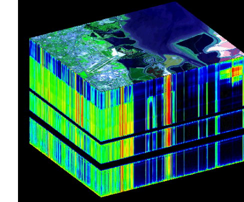
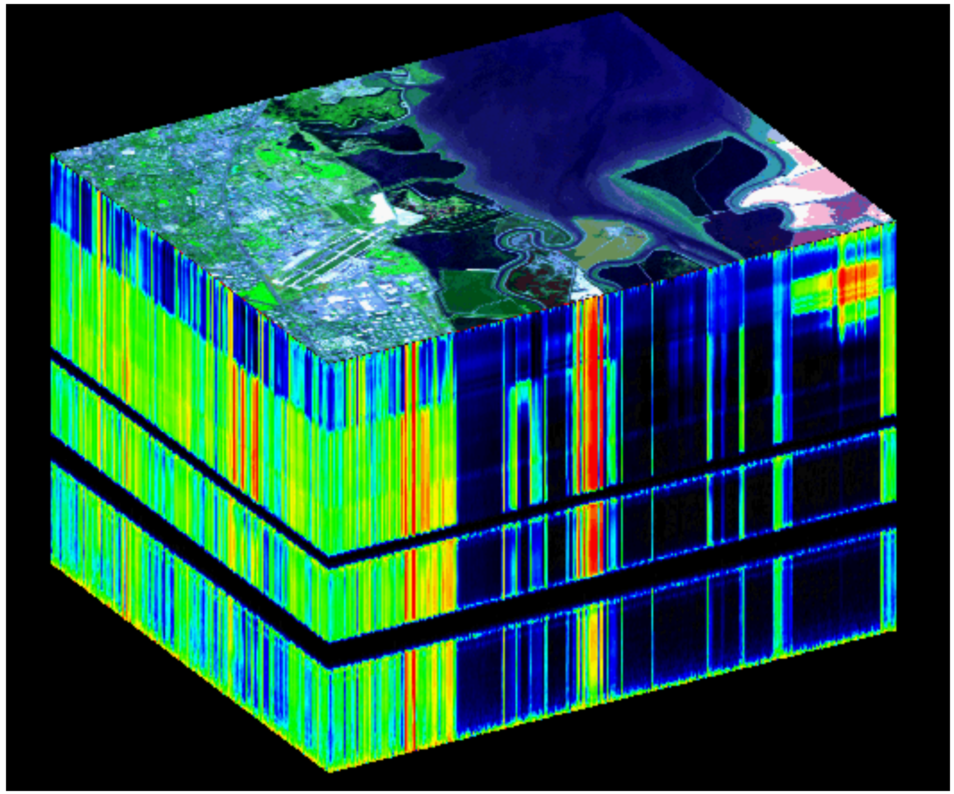
Imaging Spectroscopy, Past, Present, and Future

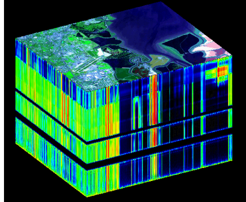


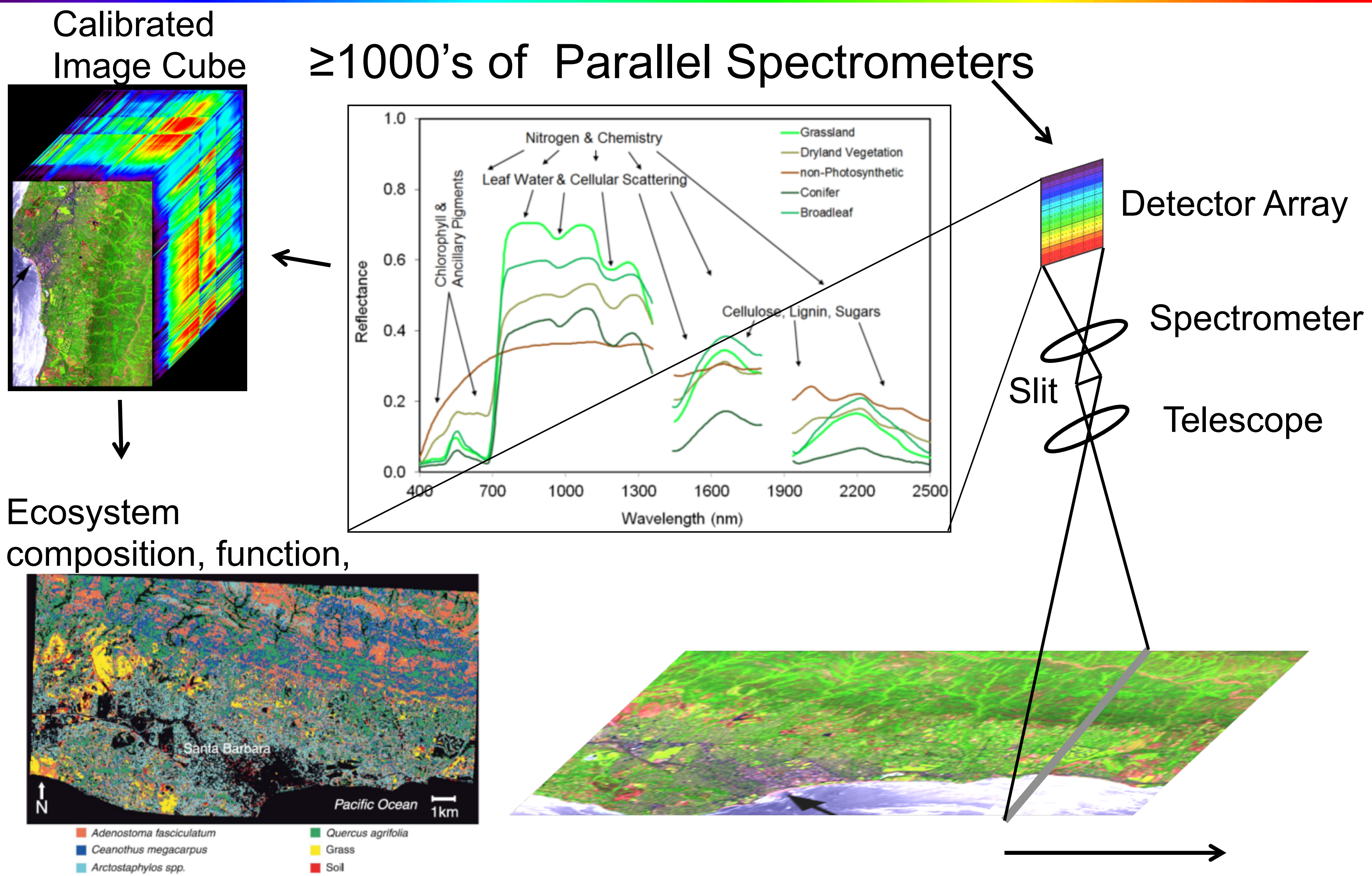


Robert O. Green[1] and the Imaging Spectroscopy Community

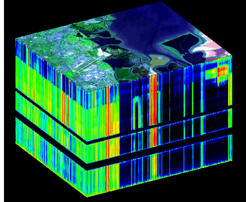
[1]Jet Propulsion Laboratory, California Institute of Technology

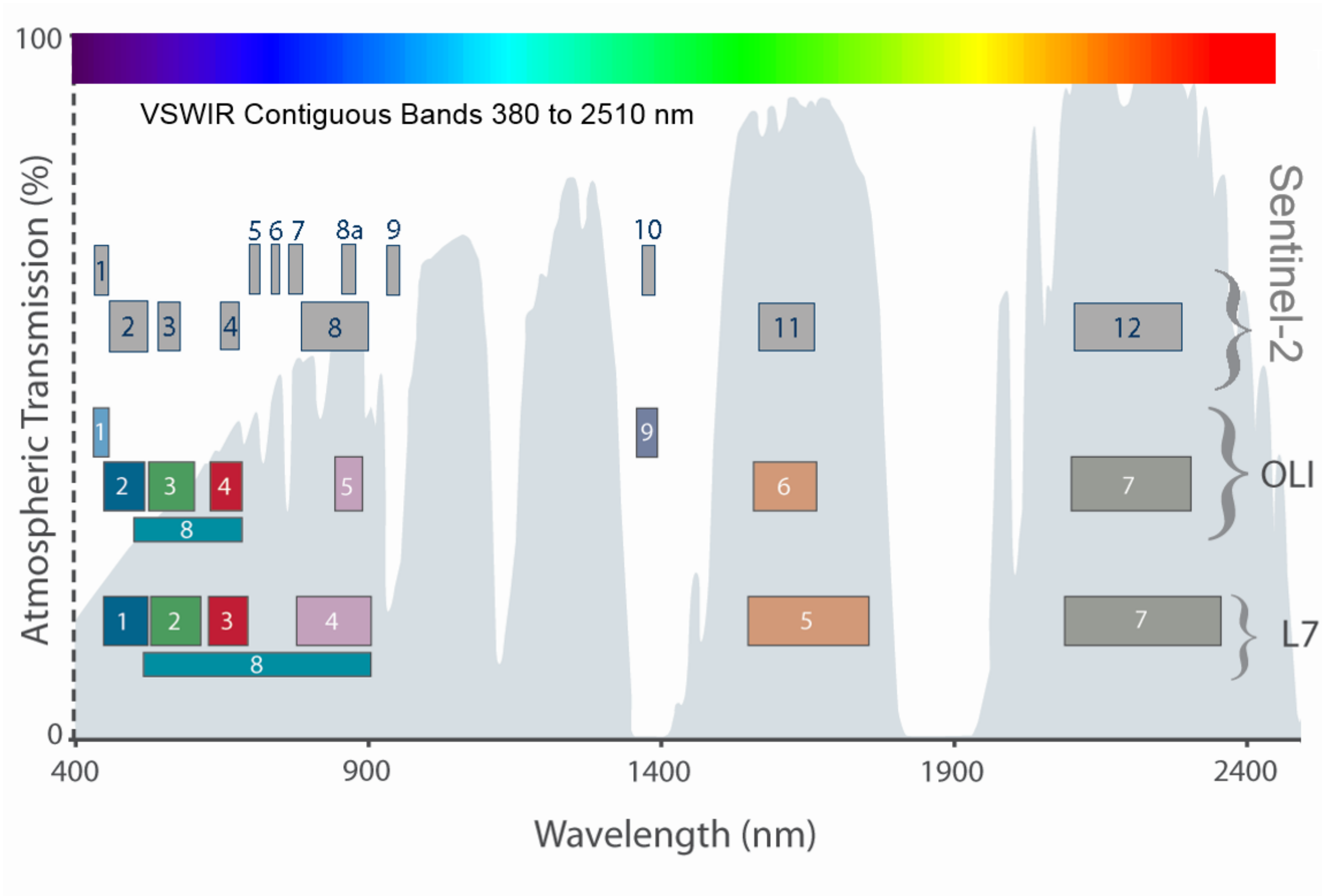
Example: Imaging Spectroscopy for Carbon Cycle and Ecosystem Science





Full Continuity with Landsat

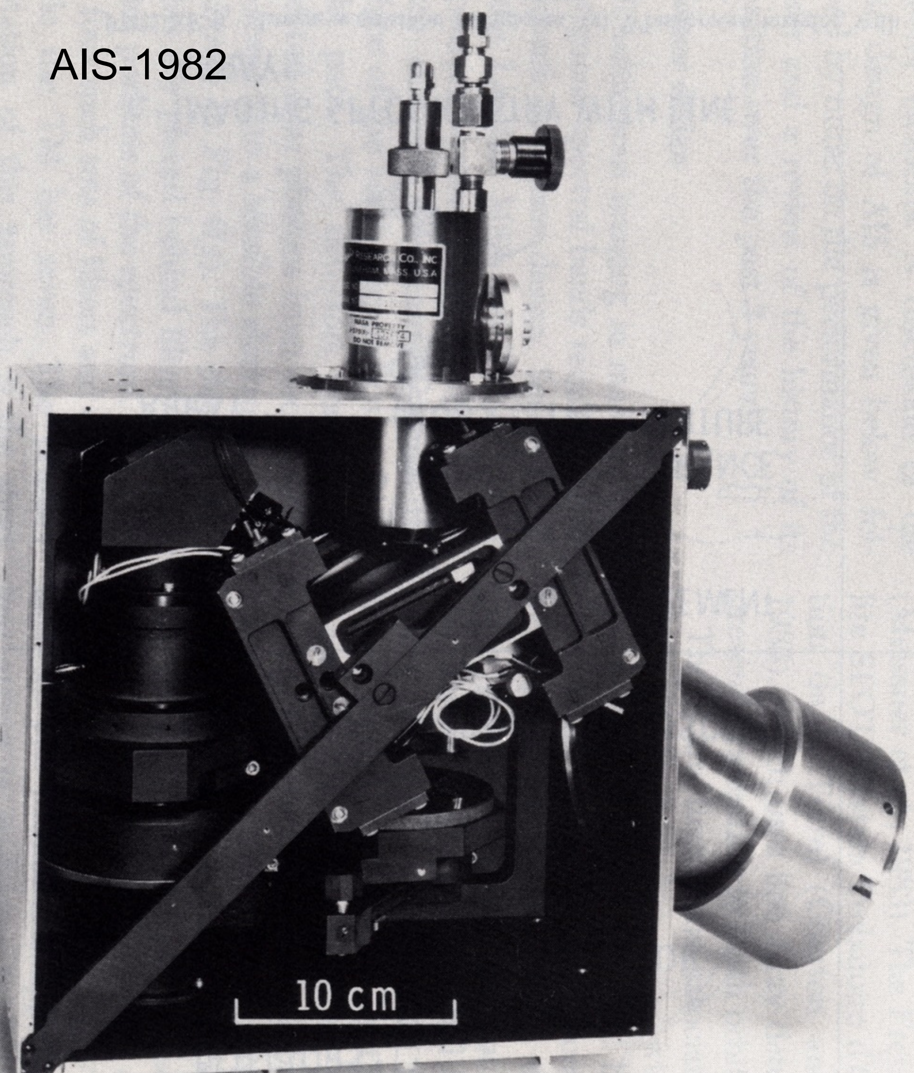




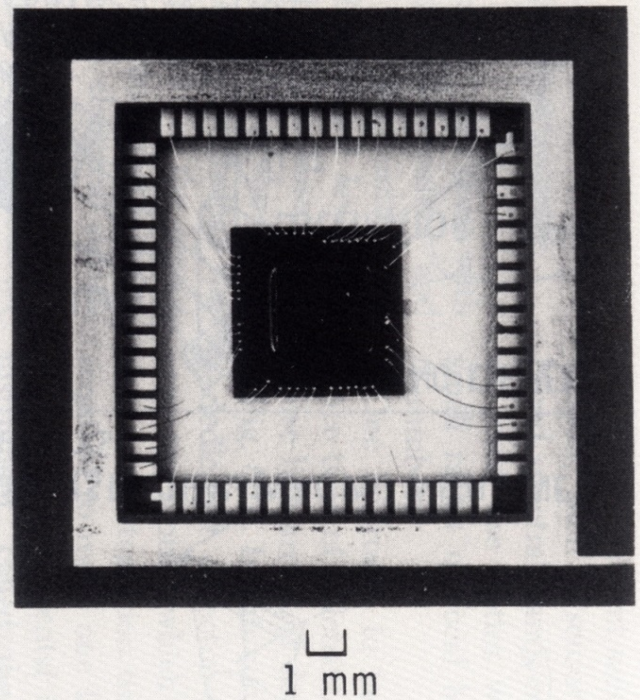
Past: The Airborne Imaging Spectrometer

Proposed at JPL in 1979 (IRAD)

AIS-1982

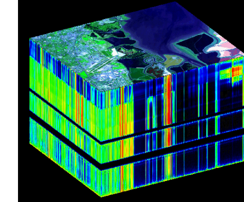


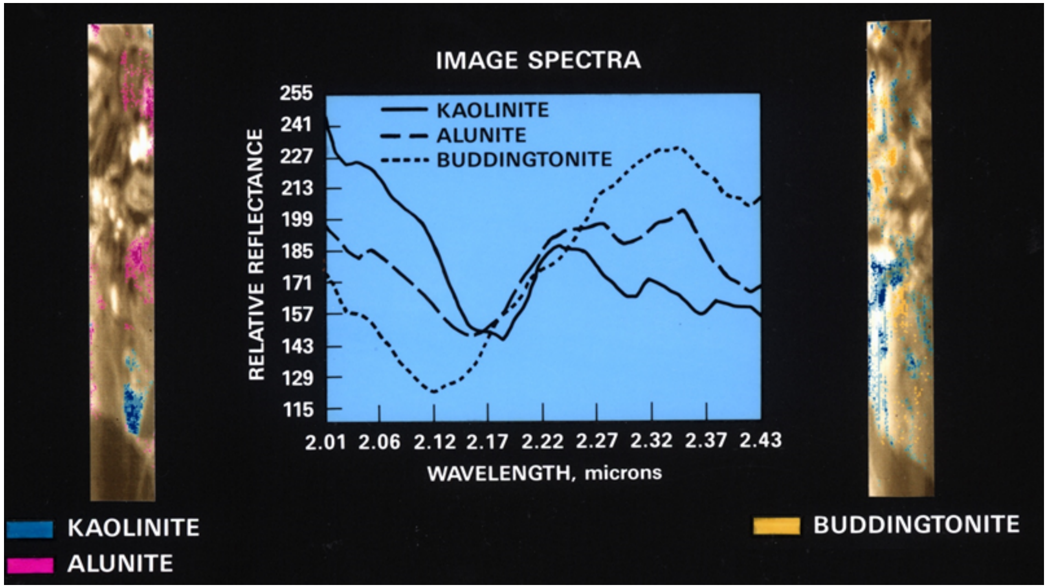
32x32 HgCdTe Detector
Rockwell Scientific

