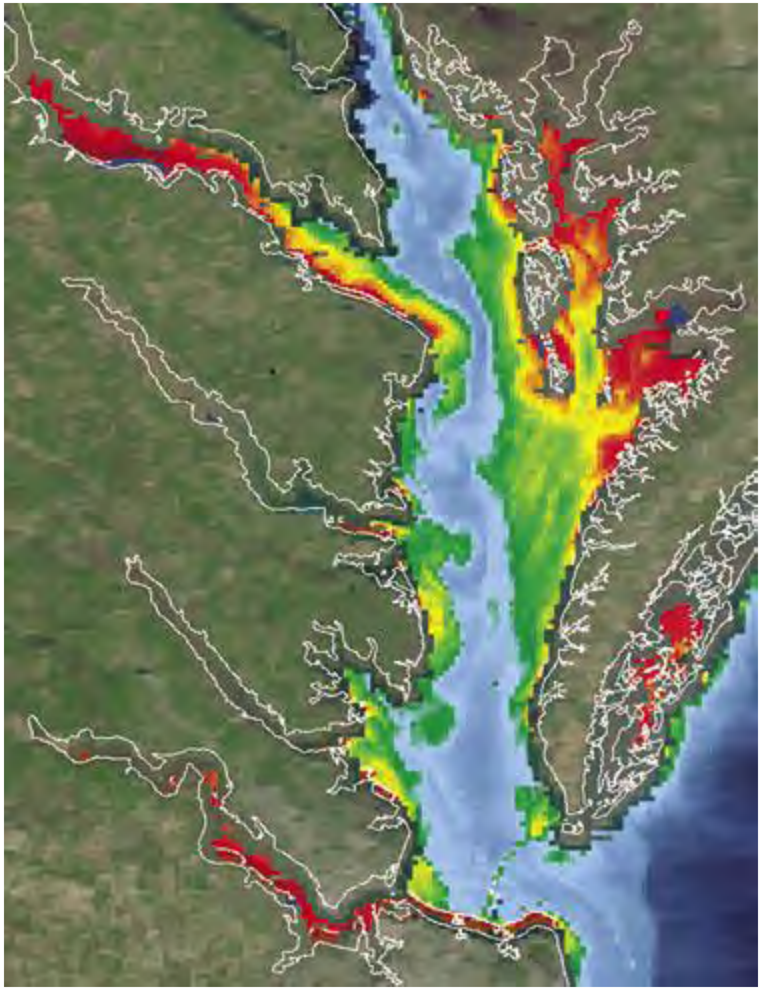
SeaWiFS Global Ocean Chlorophyll

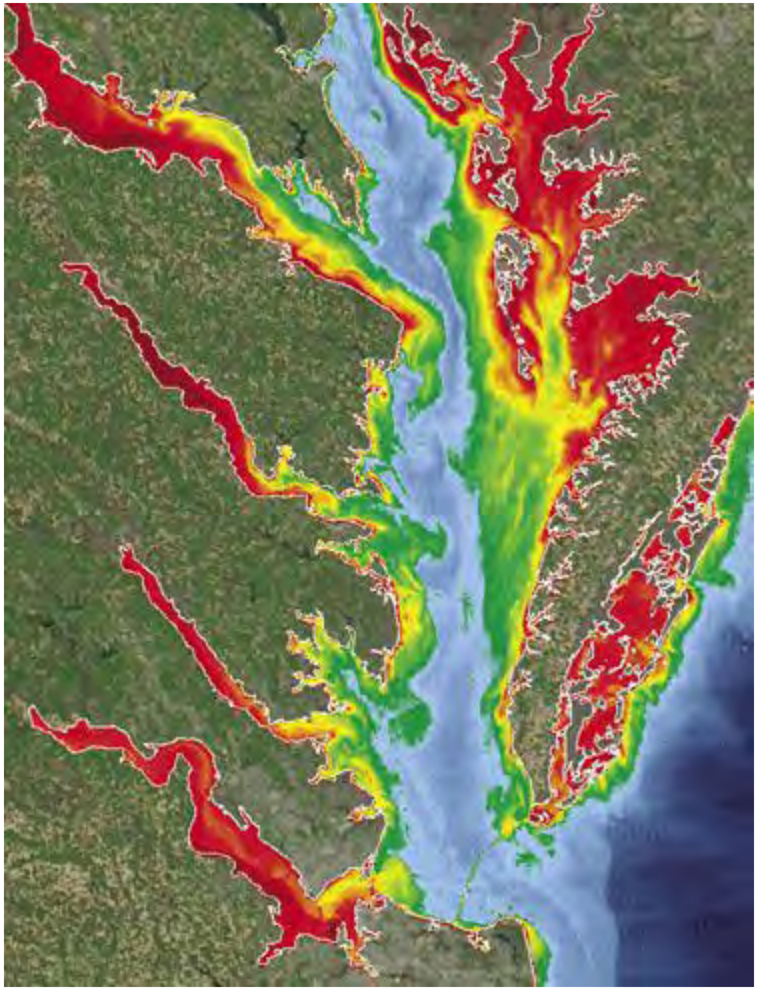


Seven year composite of the global distribution of chlorophyll from SeaWiFS data (blue low and yellow high concentrations).

For Coastal Management we need Higher Resolution

Images of Chesapeake Bay and surrounding area





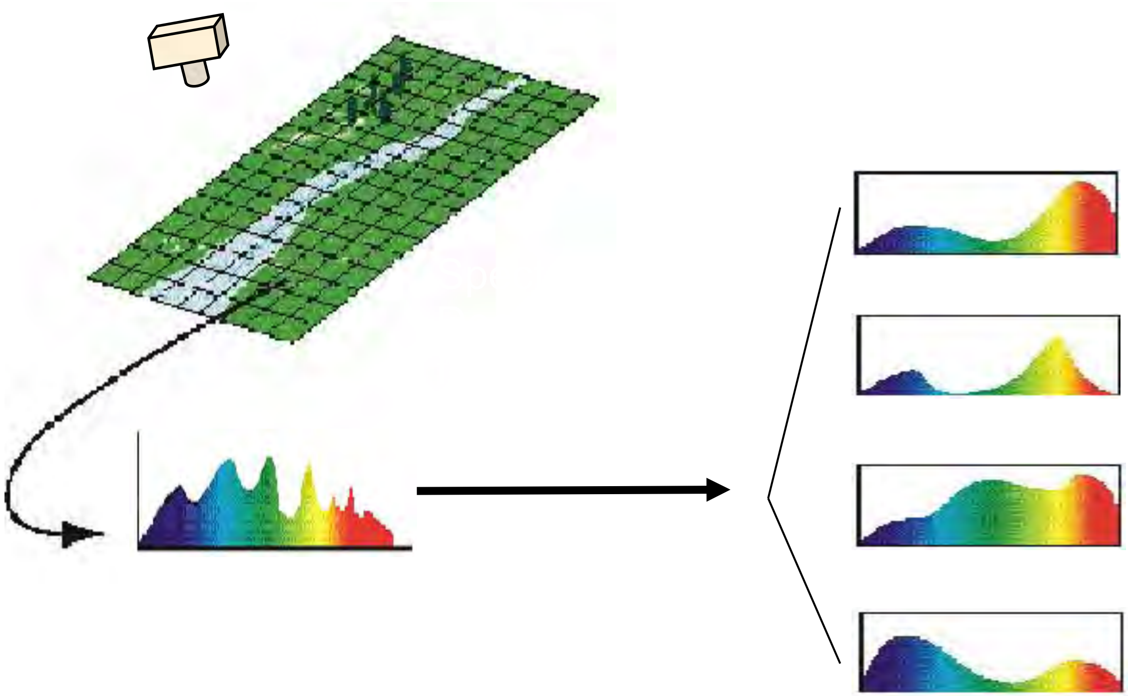
MODIS 1 km water clarity   MODIS simulated water clarity at 250 m

The Coastal Challenge

- In the **open ocean** there are two optical components the water and the Phytoplankton (single celled plants that are the base of the ocean food chain)
  - 4-5 spectral channels can resolve this (e. g. SeaWiFS)
- In the **coastal ocean** we add suspended sediments from rivers or re-suspension from the bottom and colored dissolved organic matter from decaying plants.
  - Need 10 or more channels (e.g. MERIS)
- **Near shore we can also image the bottom** (to 20 m in clear waters) which can have reflectance from the sediments, rocks, coral reefs, algae, etc. Now we have a very difficult chore to resolve this complexity. Need to sample the full spectrum of light that penetrates the water column.
  - HICO with 90 channels is the first sensor in space designed to do this
  - PACE, ACE, GEO-CAPE and HyspIRI planned to be hyperspectral

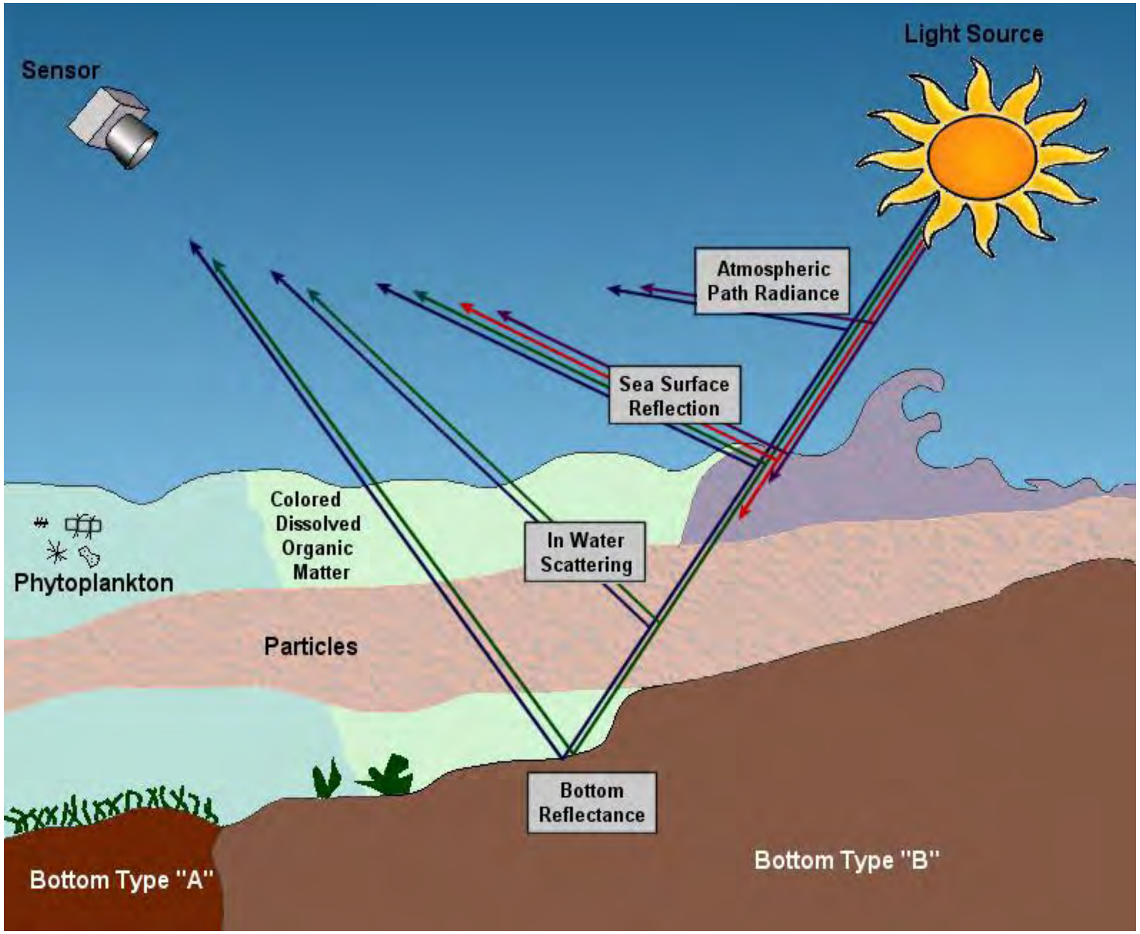
Introduction to Hyperspectral Imaging

- A hyperspectral imager records a spectrum of the light from each pixel in the scene
- Hyperspectral image analysis exploits this extra spectral information



The imager and method of exploitation must be tailored to the scene and the desired products.

Optical Components of a Coastal Scene



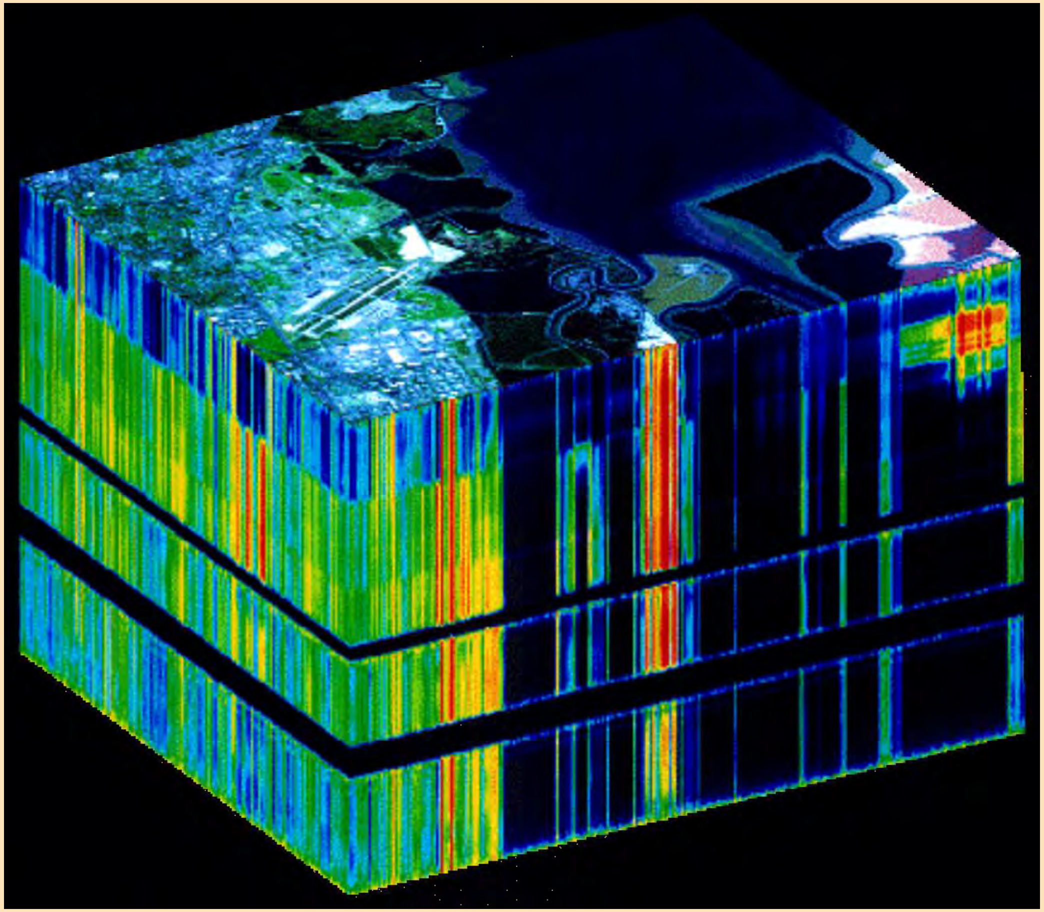
- Multiple light paths
- Scattering due to:
  - atmosphere
  - aerosols
  - water surface
  - suspended particles
  - bottom
- Absorption due to:
  - atmosphere
  - aerosols
  - suspended particles
  - dissolved matter
- Scattering and absorption are convolved

Physical and biological modeling of the scene is often required to analyze the hyperspectral image.

What we need to solve this problem

- A stable, well-calibrated sensor with high SNR, Good Characterization and Calibration
- Airborne:
  - AVIRIS
  - PHILLS
  - SAMSON
  - CASI-1500 (CHARTS)
  - PRISM
- Spaceborne:
  - Hyperion
  - HICO
- HICO Data Access
- Algorithms (next lecture)

Airborne Visible/Infrared Imaging Spectrometer (AVIRIS)



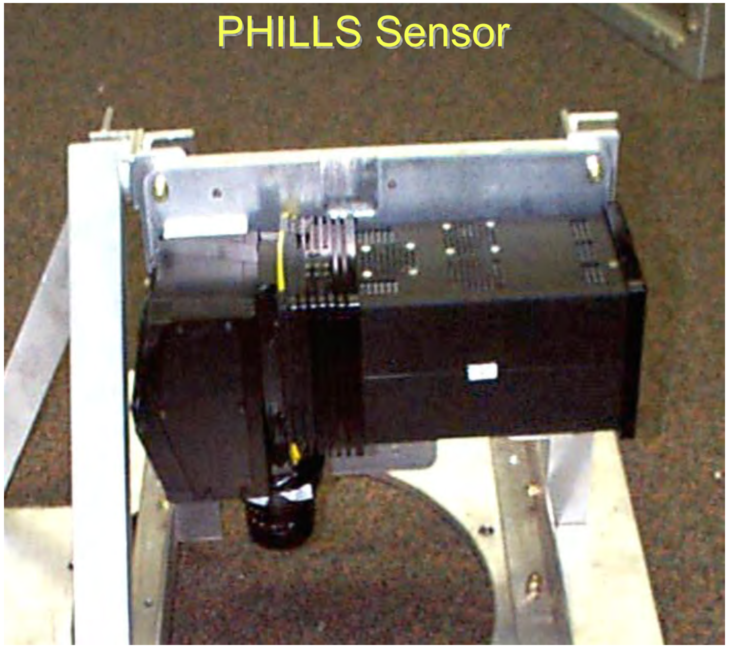
- One of a Kind Instrument Built and Operated by JPL for NASA http://aviris.jpl.nasa.gov/
- Flown on NASA's ER-2 at 20km Altitude 20m Ground Sample Distance (GSD), or on a Twin Otter for 4 m GSD
  - 220 (10nm) Spectral Bands
  - 0.4 to 2.5 µm
- AVIRIS Image Cube
  - Moffet Field, CA
  - Top of Image RGB From 3 Spectral Bands
  - Sides - Spectral Dimension of the Edge Pixels
    - Red ⇒ High Signal
    - Purple ⇒ Low Signal

The NRL Portable Hyperspectral Imager for Low-light Spectroscopy (PHILLS)

Ocean PHILLS is a push-broom imager.

