Hyperspectral Imaging of the Littoral Battlespace

Curtiss O. Davis
Code 7203
Naval Research Laboratory
Washington, DC
202-767-9296
davis@rsd.nrl.navy.mil

Who We Are and Presentation Outline

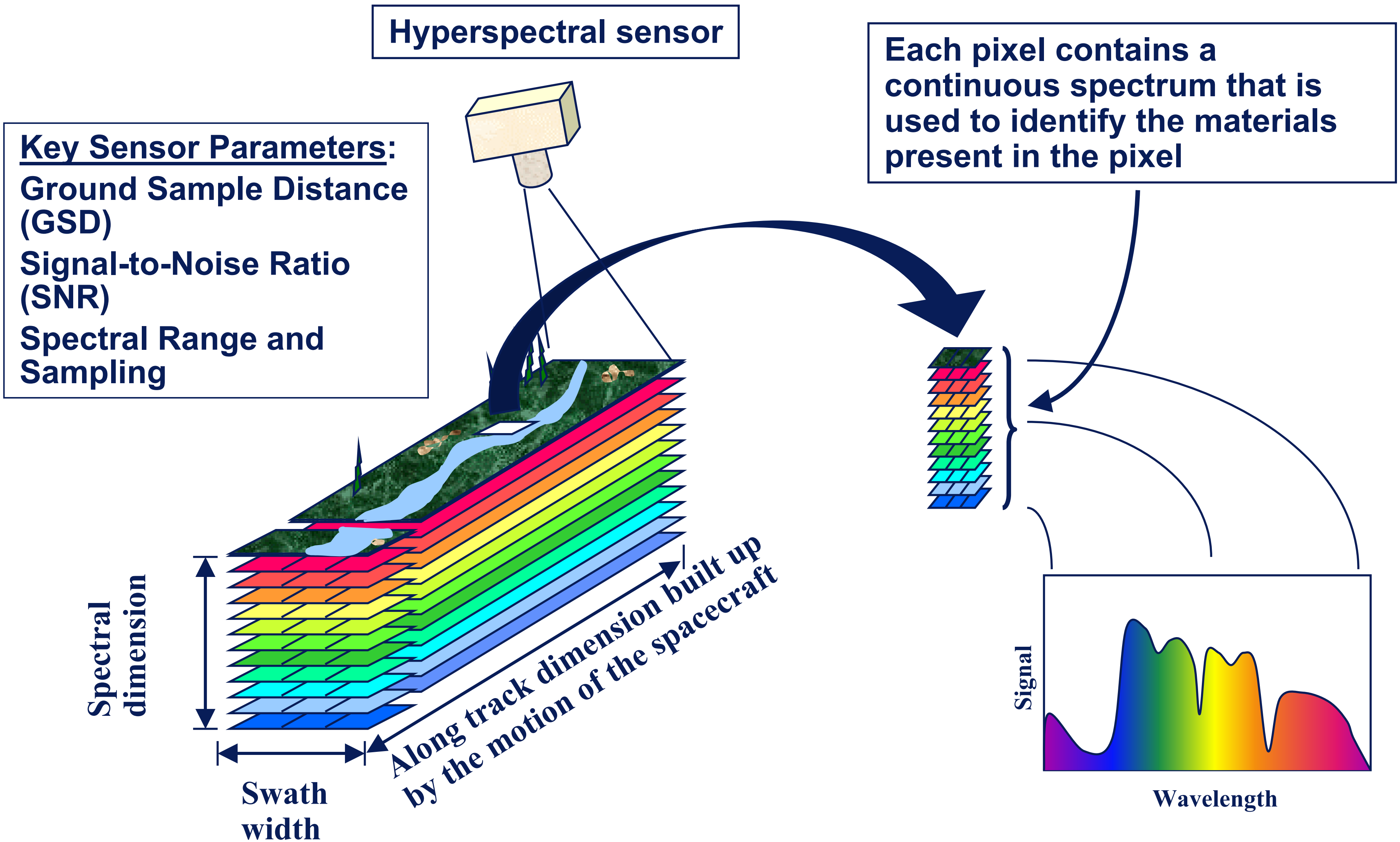
The role of the Optical Sensing Section (Code 7212) is the development and exploitation of optical remote sensing for Naval and other DoD and civilian needs.

Our specialty is the exploitation of hyperspectral imaging for the littoral environment. We provide a complete solution including instrument design, construction, calibration, characterization, automated processing, atmospheric correction, land and ocean product algorithms, and field validation of the data. (http://rsd-www.nrl.navy.mil/7212/)

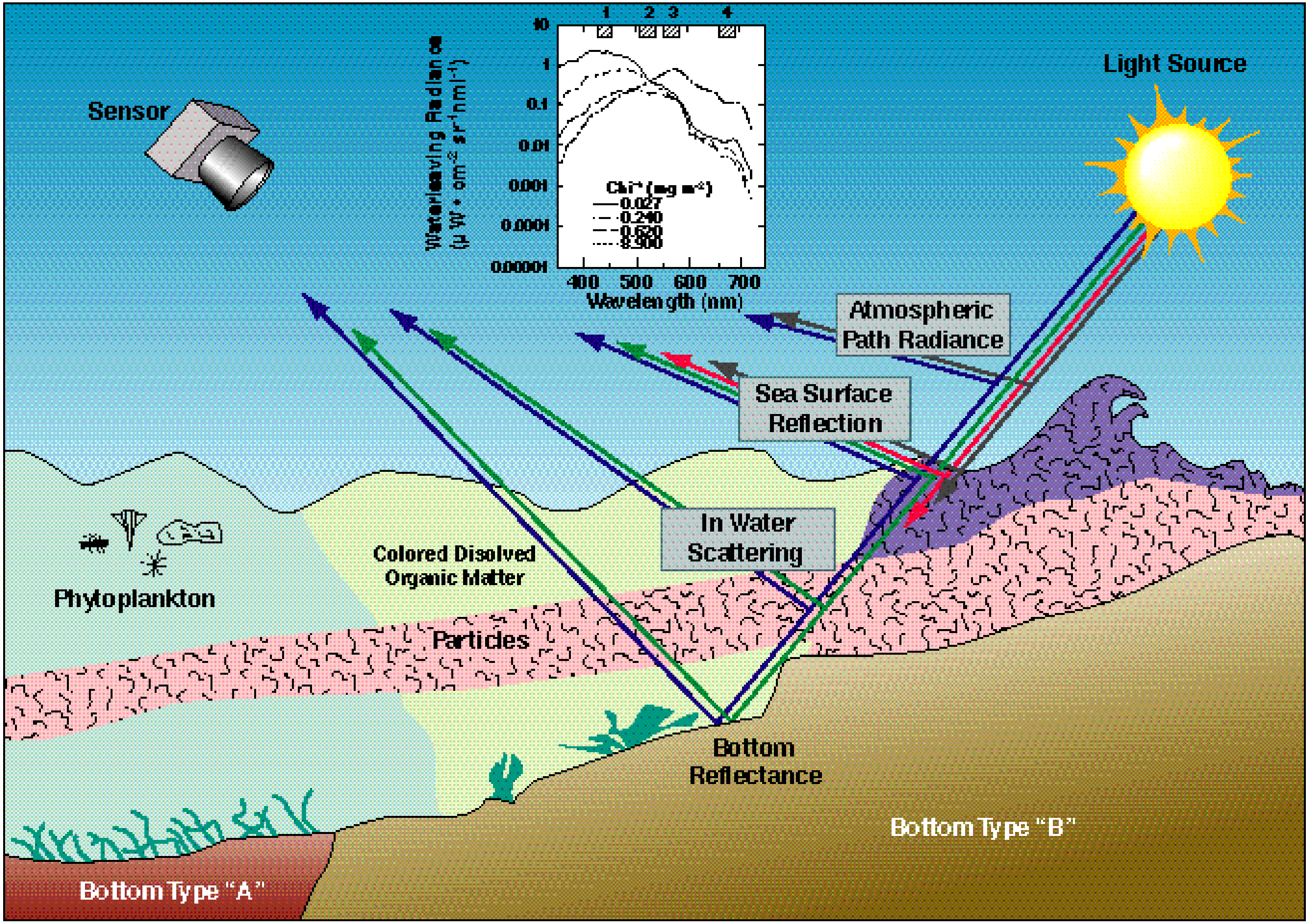
PRESENTATION OUTLINE

- **The Ocean Problem and Example Results with AVIRIS data from Tampa Bay.**
- **The Portable Hyperspectral Imager for Low Light Spectroscopy (PHILLS)**
- **Calibration and Characterization**
- **Atmospheric Correction (Tafkaa)**
- **Ocean and Coastal Land Products**
- **Field Validation**
- **ORASIS data compression**
- **The Coastal Ocean Imaging Spectrometer (COIS)**
- **The Coastal Ocean Imager (COI)**
- **Summary.**