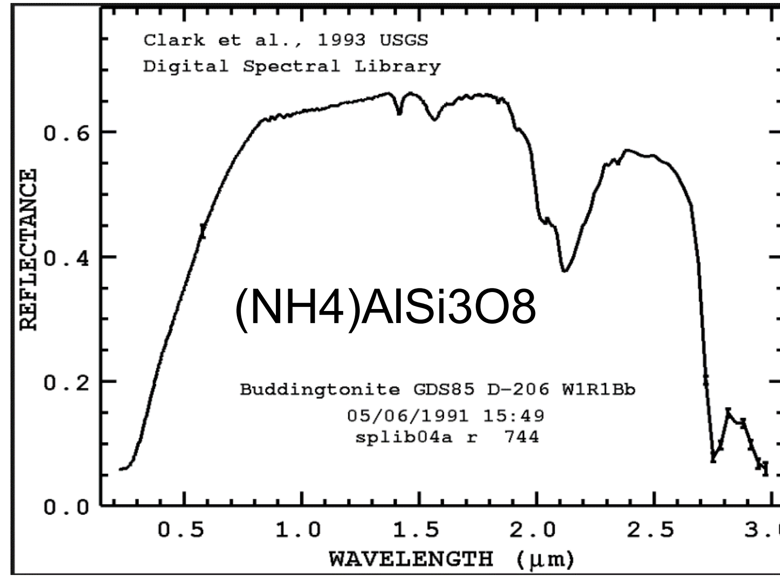


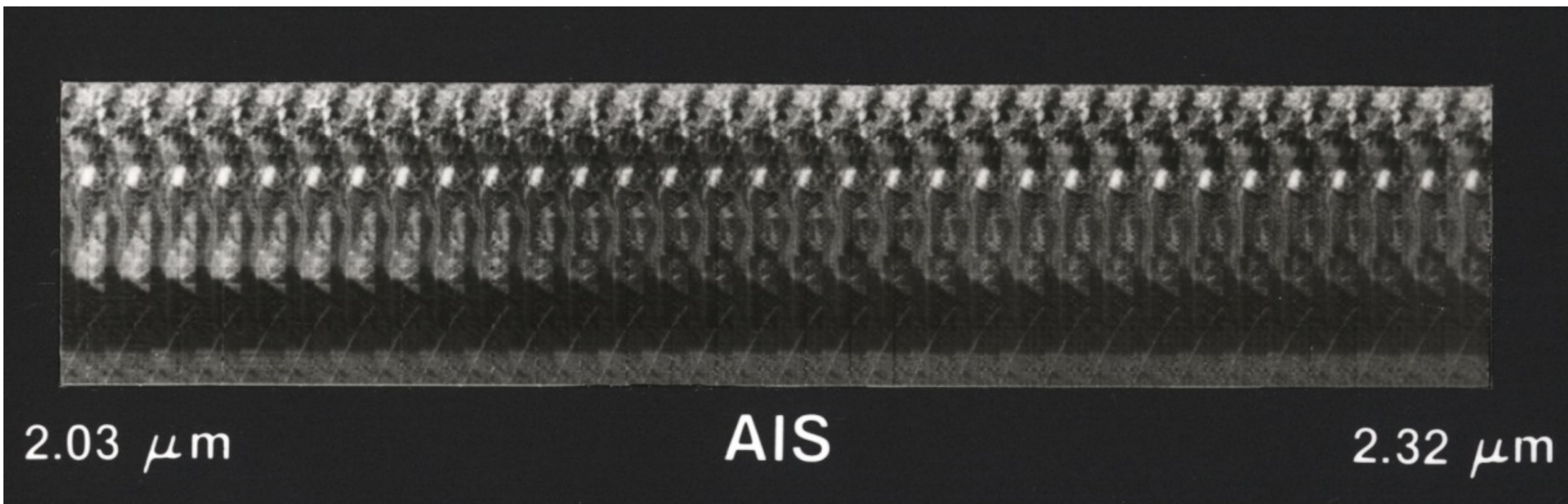
AIS First Flight Discovery

Buddingtonite Occurrence at Cuprite, NV

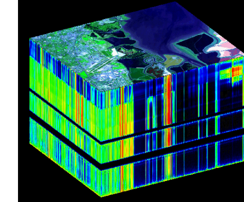


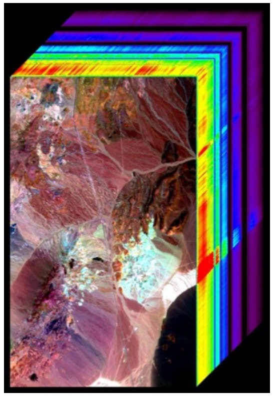


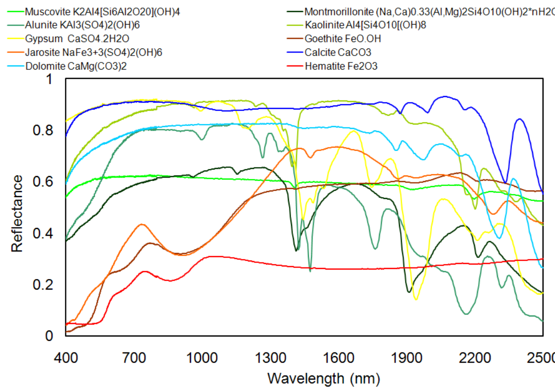


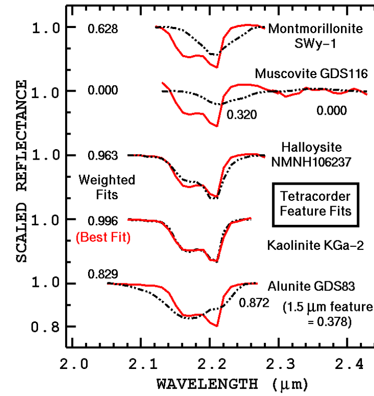


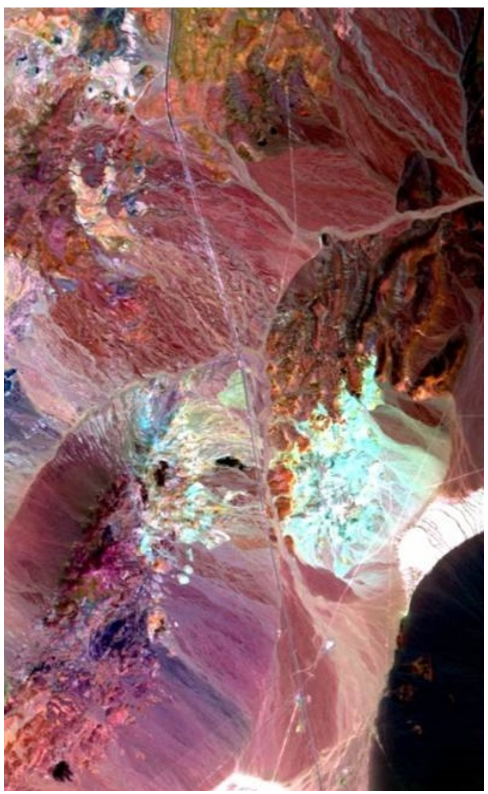
Present: Airborne Local Mineral Mapping Spectral Fitting from a Library (USGS)

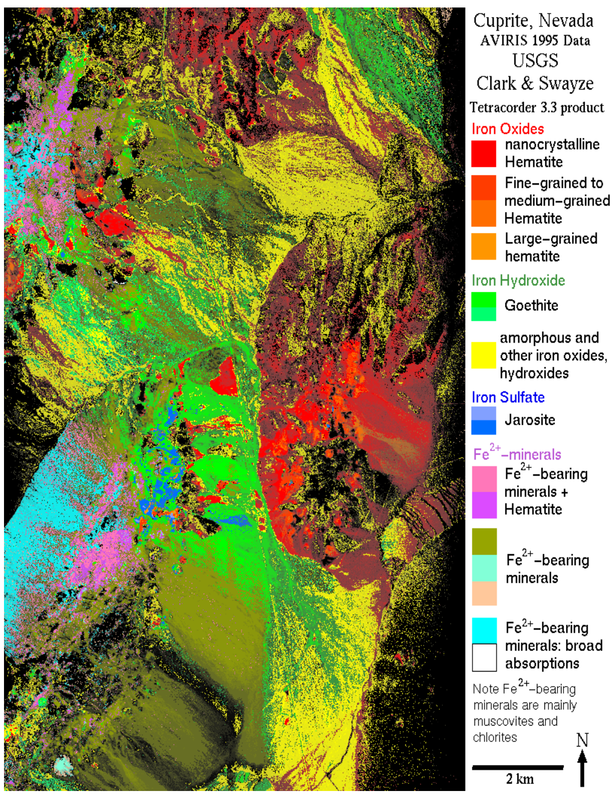


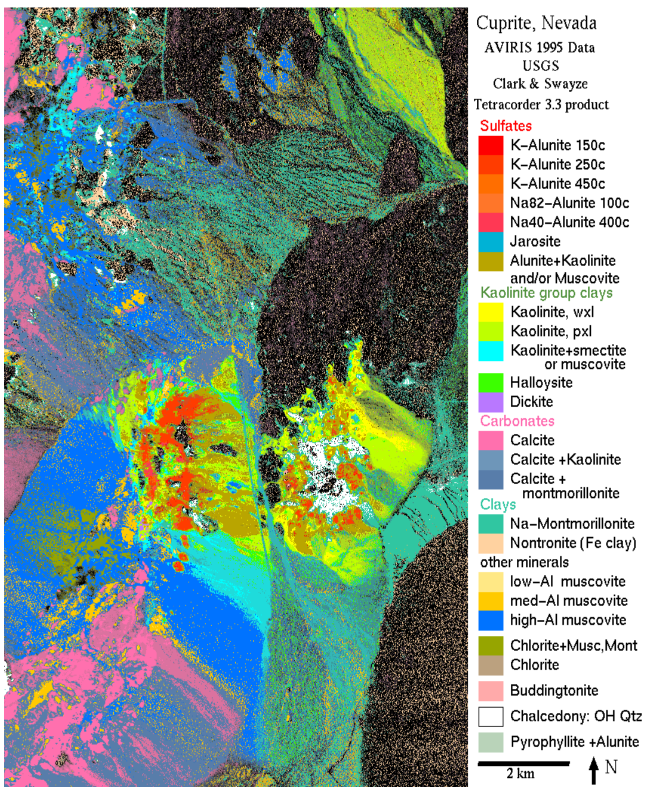






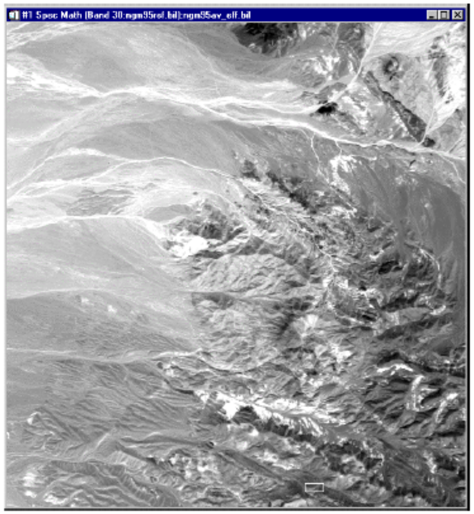


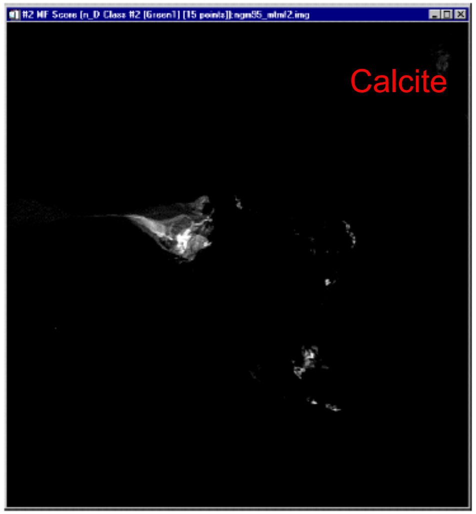


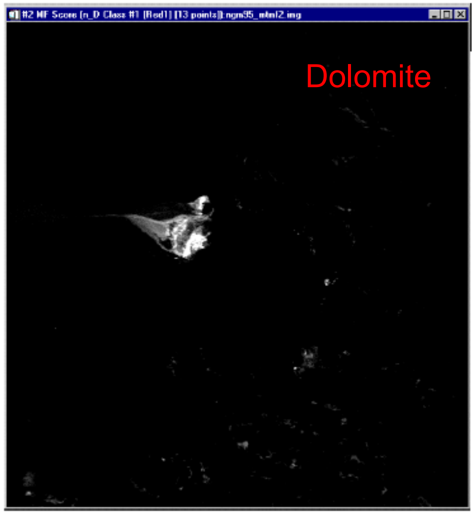


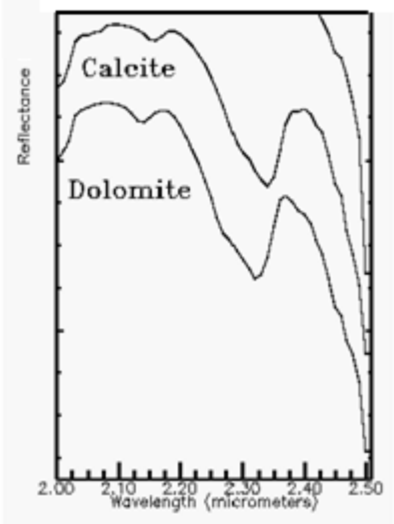
Spectroscopy Enables Sub-pixel Detection

- Grapevine Mountains 20m x 20m AVIRIS measurements





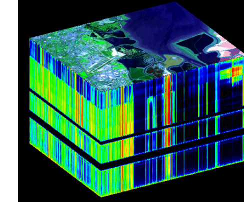


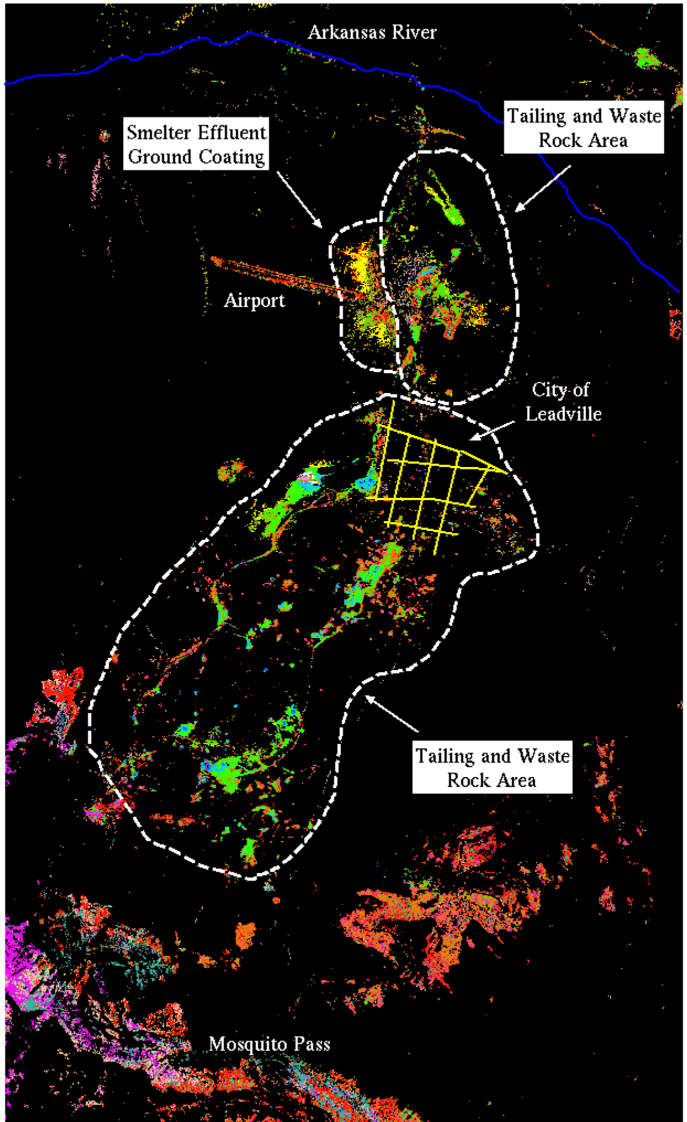


3m x 1m Dolomite discovered with 20m x 20m AVIRIS imaging spectrometer measurement

Boardman and Kruse

Mapping Superfund Hazards at Leadville, CO





Leadville, Colorado
AVIRIS 1995 Data
USGS
Swayze, Clark, & Livo
Tricorder 3.4 Product