- f 1.4 high quality lens, color corrected and AR coated for 380 –1000nm.
- all reflective spectrograph with a convex grating in an Offner configuration to produce a distortion free image (Headwall, Fitchburg, MA).
- 1024 x 1024 thinned backside illuminated CCD camera (Pixel Vision, Inc, Beaverton, OR).
- Images 1000 pixels cross track and is typically flown at 3000 m altitude yielding 1.5 m GSD and a 1500 m wide sample swath.

(C. O. Davis, et al., (2002), Optics Express 10:4, 210--221.)



SAMSON

Spectroscopic Aerial Mapping System with On-board Navigation

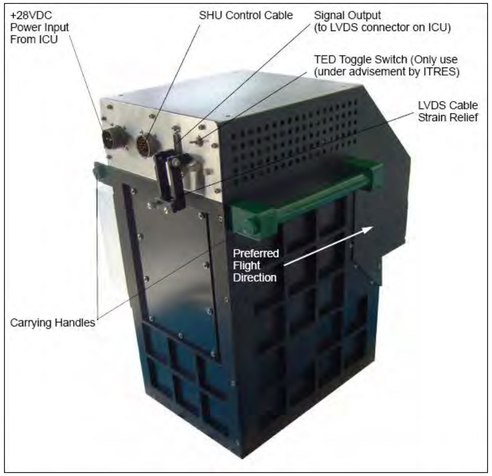
- The Florida Environmental Research Institute (FERI) has developed a low-cost, robust Hyperspectral Imager, the Spectroscopic Aerial Mapper with On-board Navigation (SAMSON).

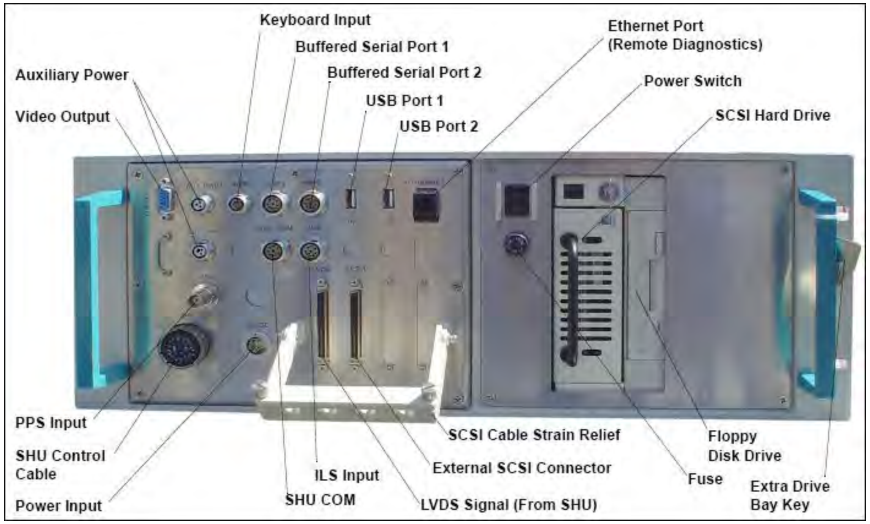
- SAMSON provides for a full HSI dataset 256 bands in the VNIR (3.5 nm resolution over 380 to 970 nm range) at 75 frames per second, with a SNR, stability, dynamic range, and calibration sufficient for dark target spectroscopy.

- Data sampled at 5 m GSD and binned to 10, 100, and 300 m to evaluate need for higher GSD.

CASI-1500 (ITRES, Calgary, Canada)

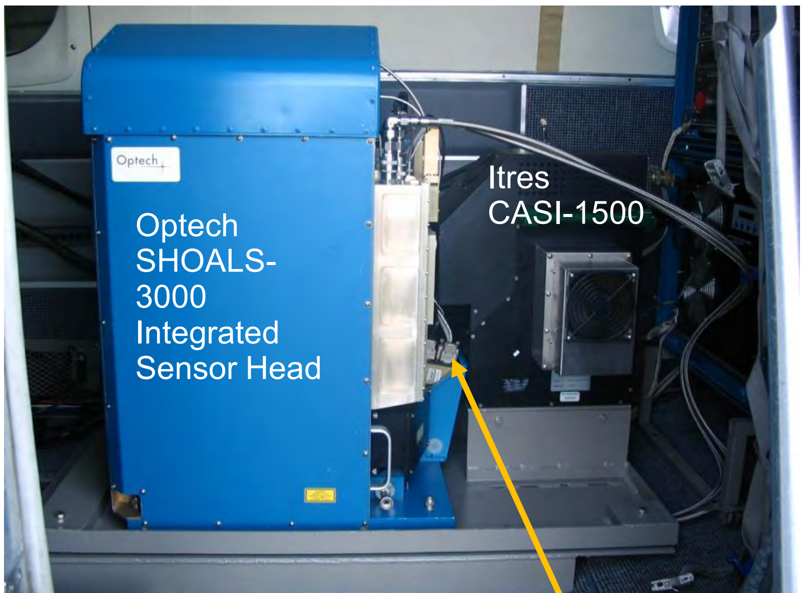
- Field of view
  - 40 acrosstrack
  - 0.028 alongtrack
- Spectral range
  - 375-1050 nm
- Spectral samples
  - 288 at 1.9 nm intervals
- Aperture
  - f/2.8 to f/10
- Dynamic range
  - 16384:1 (14 bits)
- Noise floor
  - ~ 3.0 DN
- Signal to noise ratio
  - 480:1 peak
- Calibration accuracy
  - 470 – 800 nm 2%
  - 430 – 870 nm 5%





JALBTCX CHARTS sensor suite

CHARTS
COMPACT HYDROGRAPHIC AIRBORNE RAPID TOTAL SURVEY

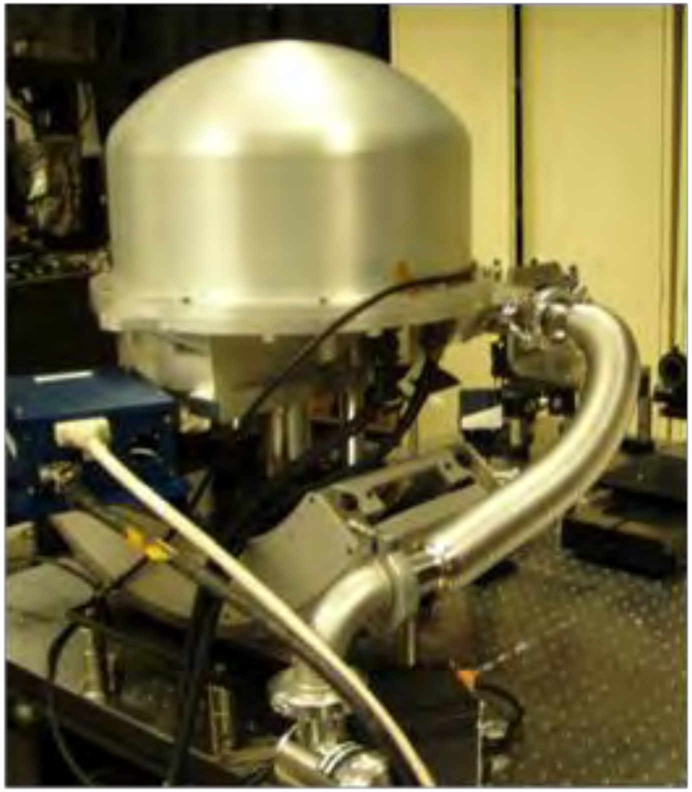


Duncan Tech-400 RGB Camera

PRISM

Portable Remote Imaging Spectrometer JPL facility instrument built specifically for ocean color

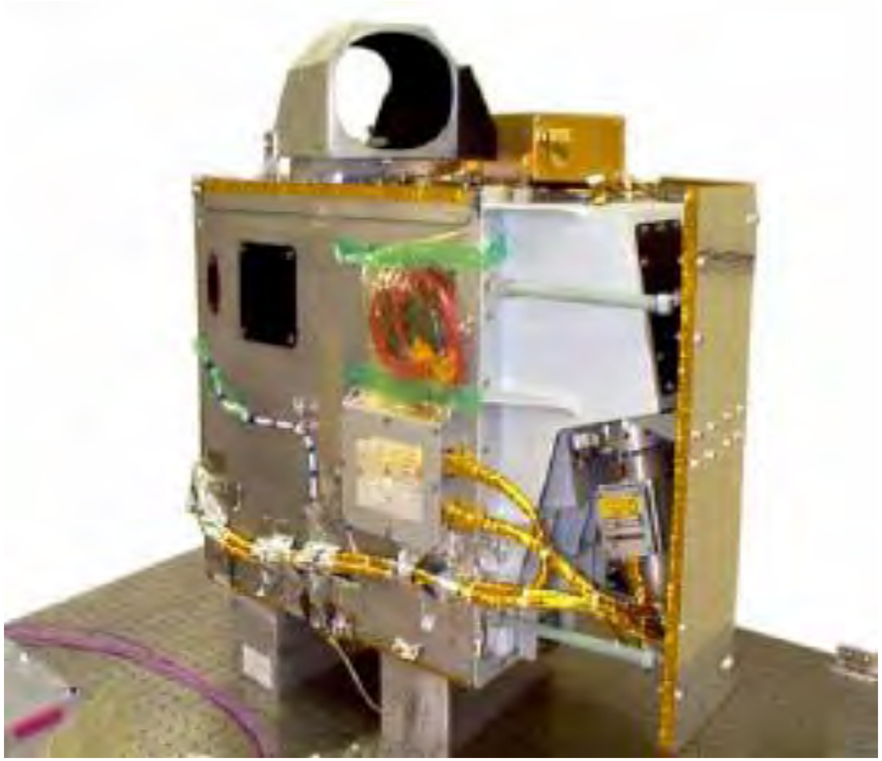
- Dyson Spectrometer
- 350 nm and 1050 nm at 5 nm
- <1% polarization sensitivity
- GSD of 2-5 m
- Very High SNR (>1500:1)
- two-channel spot radiometer at short-wave infrared (SWIR) band (1240 nm and 1640 nm)
- Completing test flights in 2012



Hyperion on EO-1

Hyperion is a push-broom imager

- 220 10nm bands covering 400nm - 2500nm
- 6% absolute rad. accuracy
- Swath width of 7.5 km
- IFOV of 42.4 μradian
- GSD of 30 m
- 12-bit image data
- Orbit is 705km alt (16 day repeat)
- Designed as a land imaging demonstration
- Low SNR for ocean imaging



HICO based on experience with PHILLS

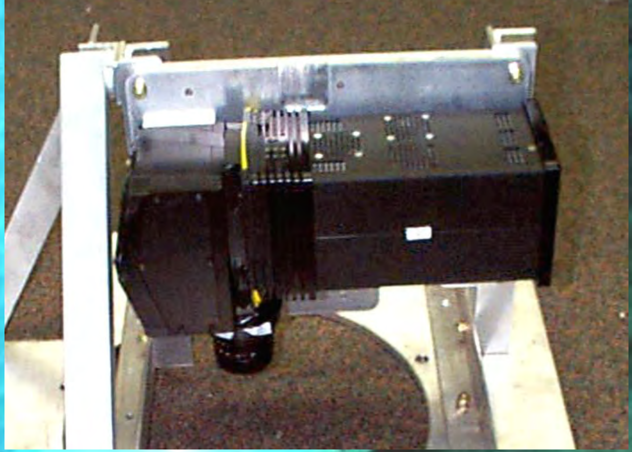
AN-2 Aircraft

PHILLS image of shallow water features near Lee Stocking Island, Bahamas as part of CoBOP Experiment

Airborne Experiments with the Portable Hyperspectral Imager for Low-Light Spectroscopy (PHILLS) demonstrated:

- Sensor design.
- Processing algorithms.
- Shallow water bathymetry, hazards to navigation, and beach trafficability from hyperspectral remote sensing data.

PHILLS Sensor



NRL Radiometric and Image Calibration Facilities

17" off-axis collimated beam source and reticule projector system

Uniform field radiometric calibration sources, standardized in-lab using NIST-traceable lamps and transfer radiometer

NASA Calibration Round-Robin Results

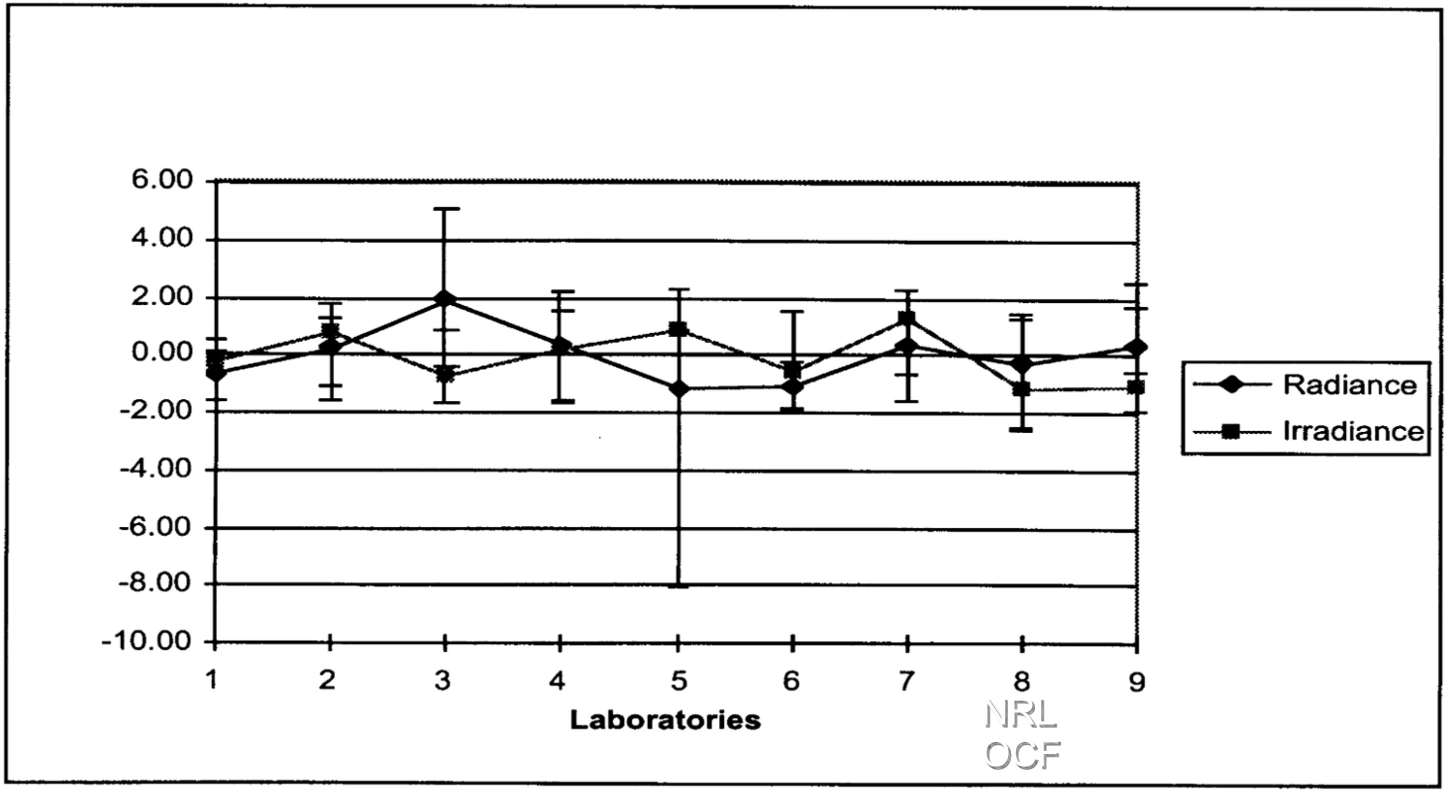


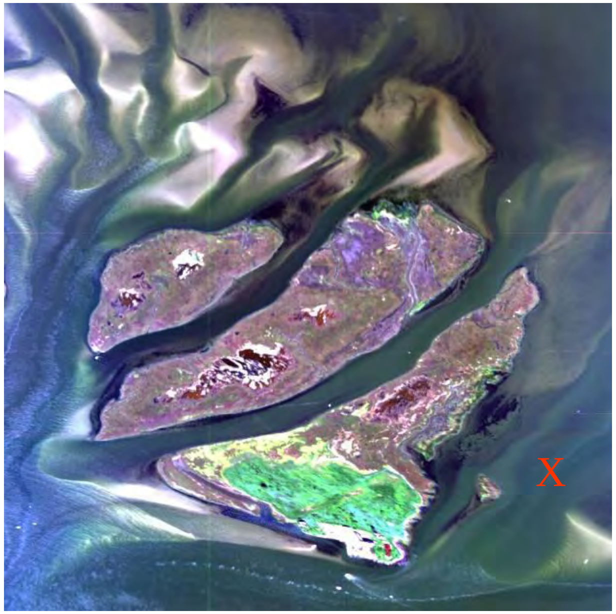
Figure 6. Percent Difference From Mean, Radiance and Irradiance