Hyperspectral Imaging Concept

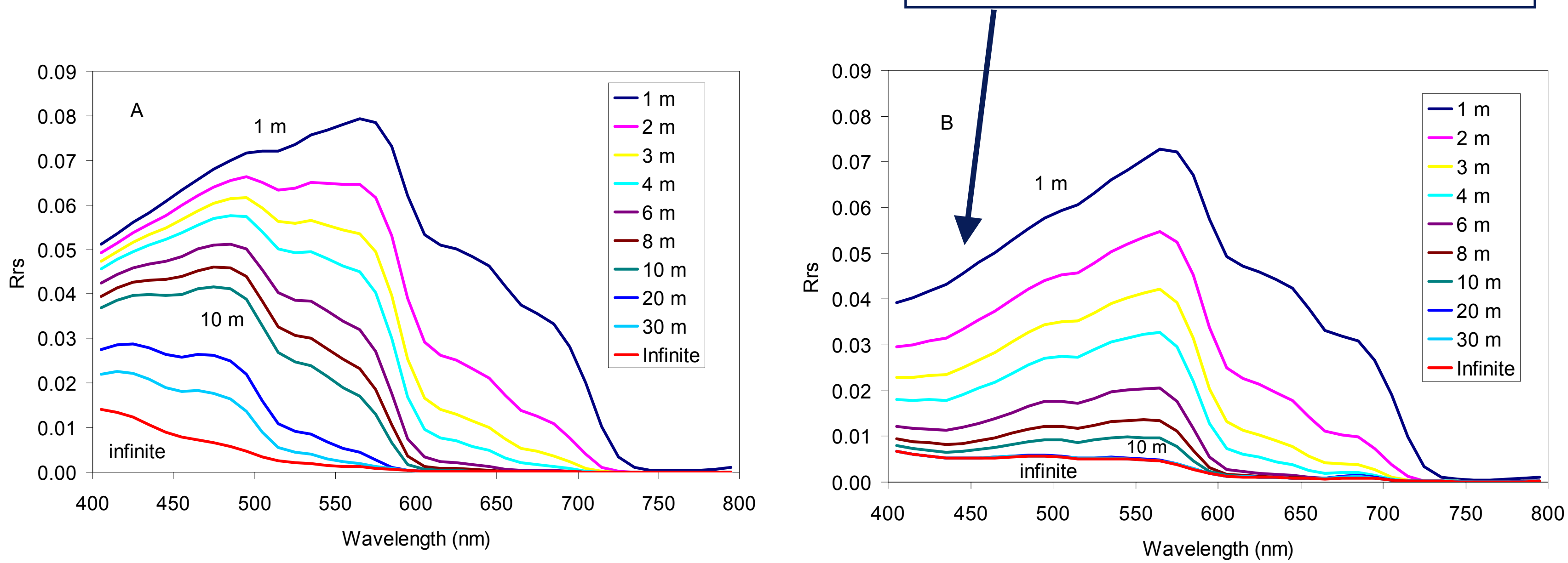


Resolving the Complexity of Coastal Optics Requires Hyperspectral Remote Sensing



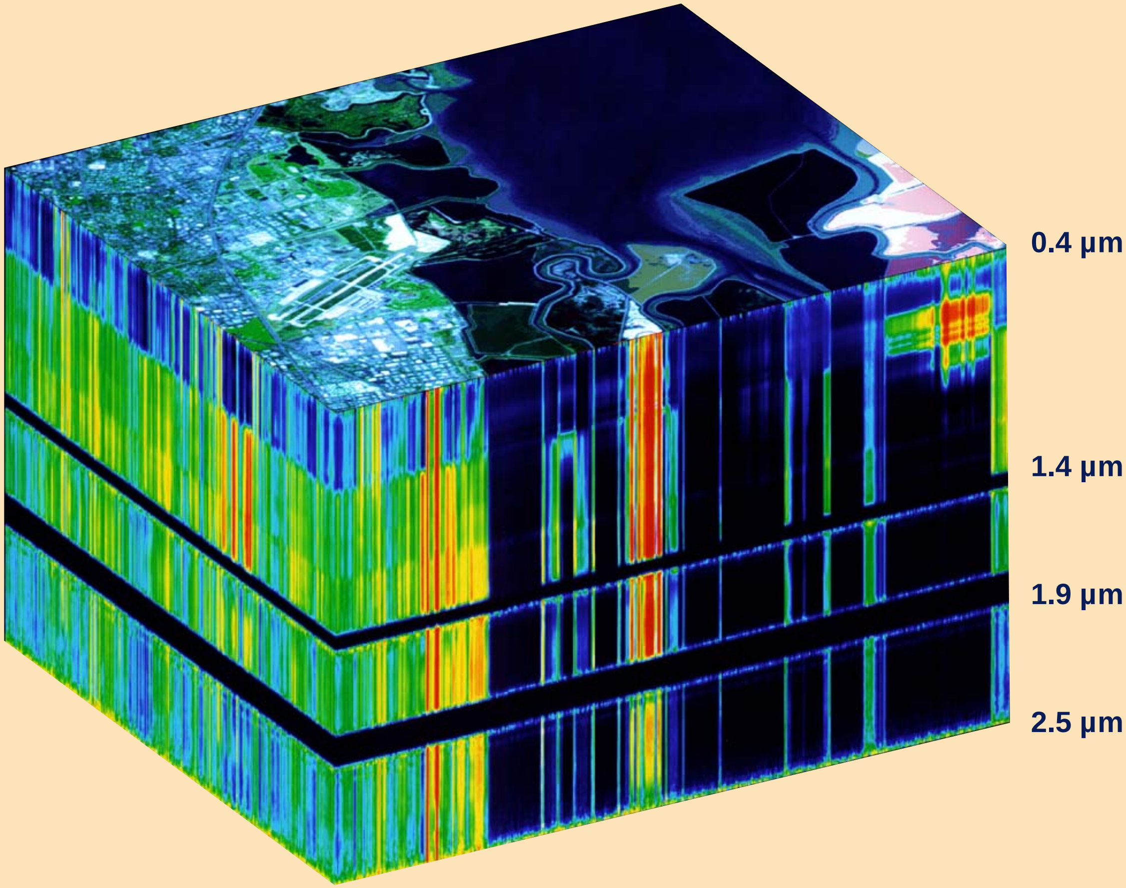
Changes in Remote Sensing Reflectance as a function of water clarity and depth

Decrease due to Absorption by Phytoplankton Pigments



Changes in remote sensing reflectance at the surface as a function of water depth for a coral sand bottom. A) With a phytoplankton chlorophyll content of 0.01 mg/m^3. B) With a phytoplankton chlorophyll content of 2.0 mg/m^3. Results calculated using HYDROLIGHT 4.1 (Sequoia Scientific, Inc).

