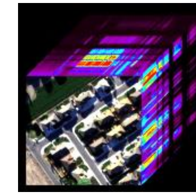
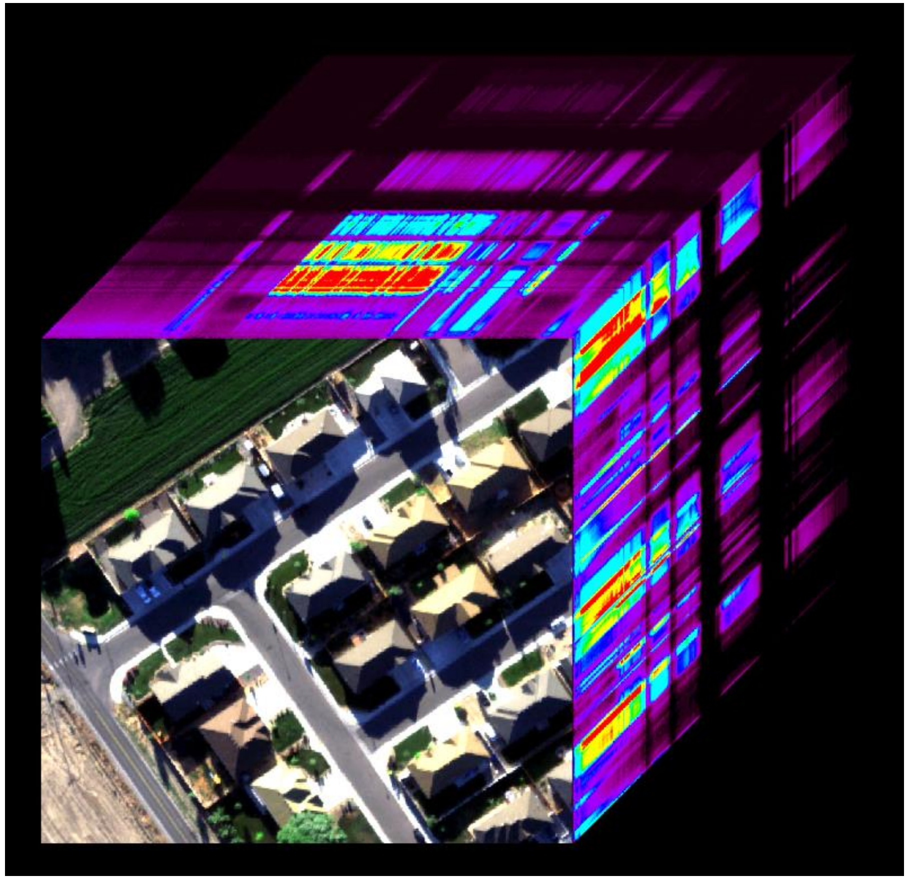
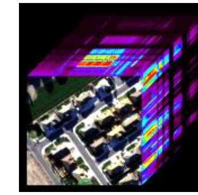
Understanding Worlds through 30 years of Infrared Imaging Spectroscopy





Robert O. Green and the Imaging Spectroscopy Community

Jet Propulsion Laboratory, California Institute of Technology

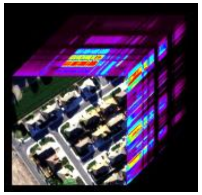


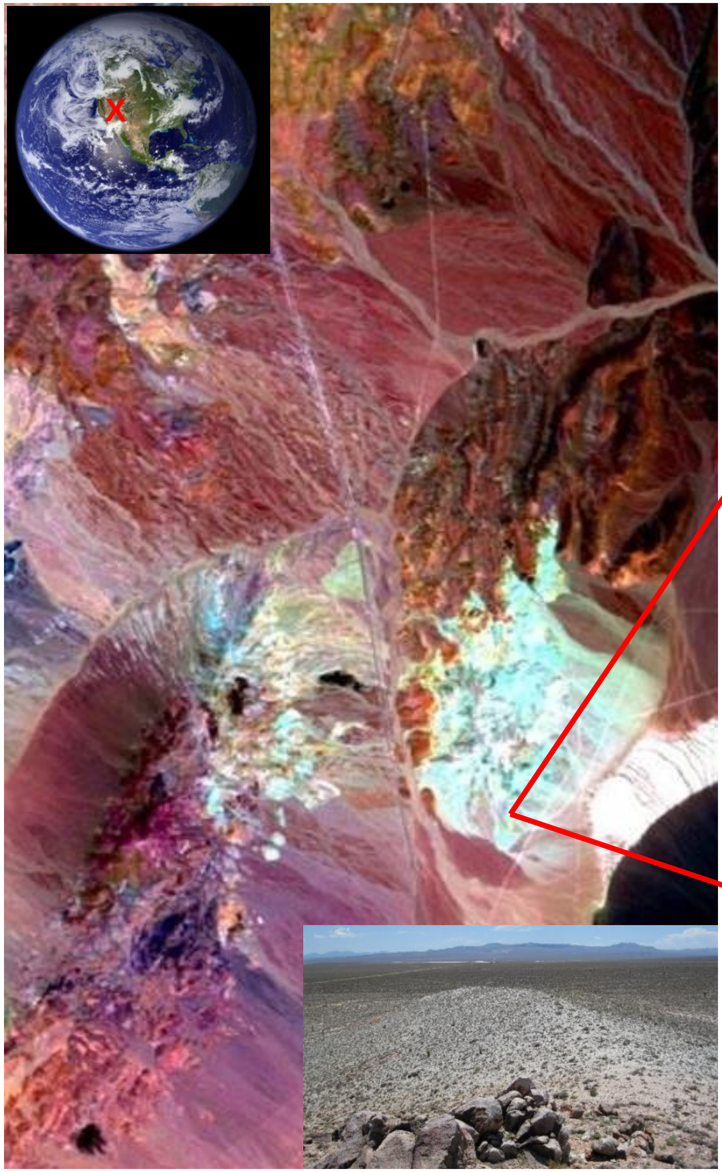
Overview

- Remote Sensing or
  Remote Measurement
- Imaging Spectroscopy
- Earth Measurements Examples
- Other Planets and the Moon
- Instrument Evolution and
  Next Generation Measurements
- Conclusions