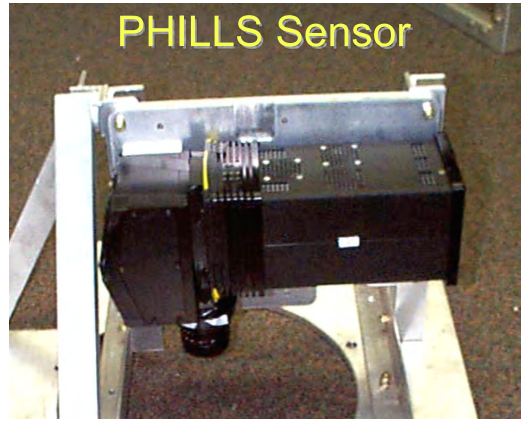
- One can Expect +/- 2% Accuracy From Quality Laboratory Calibrations
- NRL has participated in three NASA round-robins over the past 6 years

Calibration of PHILLS and AVIRIS and Validation of Algorithms

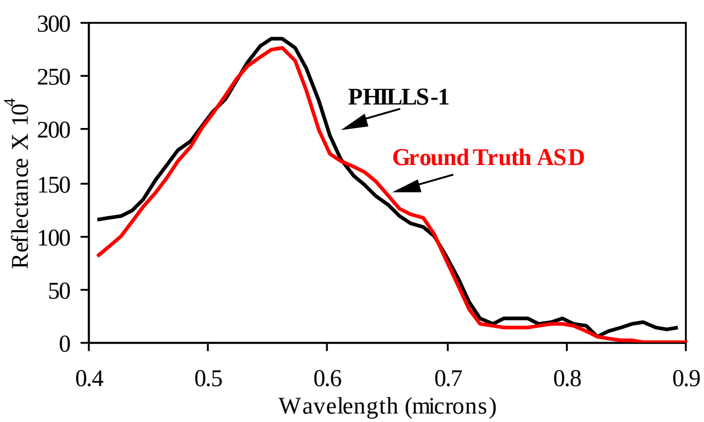
- Sensors are characterized in the laboratory to assess performance and identify any artifacts, such as, misalignment, smile or keystone.
  - Instruments are adjusted to correct the defect, or software is created to correct the data.
- Calibration data to be maintained are:
  - The center position of each spectral channel (< +/- 1 nm)
  - The gain and offset for conversion from counts to radiance (< +/- 2%).
- PHILLS Calibration is based on laboratory calibration measurements and ground validation sites.
- We validate the atmospheric correction by comparing surface reflectance from PHILLS or AVIRIS data with direct measurements of that parameter.
- Testing and validation of algorithms using PHILLS and AVIRIS data with extensive ground truth from the ONR HyCODE and CoBOP experiments.

Extensive In-situ data for product validation at LEO-15 site, New Jersey, USA (HyCODE)

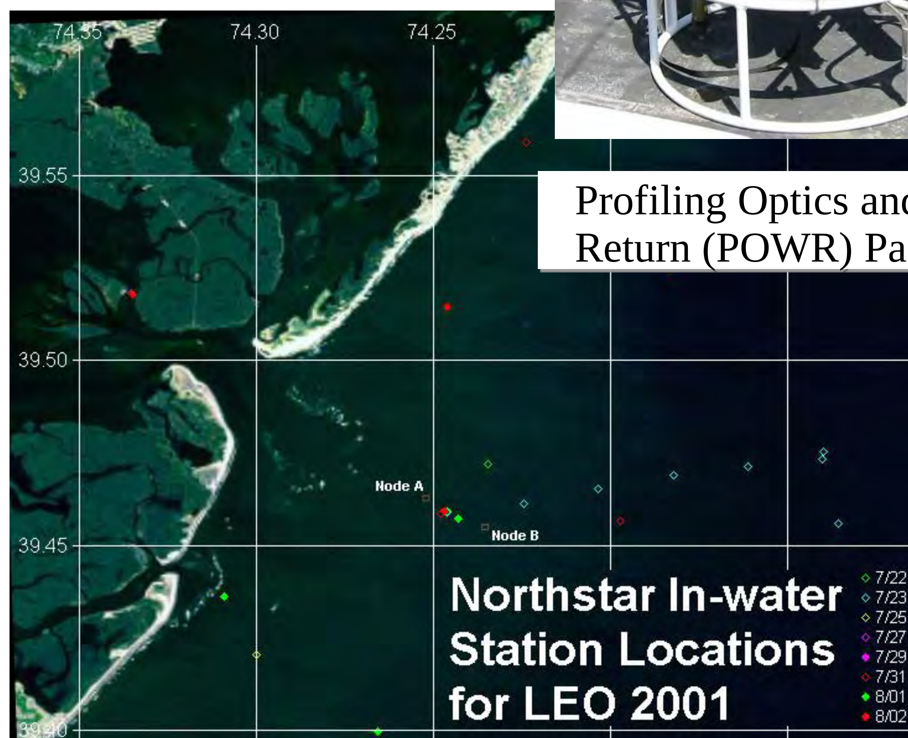




Profiling Optics and Water Return (POWR) Package



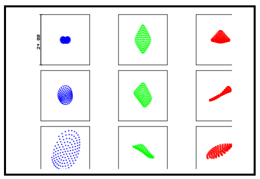
Comparison at the X. (C. O. Davis, et al., (2002), Optics Express 10:4, 210--221.)

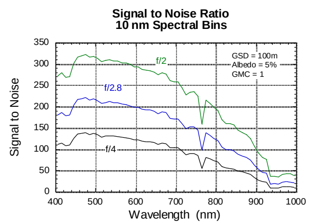


NRL Airborne Coastal Environmental Hyperspectral Program

20 years end-to-end development of airborne coastal hyperspectral imaging

Sensor Performance Modeling





Sensor Development

Sensor Calibration

Flight Campaigns

Ground Truth

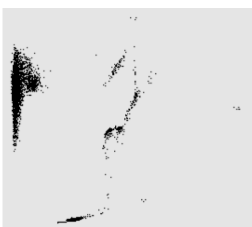
Data Processing

Product Extraction

Product Evaluation

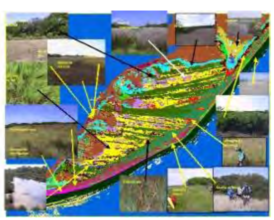
Requirements Evaluation

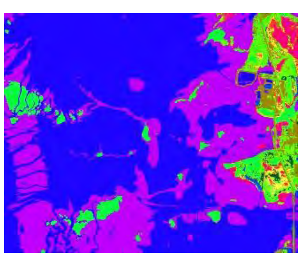
Spiral Development



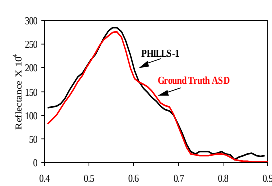
Nonlinear Manifold Analysis

PURSUIT Pattern Recognition / Classification





ORASIS Spectral Identification



TAFKAA Atmospheric Removal Algorithm

Georectification

What is the Hyperspectral Imager for the Coastal Ocean (HICO)?

- HICO is an experiment to see what we gain by imaging the coastal ocean at higher resolution from space.
- The HICO sensor:
  - first spaceborne imaging spectrometer for coastal oceans
  - samples coastal regions at <100 m GSD (400 to 900 nm: at 5.7 nm)
  - high signal-to-noise ratio to resolve the complexity of the coastal ocean
- Sponsored as an Innovative Naval Prototype (INP) by the Office of Naval Research: Goal to reduce cost and a greatly shortened schedule.
  - Start of Project to Sensor Delivery in 16 months
  - Launched to the ISS September 10, 2009

HICO image of Hong Kong, October 2, 2009.

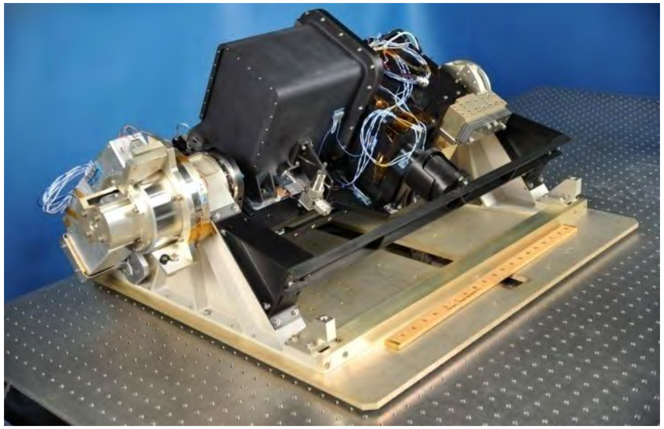
HICO is integrated and flown under the direction of DoD's Space Test Program

HICO Development Timeline

- March 2007: HICO manifested on Space Station JEM-EF

Beginning of HICO Space Station project

- June 2007: Preliminary Design Review
- November 2007: Critical Design Review
- May 2008: HICO imager delivery
- July 2008: HICO Test Readiness Review
- September 2008: HICO delivery to the HICO RAIDS Experimental Payload (HREP)



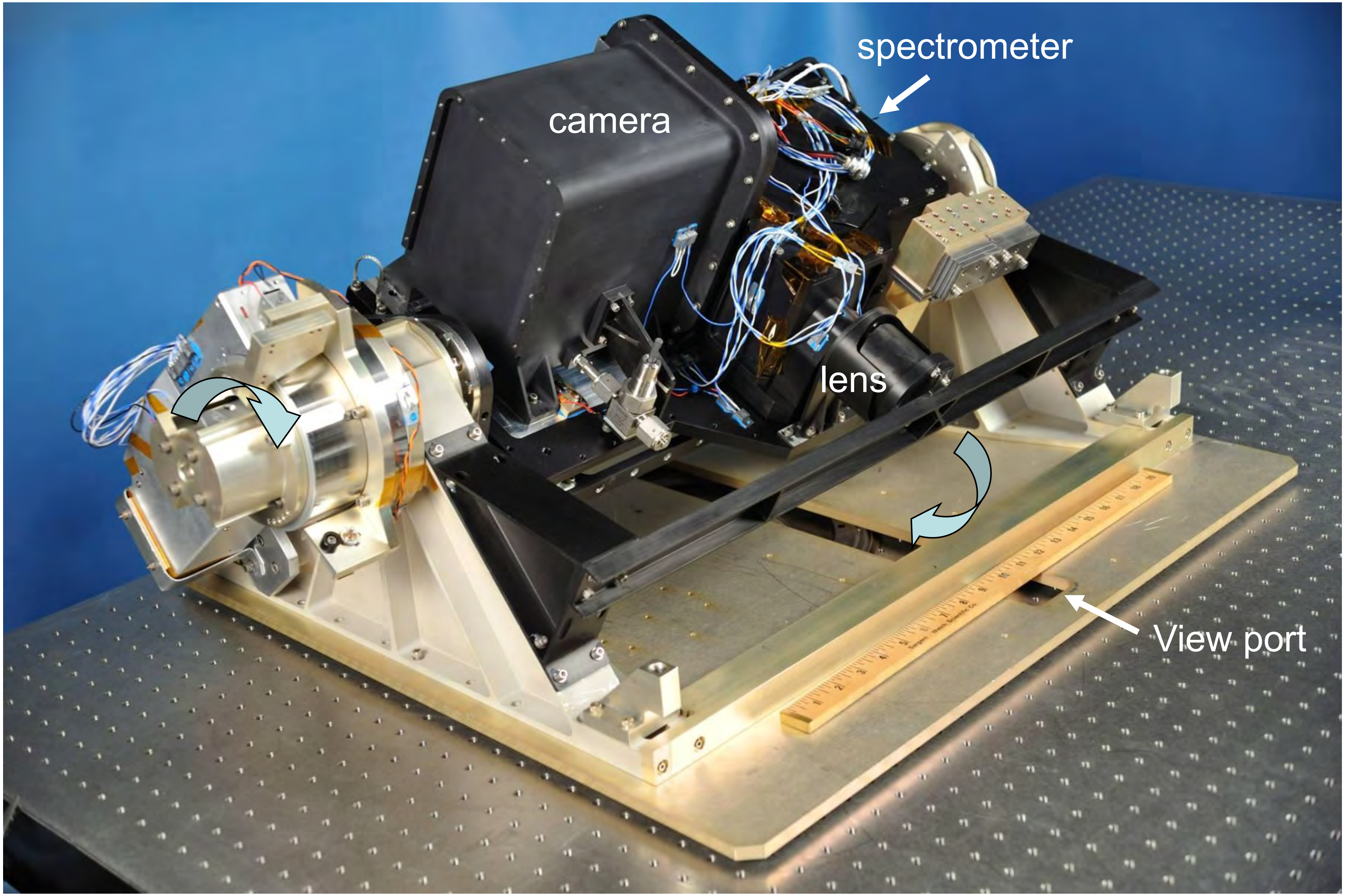
HICO flight imager

Project start to sensor delivery in 16 months

- September 10, 2009: Launch to Space Station
- September 24, 2009: HREP installed on Japanese Experiment Module and activated

HICO built and launched in 28 months vs. the norm of 10 years.

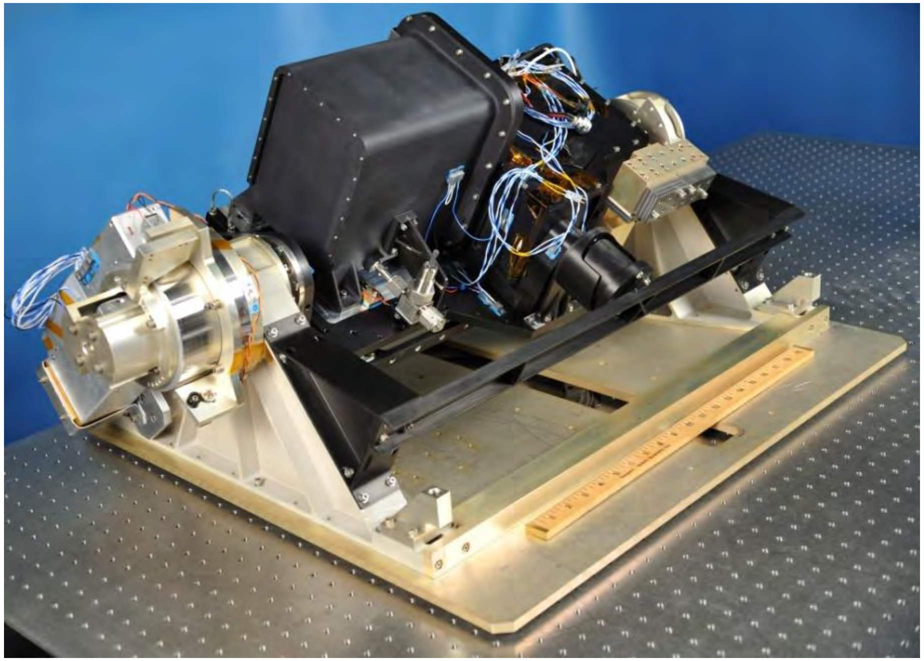
HICO Flight Sensor - Stowed position



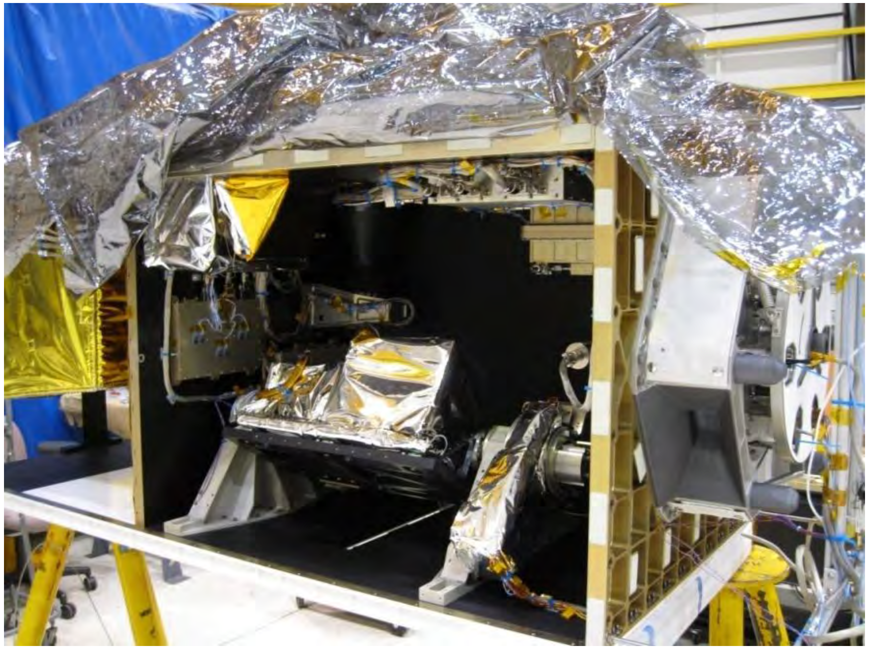
HICO meets Performance Requirements

Parameter	Performance	Rationale
Spectral Range	380 to 960 nm	All water-penetrating wavelengths plus Near Infrared for atmospheric correction
Spectral Channel Width	5.7 nm	Sufficient to resolve spectral features
Number of Spectral Channels	102	Derived from Spectral Range and Spectral Channel Width
Signal-to-Noise Ratio for water-penetrating wavelengths	> 200 to 1 for 5% albedo scene (10 nm spectral binning)	Provides adequate Signal to Noise Ratio after atmospheric removal
Polarization Sensitivity	< 5% (430-1000 nm)	Sensor response to be insensitive to polarization of light from scene
Ground Sample Distance at Nadir	92 meters	Adequate for scale of selected coastal ocean features
Scene Size	42 x 192 km	Large enough to capture the scale of coastal dynamics
Cross-track pointing	+45 to -30 deg	To increase scene access frequency
Scenes per orbit	1 maximum	Data volume and transmission constraints