Airborne Visible/Infrared Imaging Spectrometer (AVIRIS)



- NASA Instrument Built and Operated by JPL
- Flown on NASA's ER-2 at 20km Altitude
  - 220 (10nm) Spectral Bands
  - 0.4 to 2.5 µm
  - 20m Ground Sample Distance (GSD)
- 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

Solving the Shallow Ocean Remote Sensing Problem using Hyperspectral Data

Remote-sensing reflectance (R_{rs}) is a function of properties of the water column and the bottom,

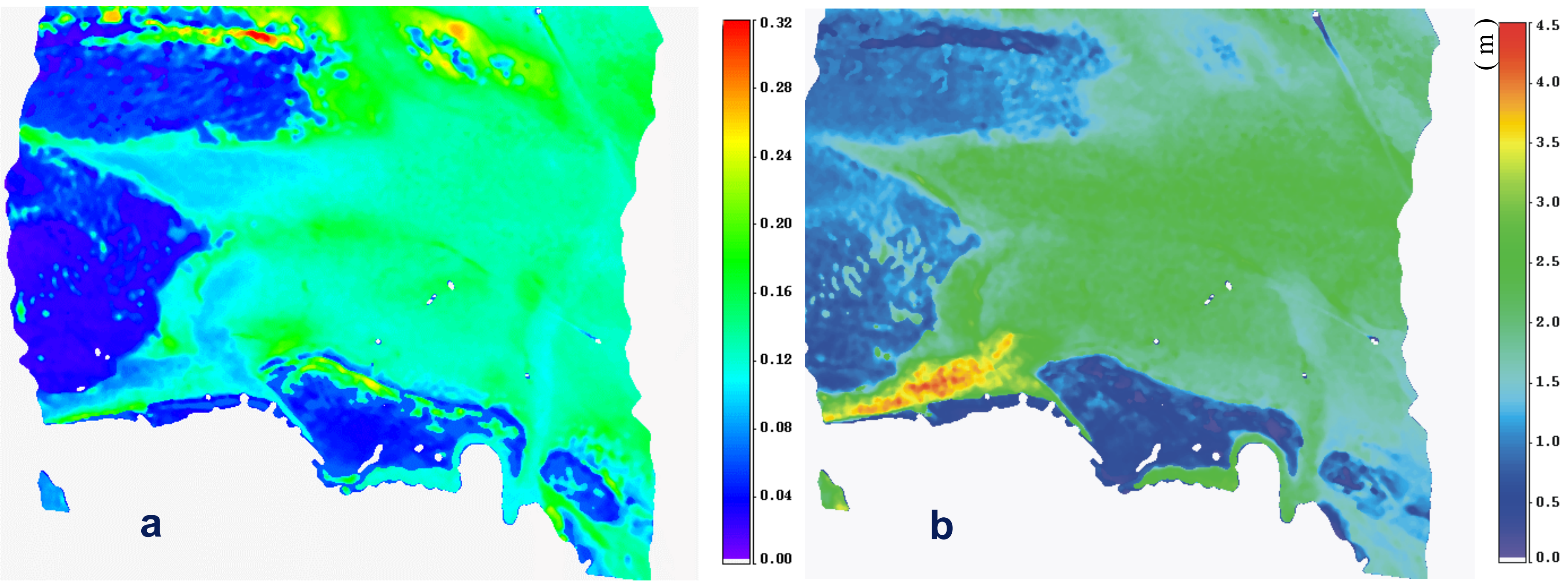
$$R_{rs}(\lambda) = f[a(\lambda), b_b(\lambda), \rho(\lambda), H], \qquad (1)$$

where a(λ) is the absorption coefficient, $b_b(\lambda)$ is the backscattering coefficient, $\rho(\lambda)$ is the bottom albedo, H is the bottom depth.

It is desired to *simultaneously* derive bottom depth and albedo and the optical properties of the water column.

Lee et al. (*Appl. Opt.*, 38: 3831-3843, 1999) proposed a new model which can be used with hyperspectral data without the need for ancillary data. They used a semi-analytic model (Lee et al., *Appl. Opt.*, 37: 6329-6338, 1998) 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.

Bathymetry and Bottom type from AVIRIS Image of Tampa Bay

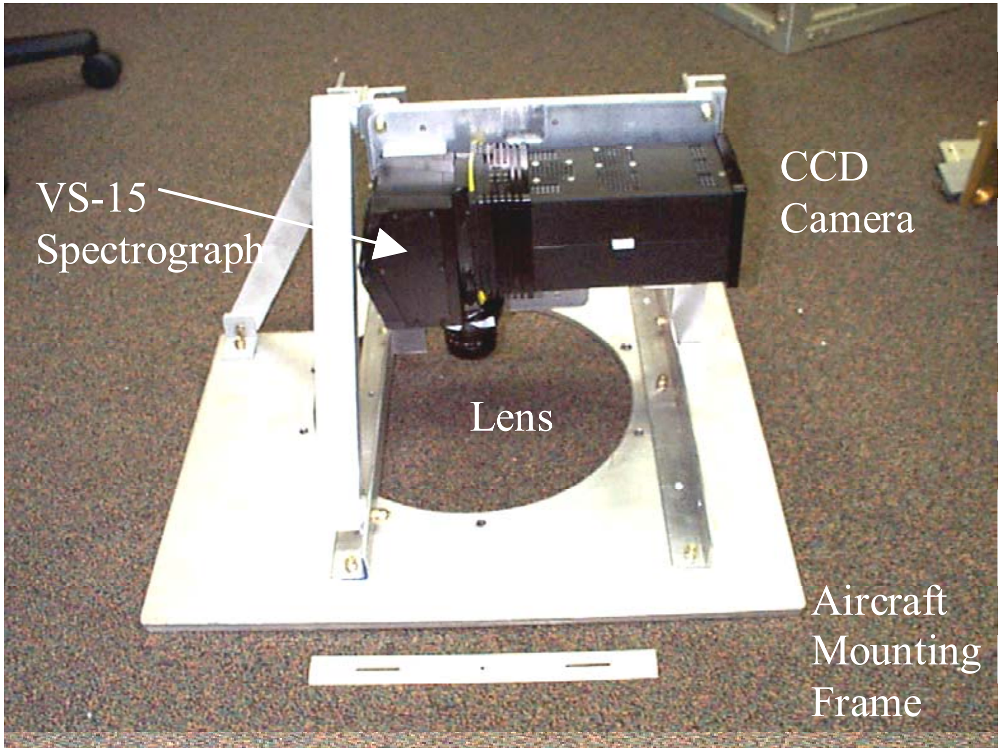


a) Bottom albedo at 550 nm and b) bathymetry derived from AVIRIS data for Tampa Bay, FL. Accurate values were retrieved in spite of the fact that water clarity is poor and varies greatly over the scene.

Alternative Approaches

- The model driven optimization technique presented here works well with AVIRIS data from Tampa Bay a very diverse and challenging optical environment. However, this procedure is iterative, and computationally intensive (several hours per AVIRIS scene). Alternative approaches being tested elsewhere may prove to be more efficient.
- Ocean radiative transfer models provide an exact calculation of the remote sensing reflectance for a given combination of water properties, bottom reflectance and depth. An ocean radiative transfer model could be used to generate look-up tables for the expected range of ocean conditions. Given a remote sensing reflectance value the table is searched for the combination of properties that minimizes the error in all spectral channels.
- Neural networks have been applied for bathymetry and bottom type and a neural network algorithms are planned as the standard algorithms for water quality parameters for the MERIS instrument when it is launched in 2002. Neural networks require extensive training, but a well trained network can process data very quickly and potentially makes a good operational algorithm.

Ocean Portable Hyperspectral Imager for Low-Light Spectroscopy (Ocean PHILLS)



- Ocean PHILLS is a push-broom imager.
- f 1.4 high quality video camera lens with a 30 degree field of view as the fore optic.
- all reflective spectrograph with a convex grating in an Offner configuration to produce a distortion free image (available through Agilent Technologies, 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.
- The data is captured with a frame grabber in a windows-NT computer with a 36 GB data storage system.

Calibration of PHILLS and COIS 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 (goal +/- 1 nm)
  - The gain and offset for conversion from counts to radiance (goal +/- 2%).
- PHILLS Calibration is based on laboratory calibration measurements and ground validation sites.
- COIS calibration will be maintained using Moon imaging, on-board lamps and ground validation sites.
- We will validate the atmospheric correction by comparing surface reflectance from PHILLS, AVIRIS or COIS data with direct measurements of that parameter.
- Testing and validation of algorithms is underway using PHILLS and AVIRIS data with extensive ground truth from the HyCODE and CoBOP experiments.