Highly Acidic Mineral Assemblages

- Low pH water
- Pyrite
- Jarosite
- Jarosite + Goethite Mix

Acidic to Neutral Mineral Assemblages

- Goethite
- Hematite 1
- Hematite 2
- Amorphous Fe–hydroxide

Mineral Drainage Assemblages

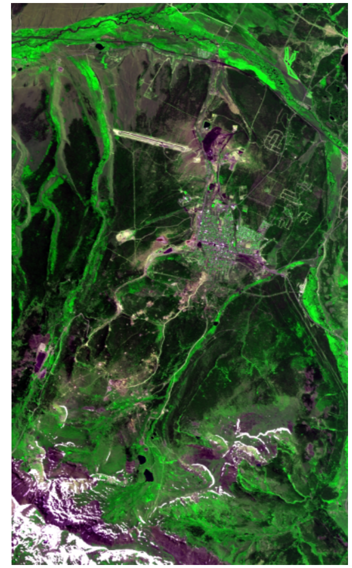
- Assemblage 1
- Assemblage 2
- Assemblage 3

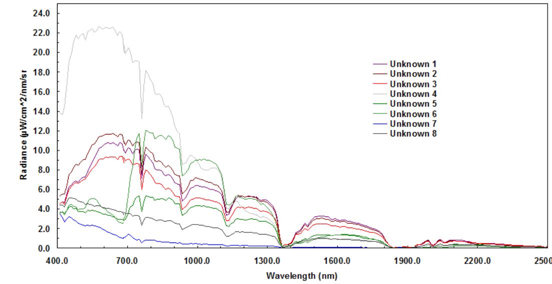
Other Minerals

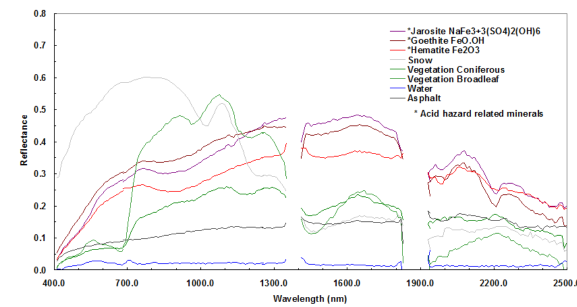
- Black Slag
- Fe2+ – Minerals 1
- Fe2+ – Minerals 2
- Chlorite

N

2 km





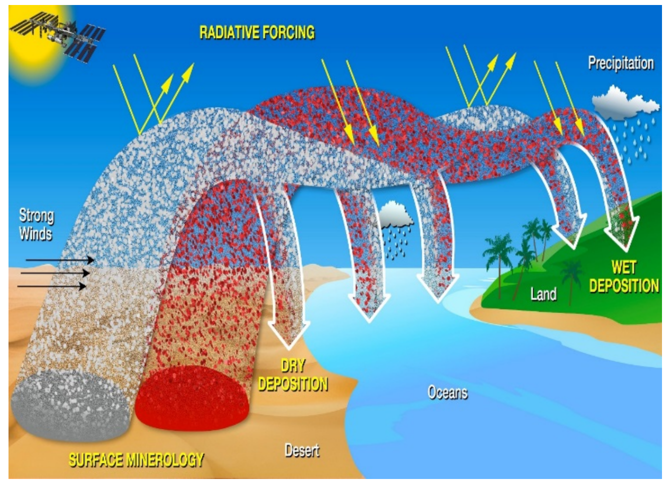


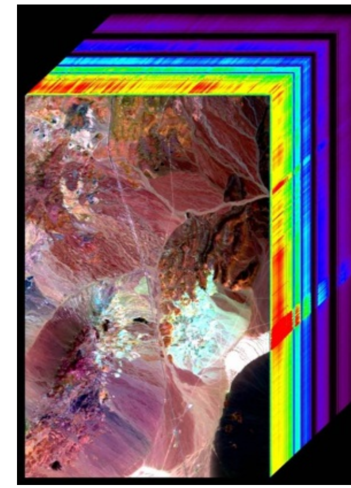
I am writing to convey the support of my office and staff for the AVIRIS program. Remote sensing data collected by NASA/JPL with the Airborne Visible-Infrared Imaging Spectrometer (AVIRIS) instrument of the California Gulch NPL Site near Leadville, Colorado has provided information aiding in the to remediation of heavy metal contamination at this site. AVIRIS data was collected in July of 1995 and was calibrated and mapped using the Tricorder algorithm at the USGS. Similar work was done at the Summitville NPL site and is beginning in the Upper Animas Basin. This work has resulted in, and will continue to produce significant cost savings in site investigations and cleanup activities.

Use of the AVIRIS data and technology has provided an estimated $2 million dollar saving in site investigation study expenditures. The AVIRIS technology has also resulted in shortening of the site investigation process by an estimated 2 ½ years.

The Environmental Protection Agency, Region VIII has just completed discussions with other Federal and State agency stakeholders in minewaste cleanup in the western United States. Based on these preliminary discussions interest is building in further use and application of this technology. We are very enthused by our applications of this technology and encourage NASA/JPL to provide continued funding for the AVIRIS instrument and its flight program.

Advances in Mineral Dust Source Composition Measurement with Imaging Spectroscopy Demonstrated at the Salton Sea, CA





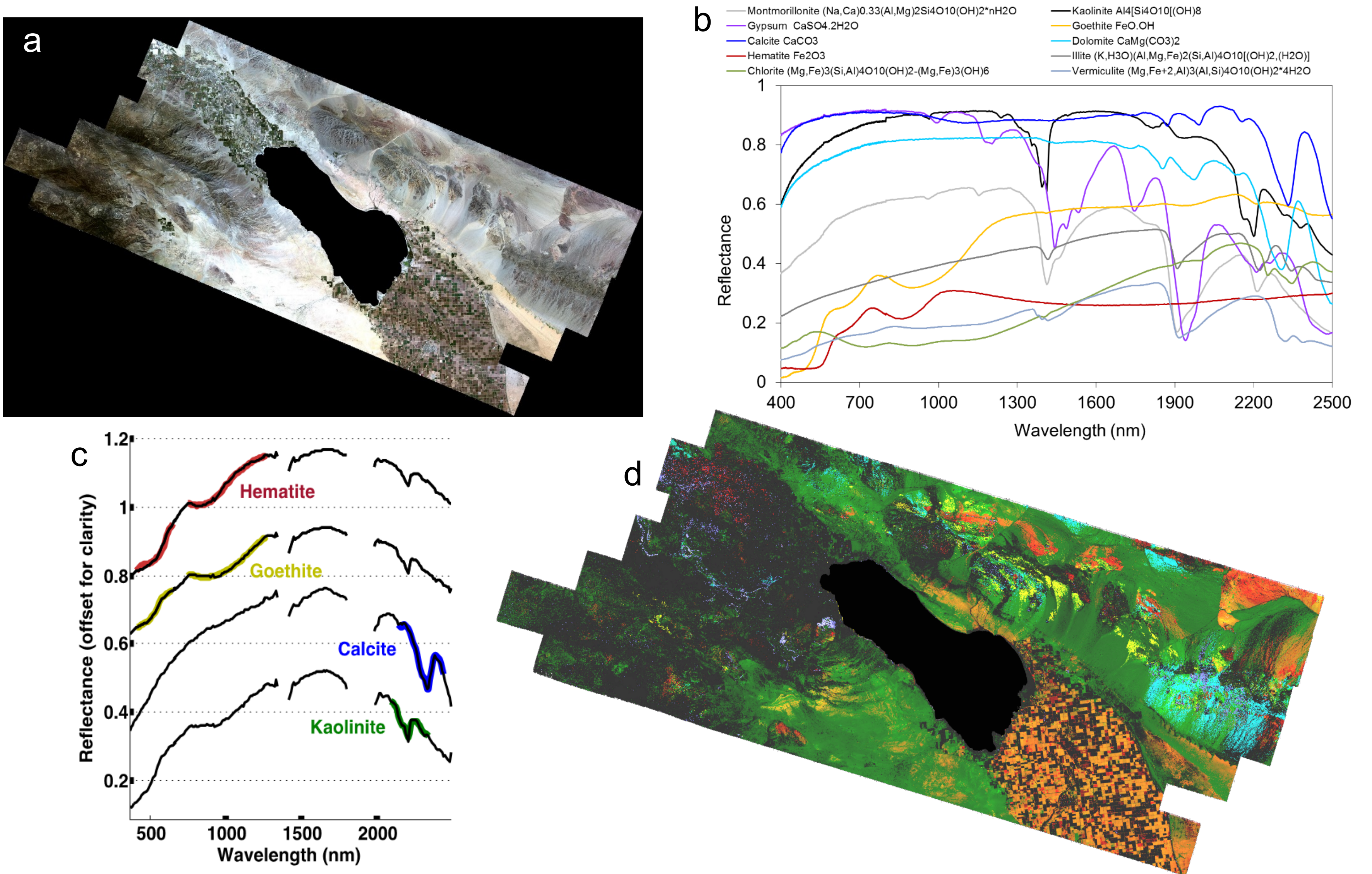
Mineral dust emitted by the surface into the atmosphere affects climate through direct radiative forcing and indirectly through cloud formation as well as changes in the albedo and melting of snow/ice.

Based on their chemistry, the minerals in dust react and modify tropospheric photochemistry and acidic deposition.

Mineral dust aerosols affect ocean and terrestrial ecosystem biogeochemical cycling by supplying limiting nutrients such as iron and phosphorus.

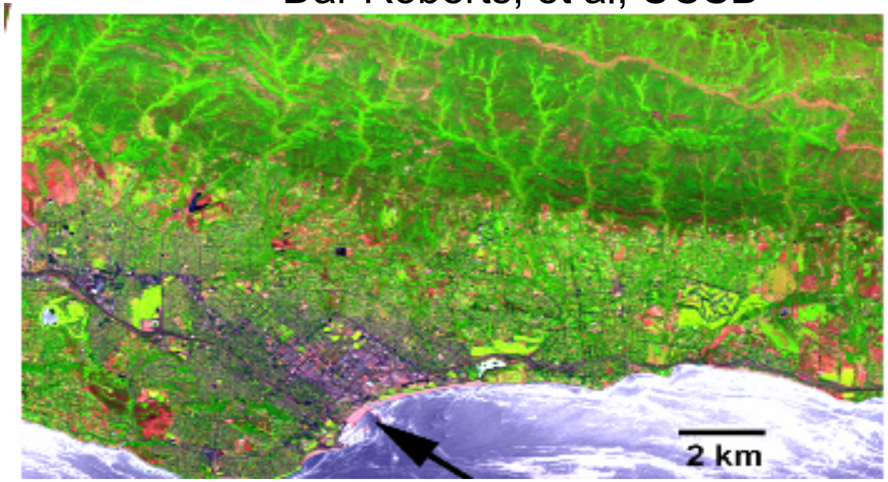
In populated regions, mineral dust is a natural hazard that affects human health and safety.

Test of Imaging Spectroscopy Retrieval from HyspIRI Preparatory Campaign AVIRIS Measurements

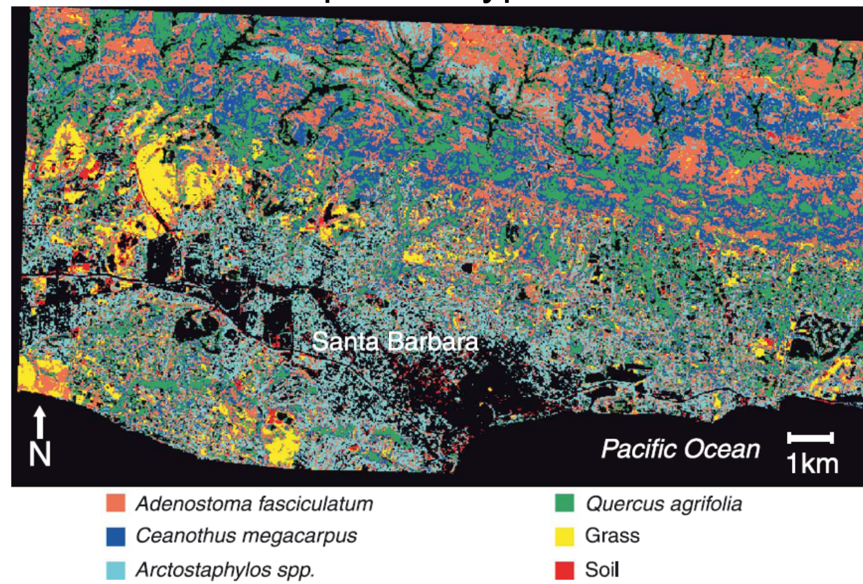


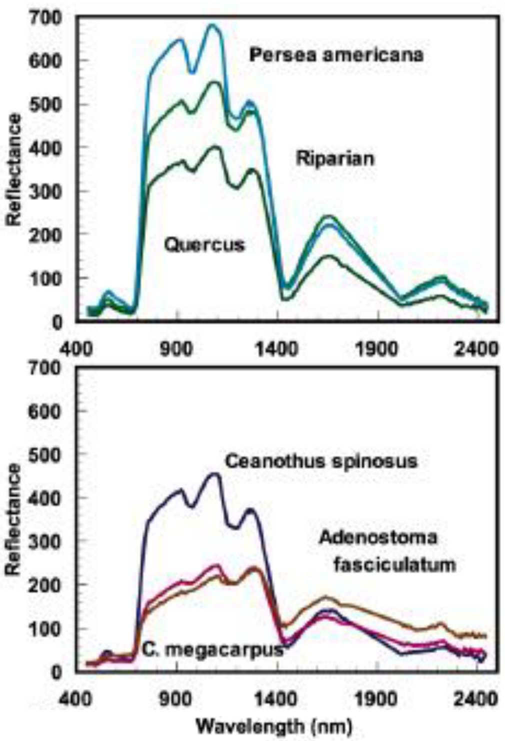
Mapping Vegetation Species with Imaging Spectroscopy

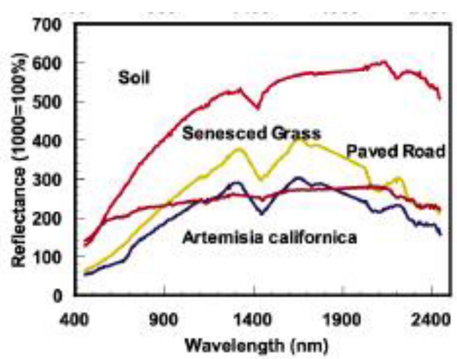
Dar Roberts, et al, UCSB



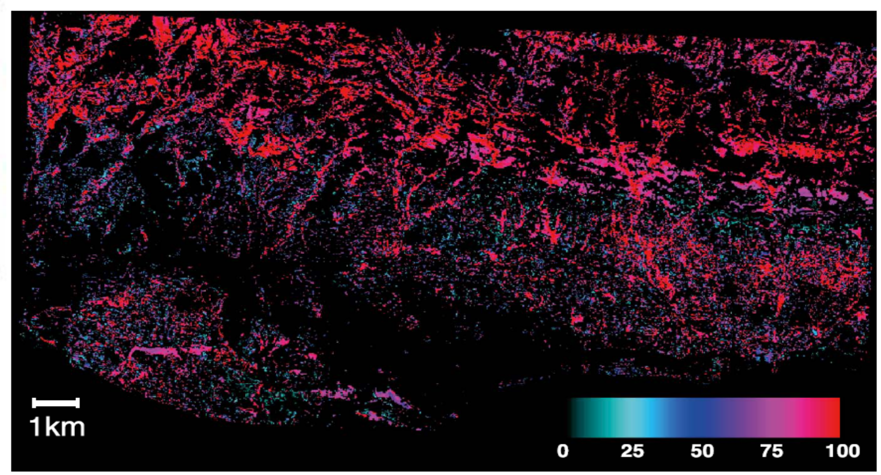
MESMA Species Type 90% accurate



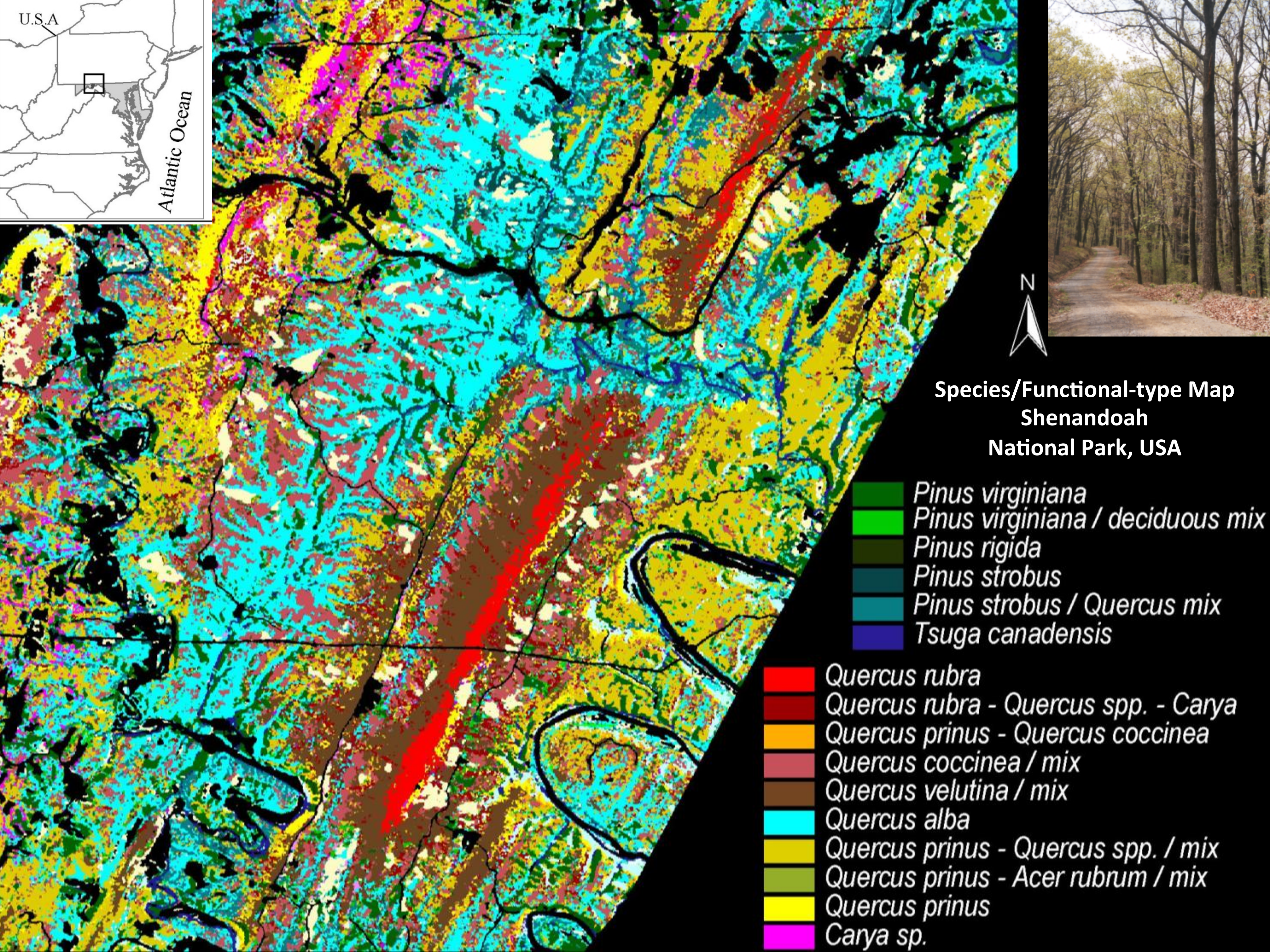




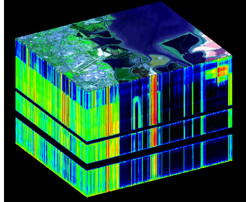
Species Fractional Cover Quercus agrifolia



Airborne Imaging Spectroscopy, Santa Barbara, CA


U.S.A
Atlantic Ocean
N
Species/Functional-type Map
Shenandoah
National Park, USA
Pinus virginiana
Pinus virginiana / deciduous mix
Pinus rigida
Pinus strobus
Pinus strobus / Quercus mix
Tsuga canadensis
Quercus rubra
Quercus rubra - Quercus spp. - Carya
Quercus prinus - Quercus coccinea
Quercus coccinea / mix
Quercus velutina / mix
Quercus alba
Quercus prinus - Quercus spp. / mix
Quercus prinus - Acer rubrum / mix
Quercus prinus
Carya sp.