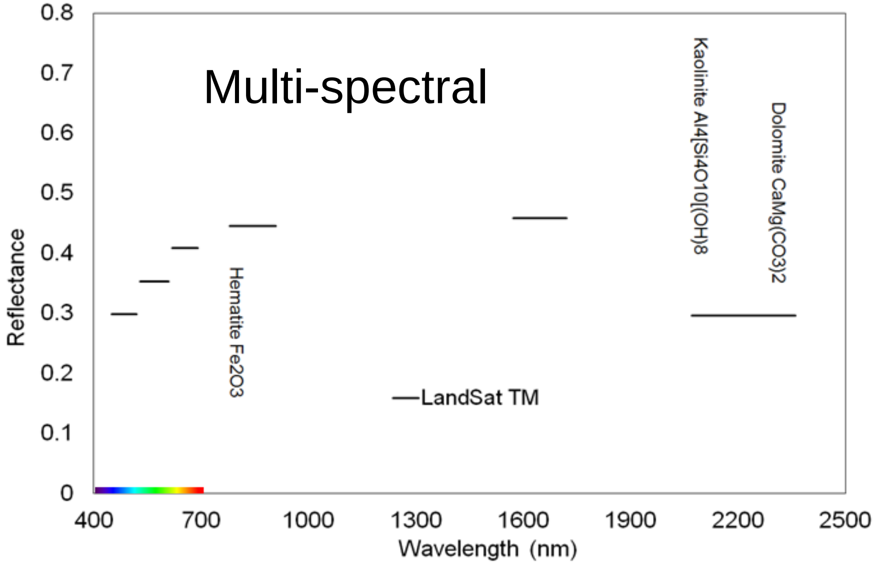
Remote Sensing or Remote Measurement

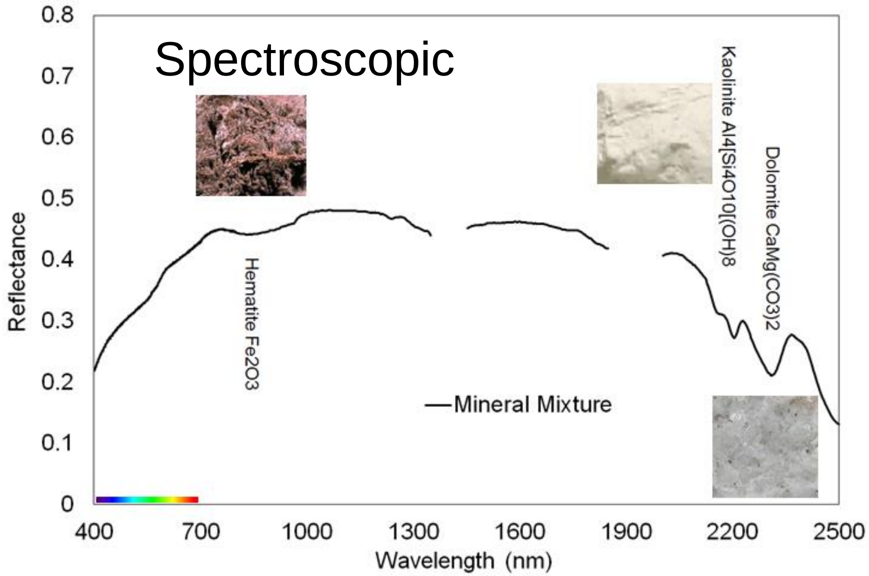
Remote Sensing or Remote Measurement





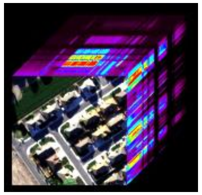
or





Reflected sunlight visible to short wavelength infrared

The Origin of Spectroscopy

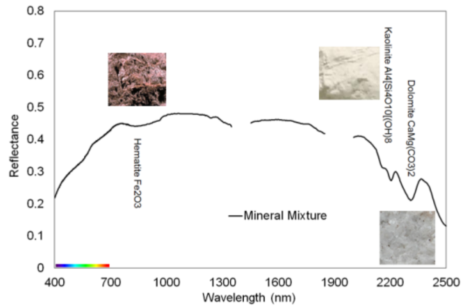


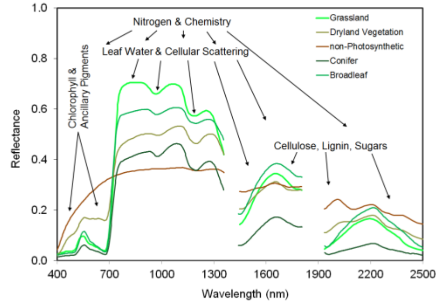
- Newton generated a rainbow with a prism and described many characteristics of light in Opticks, 1704

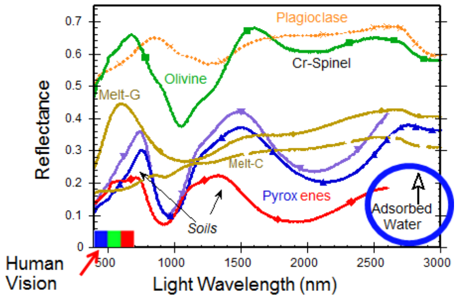
- Fraunhofer developed a spectroscope in 1814 and used the observation of dispersed light to understand glass composition as well as to discover the absorption lines in flames and the solar spectrum

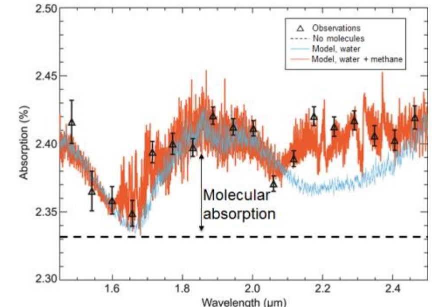
- Edwin Hubble used spectroscopy to understand the expanding nature of our universe in 1929

- Spectroscopy is a powerful analytical method that enables remote measurement for scientific discovery and other applications