NASA Calibration Round-Robin Results

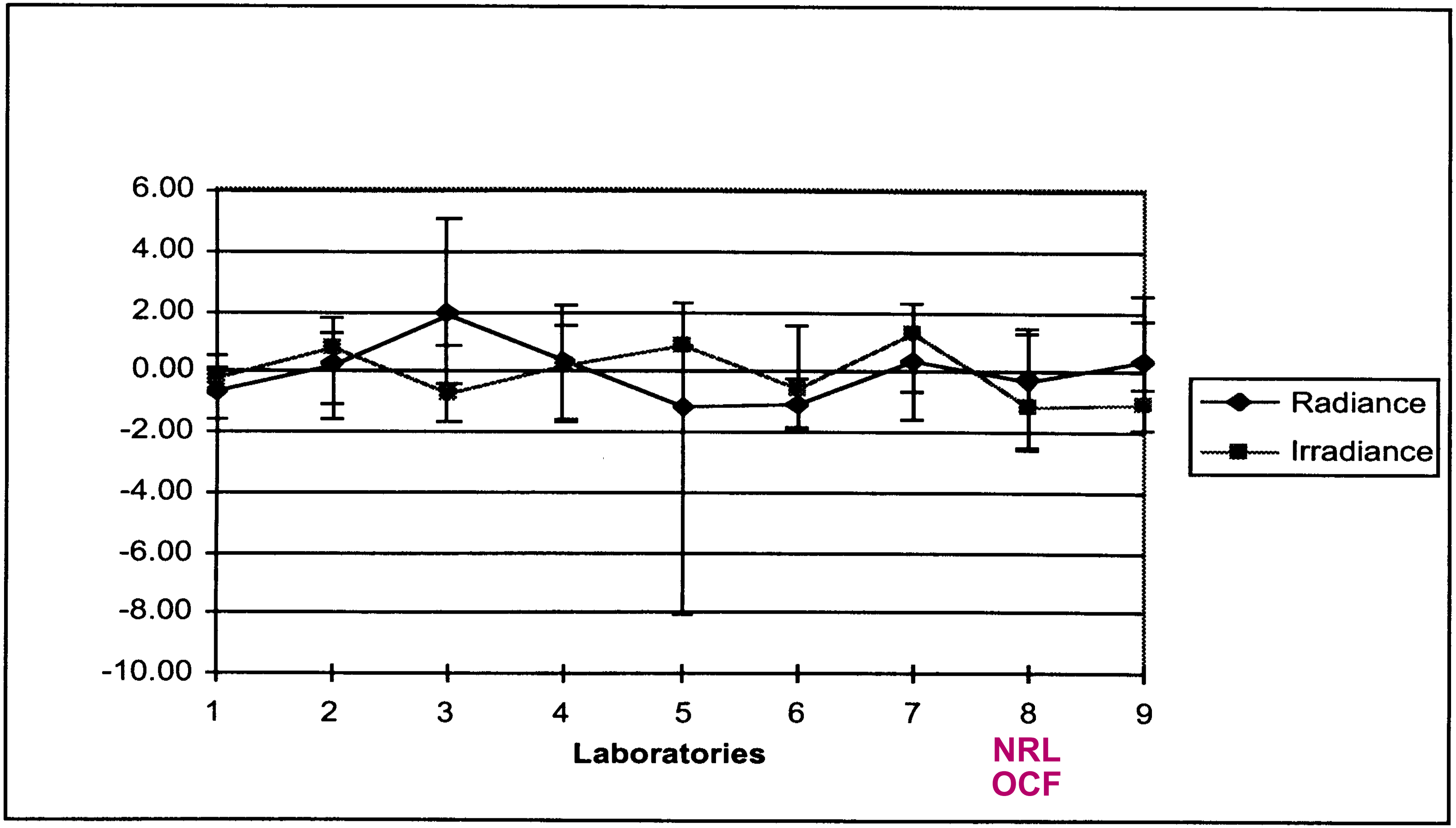
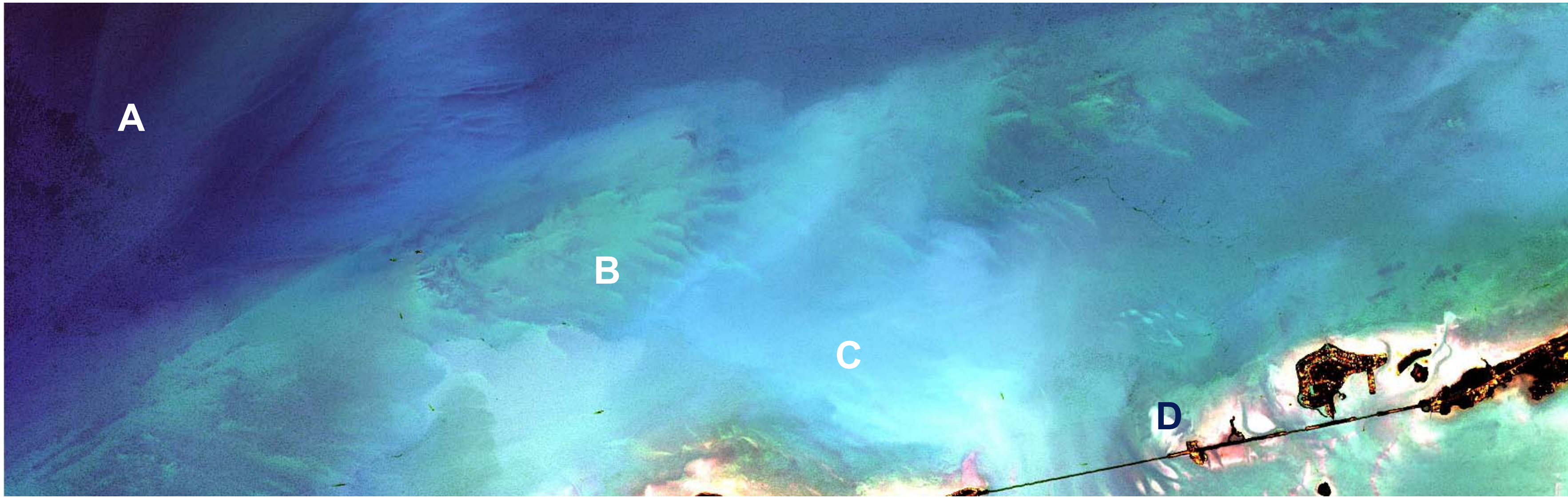


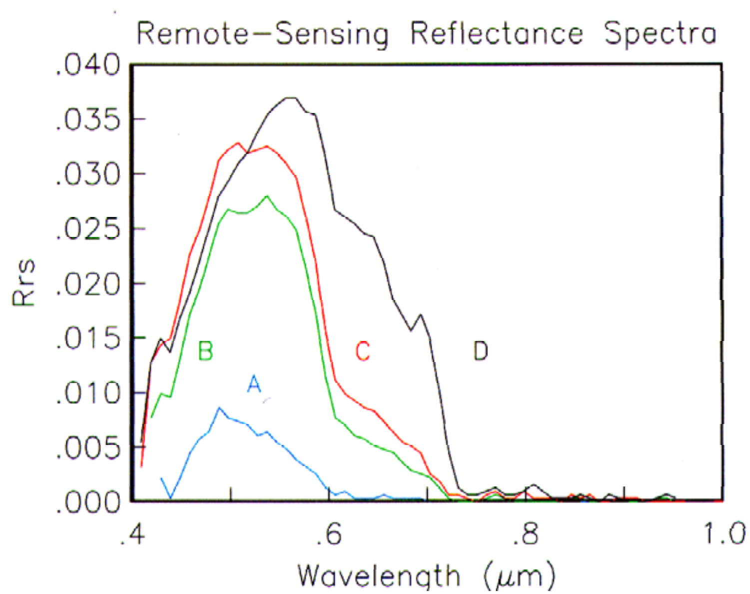
Figure 6. Percent Difference From Mean, Radiance and Irradiance

One can Expect +/- 2% Accuracy From Quality Laboratory Calibrations

Tafkaa Atmospheric Correction Including Surface Glint Correction for Ocean Scenes



AVIRIS data were atmospherically corrected using the Tafkaa algorithm for ocean scenes. The data are corrected for skylight reflected off the sea surface and then it is assumed that the water leaving radiance is 0 for wavelengths greater than 1.0 micron. (Gao, et al., *Appl. Opt.* 39, 887-896, 2000)