Integrating HICO into HREP



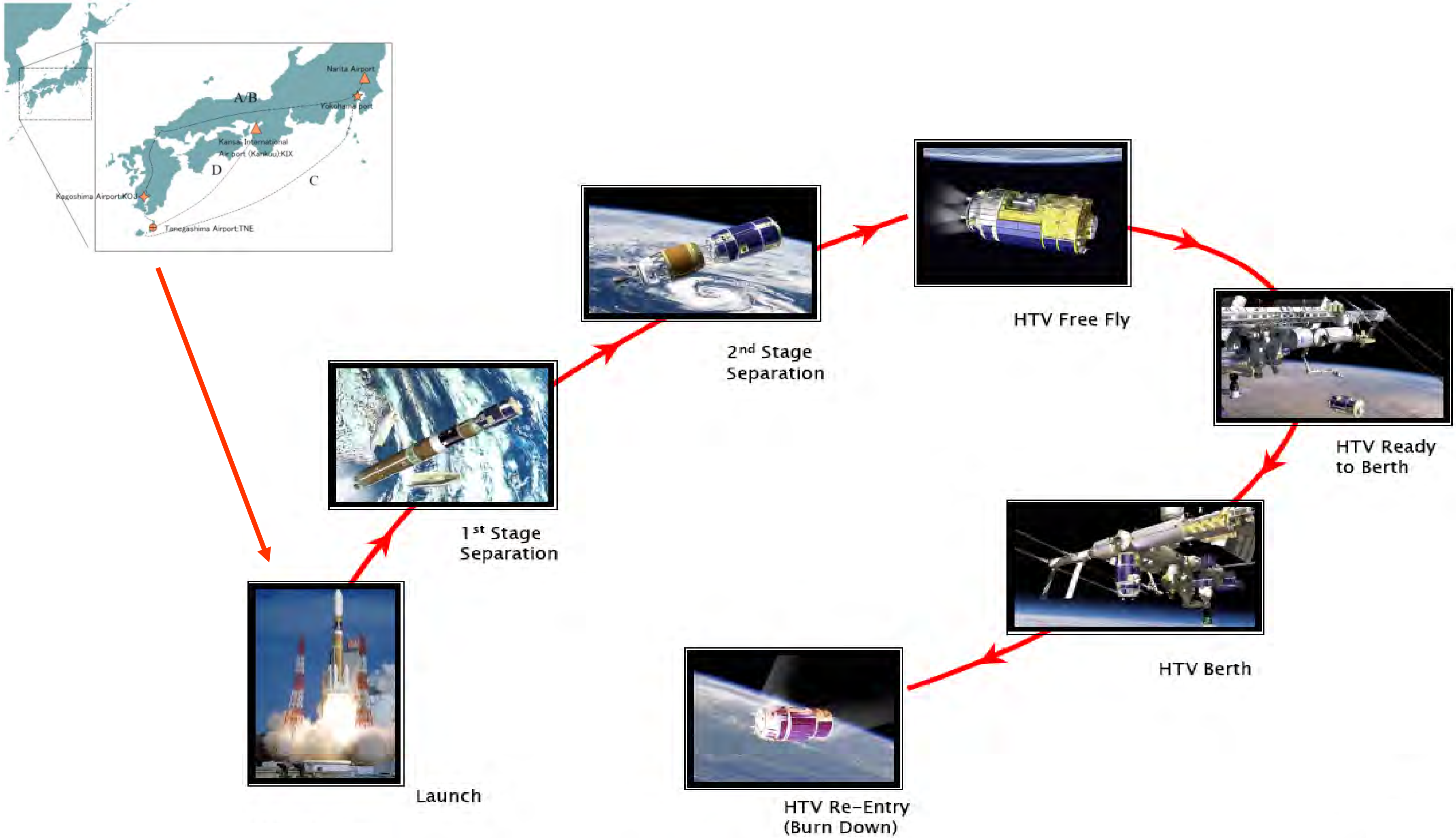
HICO flight imager in the Laboratory



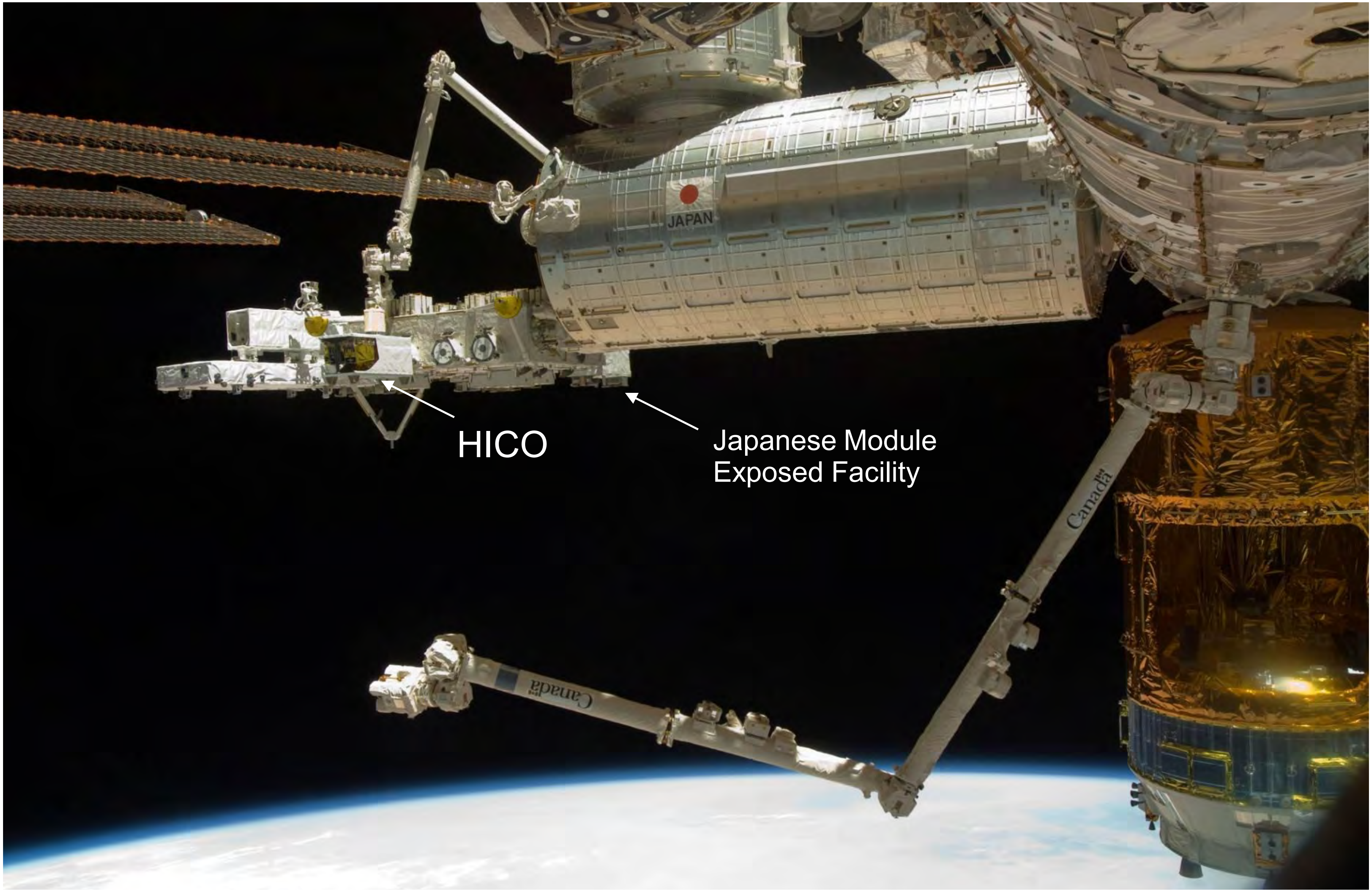
HICO with thermal blankets in HREP

HICO Launched to the ISS September 10, 2009

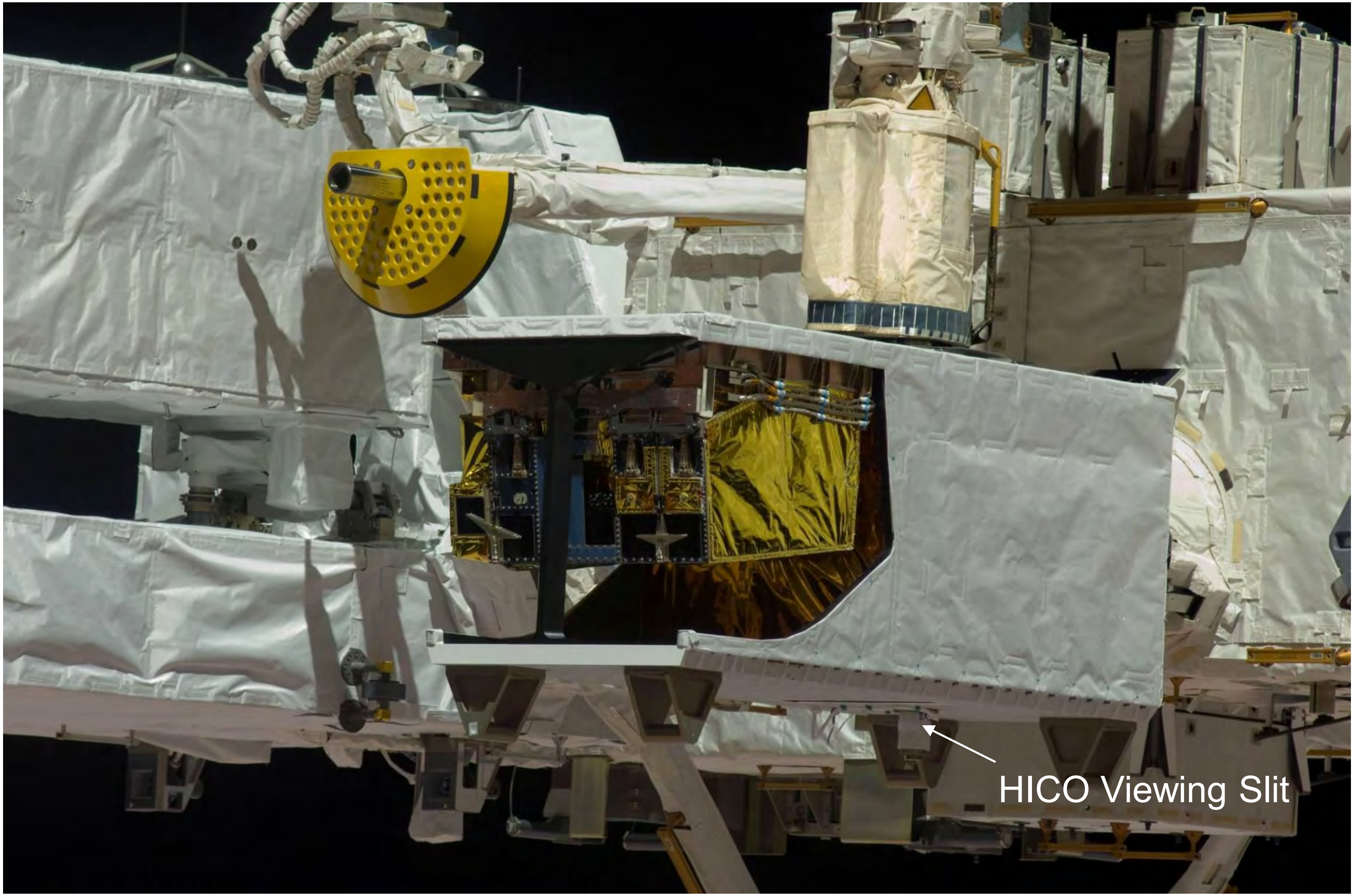
Launched from Tanegashima Island Space Center, Japan



HICO Installed on the ISS on September 24, 2009



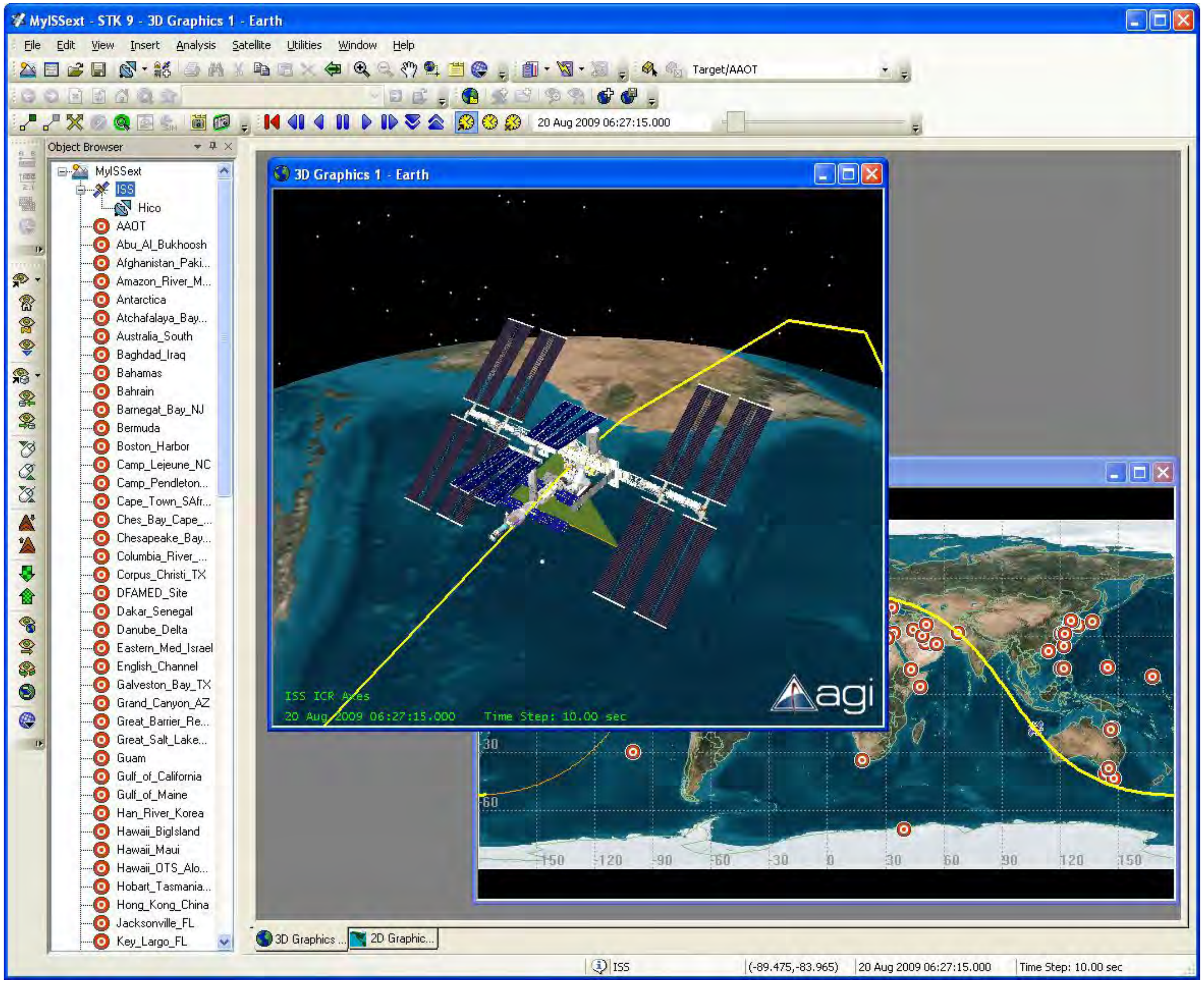
HICO docked at ISS – Now What?