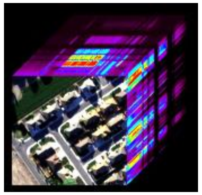


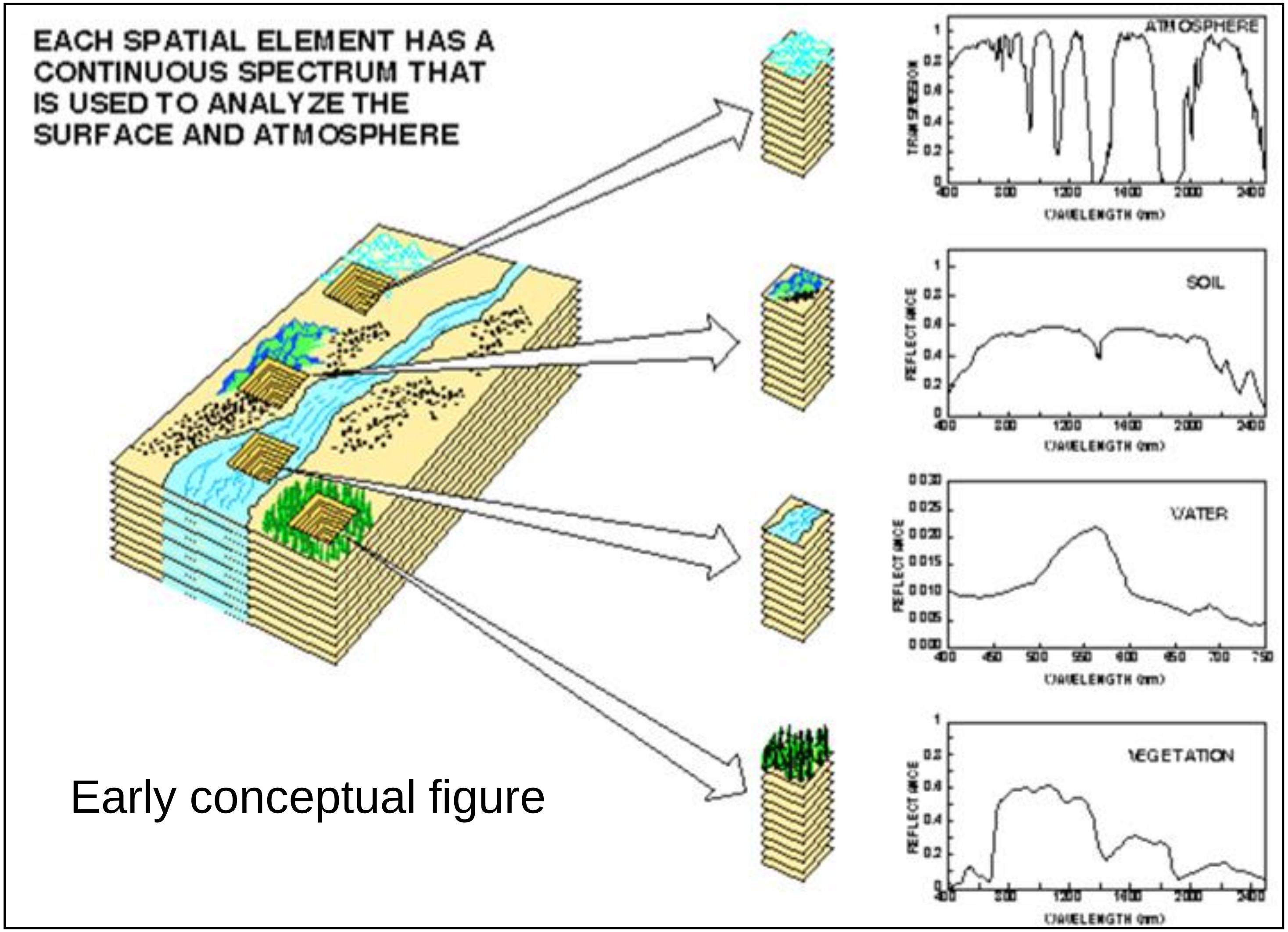






Imaging Spectroscopy

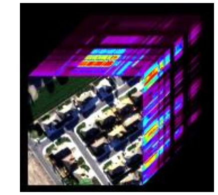


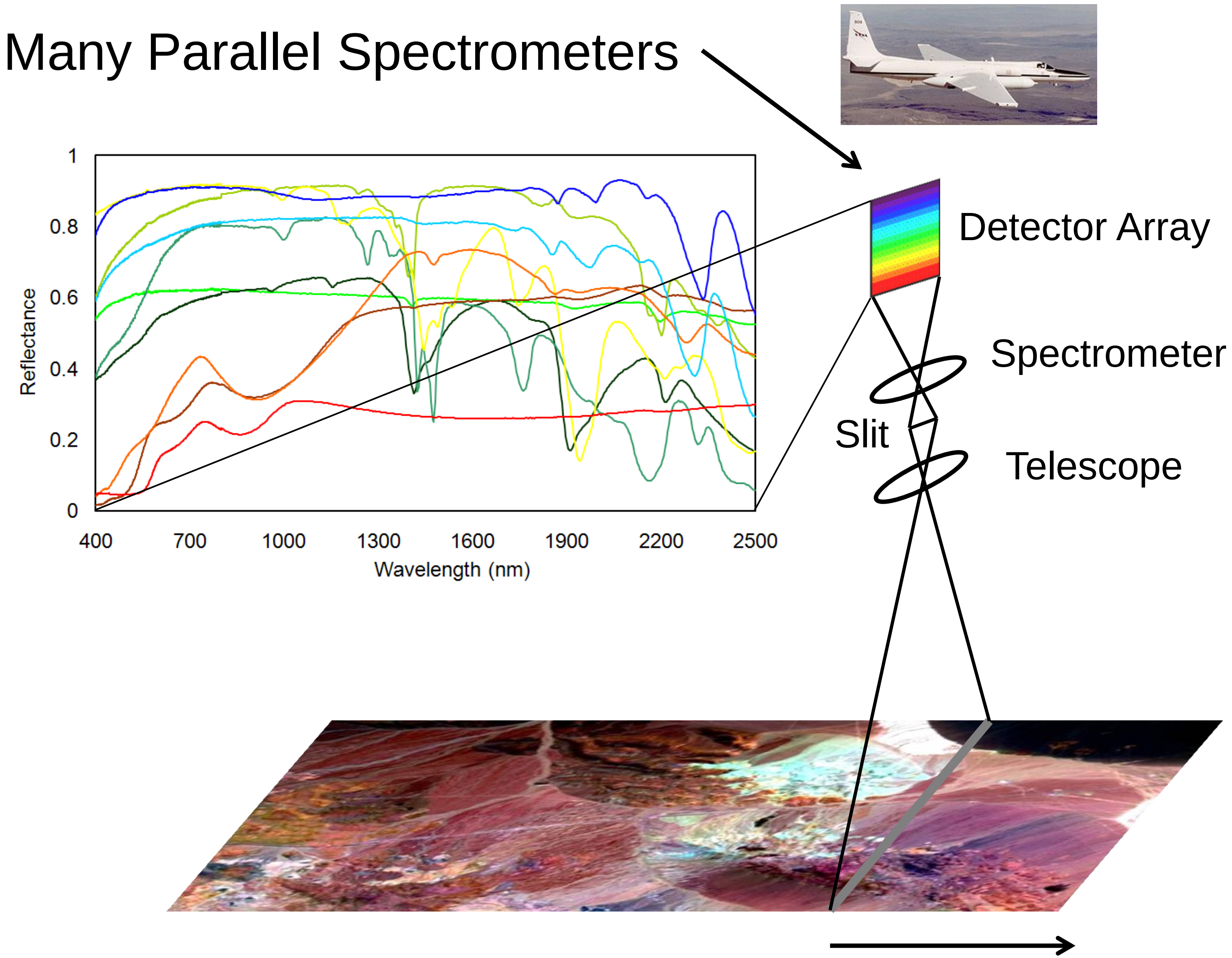


Early conceptual figure

Requires advanced: detectors, optical designs, computation, etc.

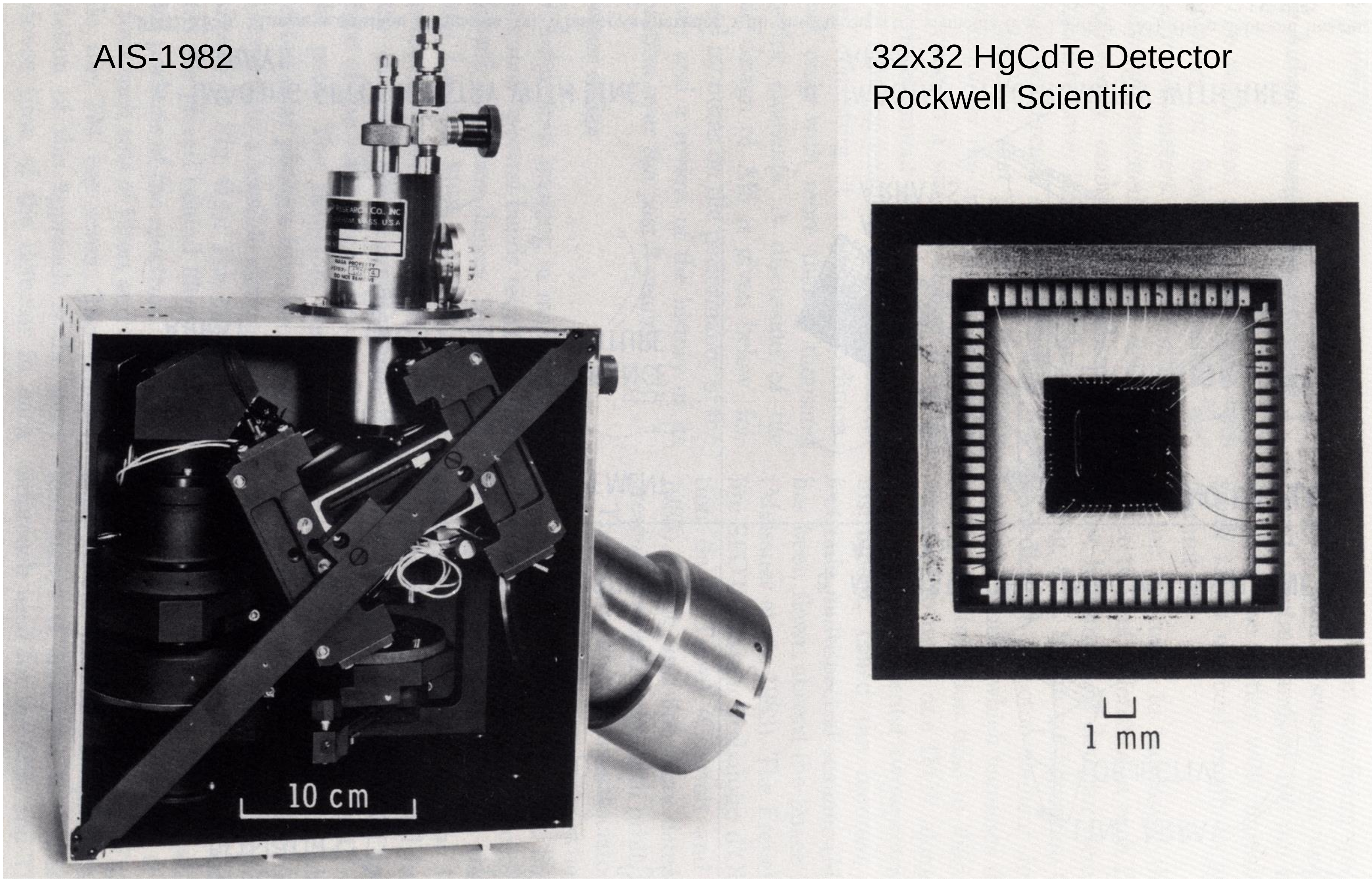
The Pushbroom Imaging Spectrometer Approach