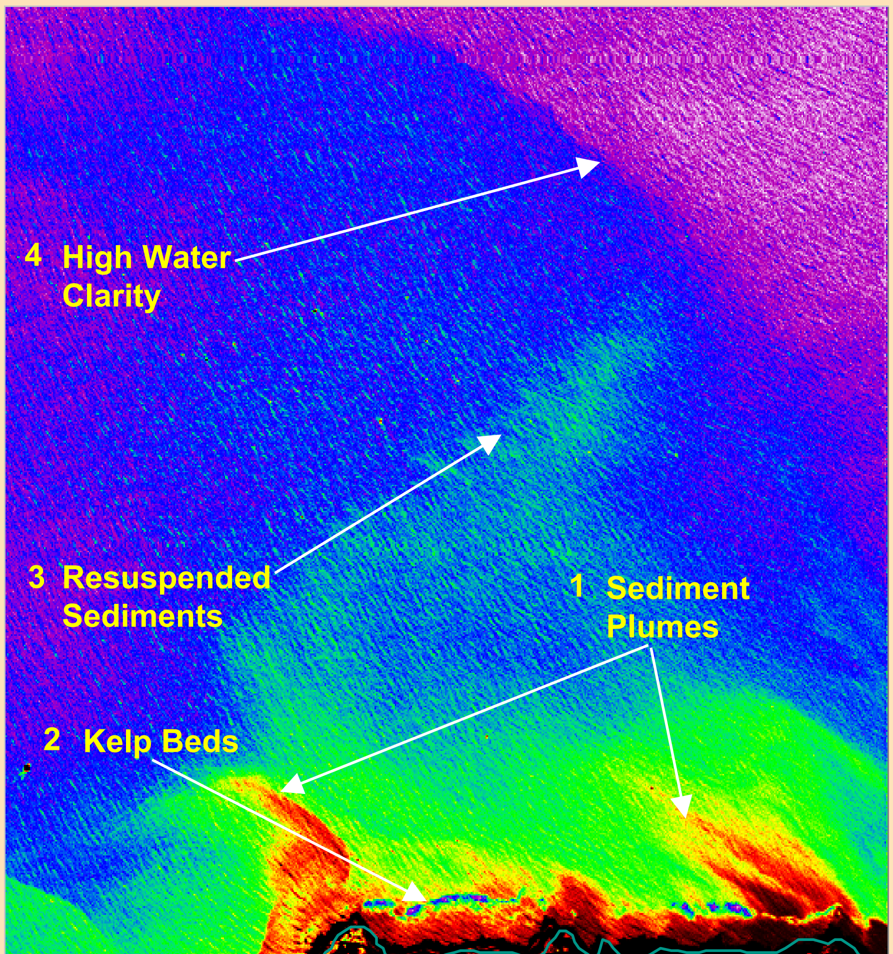


Naval Products

- Atmospheric and glint correction algorithms:
  - Atmospheric correction for ocean scenes includes correction for skylight reflected off a wind roughened sea surface
  - Atmospheric Correction of land scene assumes a Lambertian surface
- Ocean algorithms:
  - Water clarity Kd(490 nm)
  - Phytoplankton chlorophyll
  - Colored Dissolved Organic Matter (CDOM)
  - Suspended sediments
  - Bathymetry, bottom type and reflectance
- Beach and beach egress zone characterization
  - Vegetation and soil types
  - Terrain categorization
  - Trafficability

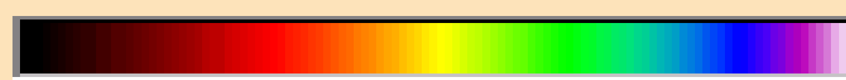
Water Clarity Products

- **White Point Outfall, CA Hyperspectral Image From AVIRIS (20 m GSD); Shows Freshwater Plume, Kelp Beds, and Resuspended Sediments**



1. **Product Shows Sediment Laden Freshwater Plume Following Recent Rainfall Event; Combine Optical Climatology with Atmospheric and Ocean Models to Predict Occurrence**
2. **Kelp Beds (Hazards to Navigation)**
3. **Resuspended Sediments (Indicates Mixing to the Bottom and High Turbulence)**
4. **Water Clarity (Predicts Mine Hunting Performance of Laser Line Scanners and Swimmer Visibility)**

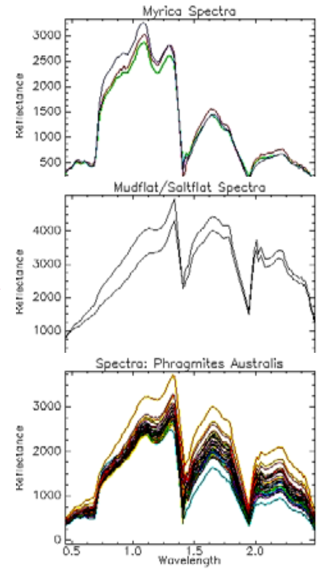
Simulation of Mine Detection Using Laser Line Scanner



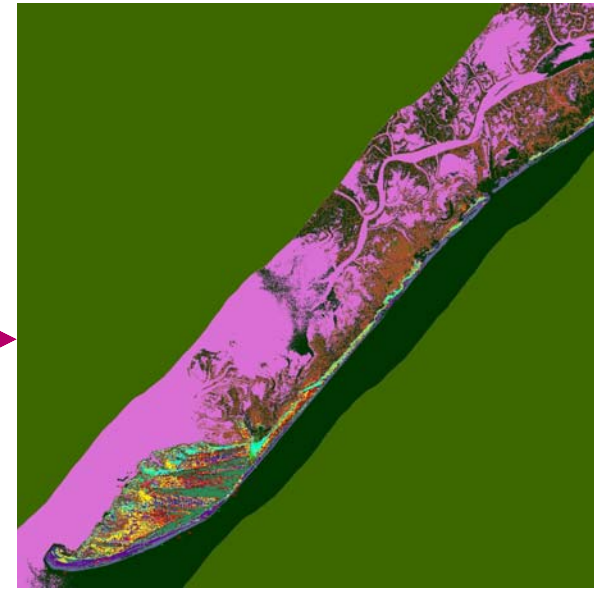
Low <=== Water Clarity Color Scale ===> High

Automated land Cover Classification Using PURSUIT Package

HYMAP Hyperspectral Imagery of Smith and Myrtle Islands, VA Field validation sites in Red

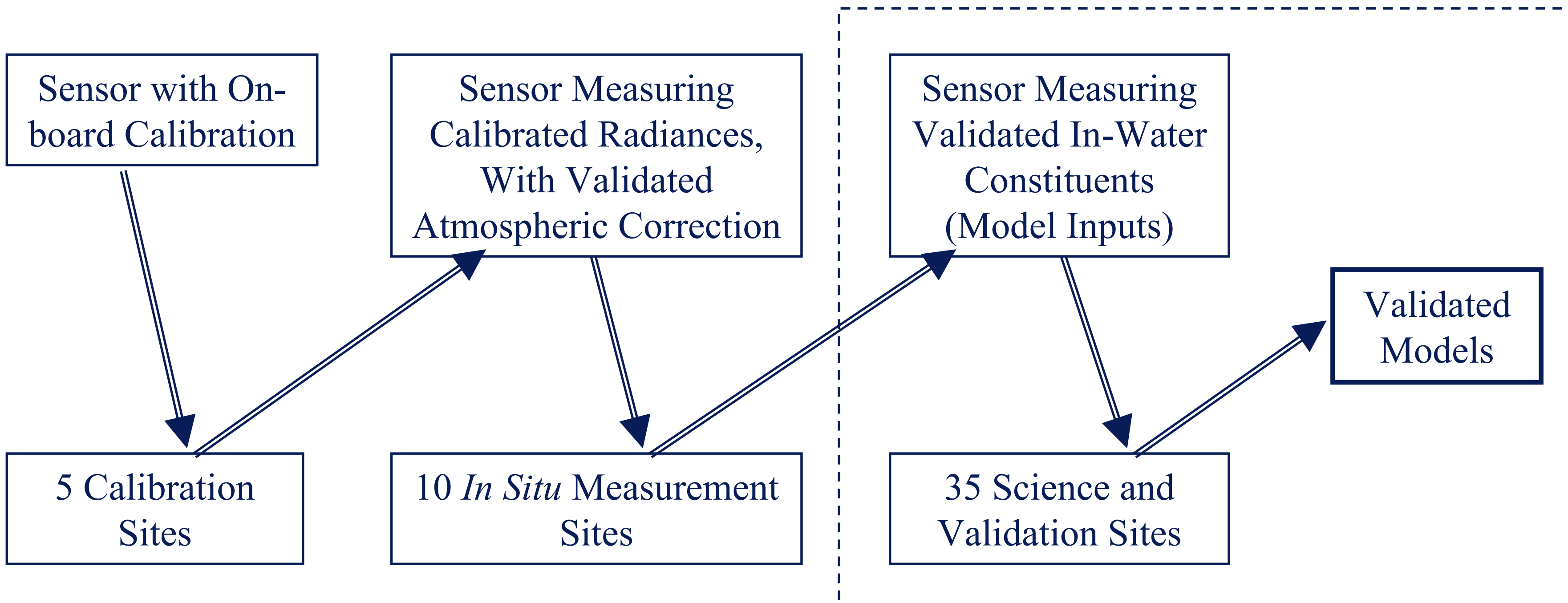


Automated processing of spectral signatures with Projection Pursuit



16-Category Land-Cover Automatic Classification Map

Data Validation and Model Development



Observations of the calibration sites fix the radiance calibration and validate the atmospheric correction model.