Data Collection, Processing and Results

- Commanding HICO data collections
- HICO Image Locations
- Data Processing flow
- Example Images and Data
- HICO Web site and data distribution

Mission Planning with Satellite Tool Kit (STK)



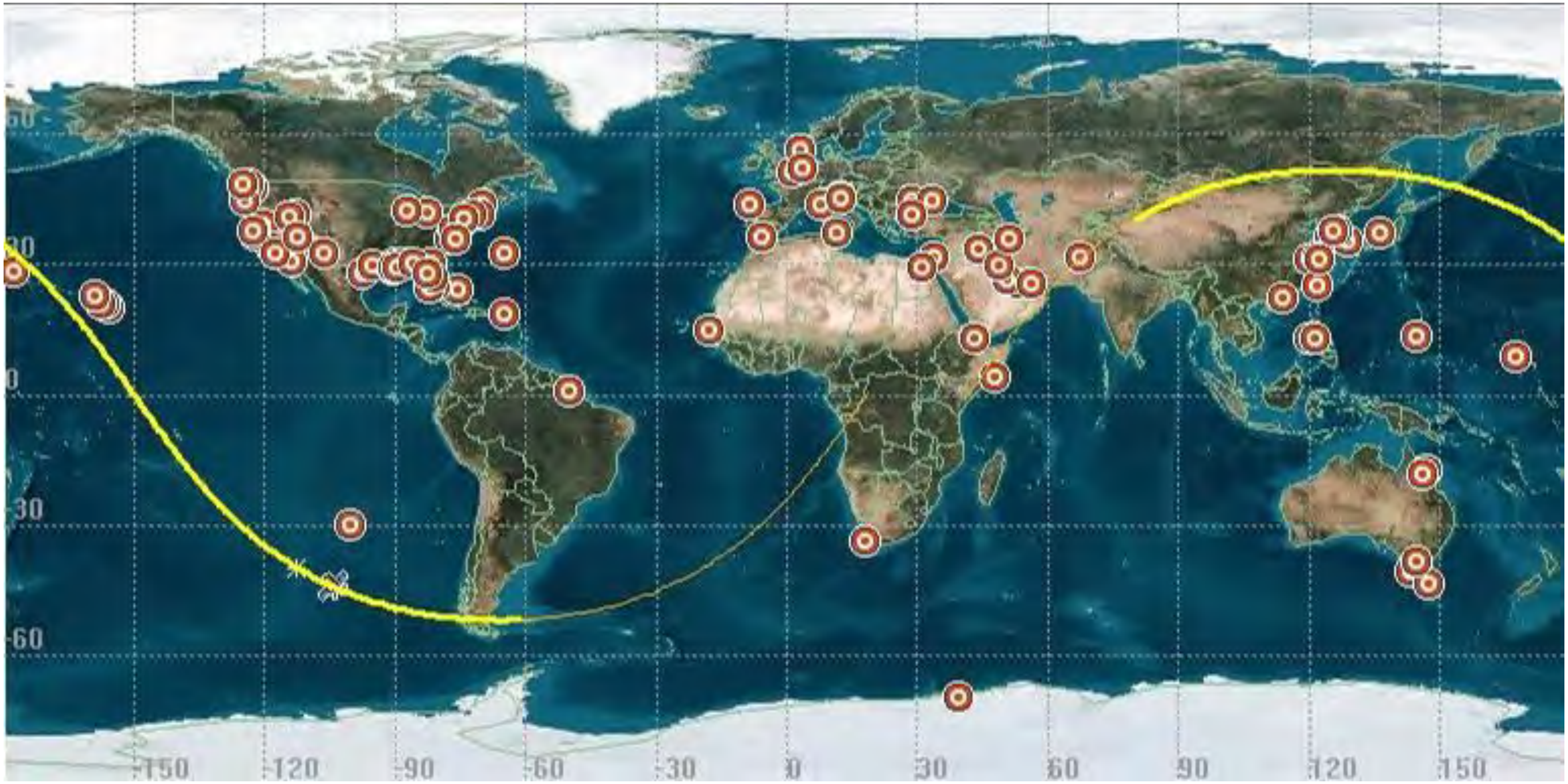
Combines scene locations, ISS attitude, ISS ephemeris, HICO pointing and constraints to produce list of all possible observations in particular time period

HICO Image Locations

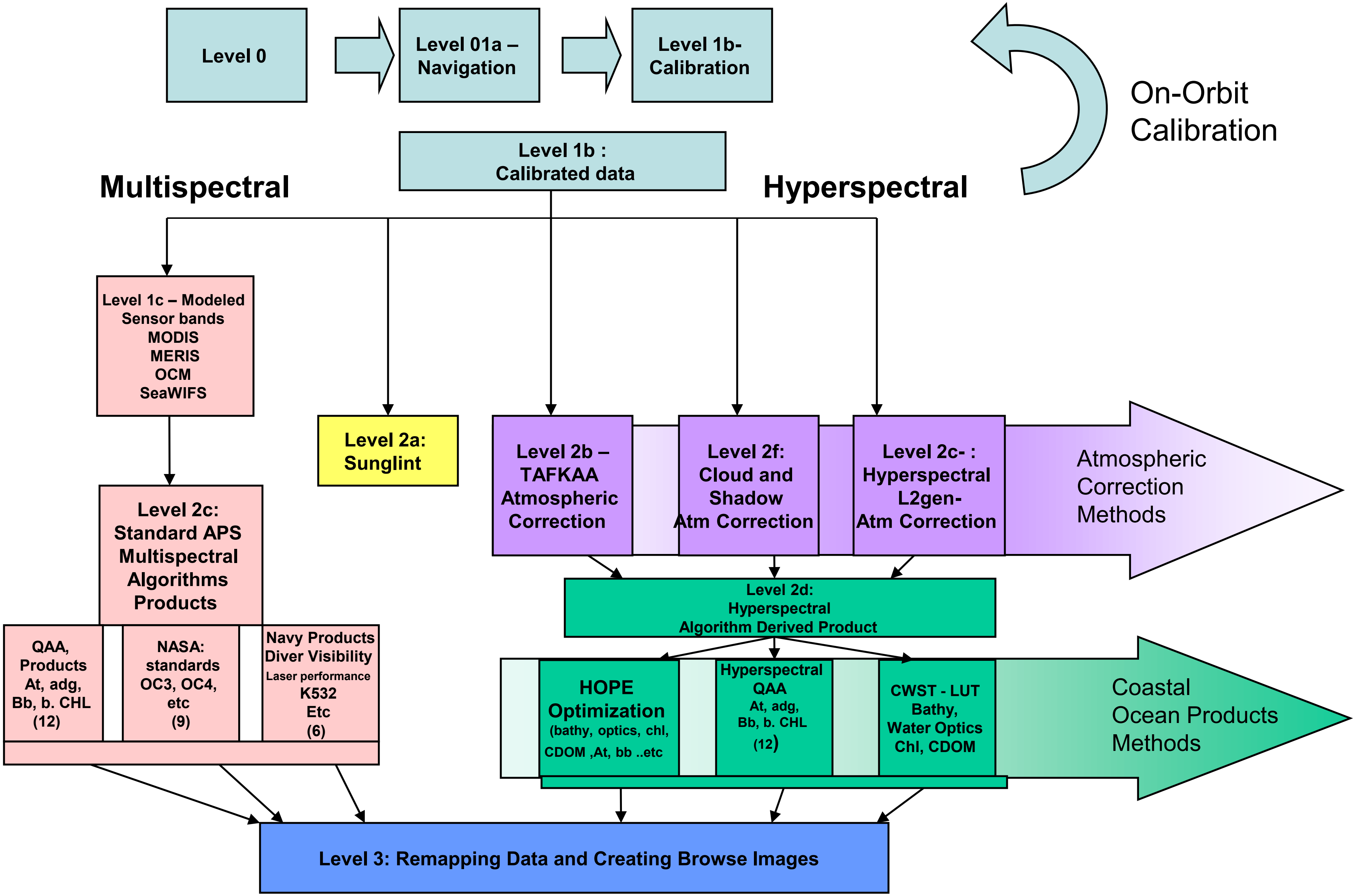
Locations chosen based on:

1. Location – within latitude limits of ISS orbit
2. Type – ocean, coast, land
3. Use – CalVal, Science, Navy, etc

- Currently ~400 locations identified

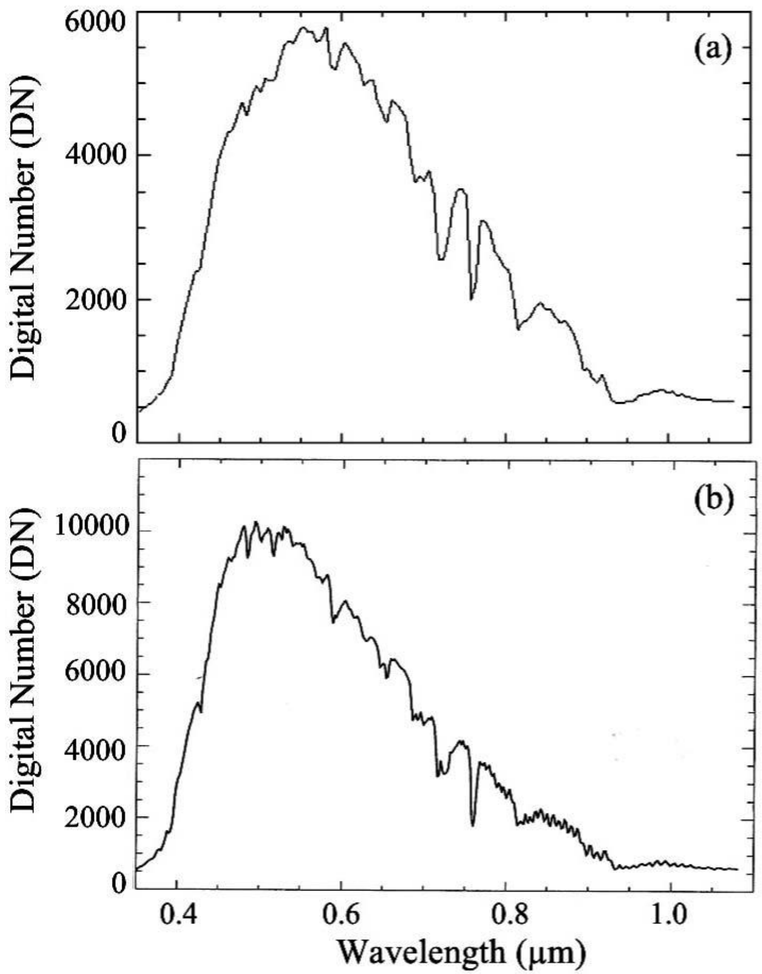


HICO Processing Activity in APS



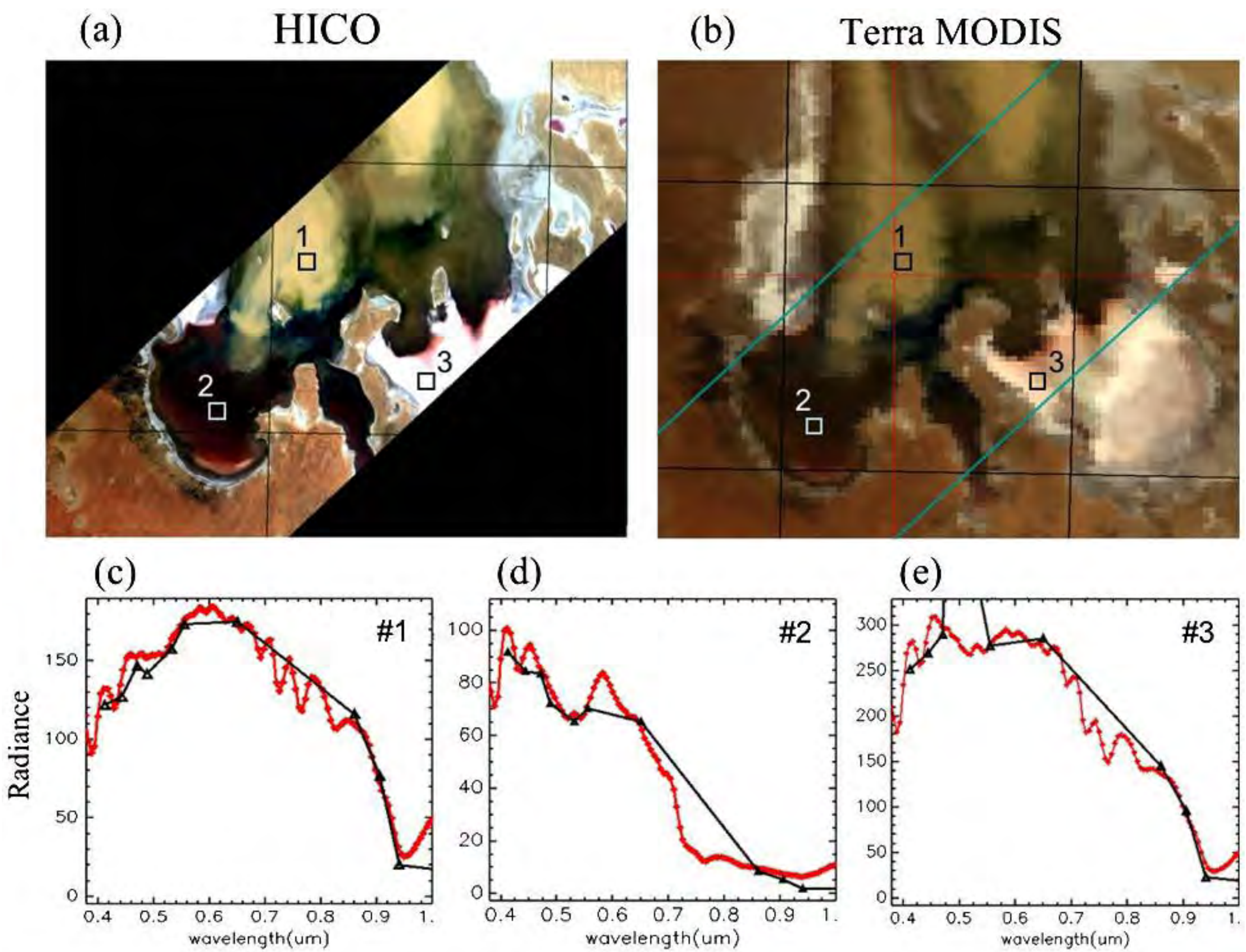
HICO On-Orbit Calibration

- HICO fully calibrated in the laboratory (Lucke et al, 2011)
  - Radiometric calibration
  - Spectral calibration
  - Dark current correction
  - Second Order correction
- HICO does not have a second order filter or an on-board calibrator.
- Cannot ask the ISS to rotate to point at the moon.
- On-orbit calibrations using natural scenes (Gao et al, 2012)
  - Spectral calibration using Fraunhofer lines and oxygen line
  - Radiometric calibration using land calibration targets
  - Second order correction using water scenes



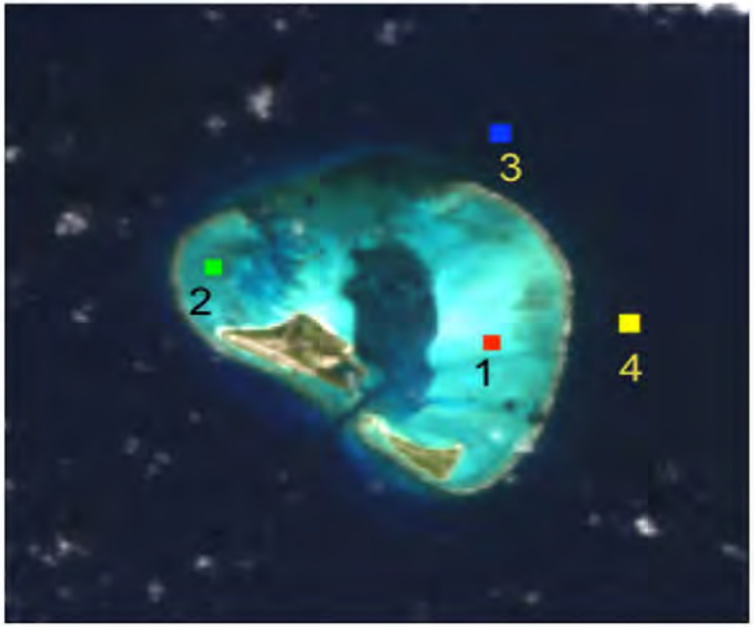
HICO spectra a) normal (5.7 nm) resolution and b) at full (1.9 nm) resolution used for spectral calibrations.

Cross Calibration with MODIS

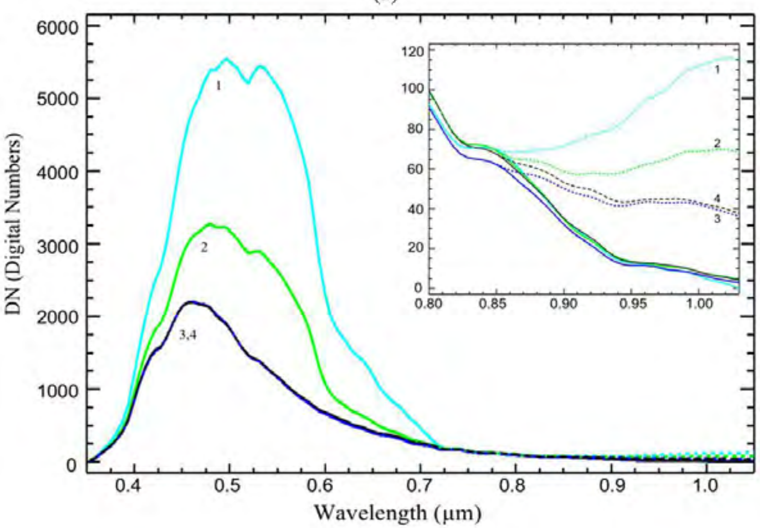


HICO true color image (a) acquired over Lake Eyre, Australia on May 11, 2010, the corresponding Terra MODIS true color image (b) acquired less than 1 hour earlier on the same day, and comparisons between HICO and MODIS data acquired over Area 1, 2, and 3, as marked in (a) and (b).