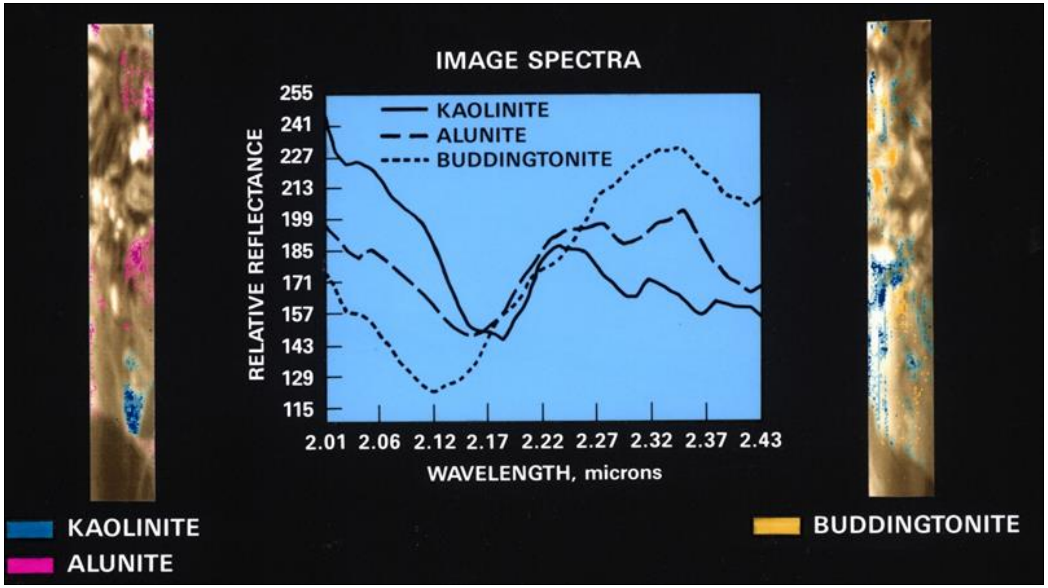
The Airborne Imaging Spectrometer

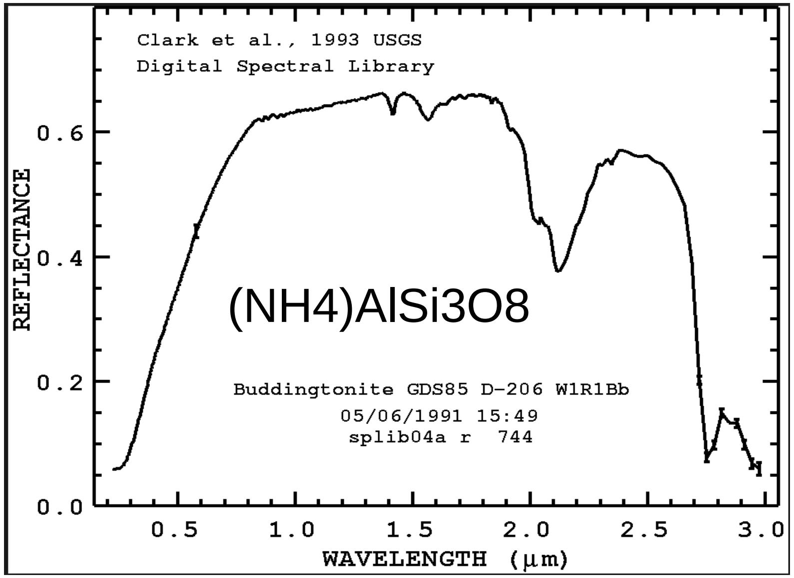
Proposed at JPL in 1979 (IRAD)

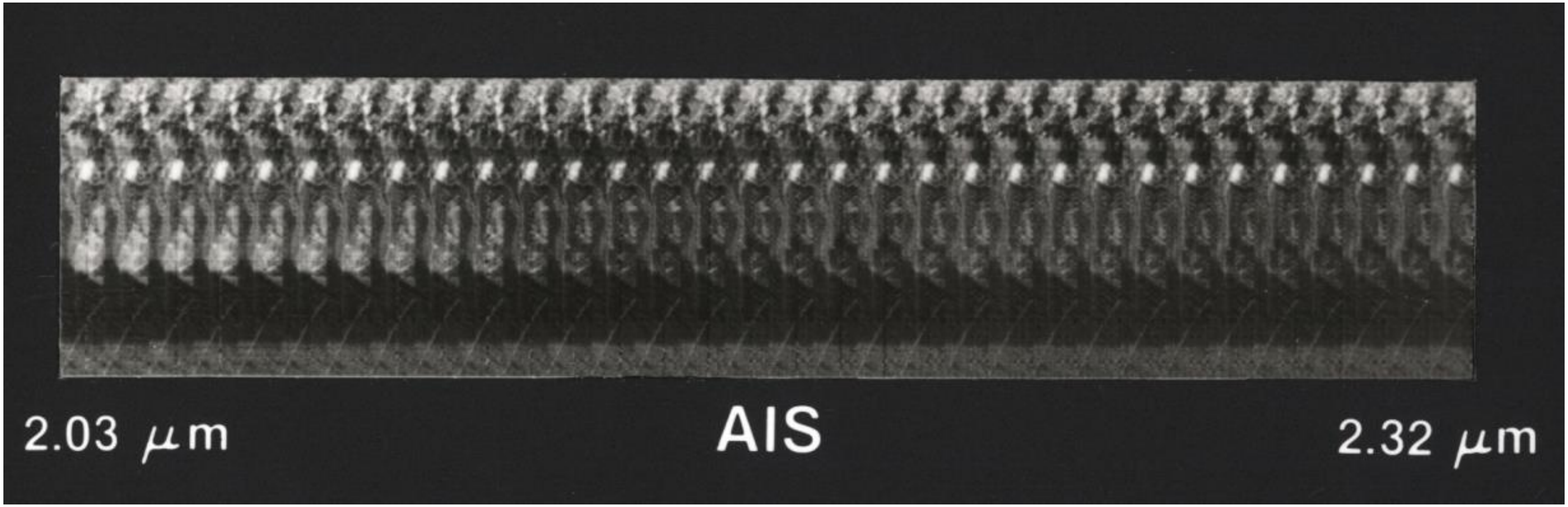


AIS First Flight Discovery

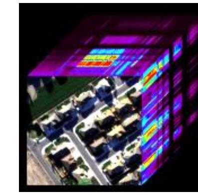
Buddingtonite Occurrence at Cuprite, NV

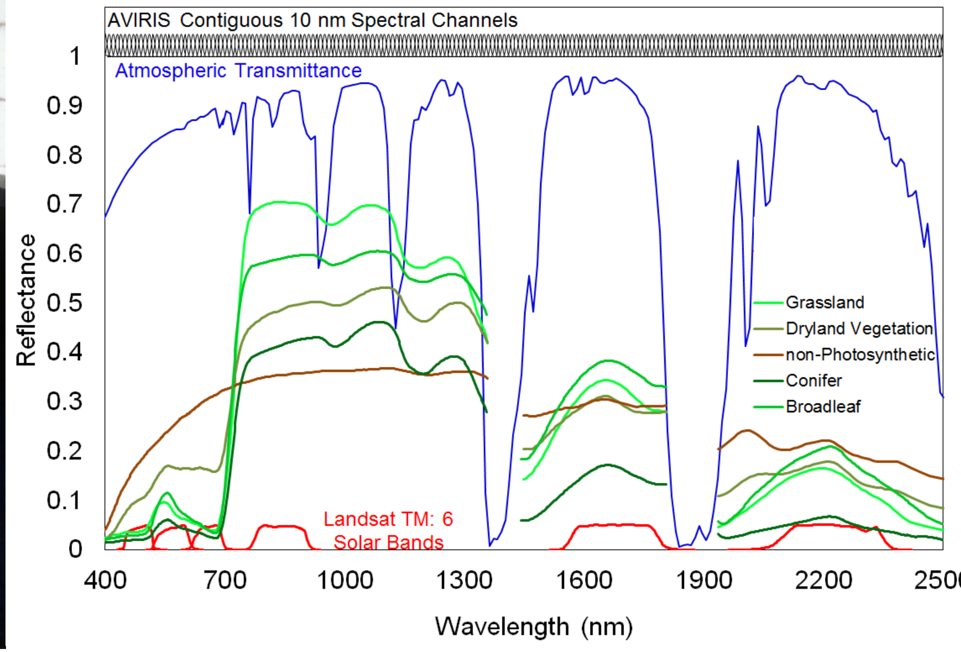






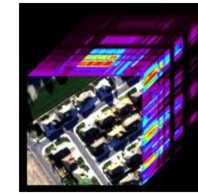
The Airborne Visible-Infrared Imaging Spectrometer (AVIRIS)