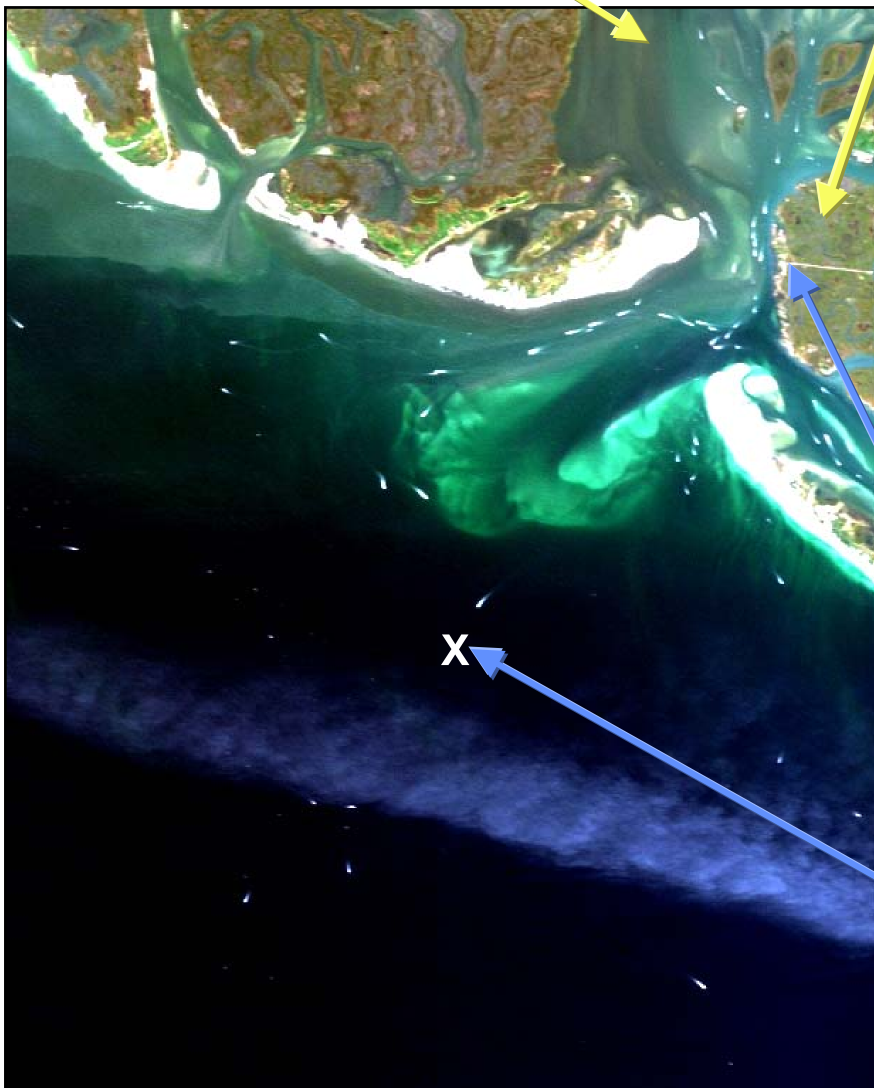
Observations of the sites with extensive ground truth provide validation of the algorithms for the in-water constituents (chlorophyll, sediments, etc.) that will be used as input to the coupled physical, bio-optical models.

The validated products now become the "ground truth" for the model validation. The process of model validation is an iterative one, comparing repeated observations with model predictions.

LEO-15, New Jersey Coast - HyCODE Optically Deep Study Site

Mullica River

Marsh



- Optically deep site for HyCODE Program.
- Continuous monitoring of vertical profiles at LEO-15 site.
- Characterization of marsh and river egress zones.
- Bio-optical model to be coupled with high resolution physical model (HyCODE).
- Underwater surveys using REMUS AUVs (Woods Hole Oceanographic Institution).
- CODAR HF Radar surface currents.
- ONR, NOAA and NOPP funding.

Rutgers University, Institute of Marine and Coastal Science, Field Station

Long-term Ecosystem Observatory at 15 m below the surface (LEO-15)

AVIRIS image July 12, 1998

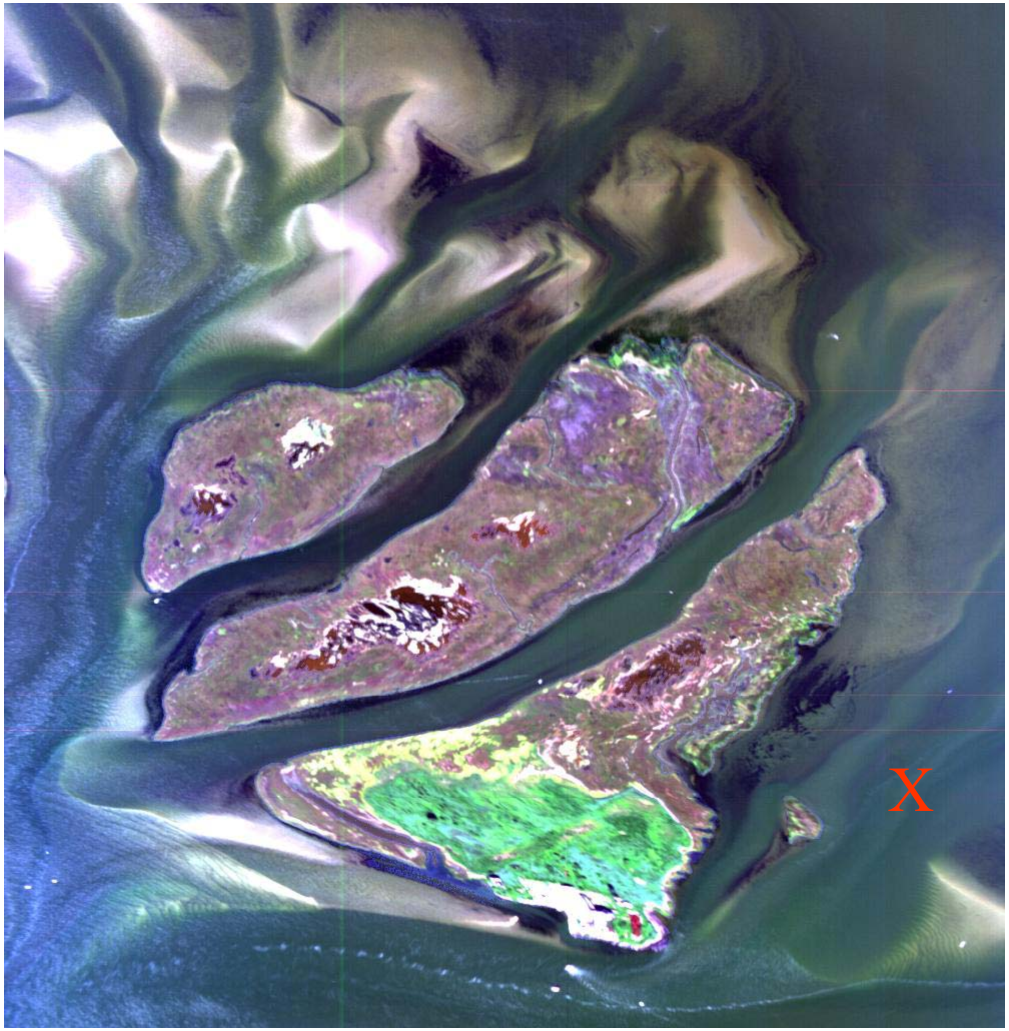
NRL Slow Descent Rate Optics Platform (SlowDROP)

State-of-the-art optical profiler with on-command water sampling for validation of hyperspectral imagery of the coastal ocean.