Biodiversity



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comment

Monitoring plant functional diversity from space

The world's ecosystems are losing biodiversity fast. A satellite mission designed to track changes in plant functional diversity around the globe could deepen our understanding of the pace and consequences of this change, and how to manage it.

Walter Jetz, Jeannine Cavender-Bares, Ryan Pavlick, David Schimel, Frank W. Davis, Gregory P. Asner, Robert Guralnick, Jens Kattge, Andrew M. Latimer, Paul Moorcroft, Michael E. Schaepman, Mark P. Schildhauer, Fabian D. Schneider, Franziska Schrodt, Ulrike Stahl and Susan L. Ustin

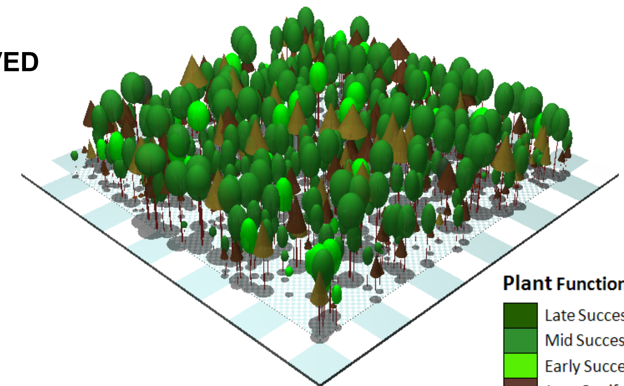
The ability to view Earth's vegetation from space is a hallmark of the Space Age. Yet decades of satellite measurements have provided relatively

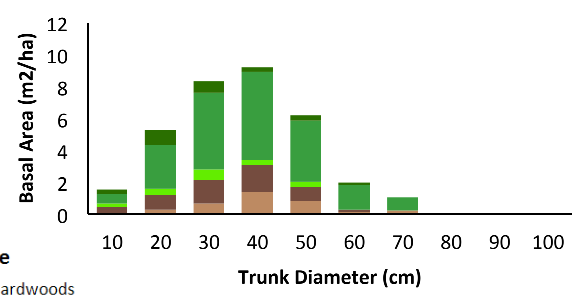
time that such a mission would provide has the potential to transform basic and applied science on diversity and function, and to pave the way to a more mechanistically

mass to leaf area. These attributes are related functionally to the uptake, allocation and use of resources such as carbon and nutrients within the plant, and to the defence against

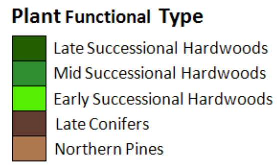
Composition for Ecosystem Modeling

FIELD OBSERVED

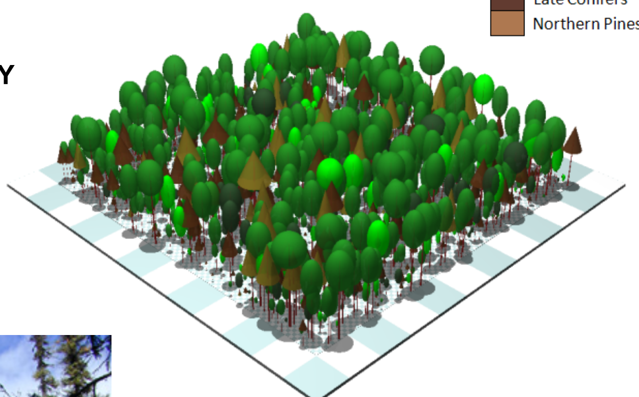


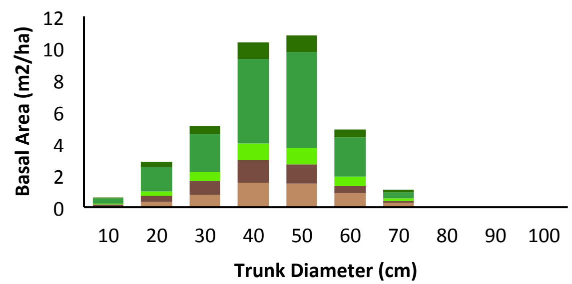


Basal Area = 33.5 m²/ha

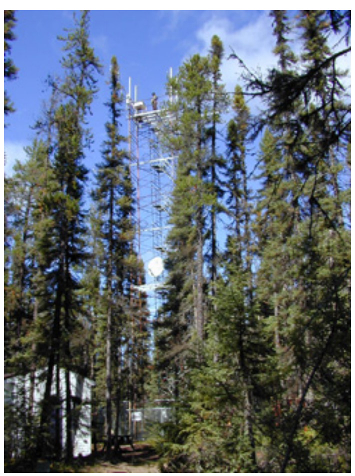


IMAGING SPECTROSCOPY DERIVED

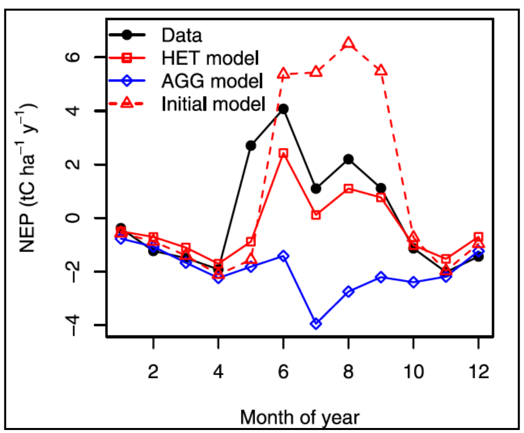




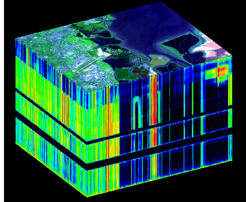
Basal Area = 35.6 m²/ha

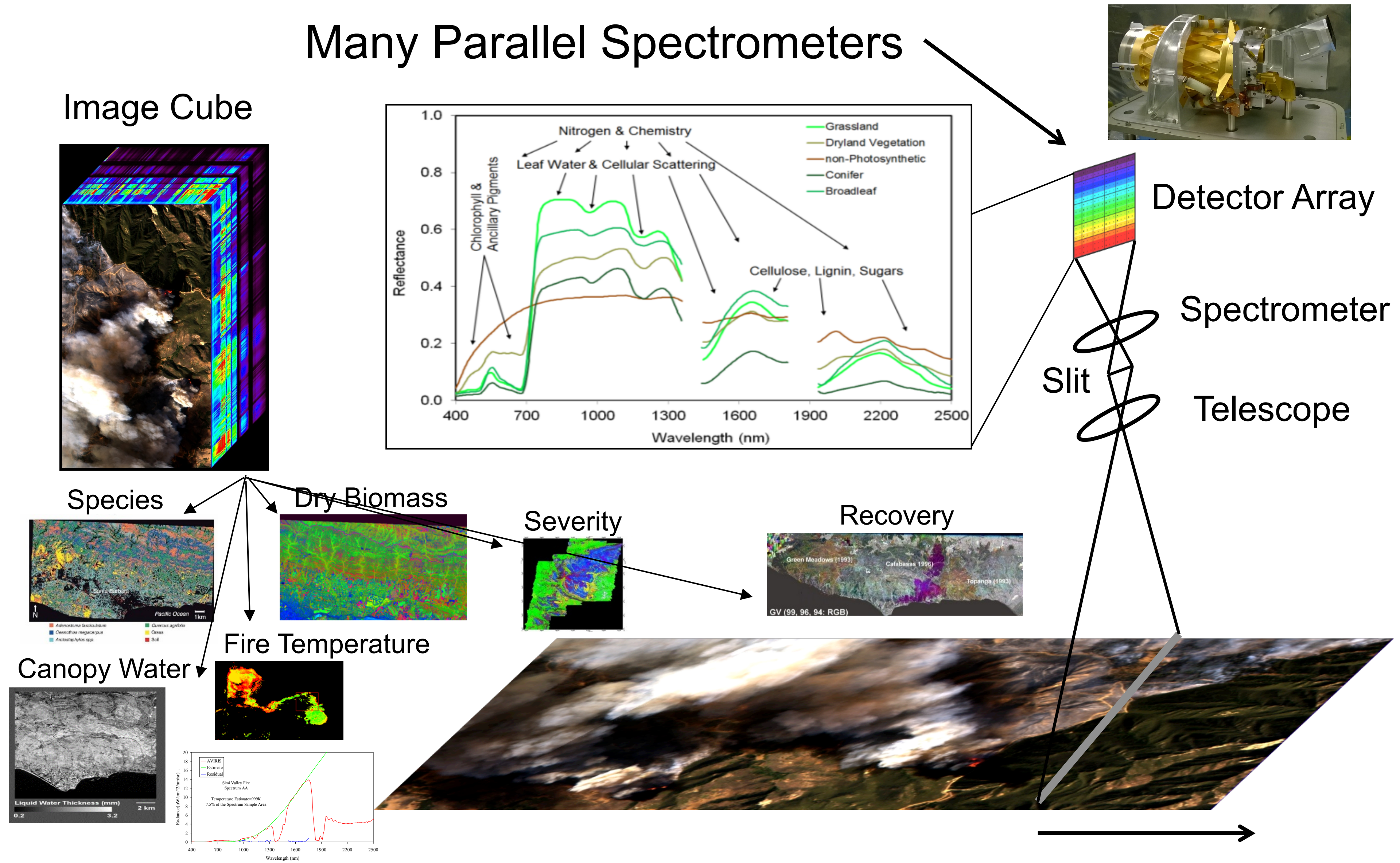


- Initial: Horizontal heterogeneity in canopy structure represented. Parameter values specified from the literature.
- HET: Horizontal heterogeneity in canopy structure. Optimized model parameters.
- AGG: ‘big-leaf’ model (aggregated model of forest canopy). Optimized model parameters
- **HET model has better predictive capability than AGG model**