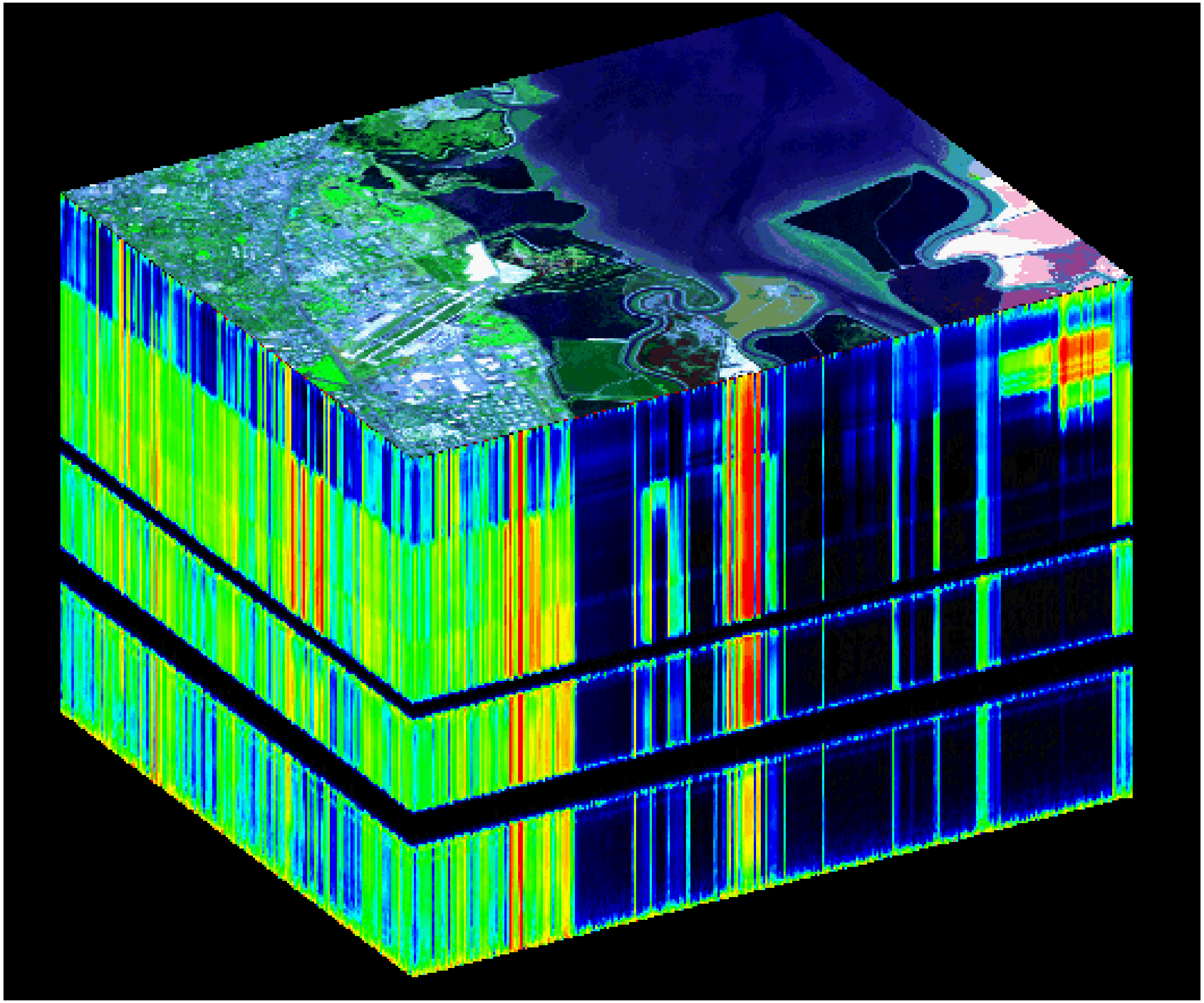




- Proposed 1983 and first flew in late1986
- F/1 optics; Si, InGaAs, InSb detectors; 200 µm class detectors
- 87 µs integration time; ≥1 M electrons in 10 nm channels for bright targets
- 8700 spectra per second; > 100 Terabytes of data and products
- AVIRIS is mentioned in more the 850 refereed journal articles
- Flew the RIM Fire, CA on the 13th of September 2013 (28 consecutive years)

AVIRIS Image Cube, San Jose, CA

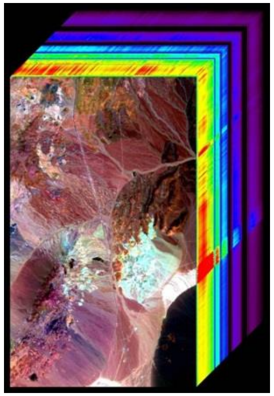


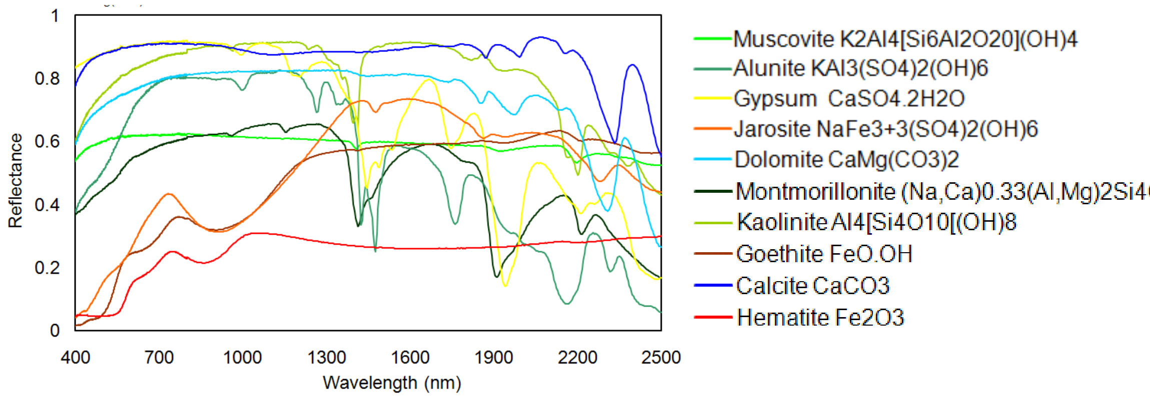


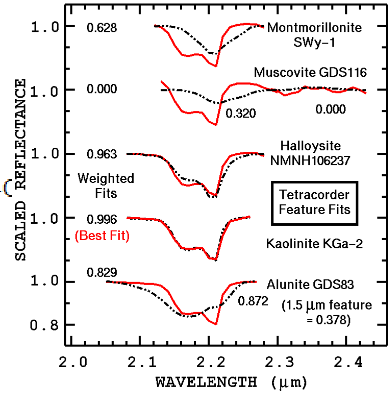
NASA ER-2
Collects images from 20 km (65,000 ft) altitude