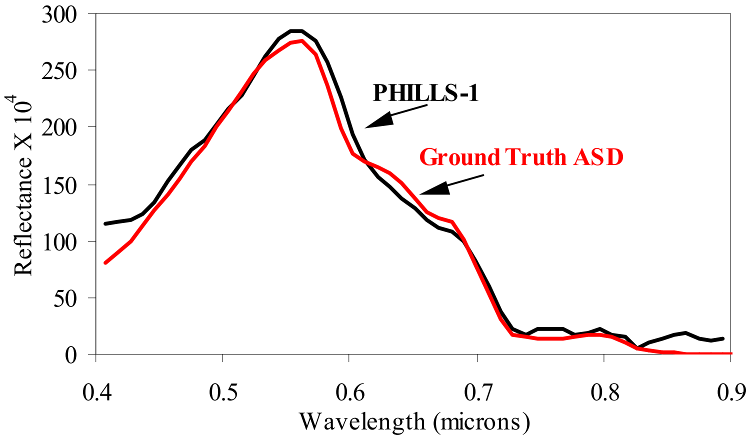
The SlowDROP Package contains:

- 1 WETLabs HiStar - Measures high spectral resolution absorption & beam attenuation
- 2 WETLabs AC9s - Measures nine wavelengths of absorption & beam attenuation for filtered and unfiltered water
- 1 WETLabs WETStar - Measures stimulated chlorophyll fluorescence
- 1 HobiLabs Hydroscat - Measures backscatter at six wavelengths
- 1 SeaBird CTD - Measures temperature, conductivity, pressure, with altimeter to measure distance above sea floor
- 4 to 10 2.5 liter water collection bottles triggered on command from deck

PHILLS data for Great Bay Region
(010731 Run15seq03)



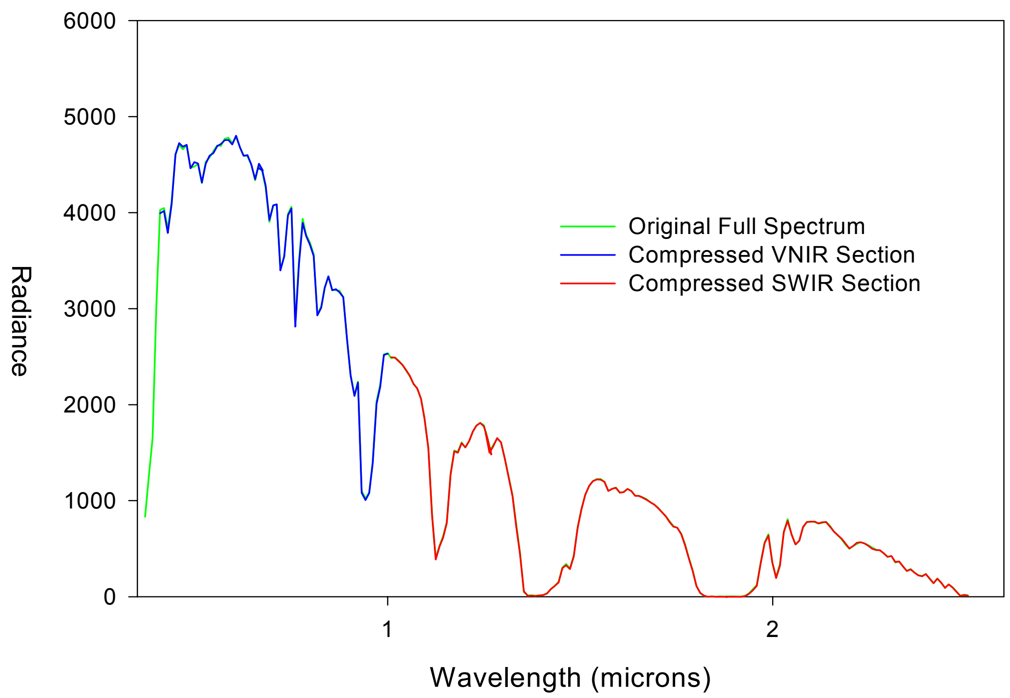
- The image is 1000 pixels wide and 1024 pixels long. The spatial resolution is 1.8 meters.
- The data was processed to R_{rs} using laboratory calibration data, and the Tafkaa atmospheric correction.
- "X" marks the location of spectra shown below.



On-Board Processing With ORASIS

- **Optical Real-time Adaptive Spectral Identification System (ORASIS)**
  - **Parallel, Adaptive Hyperspectral Method for Real-time, Scene Characterization and Data Compression.**
    - **Automatically Determines the Fundamental Spectral Signatures (Endmembers) Contained in an Arbitrary Scene Without Need for Training or *a-priori* Information**
    - **Spectrally Demixes Every Scene Pixel Into Its Fundamental Constituents Using Optimal Spectral Filters (Filter Vectors)**
    - **Fully Automated With Minimal User Training Required**
    - **High Compression (>10x) With Minimal Spectral Signature Degradation to Ease Data Storage and Downlink Requirements**
    - **Real-time Spectral Classification and Demixing Allows Real-time Tactical Downlink of End Products Directly From the Spacecraft to the Field**
- **ORASIS was to Be Run on NEMO on-board processor for Real-time Data Compression (Requirement >10:1 Compression)**

ORASIS Compression for NEMO Exceeds Speed and Compression Requirements



Comparison of an Original and Reconstructed Spectrum for the Cuprite, NV AVIRIS Scene

- **Processing on Breadboard IOBP at a Rate of ~10,000 Spectra/s/SHARC**
  - **Required Speed is ~4800 Spectra/s/SHARC for Real-Time Processing of NEMO COIS Data**
- **Achieving Compression Ratios (Combined VNIR and SWIR) of ~30:1 for the Cuprite, NV Data Set, ~17:1 (VNIR only) for the Florida Keys Data Set**
  - **Compression Requirement 10:1 (20:1 Goal)**

ORASIS - NRL's hyperspectral processor is used throughout government and industry

Organizations that have requested copies of ORASIS and are currently evaluating it for various applications

- Aerospace Corp
- Army Space Command
- Army ChemBioWarfare Com
- BioMedWare
- Boeing Autometrics
- ChemIcon Corp
- DARPA
- IMSI Corp
- Lockheed Martin Corp
- MIT Lincoln Laboratory
- Naval Space Command
- NIMA
- Observa Corp
- PAR Government Systems
- SAIC
- Tony Verna Enterprises
- Technology Research Associates

POC: Dr. Jeff Bowles, (202) 404-1021

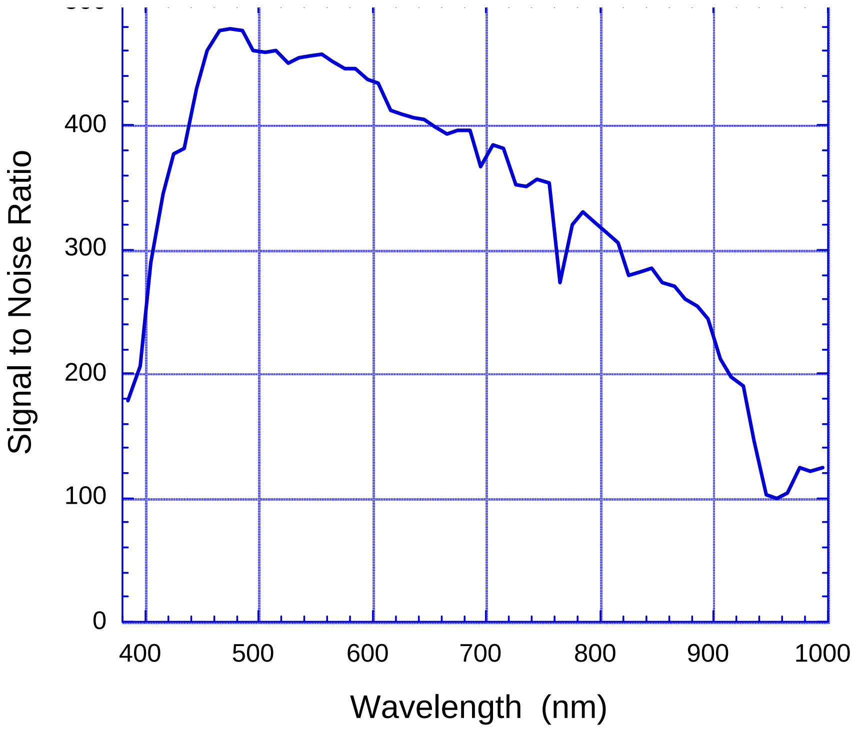
Background: NEMO

- The Office of Naval Research (ONR) and the Space Technology Development Corporation (STDC) entered into an agreement (OT) in December 1997 to build the Naval EarthMap Observer (NEMO) Satellite to provide hyperspectral data and co-registered panchromatic imagery.
  - The hyperspectral imager was designed to meet Naval requirements for shallow water bathymetry, and characterization of bottom and water optical properties.
  - STDC planned to sell land hyperspectral data for mineral exploration, agriculture and environmental applications.
  - After years of trying, the commercial partner was unable to obtain adequate funding for its half of the spacecraft.
  - ONR and STDC agreed to end the OT on April 26, 2002. The lawyers are drafting the final papers.
- However, the need still exists to fly an imaging spectrometer for the coastal ocean to meet Naval and civilian needs.