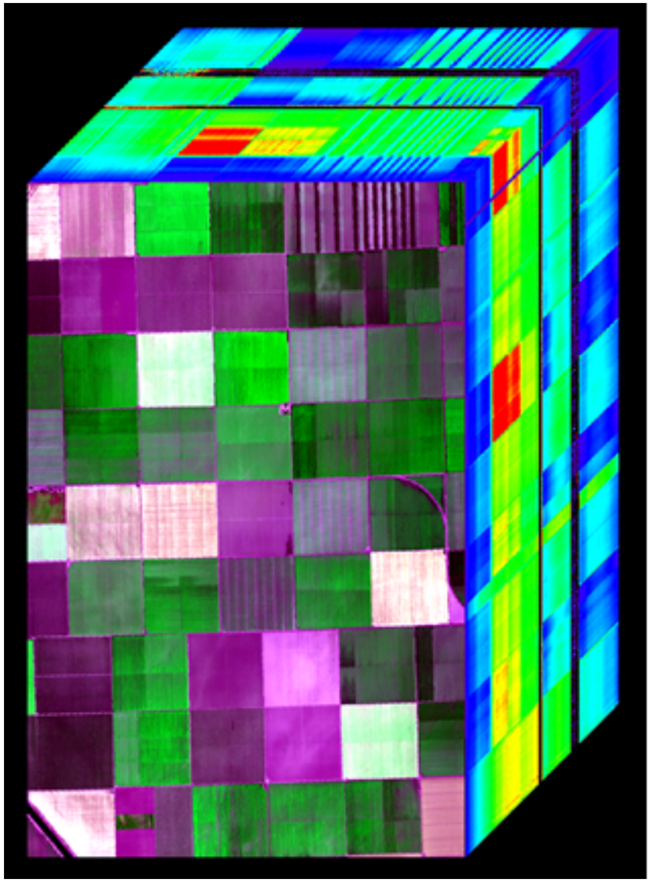


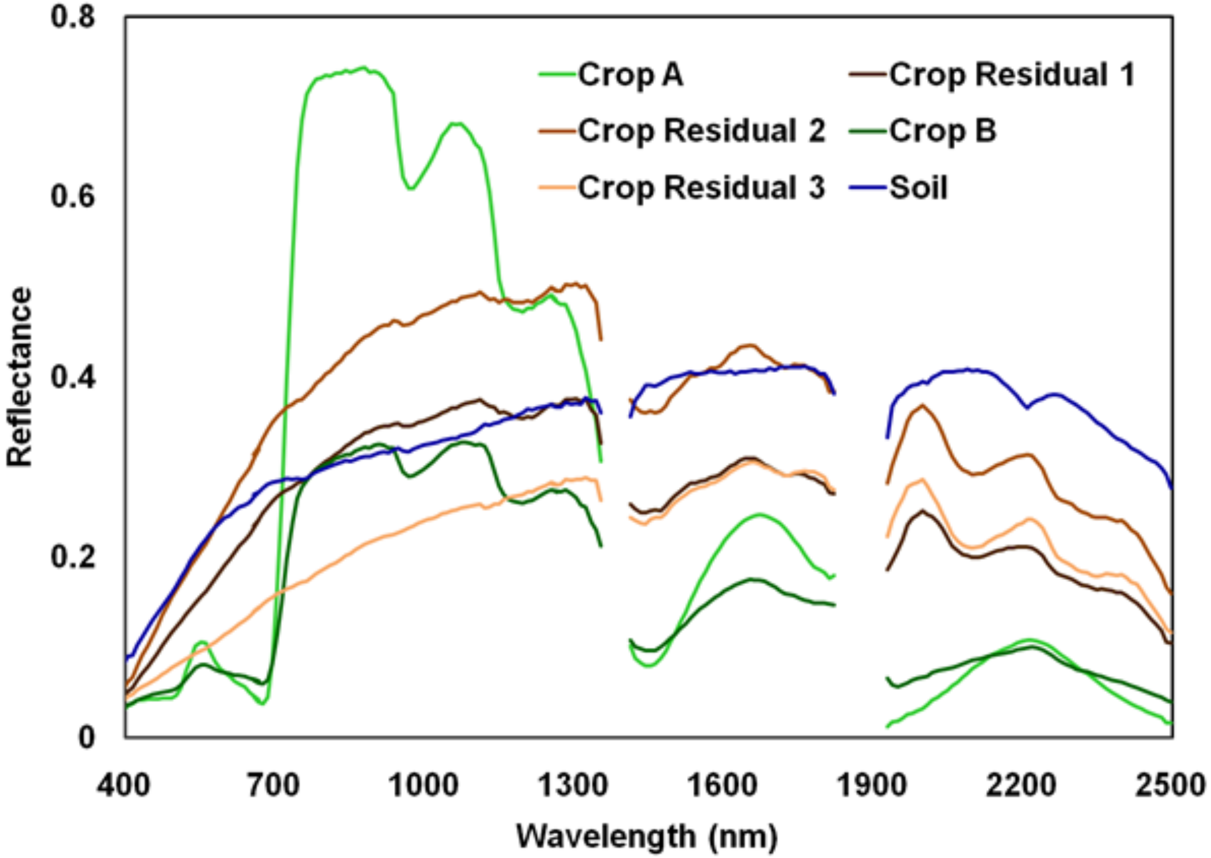
Fire Ecology with Imaging Spectroscopy





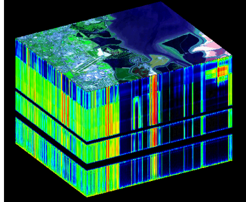
Agriculture

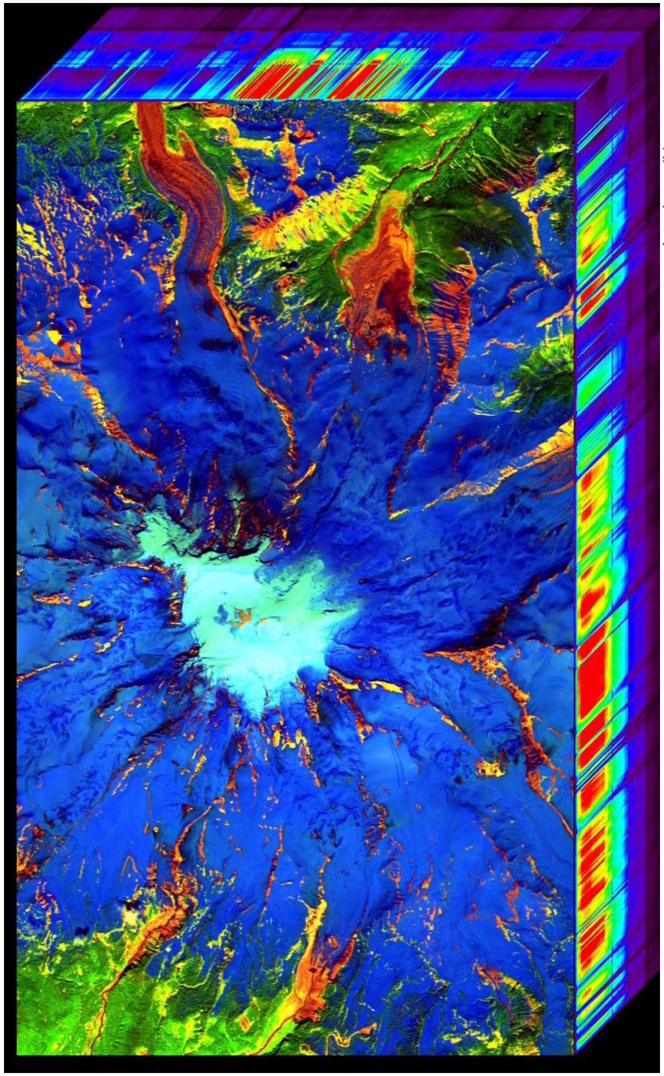


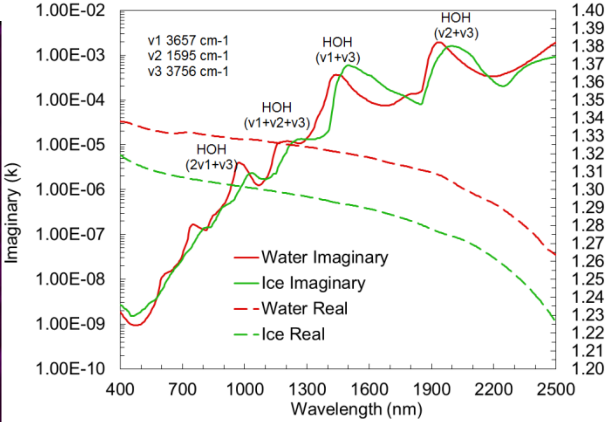


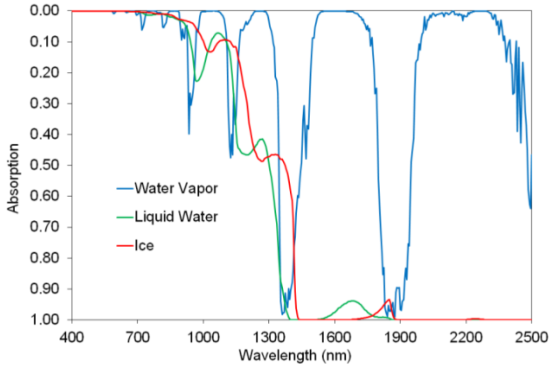
Crop type, Crop health, Nitrogen, Leaf water, Soil Composition, Soil Salinity, Soil Carbon, etc.

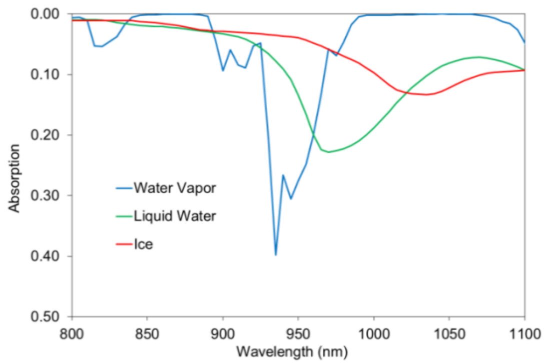
Three Phases of Water
Mount Rainier, WA

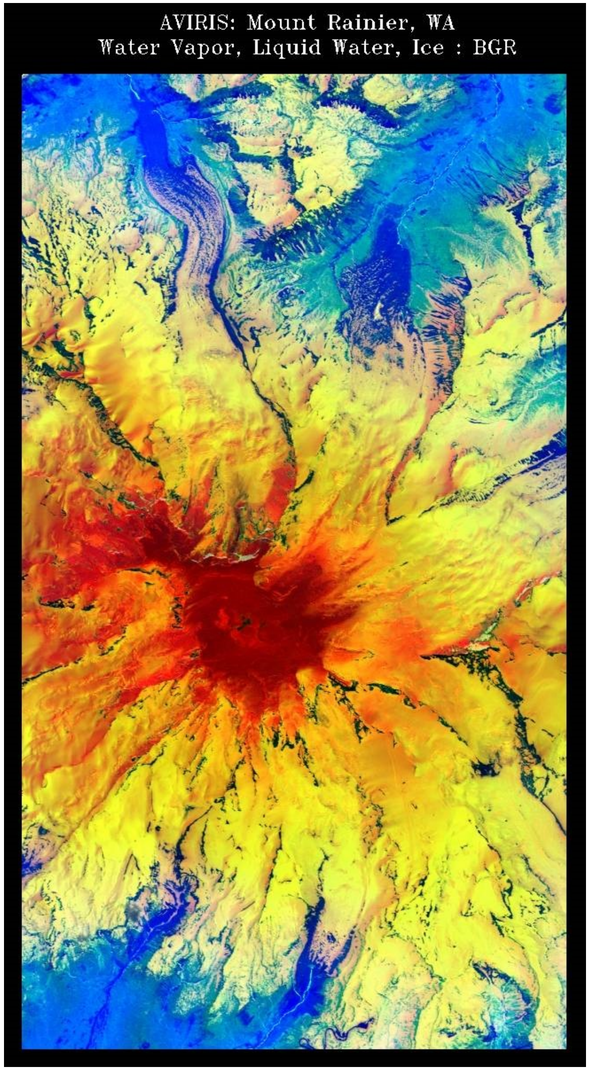




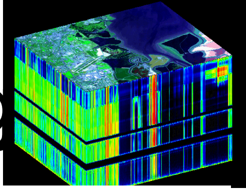






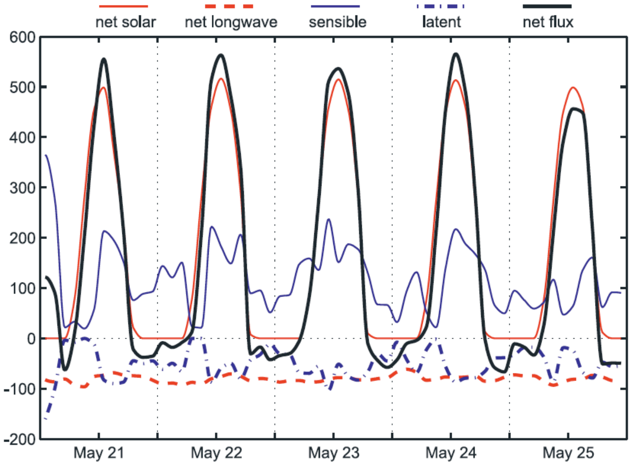


Snow and Ice: Albedo, Dust, Melting

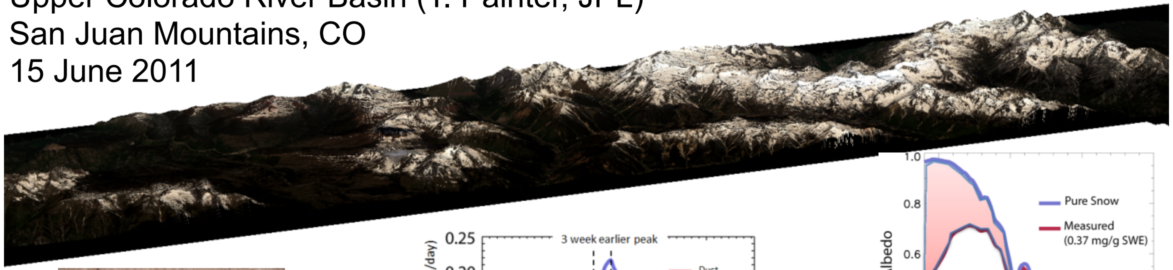


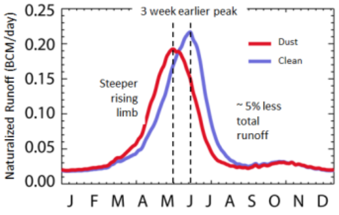
- Water availability
- Melting of the Earth's glaciers.

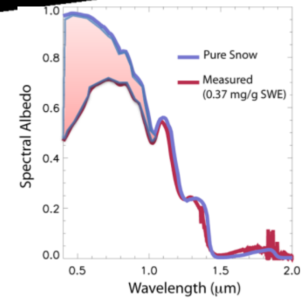
$$\frac{dU}{dt} + Q_m = (1-\alpha)S + L^* + Q_s + Q_v + Q_g + Q_r$$

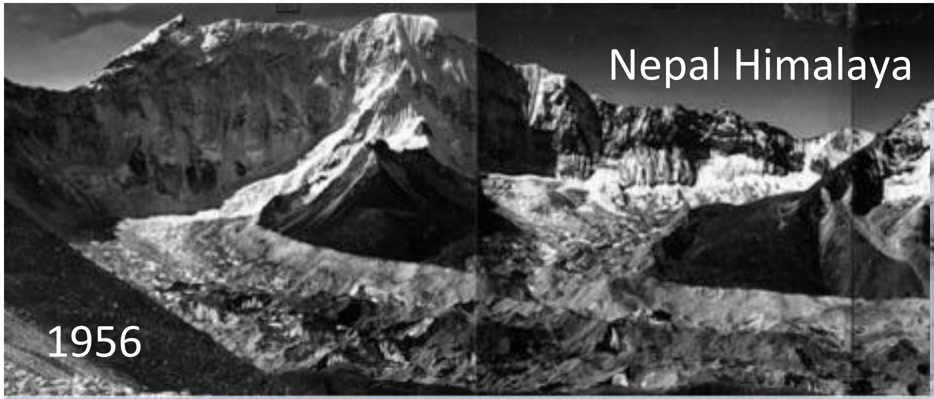


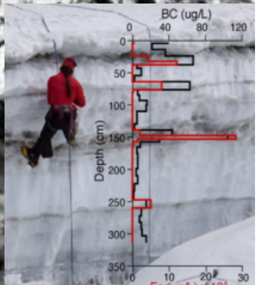
Upper Colorado River Basin (T. Painter, JPL)
San Juan Mountains, CO
15 June 2011