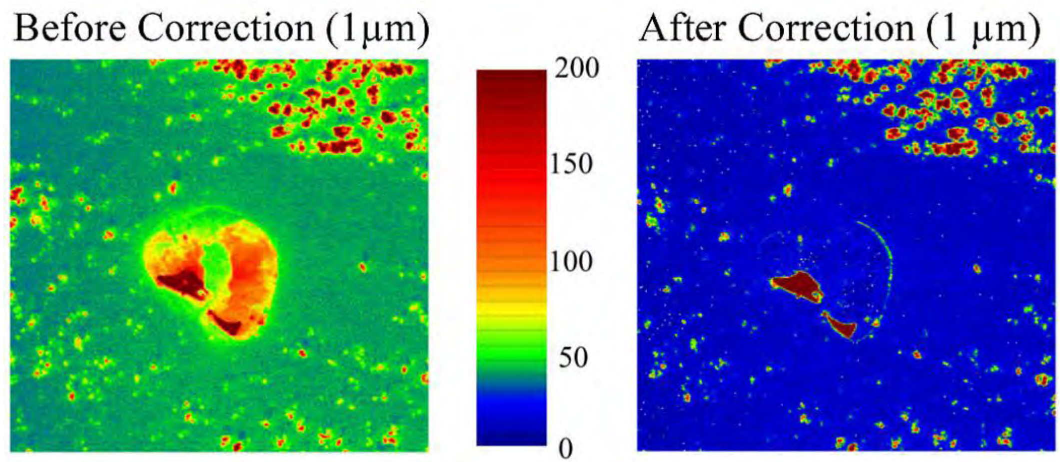
HICO On Orbit Second Order Correction



(a)



(b)



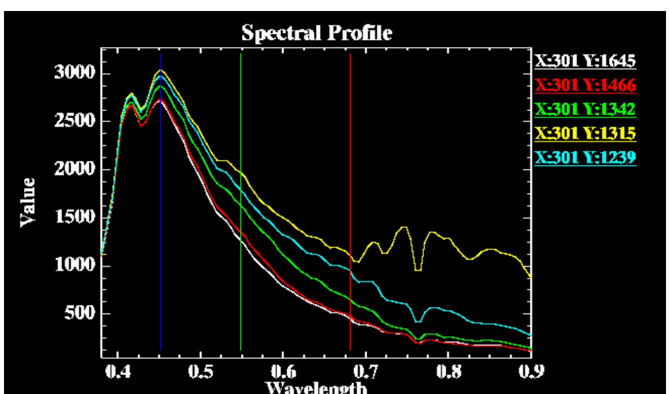
HICO image of Midway Islands on October 20, 2009 used for second order light correction (Li, et al, 2012).

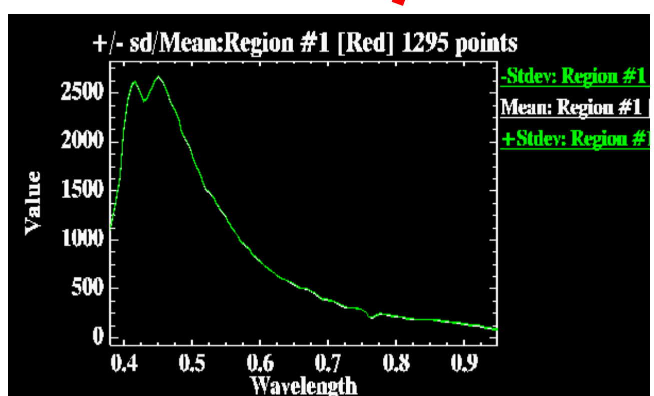
OSU HICO

Calibrated Spectral Radiances

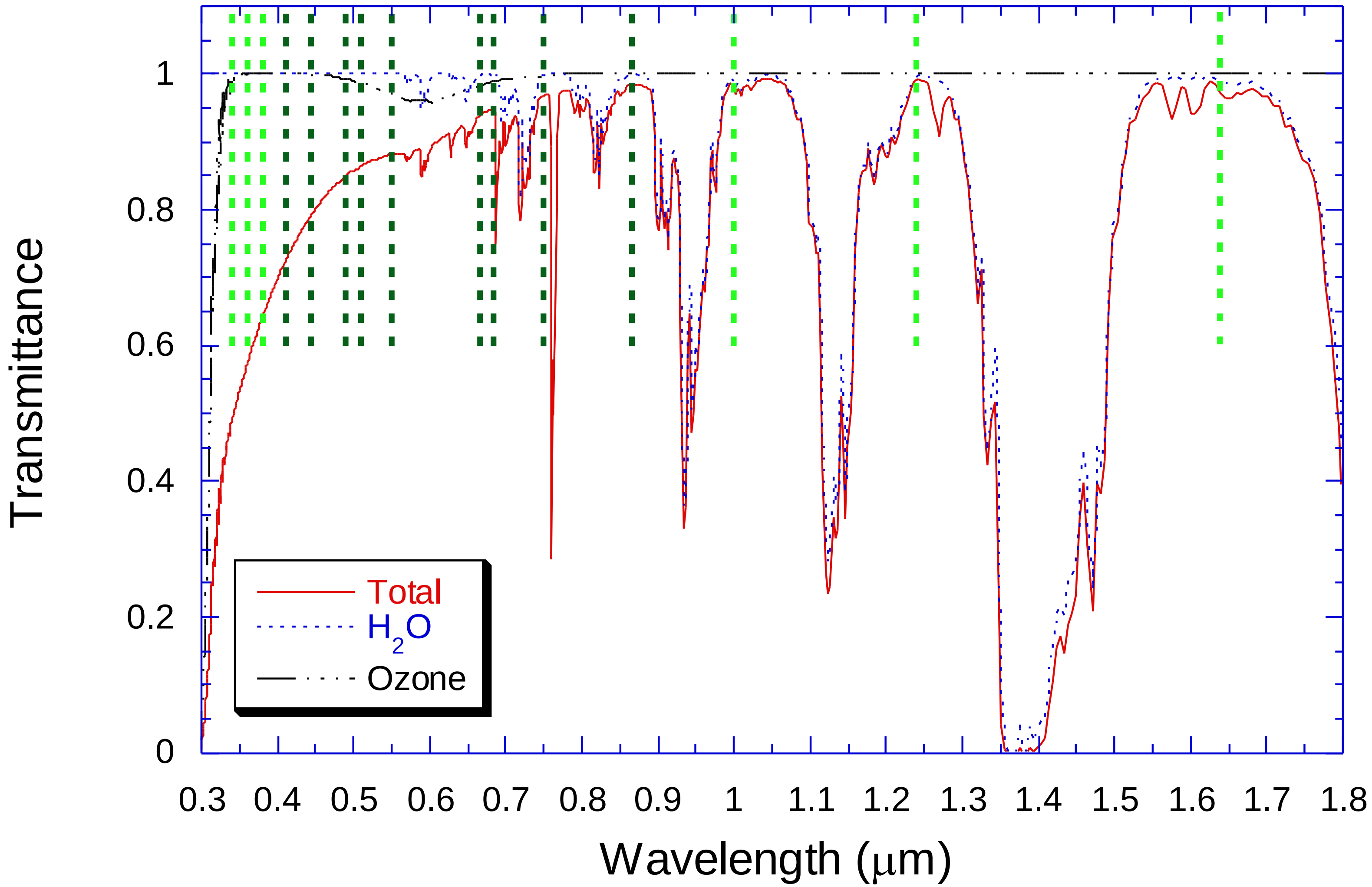
Left: Spectra extracted from pixels along the east-west transect shown in yellow. Approximate locations of the spectra are indicated by same color Xs on the image. Spectra are scaled calibrated at-sensor radiances.

Right: Mean and standard deviation of 1295 pixels in the red Region of Interest. The SNR (μ/σ including all sensor and environmental variations) is >300:1 for much of the spectra. Spectra are scaled calibrated at-sensor radiances.





Full Spectral Atmospheric Correction



- Multispectral channels selected to avoid water vapor and other absorptions
- Must correct the full spectrum for hyperspectral data

Figure From Menghua Wang, NOAA/NESDIS/STAR

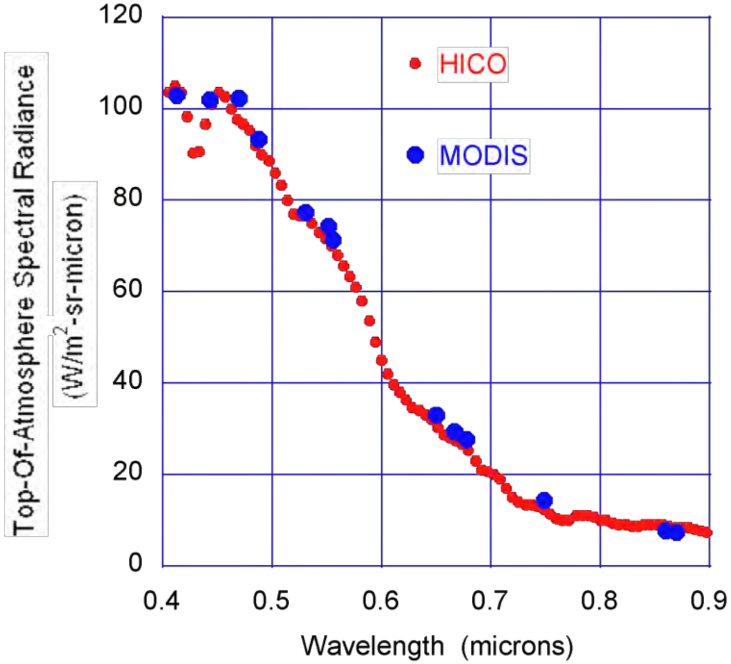
Radiometric Comparison of HICO to MODIS (Aqua)

Nearly coincident HICO and MODIS images of turbid ocean off Shanghai, China demonstrates that HICO is well-calibrated

HICO	MODIS (Aqua)
Date: 18 January 2010	Date: 18 January 2010
Time: 04:40:35 UTC	Time: 05:00:00 UTC
Solar zenith angle: 53°	Solar zenith angle: 52°
Pixel size: 95 m	Pixel size: 1000 m

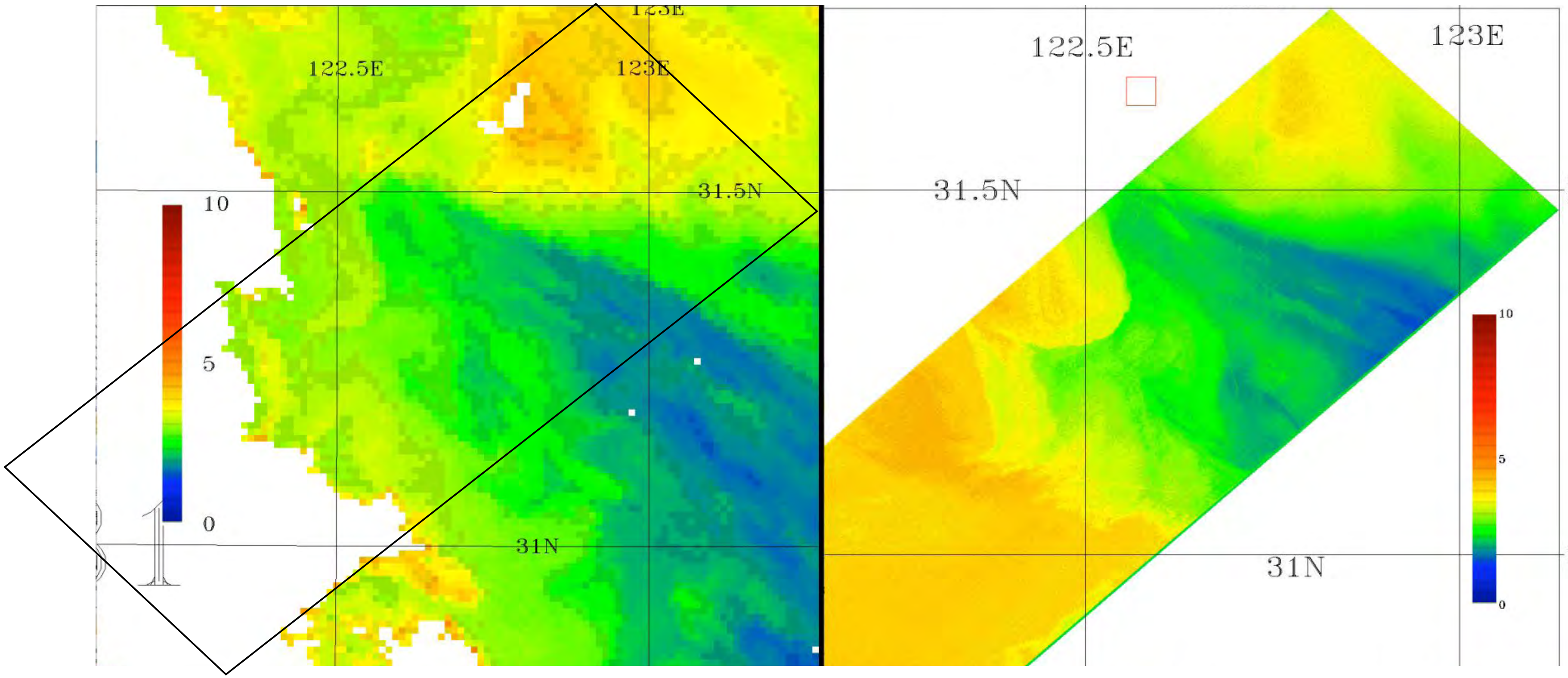
East China Sea off Shanghai

Top-Of-Atmosphere Spectral Radiance



R.-R. Li, NRL

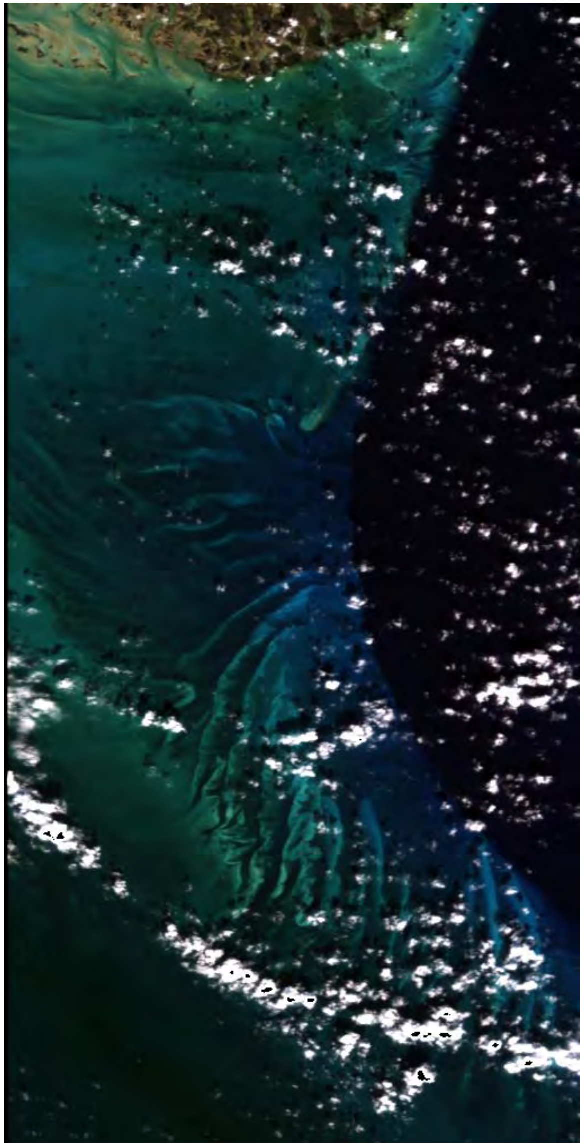
Chlorophyll Comparison of HICO to MODIS (Aqua)



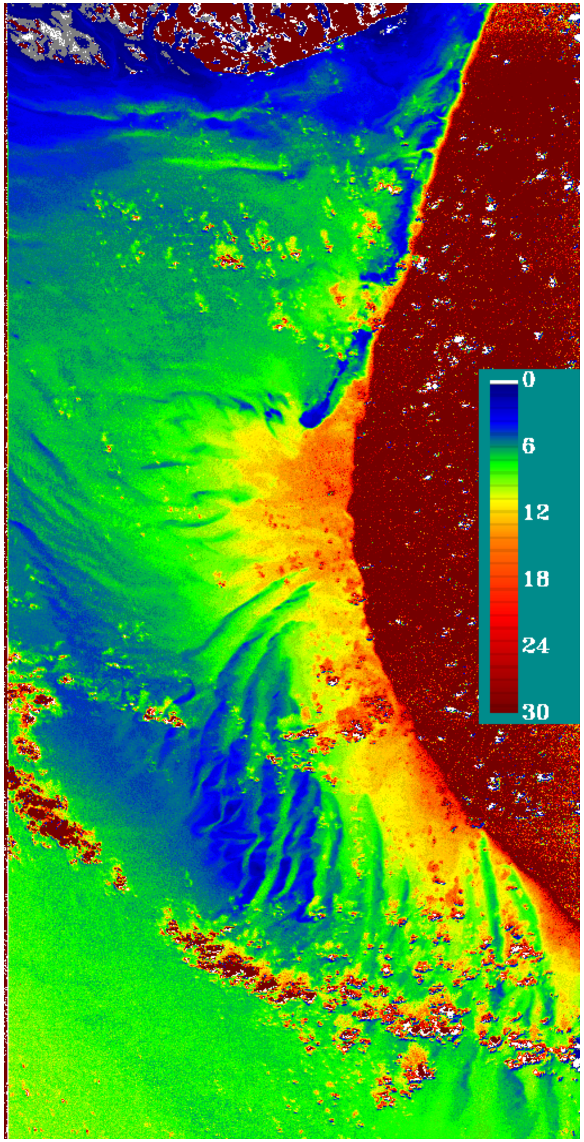
Nearly coincident MODIS and HICO™ images of the Yangtze River, China taken on January 18, 2010. Left, MODIS image (0500 GMT) of Chlorophyll-a Concentration (mg/m3) standard product from GSFC. The box indicates the location of the HICO image relative to the MODIS image. Right, HICO™ image (0440 GMT) of Chlorophyll-a Concentration (mg/m3) from HICO™ data using ATREM atmospheric correction and a standard chlorophyll algorithm. (R-R Li and B-C Gao.)