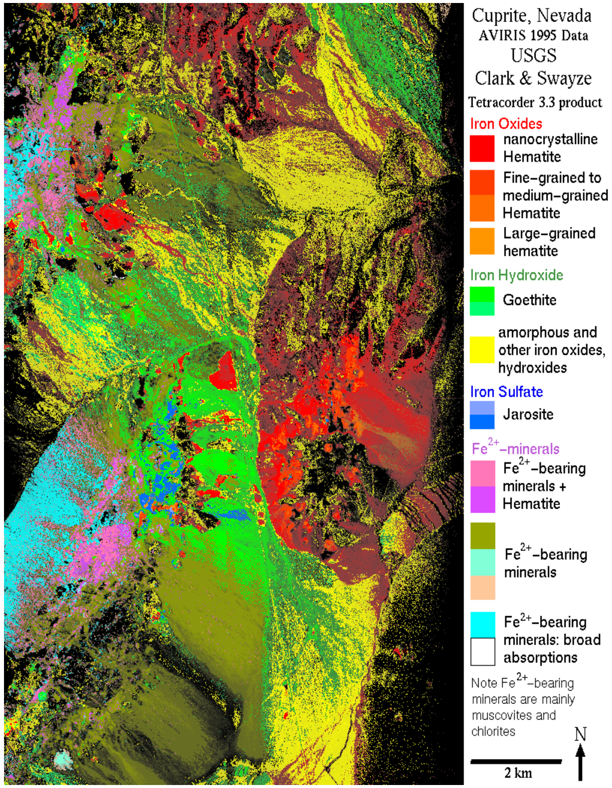
Earth Measurement Examples

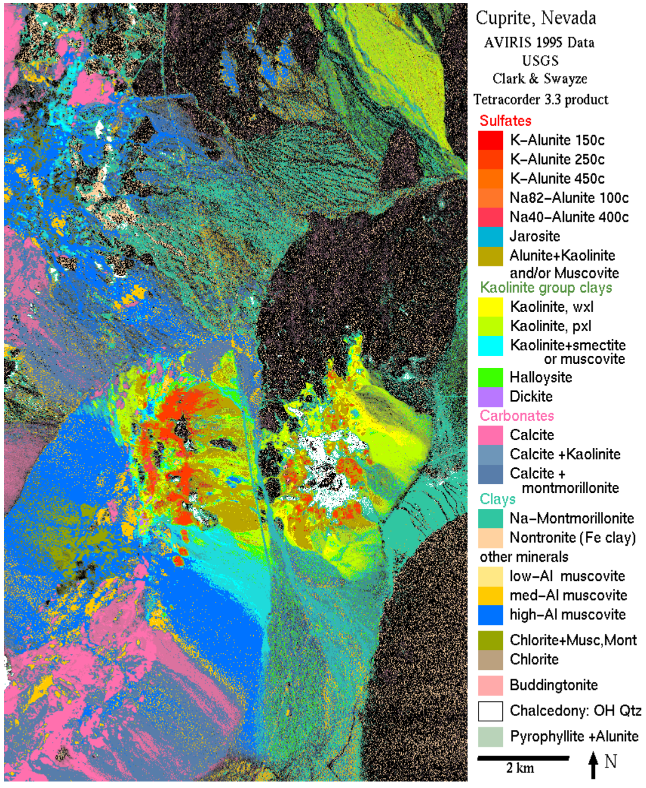
Cuprite, NV for Mineral Mapping







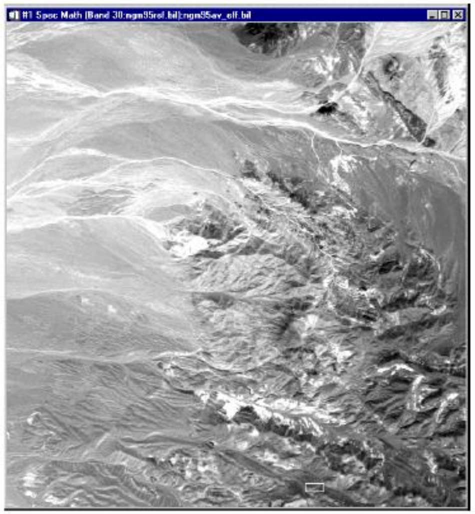


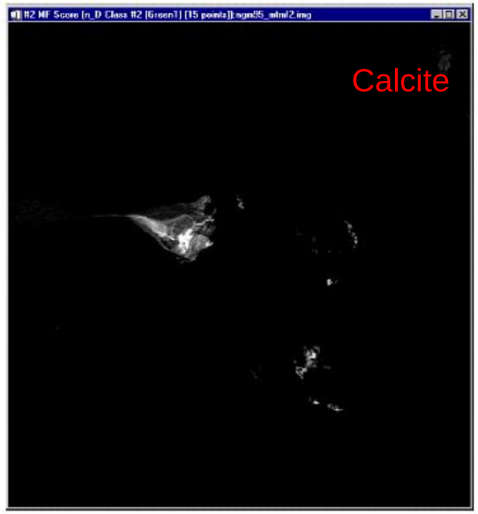


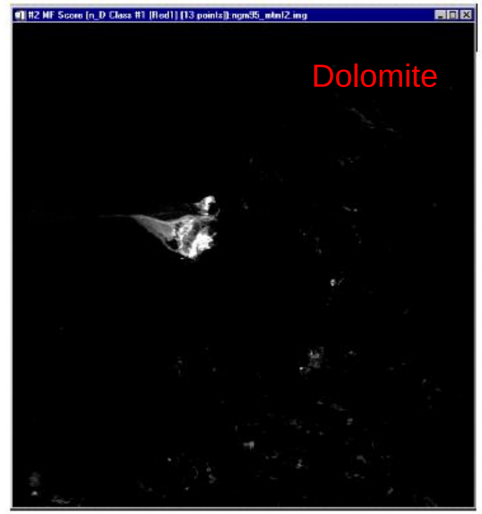
Field Checking the Spectroscopy at Cuprite, NV

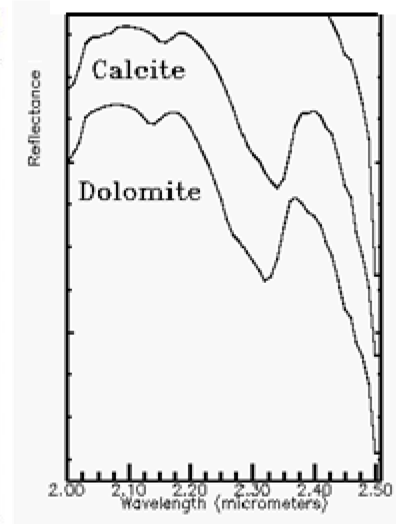
Spectroscopy Enables Sub-pixel Detection