VNIR COIS performance Specifications

- High sensitivity and high SNR for coastal ocean imaging
  - SNR > 200:1 (outside of atmospheric absorption bands) for a 5% reflectance ocean scene
  - High dynamic range – does not saturate over 90% reflectance clouds or beaches.
- Orbit (400 to 600 km) controls ground resolution and swath width
  - 20 to 30 m GSD
  - Swath is 1000 pixels (20 to 30 km)
- Off-Axis TMA telescope provides high SNR in a small package.
- Offner spectrometer provides distortion free imaging.
- Thinned, backside-illuminated CCD provides high SNR in the blue.
- Tests on engineering model indicate COIS meets design requirements.

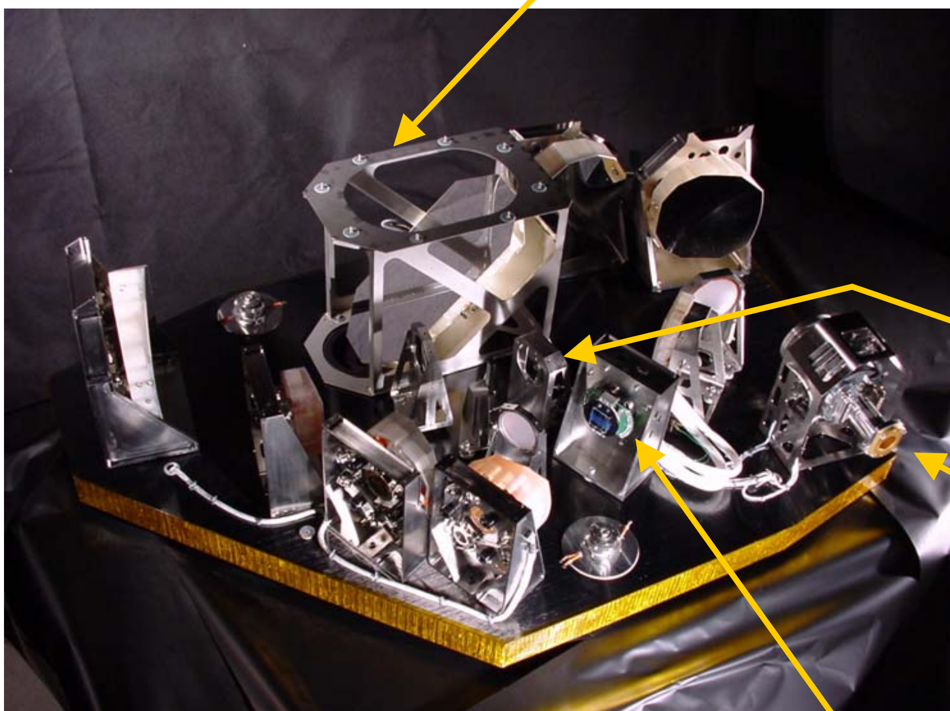
COIS SNR for 10 nm spectral channels
For an ocean scene with 5 % Reflectance

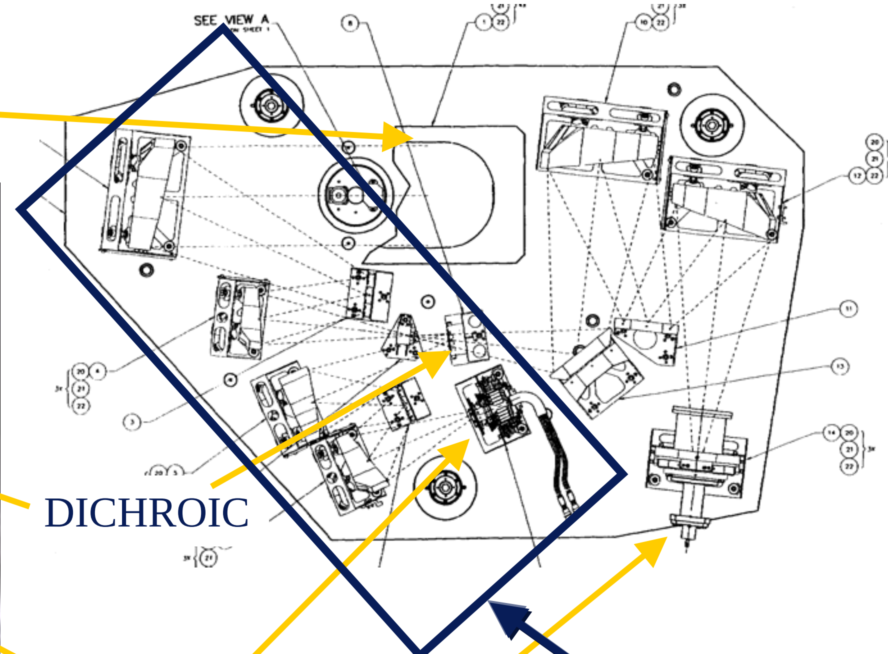


COIS Sensor Flight Hardware at NRL

Two Full sets of Flight Spare Mirrors & gratings at NRL

Support for Baffle & Cover Mechanism





DICHROIC

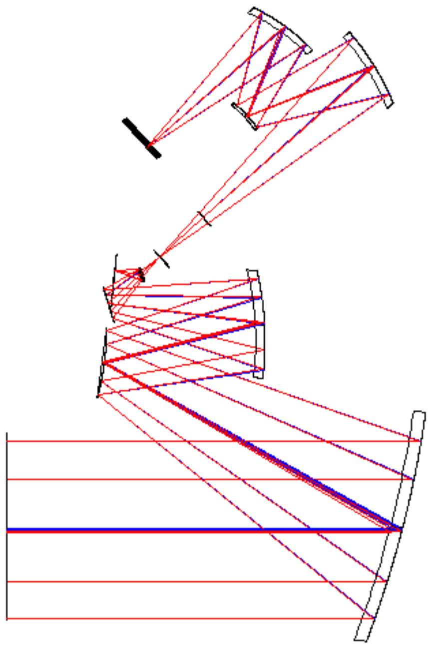
SWIR FPA in Dewar
(Flight Spare)

VNIR COIS is a much smaller package for integrating into an STP flight opportunity

- **Engineering Model at NRL for Mechanical Testing (Pictured).**
- **Flight Unit is now at NRL.**

VNIR FPA
(EM FPA)

Coastal Ocean Imager (COI) Proposed as Part of NPOESS Ocean Observer



- Description
  - Compliments VIIRS by providing higher resolution ocean color and SST data to meet Naval, NOAA and DOI requirements for coastal imagery
  - 100 m resolution 64 channel VNIR Imaging Spectrometer (380-1000nm) and two band Thermal Imager
  - +/- 45 degree field of regard, 150 km wide swath

- 130 kg
- 180 W
- Maximum Data Rate 110.9 Mbps
- Meets 10 Threshold EDRs for regional imagery, coastal ocean color, SST, land vegetation, etc.

- Uses proven Technologies:
  - NEMO telescope and spectrometer design
  - SeaWIFS scanning telescope
  - AVHRR heritage for SST
- No new technologies required.

Summary

- Hypothesis – Hyperspectral imaging is needed to resolve the complexity of the coastal ocean, particularly when the bottom is visible in the imagery.
- The NRL Remote Sensing Division has a focused program that addresses all aspects of this problem.
- Example of successful approach to the analysis of AVIRIS data of Tampa Bay by Lee, Carder, et al.
- The Portable Hyperspectral Imager for Low Light Spectroscopy (PHILLS)
  - Characteristics, calibration and example data.
- These aircraft systems are very useful, but where will we get global data?
- Possible future data sources:
  - The The Coastal Ocean Imaging Spectrometer (COIS).
  - The Coastal Ocean Imager (COI) on the NPOESS Ocean Observer.
  - Noble EYE.