Andros Island, Bahamas, Oct 22, 2009

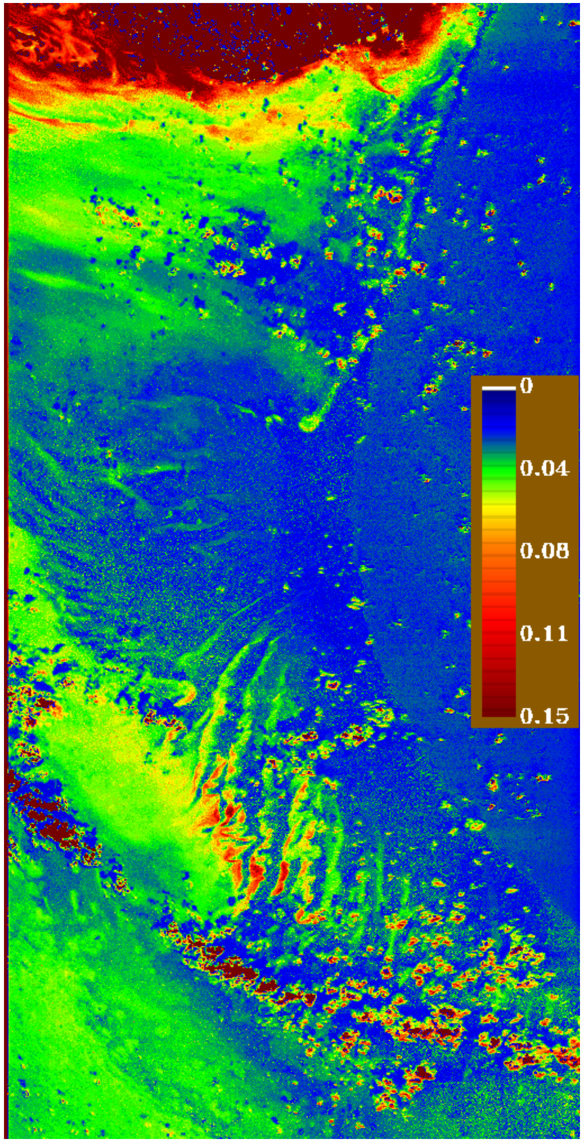
RGB image



Bathymetry



Absorption

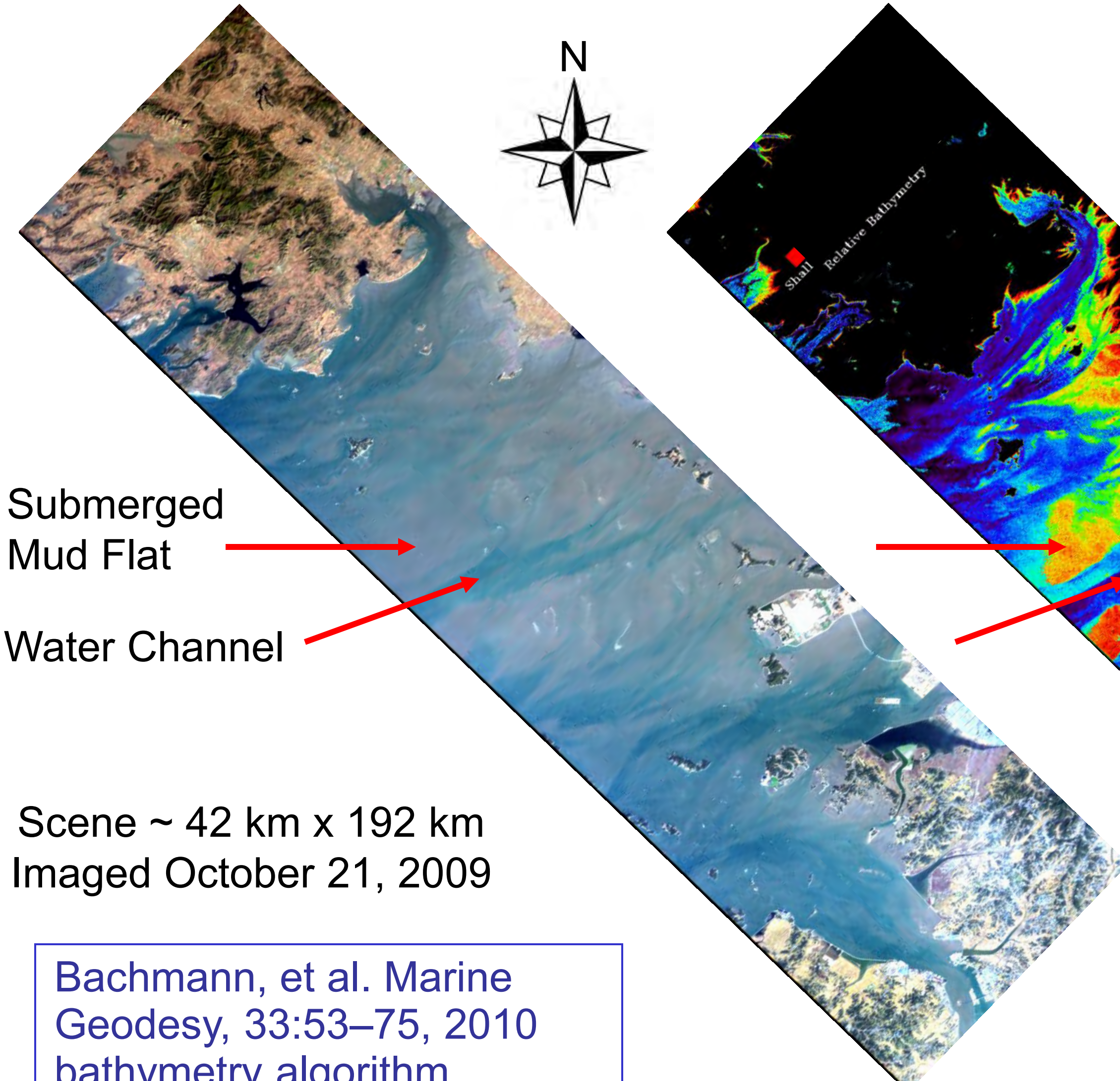


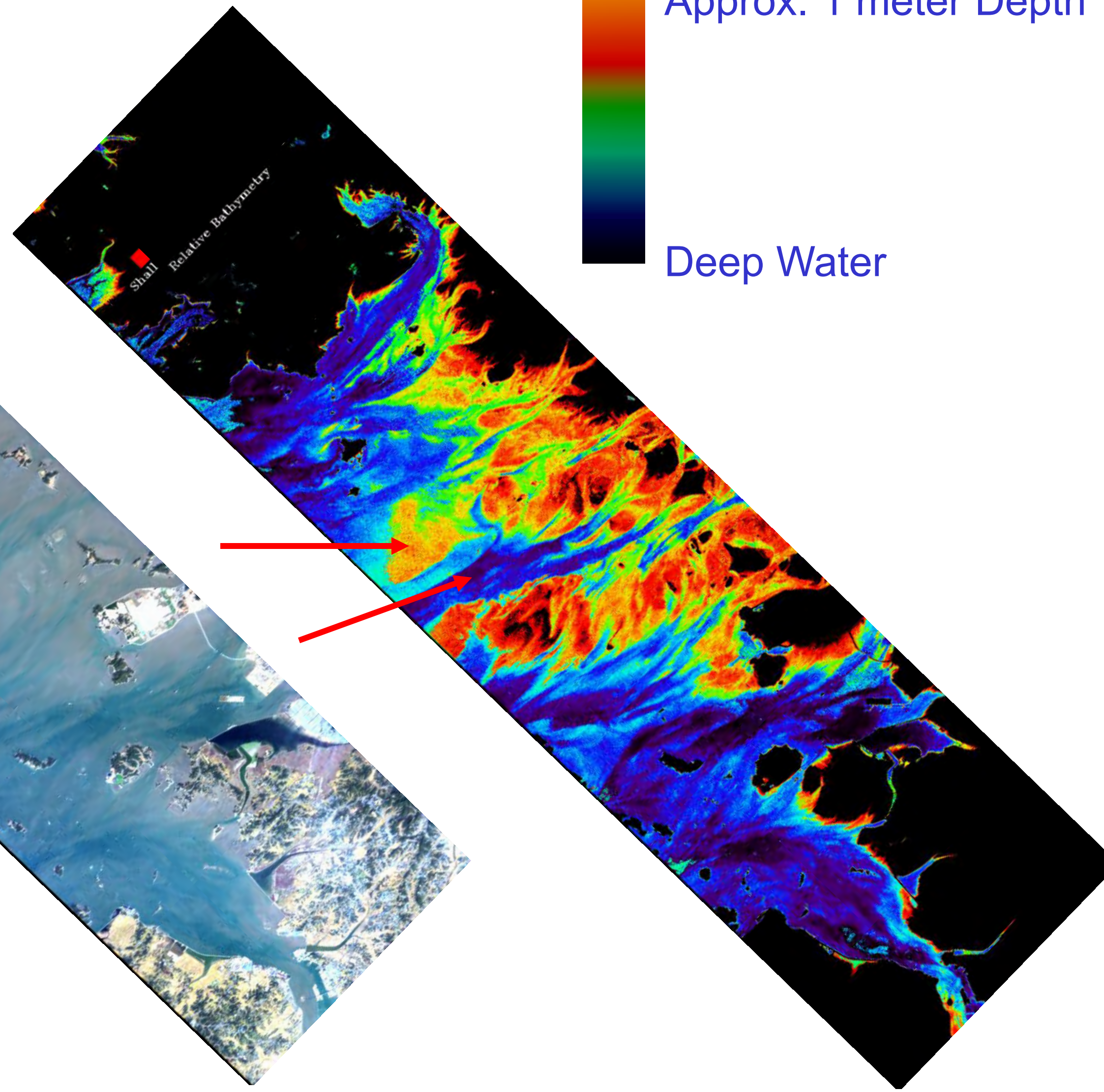
Relative Bathymetry of Han River Area Mud Flats

HICO Image off
Korean Peninsula

Relative Bathymetry Map
Retrieved from HICO Image

N





Shallow Water

Approx. 1 meter Depth

Deep Water

Submerged
Mud Flat

Water Channel

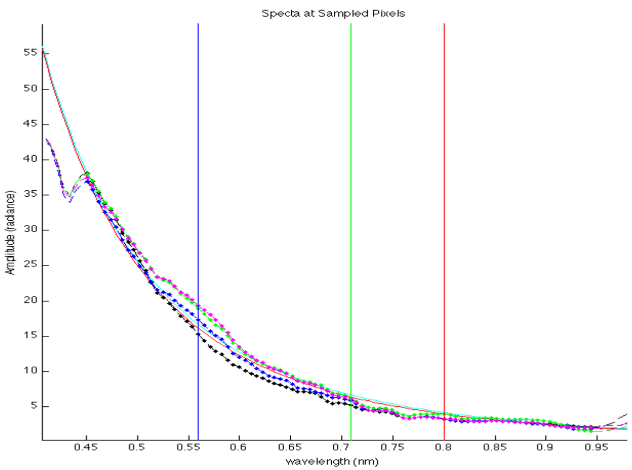
Scene ~ 42 km x 192 km
Imaged October 21, 2009

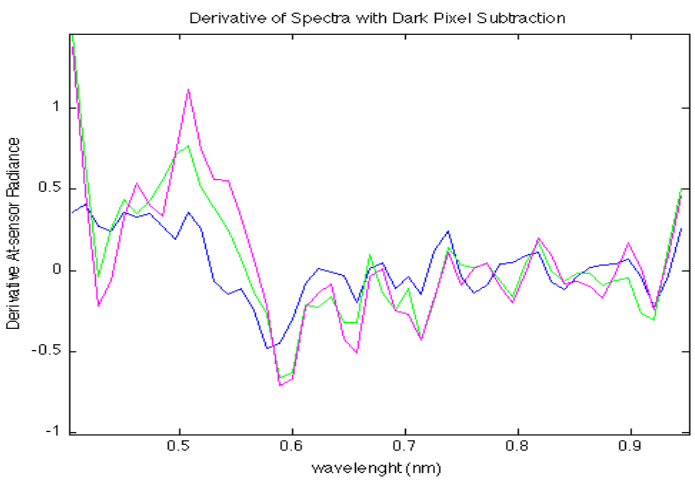
Bachmann, et al. Marine Geodesy, 33:53–75, 2010 bathymetry algorithm

Derivative Spectroscopy with HICO

Spectrum at-sensor

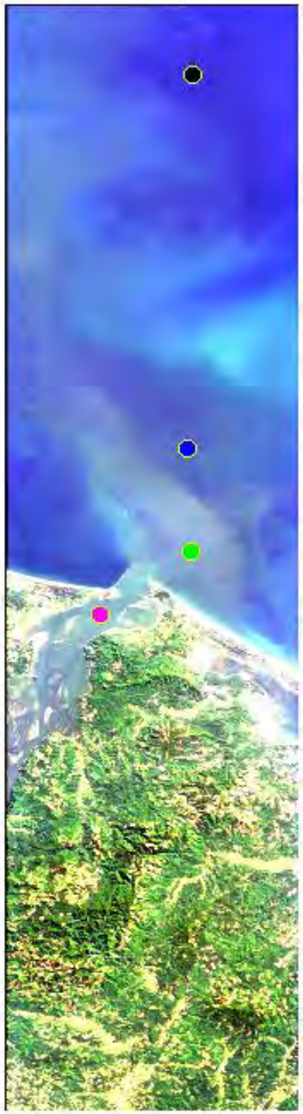
(pixel locations shown in RGB)



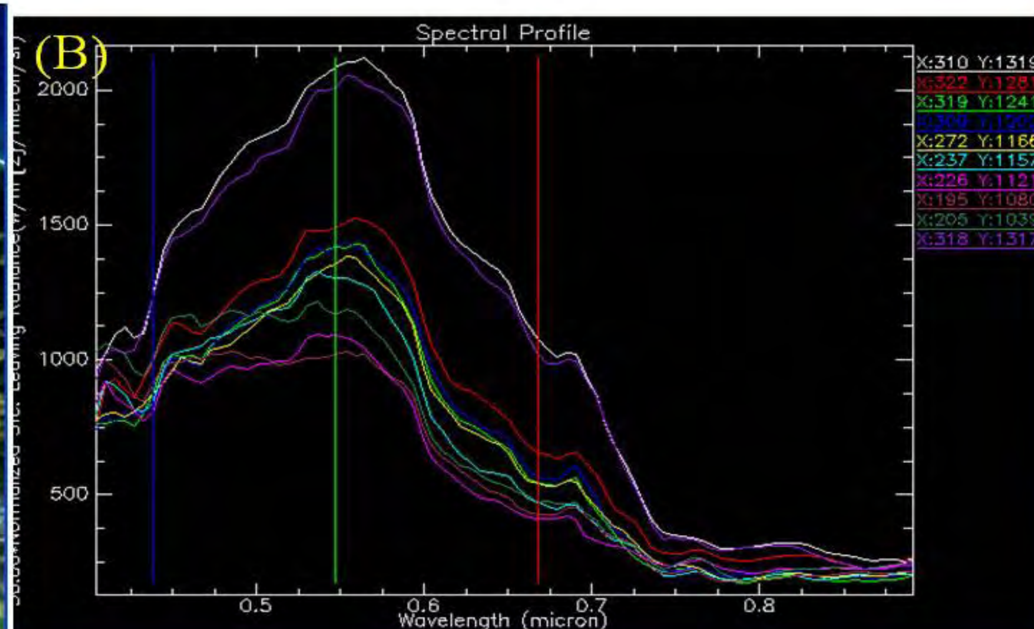


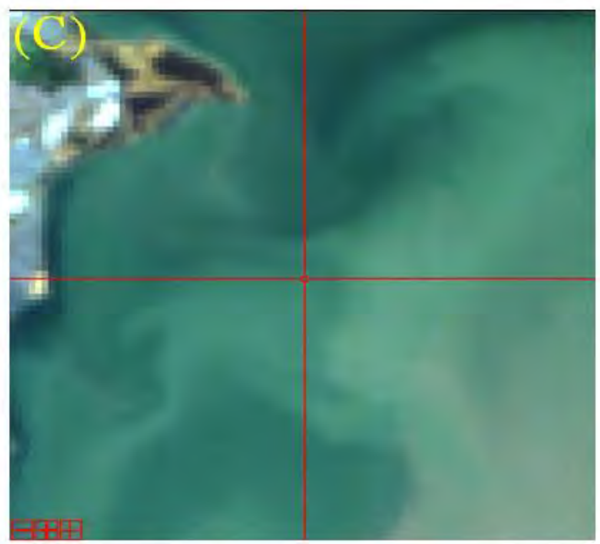
N. B. Tufillaro, preliminary results

Columbia River 13 July 2010



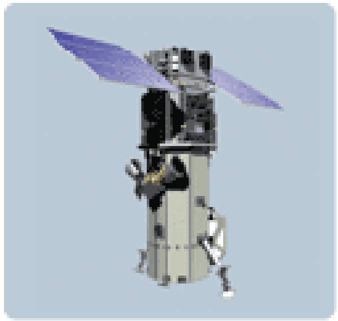
San Francisco, San Pablo and Suisun Bays