- Grapevine Mountains 20m x 20m AVIRIS measurements

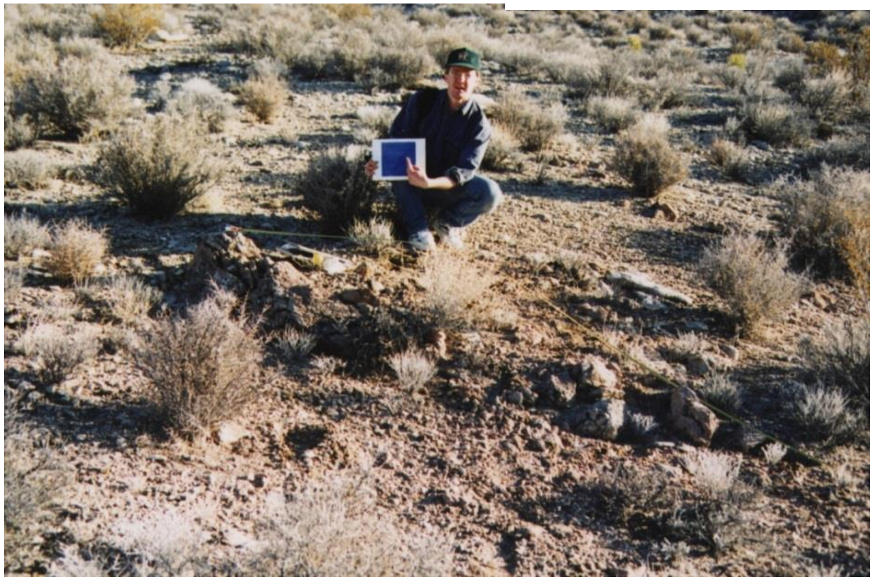






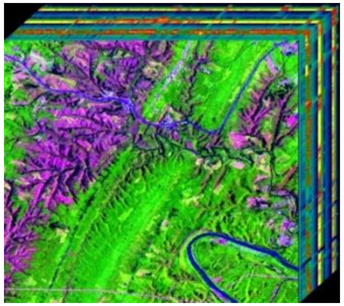


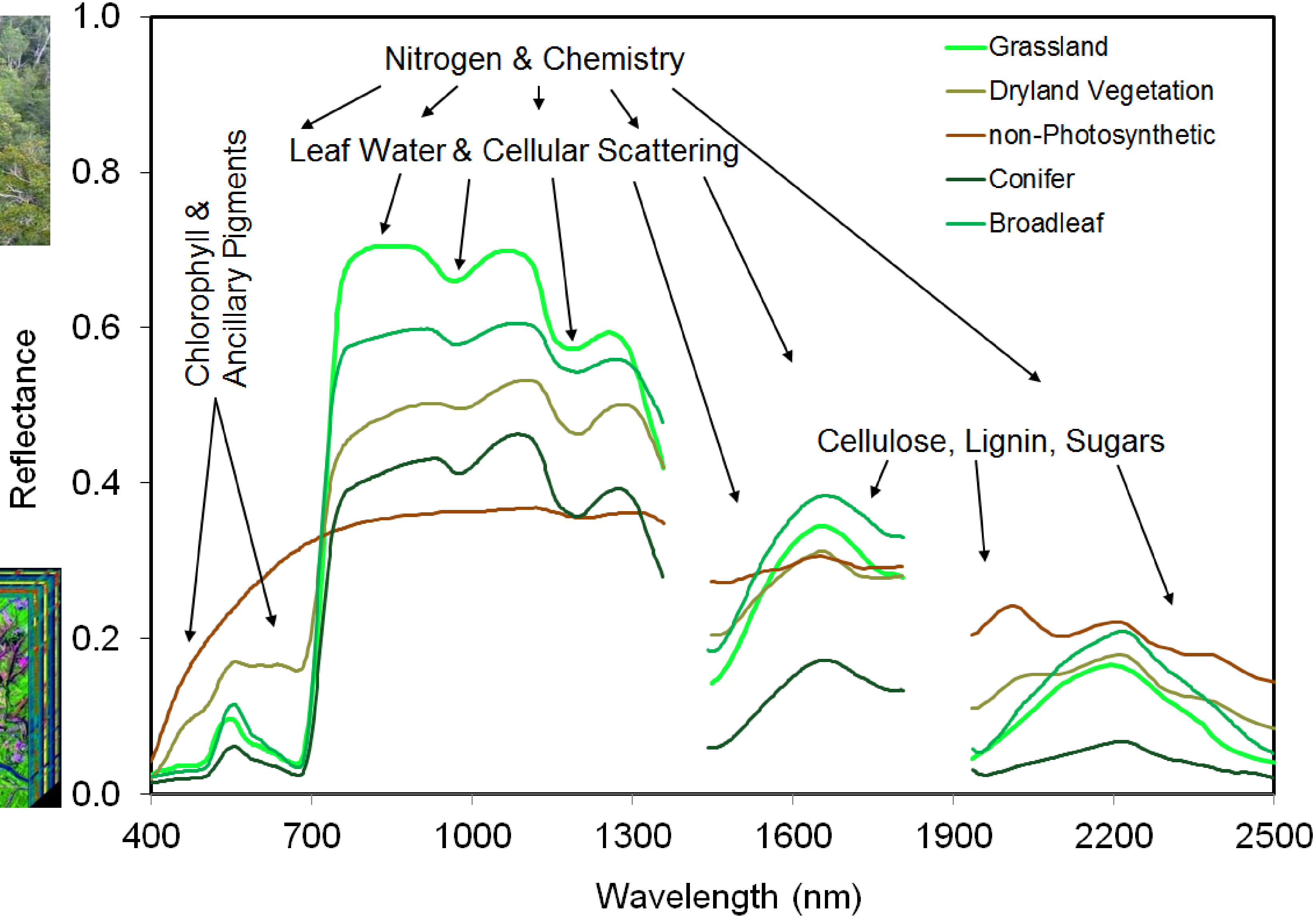
3m x 1m Dolomite discovered with 20m x 20m AVIRIS imaging spectrometer measurement



Boardman and Kruse

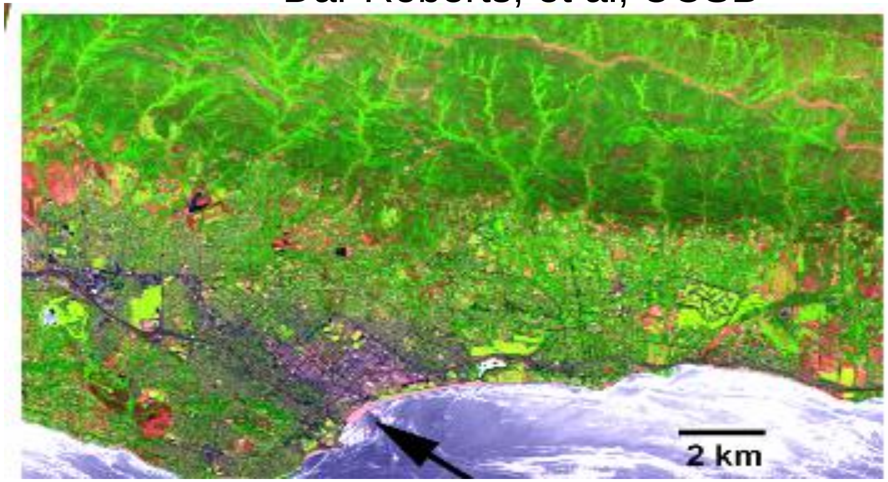
Spectroscopy of Vegetation



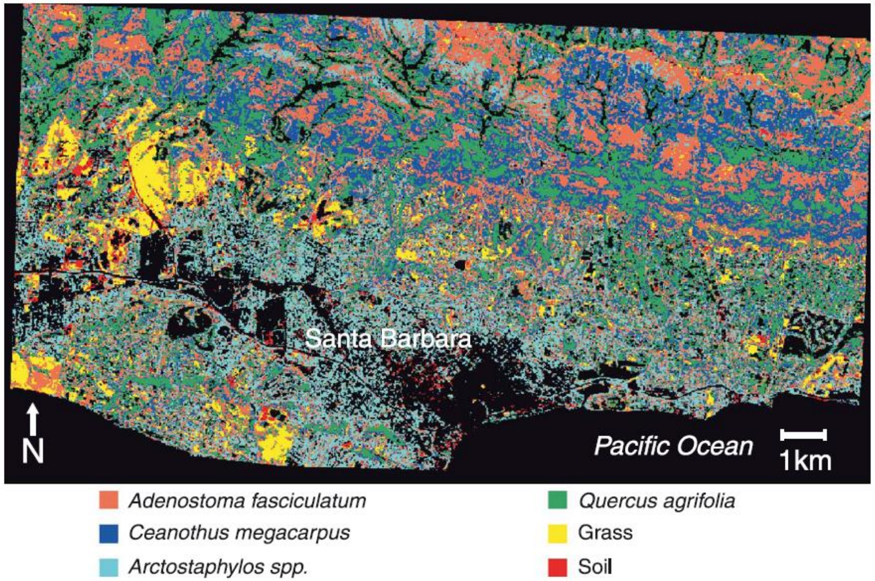


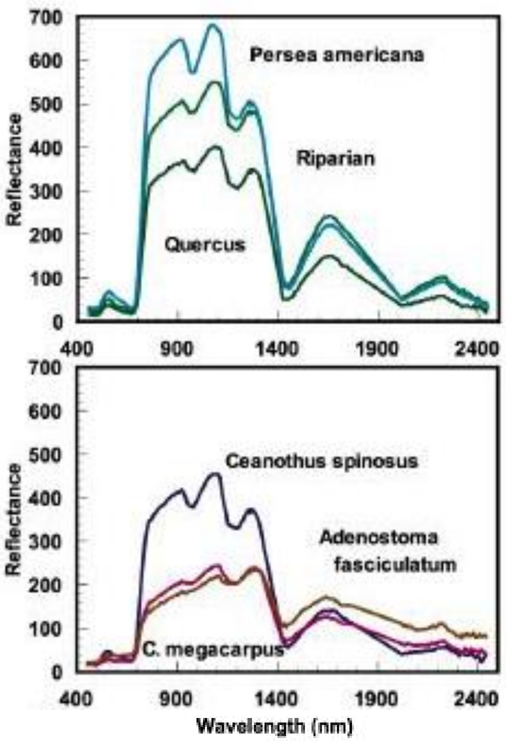
Mapping Vegetation Species with Imaging Spectroscopy