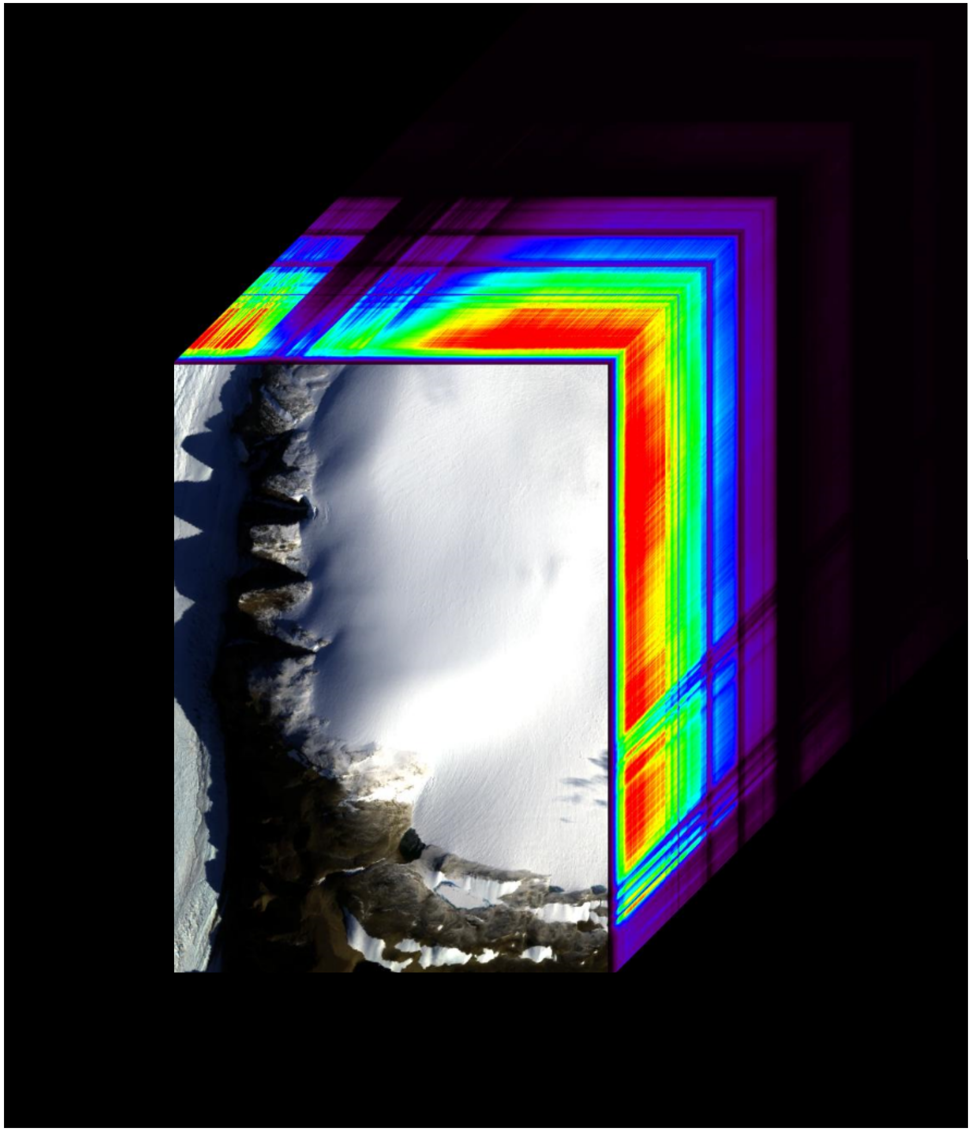


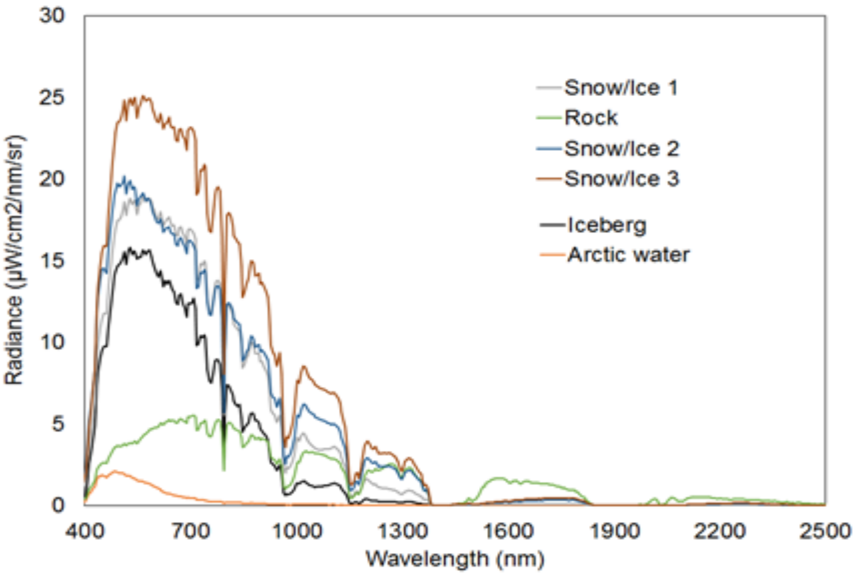


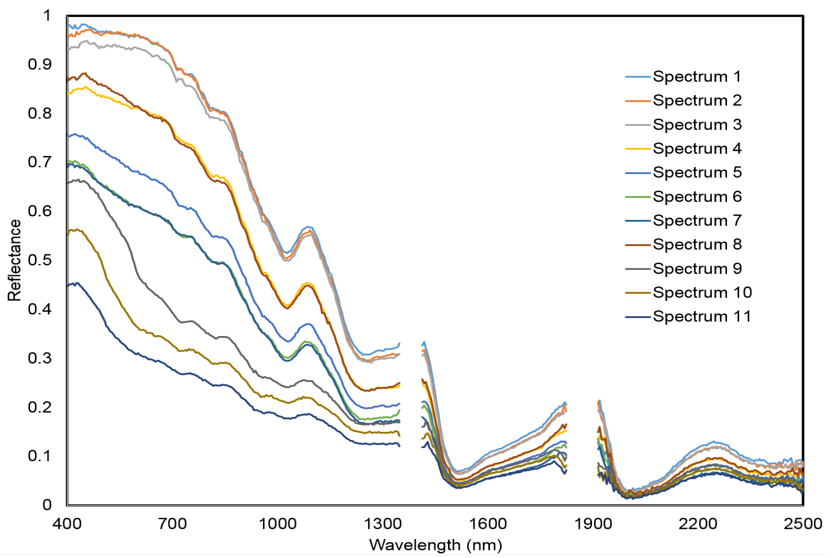


Kaspari et al. in prep

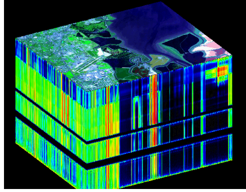
Snow and Ice: Greenland Ice sheet

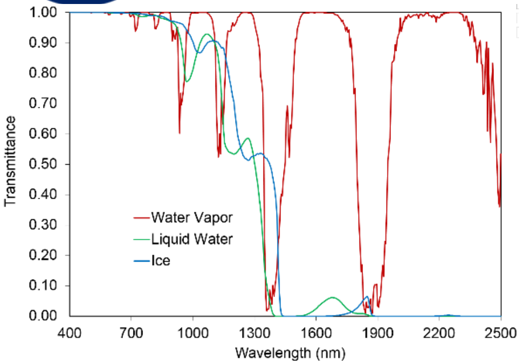


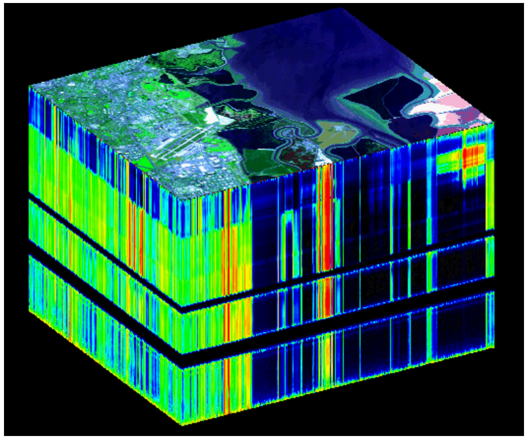




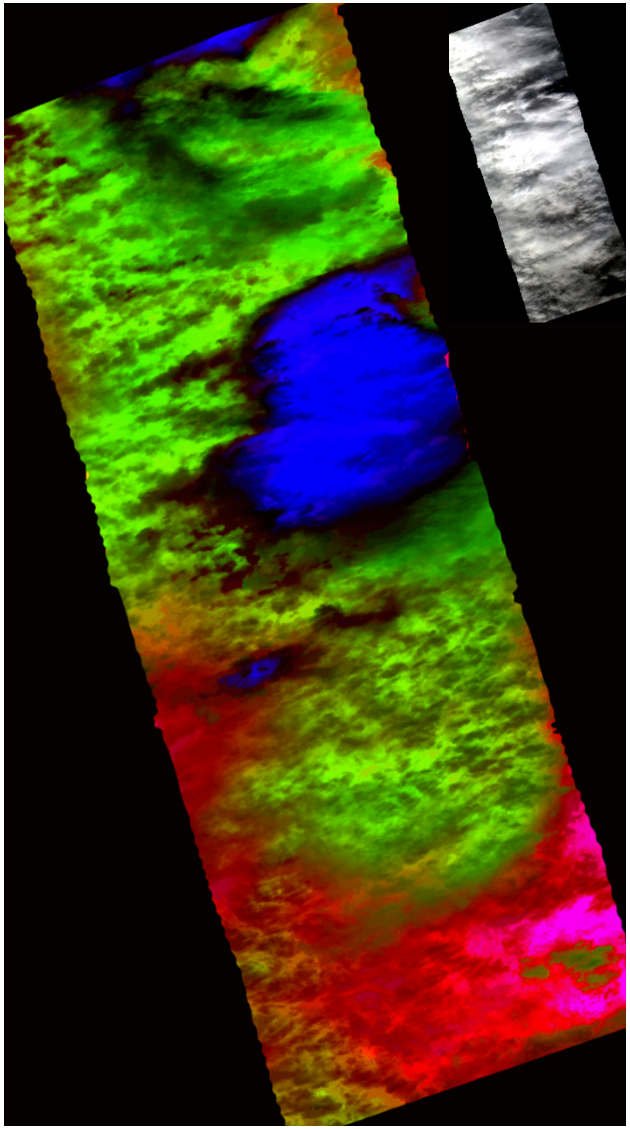
Atmospheric Spectroscopy and the three Phases of Water: Cal Water Experiment





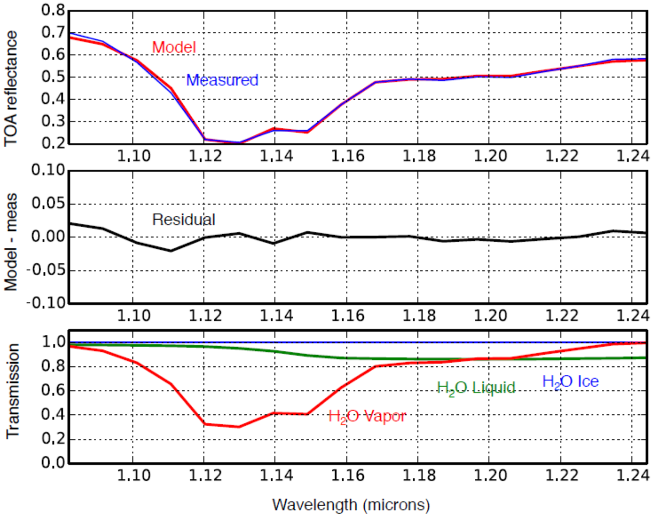


Blue: Ice, Green: Liquid Water, Red: Water Vapor

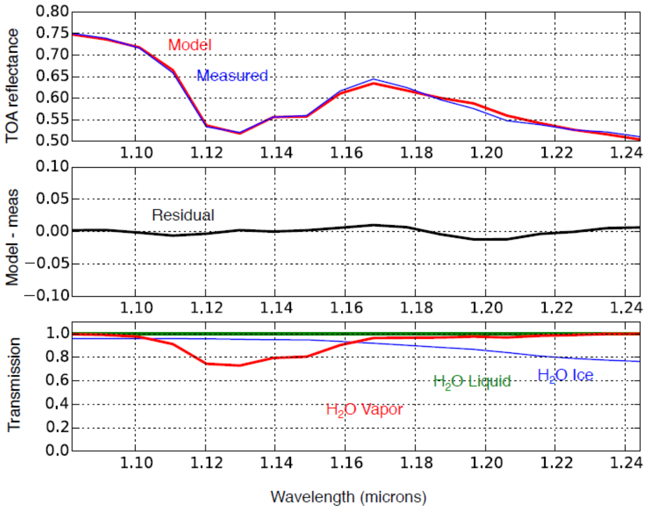


Example three phase AVIRIS spectral fits

Converged absorption for liquid-rich clouds

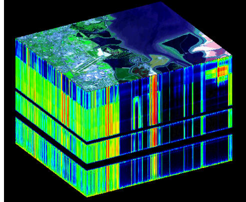


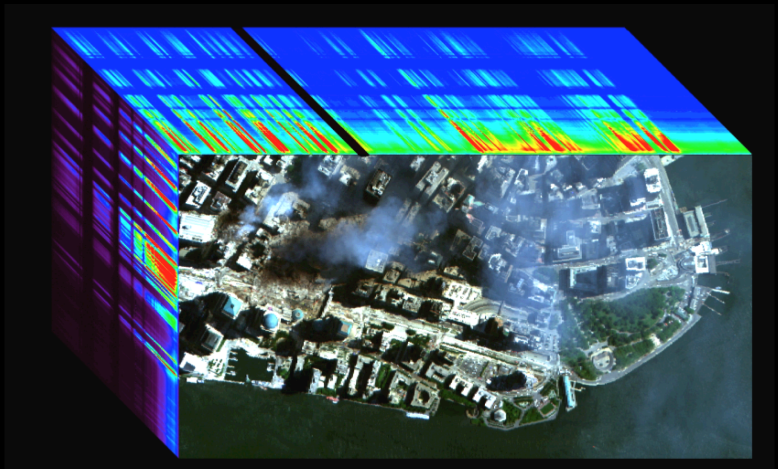
Converged absorption for ice-rich clouds

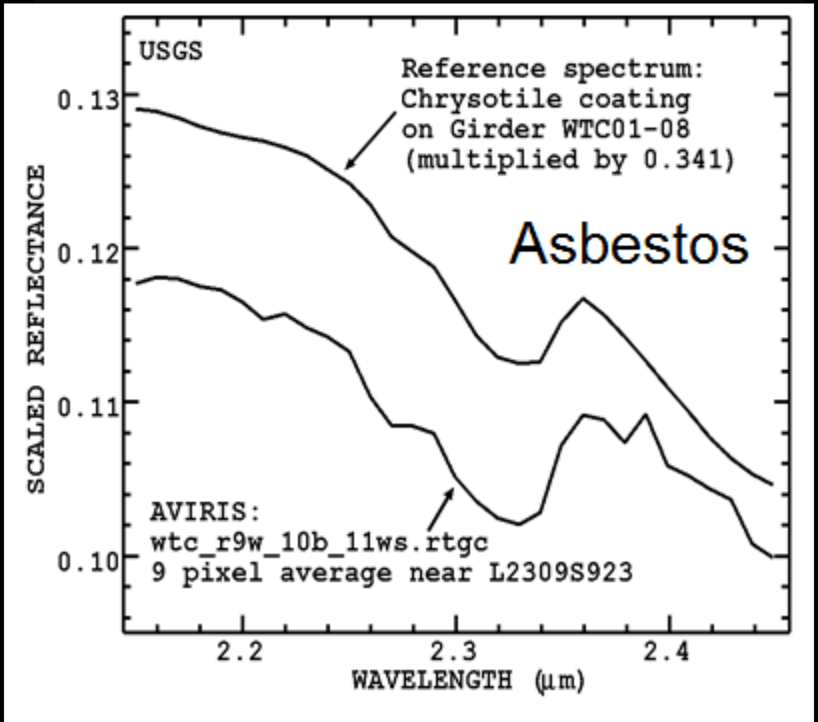


Older relevant reference: Green RO, Painter TH, Roberts DA, and Dozier, Js., “Measuring the expressed abundance of the three phases of water with an imaging spectrometer over melting snow,” WATER RESOURCES RESEARCH 42 (10): Art. No. W10402 OCT 3 2006

2001 Emergency Response After 9/11







World Trade Center area, New York

U.S. Geological Survey
Clark et al., 2001

NASA/JPL AVIRIS data
Sept 16, 2001 16:21 GMT

USGS
Imaging Spectroscopy
Tetracorder 4.0awtc2
product

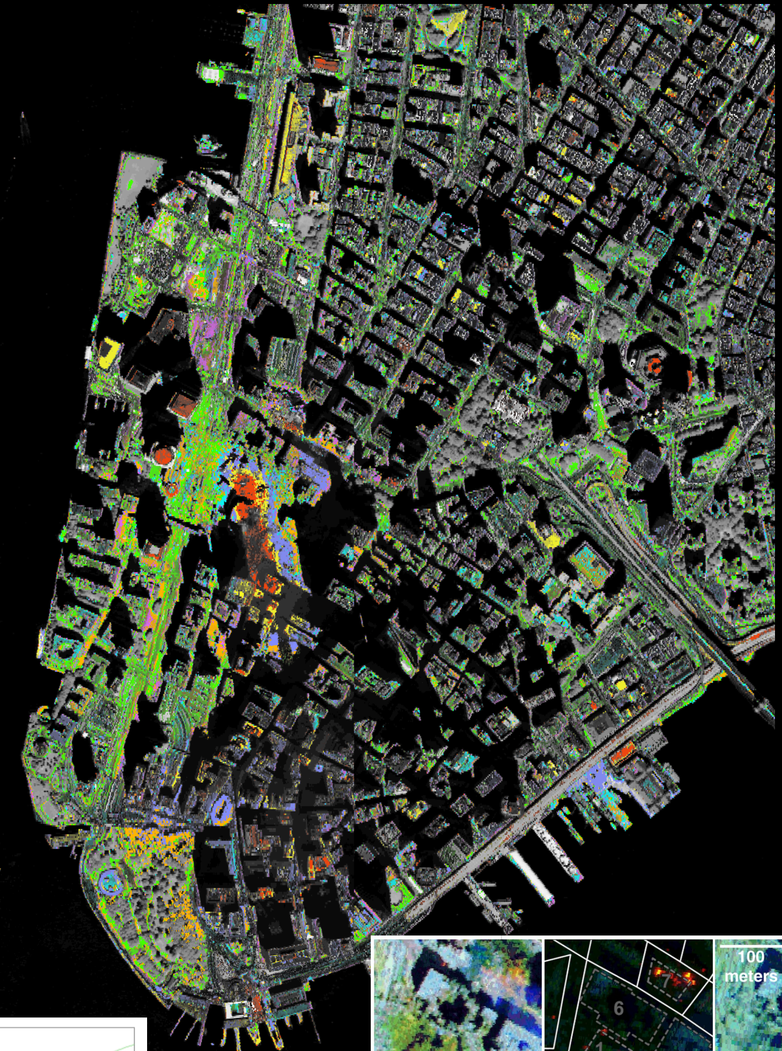
Spectral Shape Map

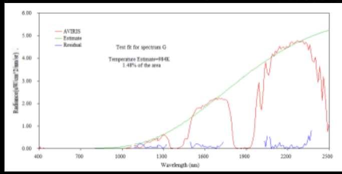
This map shows materials whose spectra are similar to the reference materials below. It is not a map of the identification of these materials. A similarity map is analogous to a map of materials with similar colors viewed with your eyes. The colors may indicate similar compositions.

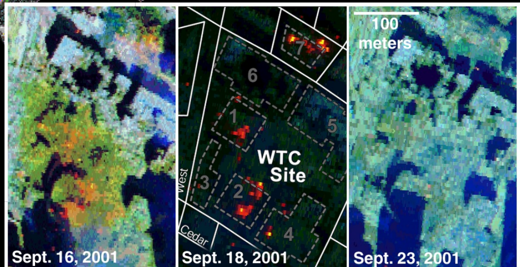
- concrete (WTC01–37B)
- concrete (WTC01–37Am)
- cement (WTC01–37A)
- dust (WTC01–15)
- dust (WTC01–28)
- dust (WTC01_36)
- gypsum wall board

Image sampling:
1.7 meters/pixel

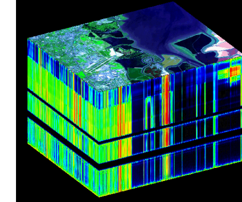
N
200 meters







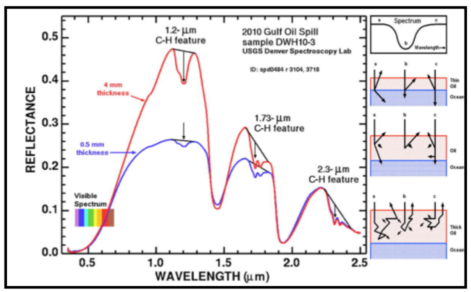
2010 Gulf Oil Spill Response



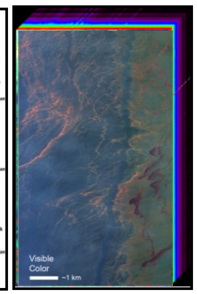
NASA AVIRIS used by USGS, NOAA and NASA science team to estimate the thickness and volume of the surface oil. Example result: High values at 131 liters/pixel*.

Oil Spill

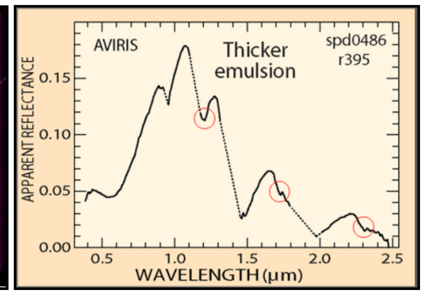
Spectroscopic Basis C-H Bond Absorptions



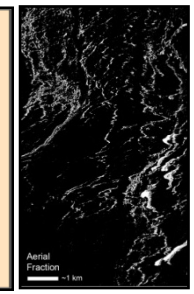
AVIRIS



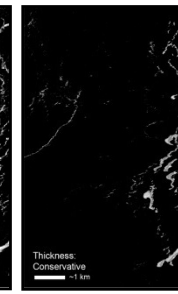
AVIRIS Spectra



Fraction



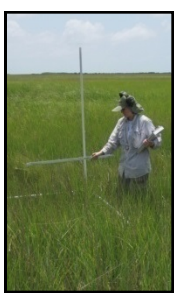
Thickness



Quantitative Volume Estimates

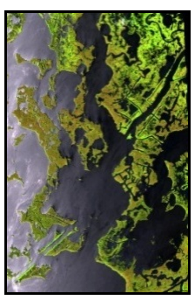
NASA AVIRIS used by a broad government and university science team to map vegetation species and physiological condition (health) before and after oil impact.