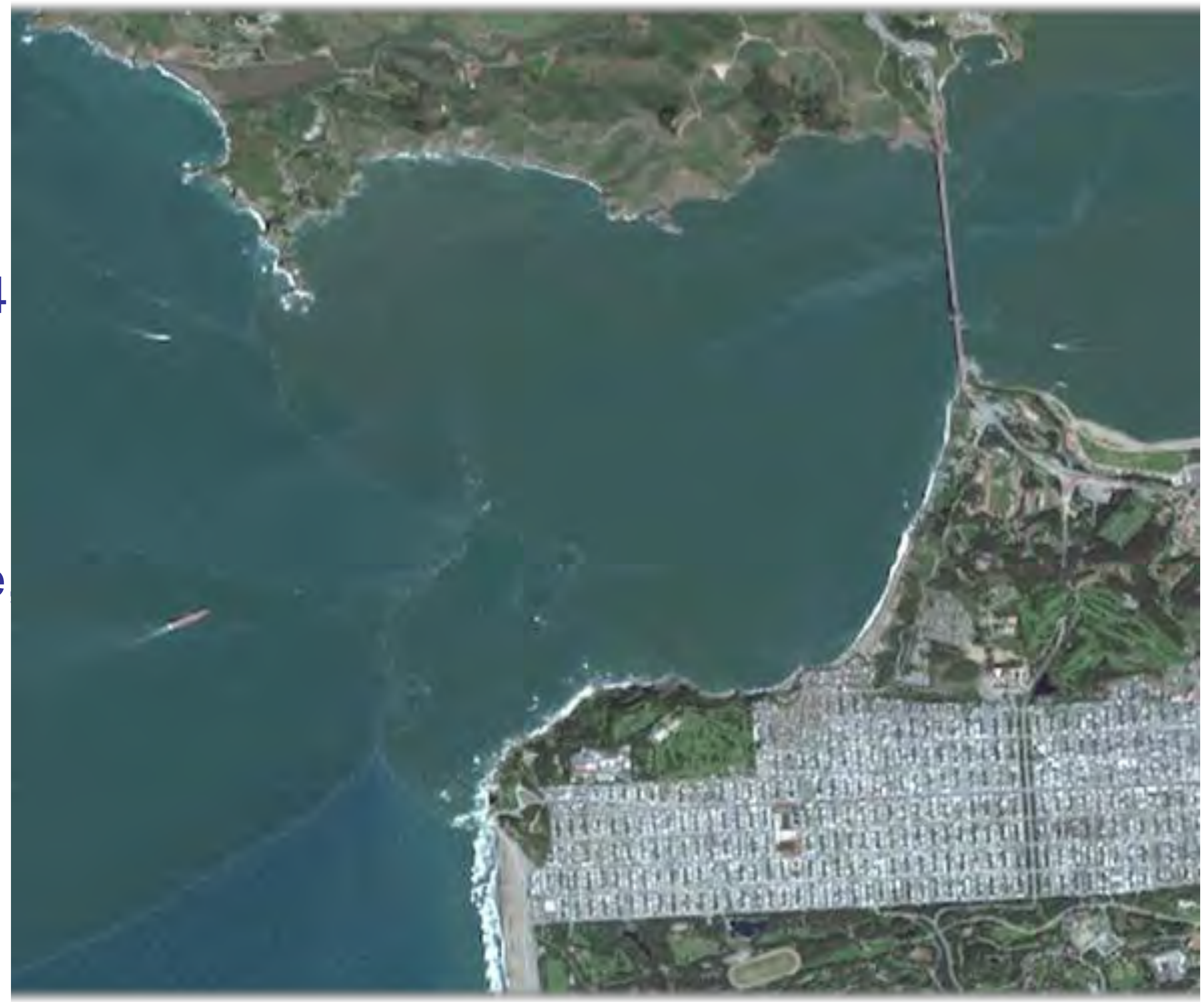


San Francisco Bay Estuary, June 24, 2011

World View-2 High resolution Imaging



Resolution: 46 cm, 1.84 m for MS
Swath Width: 16.4 kilometers at nadir
New Spectral Bands: coastal, yellow, red edge, Near-IR2 (in addition to Landsat bands)
Collection Capacity: 975,000 sq km/day**



WV-2 image of the Golden Gate Bridge, April 4, 2011

San Francisco Bay, California

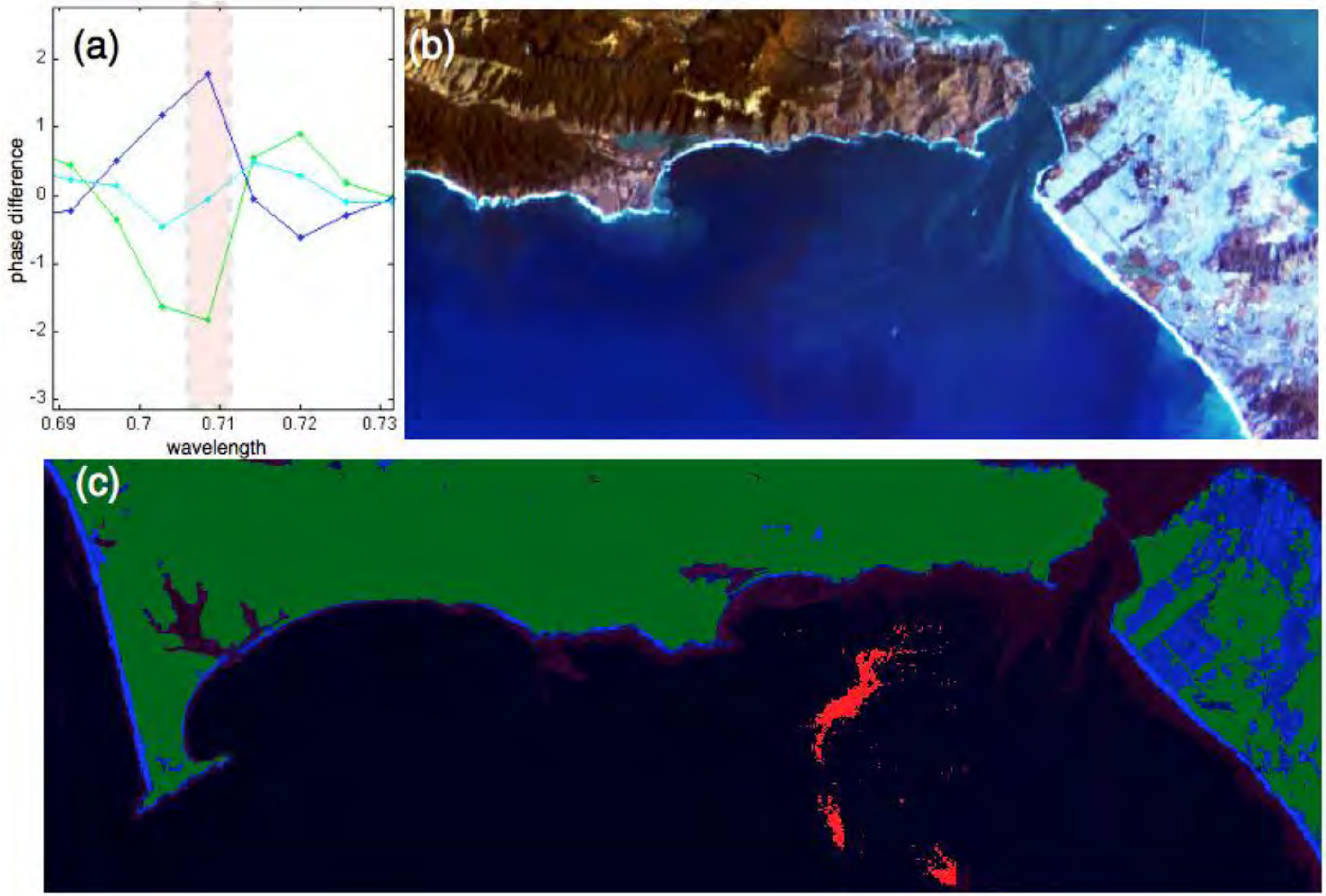
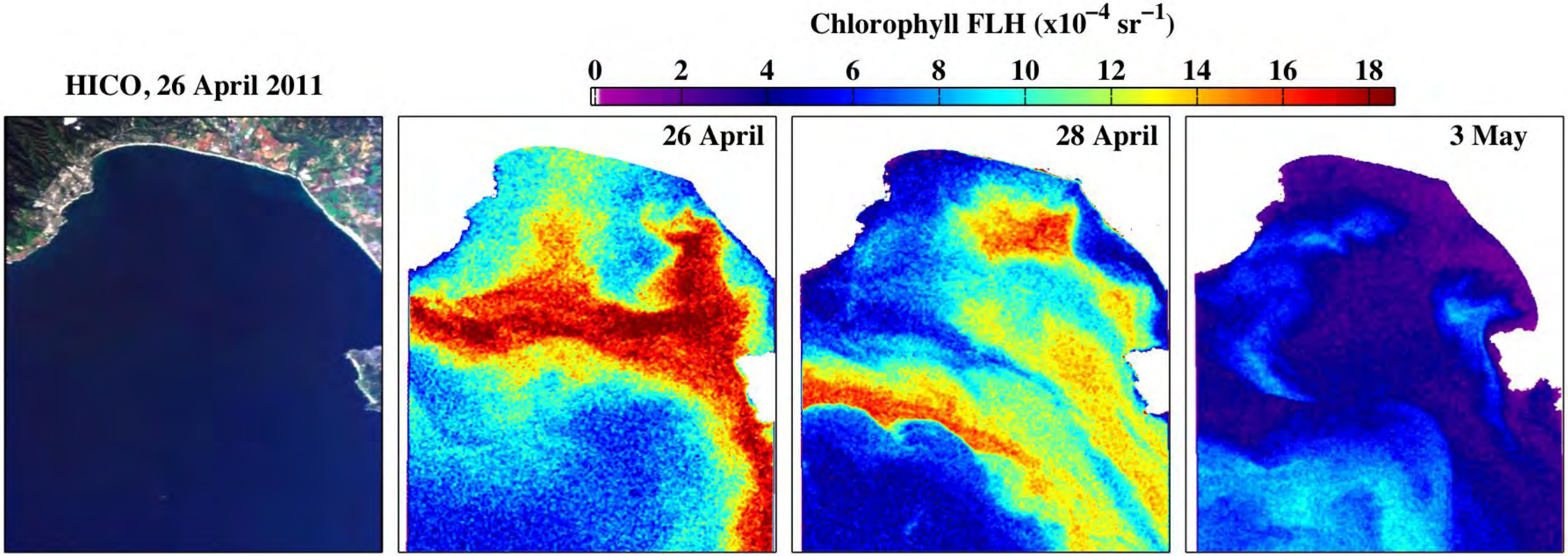


Fig. 14. (a) The phase difference function using the 709 nm HICO channel to indicate chlorophyll rich water. (b) HICO image of the mouth of San Francisco Bay, 28 September 2011. (c) Indicator function for high chlorophyll levels which shows a high concentration of chlorophyll at the interface of bay water and sea water. (N.B. Tufillaro preliminary results)

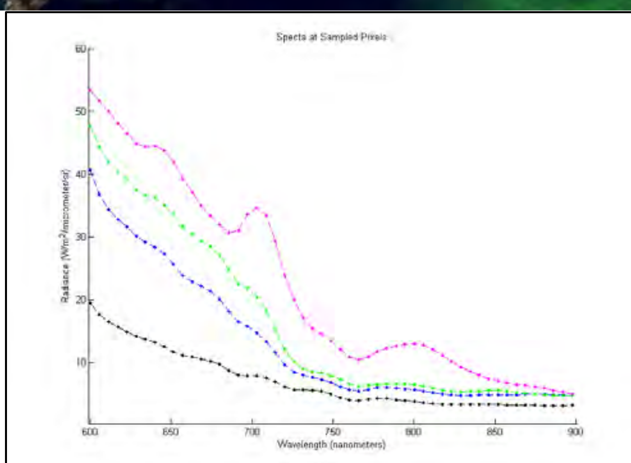
Monterey Bay, California

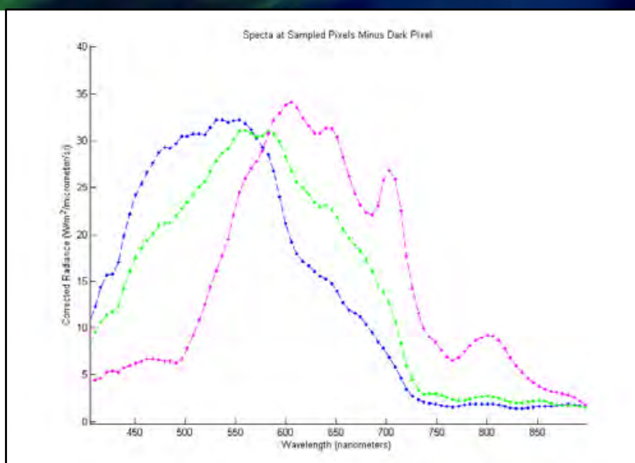


Monterey Bay plume dynamics, Spring 2011

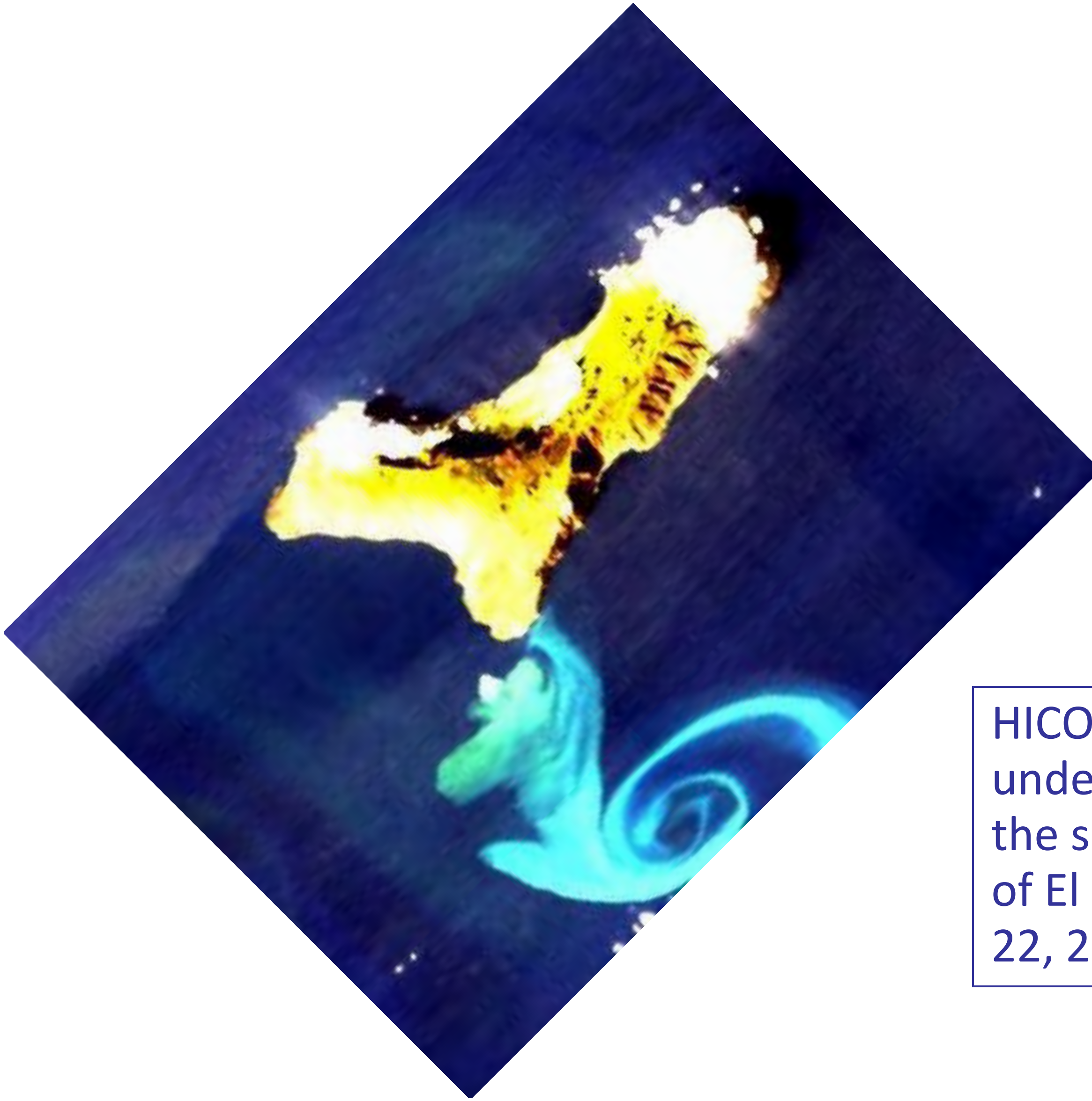
Microcystis bloom in Lake Erie

HICO Image of a massive *Microcystis* bloom in western Lake Erie, September 3, 2011 as confirmed by spectral analysis.





Birth of a New Island, Canary Islands



HICO Image of the new underwater volcano off the small Canary Island of El Hierro, December 22, 2011.

HICO Data Distribution at OSU

- **Developed HICO Public Website at OSU for distribution data, publications and presentations.**
- **Includes some example HICO data that are approved for distribution.**
- **OSU HICO Web site will be portal for data requests and distribution**
  - **Data requests require a short proposal and data agreement**
- **http://hico.coas.oregonstate.edu**
- **Full description of the data and directions for use on the website**

Are we there Yet? Need beyond HICO

HICO is a demonstrator. A new Free flying Coastal and Water Resources Imager (CWR) would offer several key advantages over HICO:

- **Broader bandwidth.** CWR will collect data from 380 to 1650 nm. to characterize beaches and plants along the shoreline and snow and ice in alpine regions and in the Arctic.
- **Finer spatial resolution.** CWR will collect data with 30-m GSD, to re-solve ocean bottom, coastal, glacier and arctic features.
- **Optimized orbit.** For best lighting and to image locations in high latitudes every day and locations in mid to low latitudes every 2nd or 3rd day.
- **Wide field of regard.** Point -30˚ to +30˚ from nadir for rapid revisit (1-3 days) to study sites.
- **Optimized calibration.** CWR will calibrate signal brightness on-orbit by scanning the full moon once a month.
- **Complete data processing system.** HICO data processed to level 1B, need routine full processing to geolocated products, including reprocessing as needed.

HICO Summary (HICO Docked on the ISS)

- **Built and launched in 28 months**
- **Over 5900 scenes collected**
- **Slot on ISS until July 2014**
- **Data from OSU HICO website**
- **http://hico.coas.oregonstate.edu**