Pre Oil

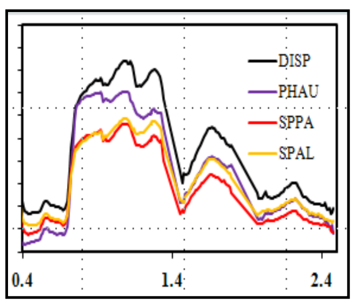


AVIRIS ER-2

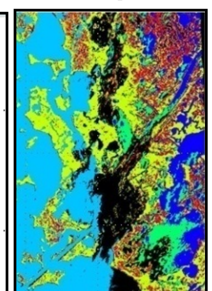
Coastal Data



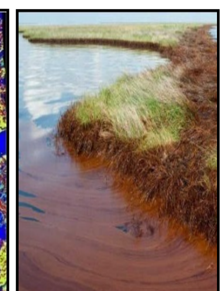
AVIRIS Vegetation Spectra



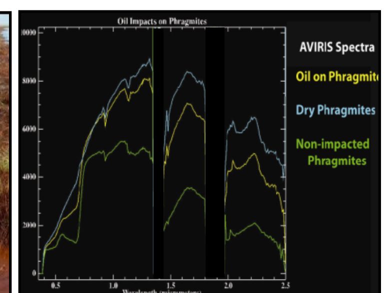
AVIRIS Species Map



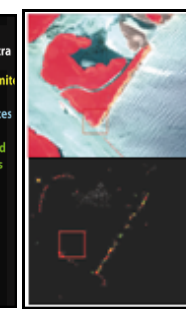
Post Oil



AVIRIS Oil Impacted Vegetation Spectra

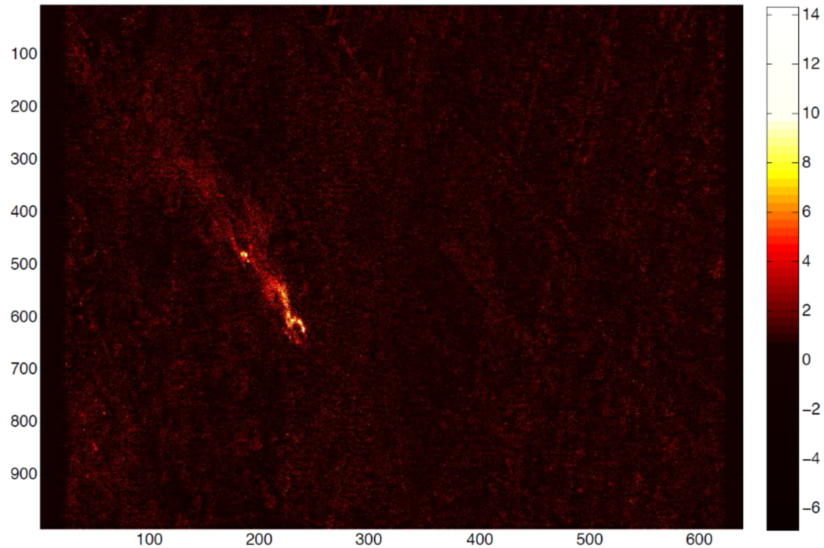


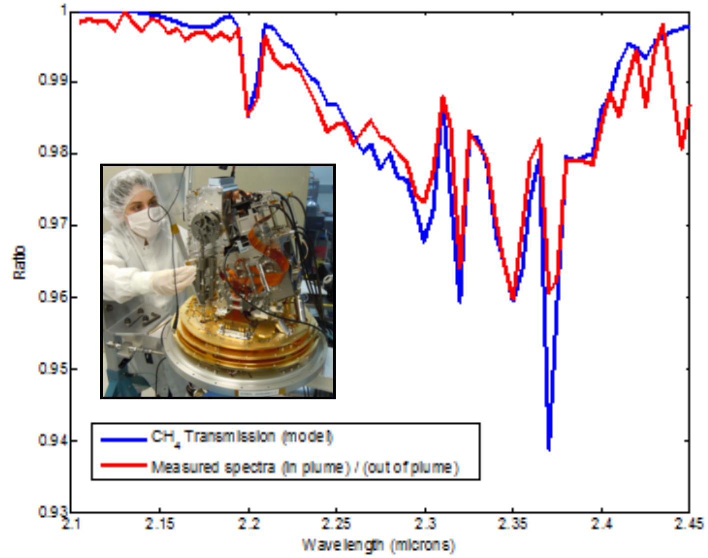
Oil Impact Product



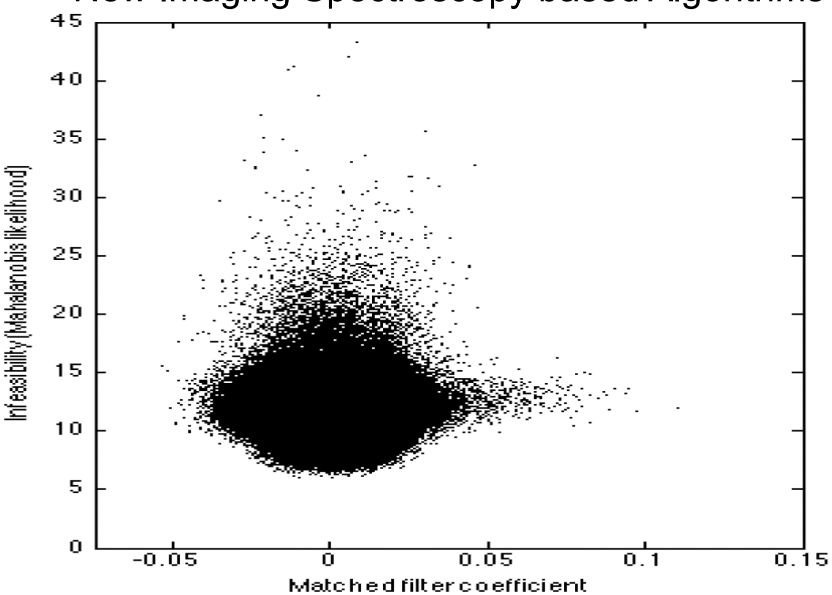
*A Method for Quantitative Mapping of Thick Oil Spills Using HyspIRI; Roger N. Clark[1], Gregg A. Swayze[1], Ira Leifer[2], K. Eric Livo[1], Raymond Kokaly[1], Todd Hoefen[1], Sarah Lundeen[3], Michael Eastwood[3], Robert O. Green[3], Neil Pearson[1], Charles Sarture[3], Ian McCubbin[4] Dar Roberts[3], Eliza Bradley[3], Denis Steele[3], Thomas Ryan[3], Roseanne Dominguez[3], and AVIRIS Team[3]; [1]USGS, [2]UCSB, [3]NASA, [4] DRI

AIRIS-NG June 2014 Methane Plume, California

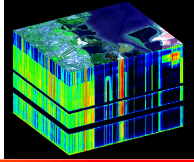




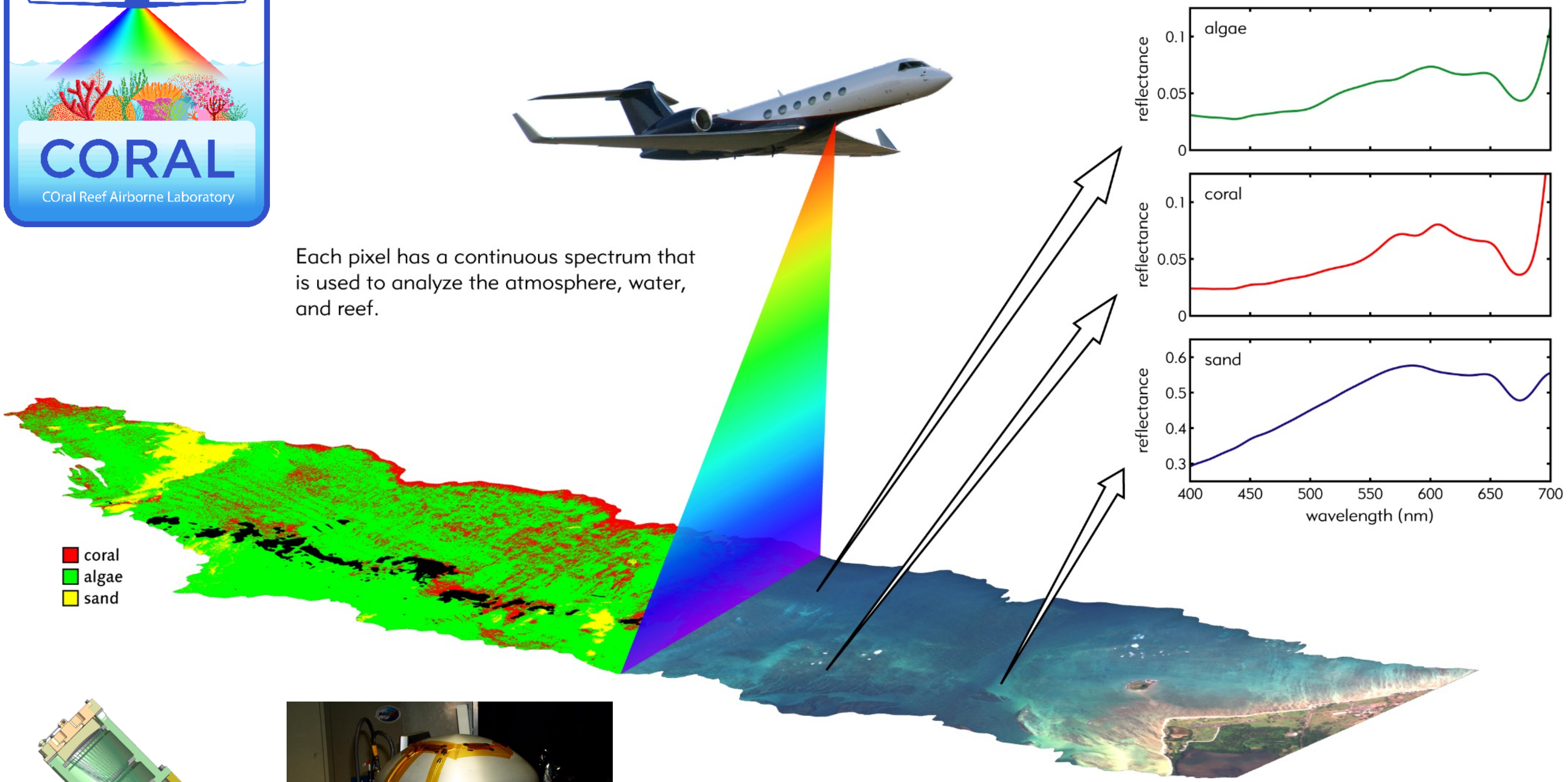
New Imaging Spectroscopy based Algorithms

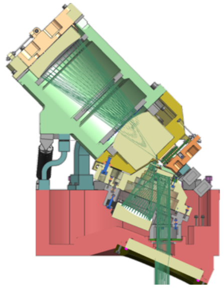


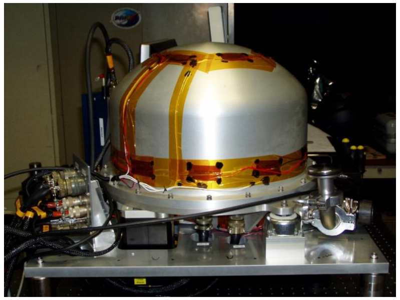
Spectroscopic Measurement Approach



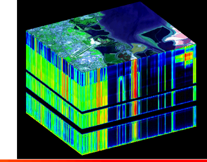
Each pixel has a continuous spectrum that is used to analyze the atmosphere, water, and reef.

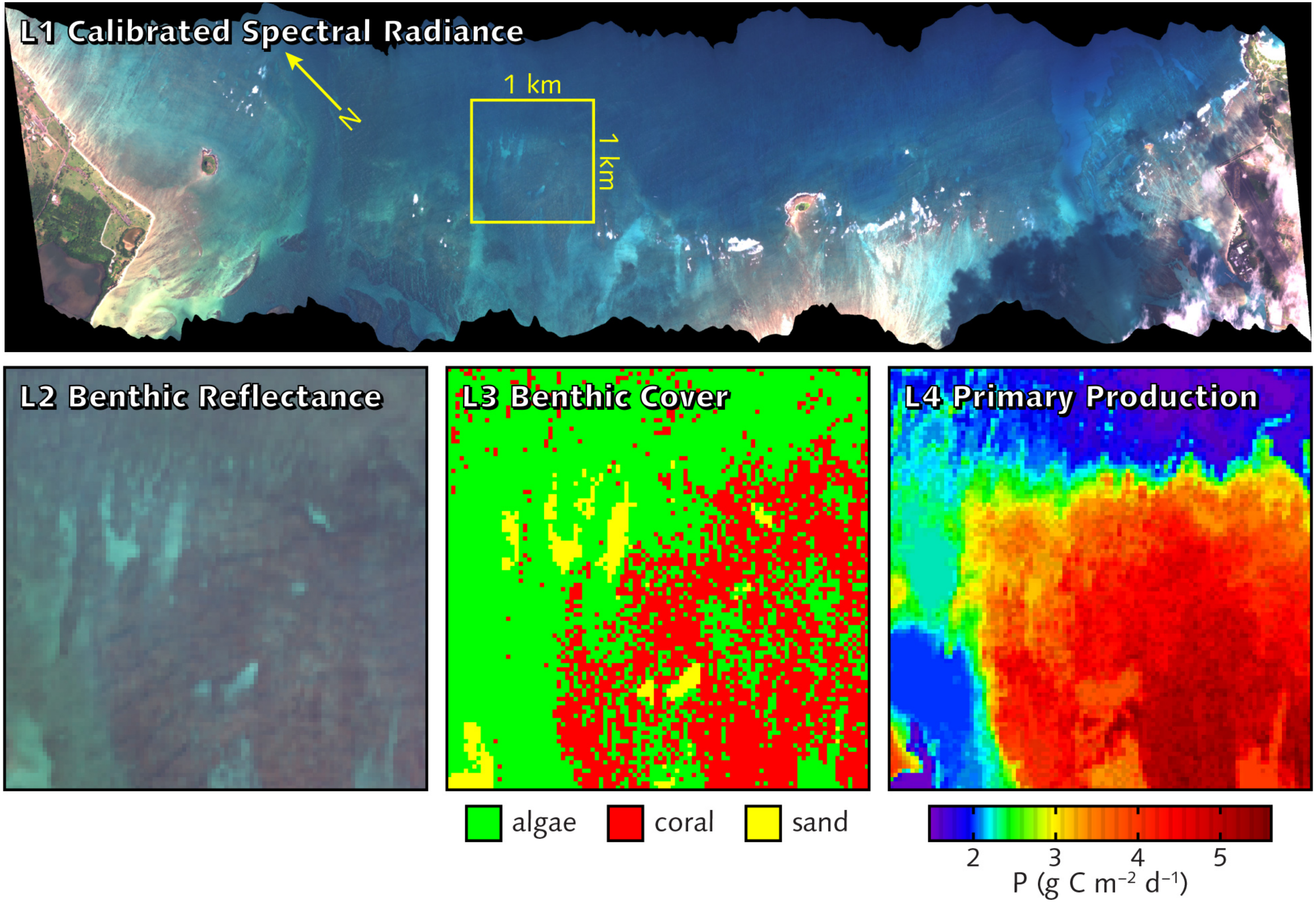






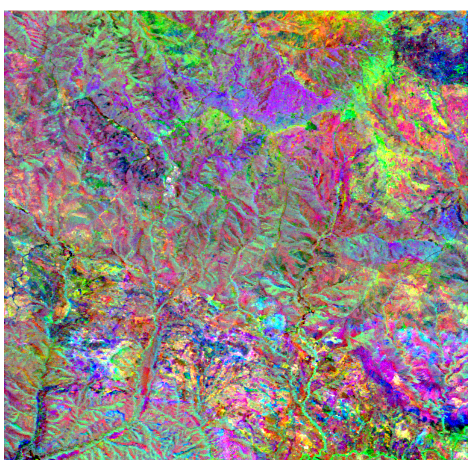
What is the relationship between coral reef condition and biogeophysical forcing parameters?





Dimensionality of the Earth System Captured with Imaging Spectroscopy

NASA HyspIRI Preparatory Campaign

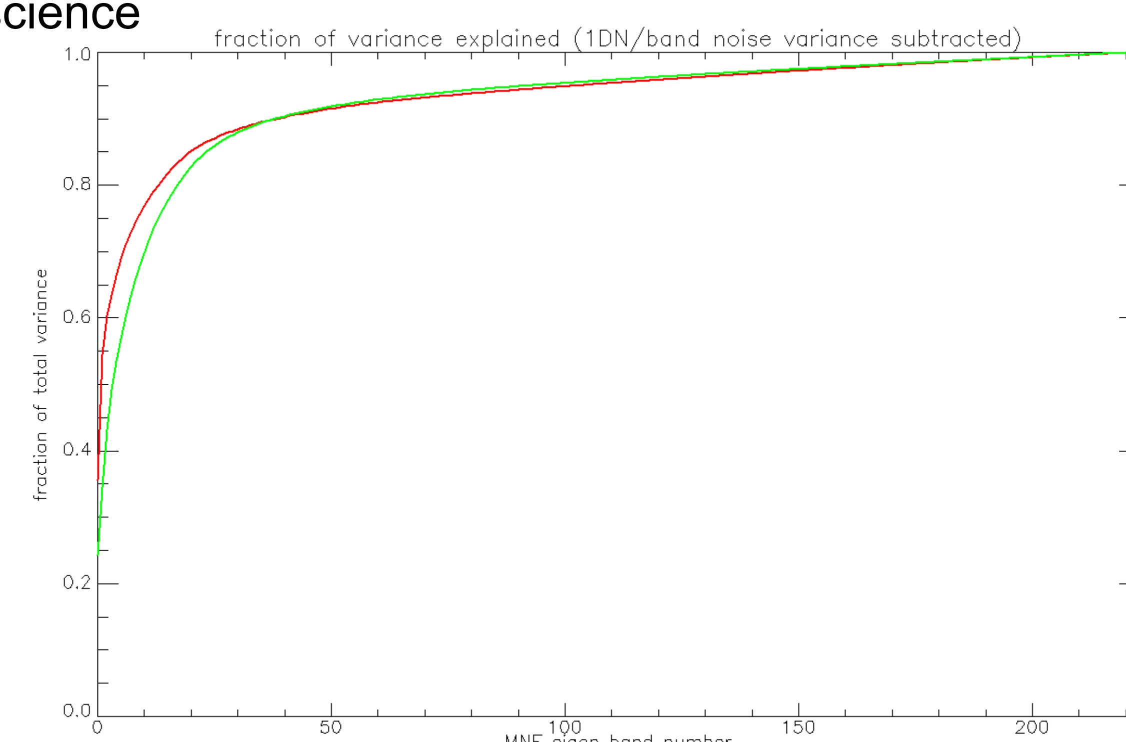


AVIRIS Flight line from Mono Lake to Santa Barbara, CA

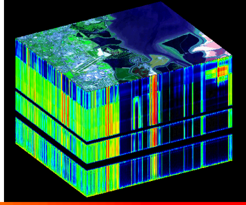
A single HyspIRI airborne campaign flight line has 50 content rich eigen images.

A single scene show up to 30 content rich eigen images.

This demonstrates huge dimensionality available for access with imaging spectroscopy for new Earth system science



Mapping Imaging Spectrometer for Europa (MISE)



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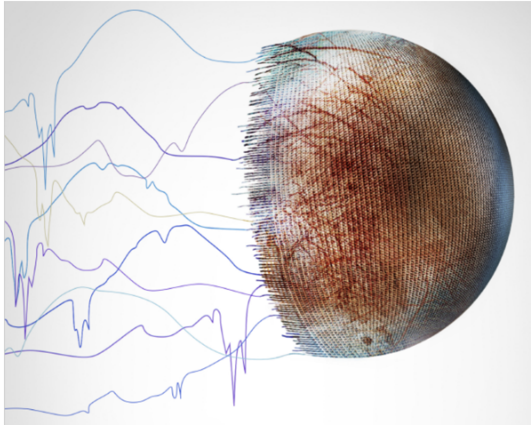


May 26, 2015
15-104

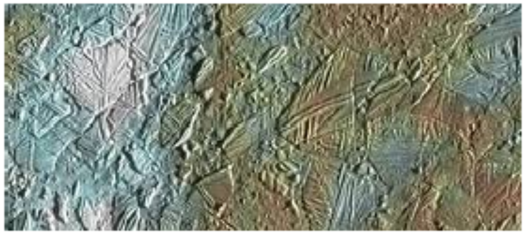
Mapping Imaging Spectrometer for Europa (MISE) -- principal investigator Dr. Diana Blaney of JPL. This instrument will probe the composition of Europa, identifying and mapping the distributions of organics, salts, acid hydrates, water ice phases, and other materials to determine the habitability of Europa's ocean.

NASA's Europa Mission Begins with Selection of Science Instruments

NASA has selected nine science instruments for a mission to Jupiter's moon Europa, to investigate whether the mysterious icy moon could harbor conditions suitable for life.

NASA's Galileo mission yielded strong evidence that Europa, about the size of Earth's moon, has an ocean beneath a frozen crust of unknown thickness. If proven to exist, this global ocean could have more than twice as much water as Earth. With abundant salt water, a rocky sea floor, and the energy and chemistry provided by tidal heating, Europa could be the best place in the solar system to look for present day life beyond our home planet.

"Europa has tantalized us with its enigmatic icy surface and evidence of a vast ocean, following the amazing data from 11



(/sites/default/files/thumbnails/image/15-104a.jpg)
Bizarre features on Europa's icy surface suggest a warm interior. This view of the surface of Jupiter's moon Europa was obtained by NASA's Galileo mission, and shows a color image set within a larger mosaic of low-resolution monochrome images. Galileo was able to survey only a small fraction of Europa's surface in color at high resolution; a future mission would include a high-resolution imaging capability to capture a much larger part of the moon's

Mapping Imaging Spectrometer for Europa (MISE)
Revealing the Geochemical Tapestry Of Europa

MISE will produce maps of organic compounds, salts, hot spots, and ices to answer key science questions about Europa ocean and its habitability.

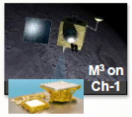
Links surface geology and composition. | Does Europa's ocean have organics? | What does surface chemistry tell us about habitability? | Is Europa currently active? | How do changes in ice crystal structure relate to the age of Europa's surface?

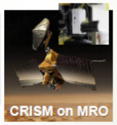
MISE Science Goals:

- **Goal 1**: Assess the habitability of Europa's ocean by understanding the inventory and distribution of surface compounds.
- **Goal 2**: Investigate the geologic history of Europa's surface and search for areas that are currently active.

JPL-APL Partnership:

- Imaging Spectrometer Heritage from JPL (Discovery M^3 on India's Chandrayaan-1) and APL (CRISM on MRO).
- Joint JPL/APL team has been working on MISE concept since 2008.
- **JPL:** PI, Project Management, System Engineering, SMA, Spectrometer, FPA, FPIE, Calibration and Archiving.
- **APL**: Deputy PI, Data Processing Unit, Scanner, Flight Software, and Science Tools.





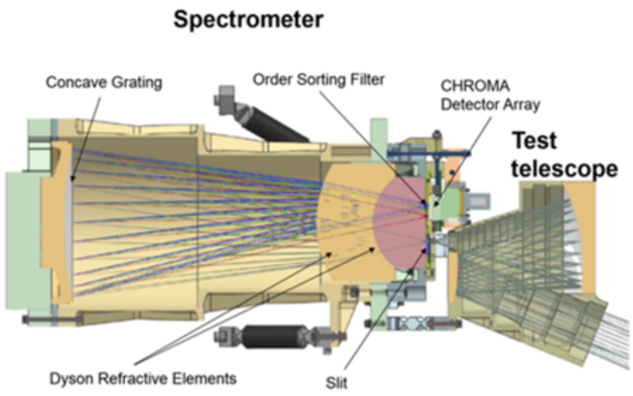
MISE Team:

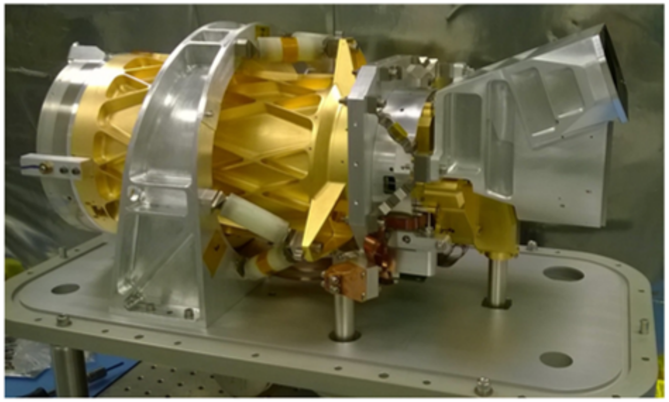
PI: Diana Blaney (JPL)
Deputy PI: Karl Hibbitts (APL)
Project Manager: Carl Bruce (JPL)
Deputy Project Manager: Andrew Santo (APL)

Science Team:

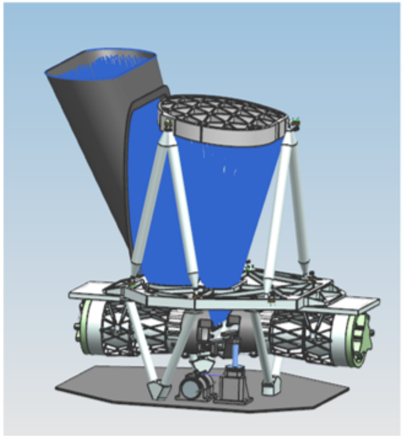
- Rob Green, Instrument Scientist (JPL)
- Roger Clark (PSI)
- Brad Dalton (JPL)
- Ashley Davies (JPL)
- Matt Hedman (U. Idaho)
- Yves Langevin (U. Paris)
- Jonathan Lunine (Cornell)
- Tom McCord (Bear Fight)
- Chris Paranicas (APL)
- Frank Seelos (APL)
- Jason Soderblom (MIT)

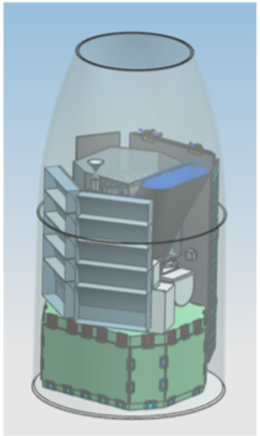
Possible Future Demonstration 16 Revisit, 30 m, Full VSWIR

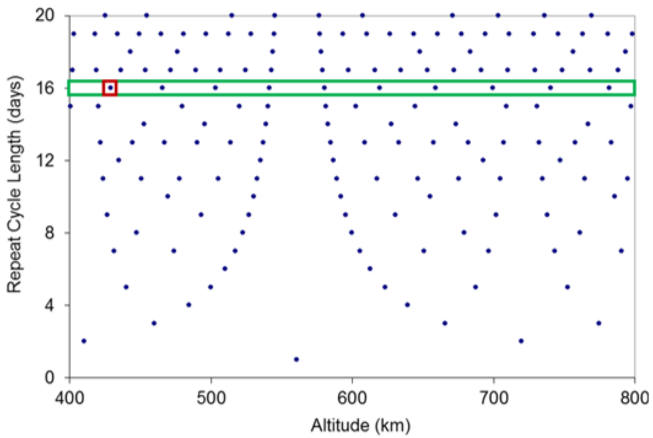




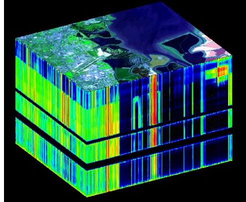
Design of a wide swath F/1.8 VSWIR Dyson covering the spectral range from 380 to 2510. (right) Dyson imaging spectrometer in qualification that uses a full spectral range HgCdTe detector array.



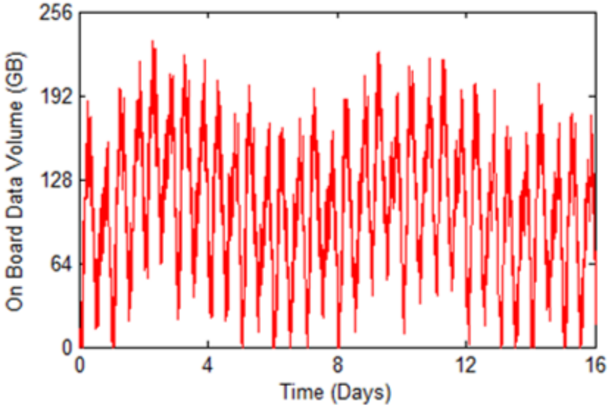




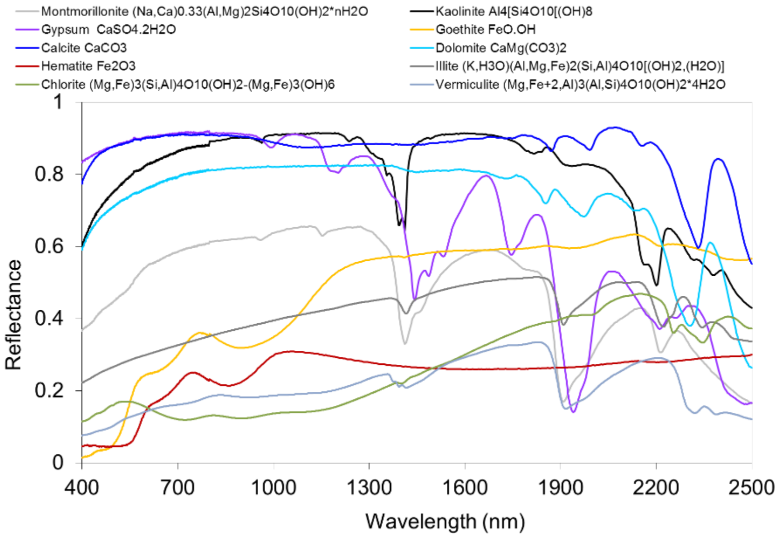
(left) Opto-mechanical configuration with one telescope feeding two field split wide swath F/1.8 VSWIR Dyson spectrometer providing 185 km swath and 30 m sampling. (center) Imaging spectrometer with spacecraft (248 kg, 670 W with margin) configured for launch in a Pegasus shroud for an orbit of 429 km altitude, 97.14 inclination to provide 16 day revisit for three years. (right) Orbital altitude and repeat options showing an altitude of 429 km with a fueled spacecraft supports the three year mission with the affordable Pegasus launch. Higher orbits are viable with a larger launch vehicle.

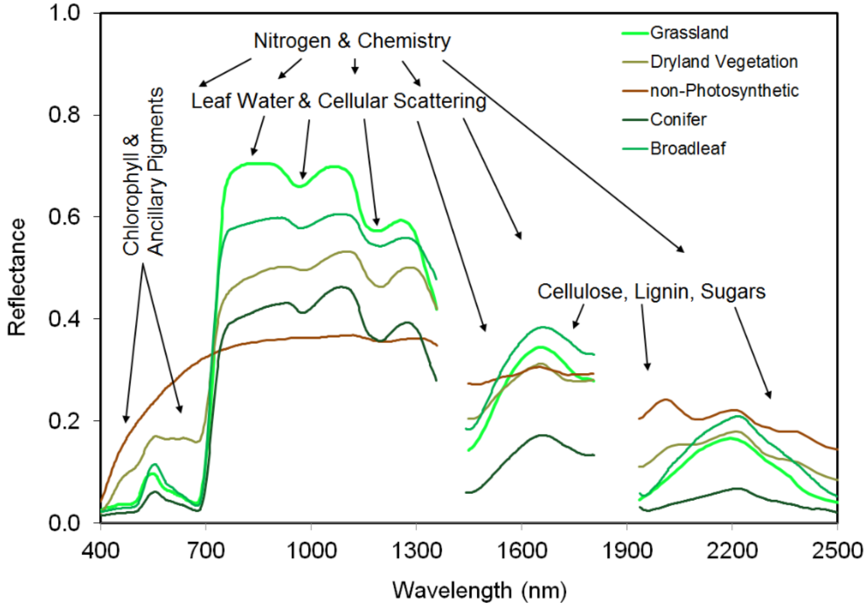


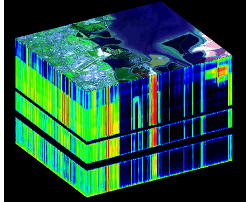
Affordable 16 day revisit for demonstration



(left) Global illuminated surface coverage every 16 days. (right) On-board data storage usage for illuminated terrestrial/coastal regions with downlink using Ka Band (<900 mb/s) to KSAT Svalbard and Troll stations. Oceans and ice sheets can be spatially averaged for downlink.

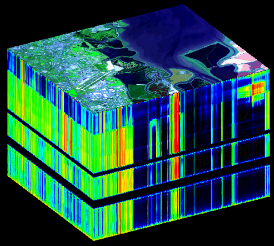


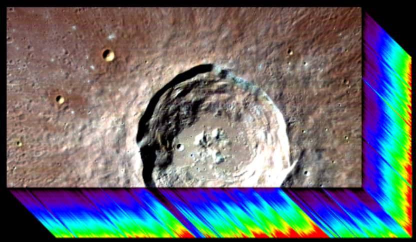


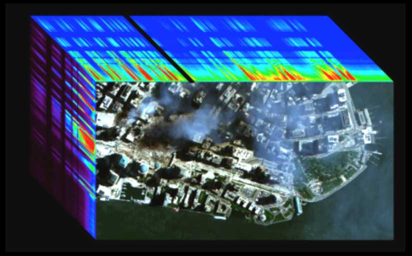


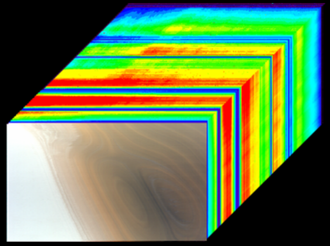
Conclusions

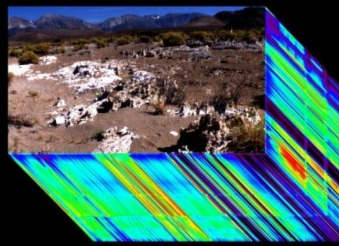
- Spectroscopy reveals physics, chemistry, and biology and related processes
- With advances in detectors, optics, and electronics, imaging spectroscopy became feasible in the late 20th Century
- Since its inception, the use of imaging spectroscopy on Earth and throughout the solar system has been proven and expanded extraordinarily
- Imaging spectroscopy enables remote measurement for the 21st Century
- Mouroulis, Pantazis, Robert O. Green, Byron Van Gorp, Lori B. Moore, Daniel W. Wilson, Holly A. Bender, “Landsat-swath Imaging Spectrometer Design,” Optical Engineering, 2016.











Images raise questions and spectra answer them!