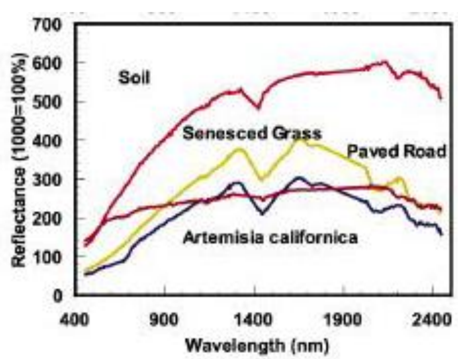
Dar Roberts, et al, UCSB



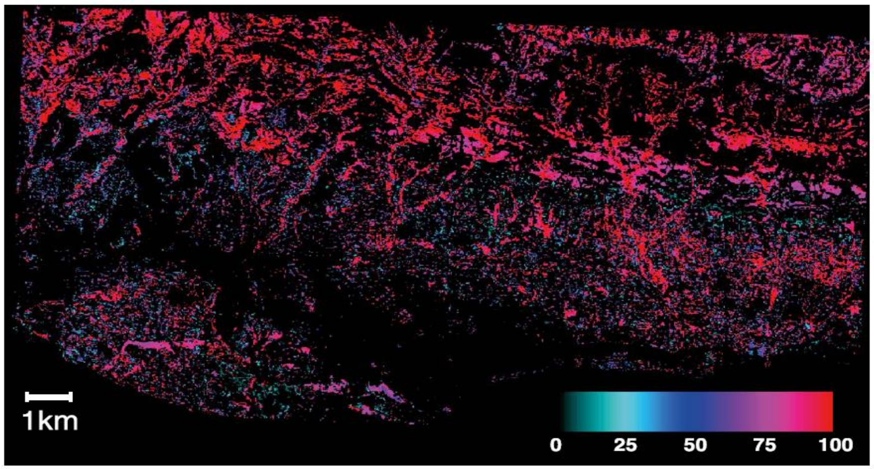
MESMA Species Type 90% accurate





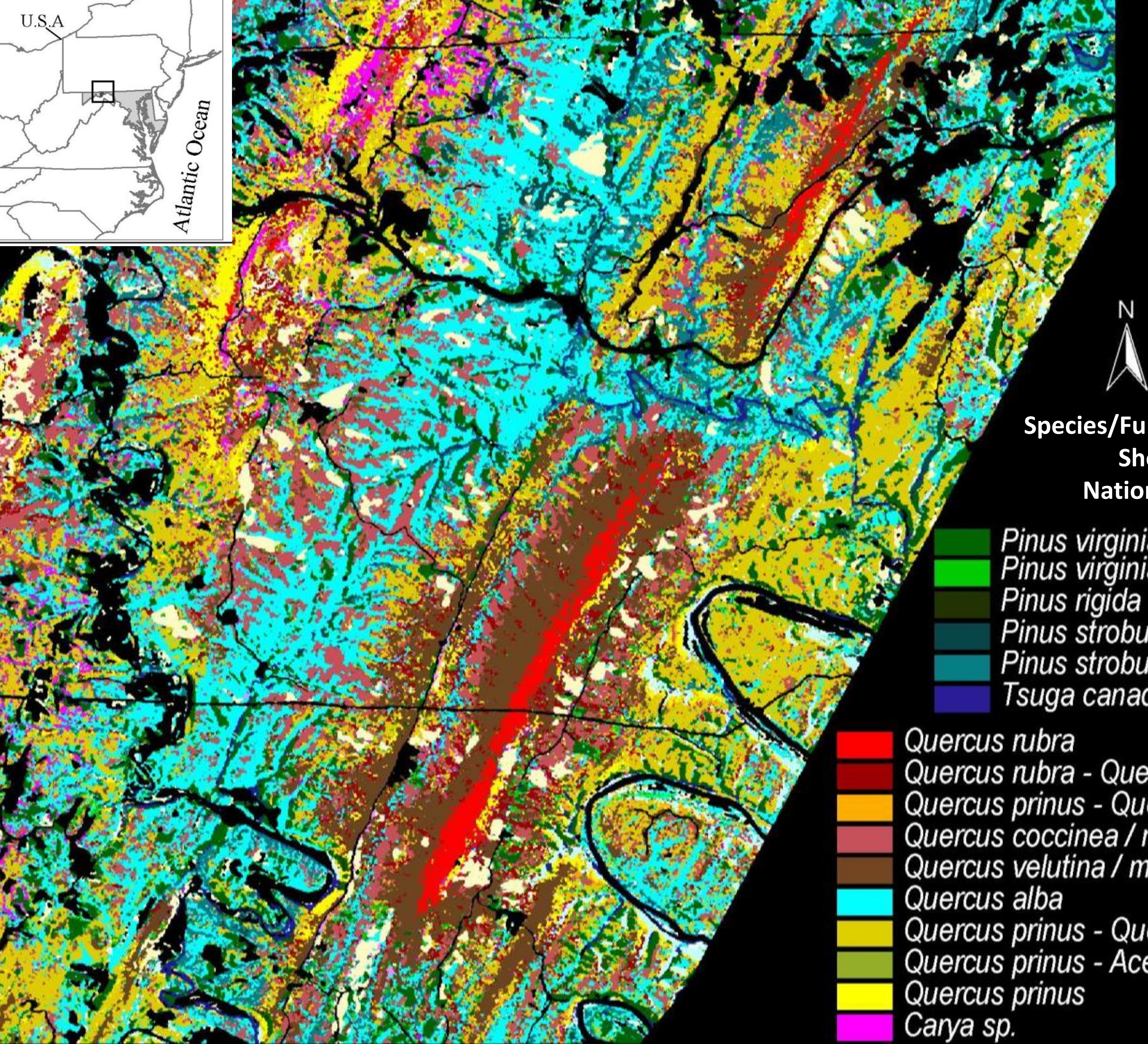


Species Fractional Cover Quercus agrifolia

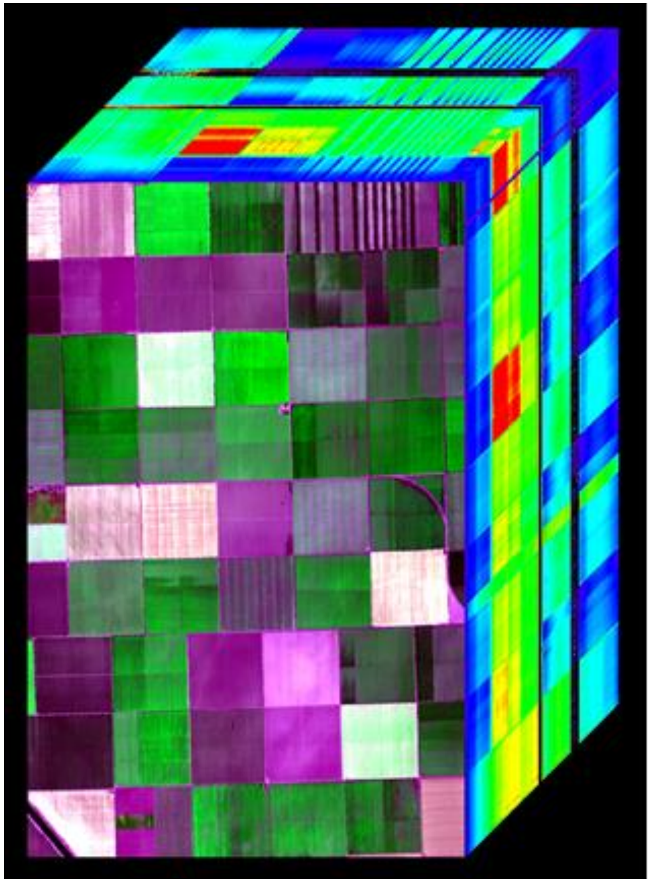


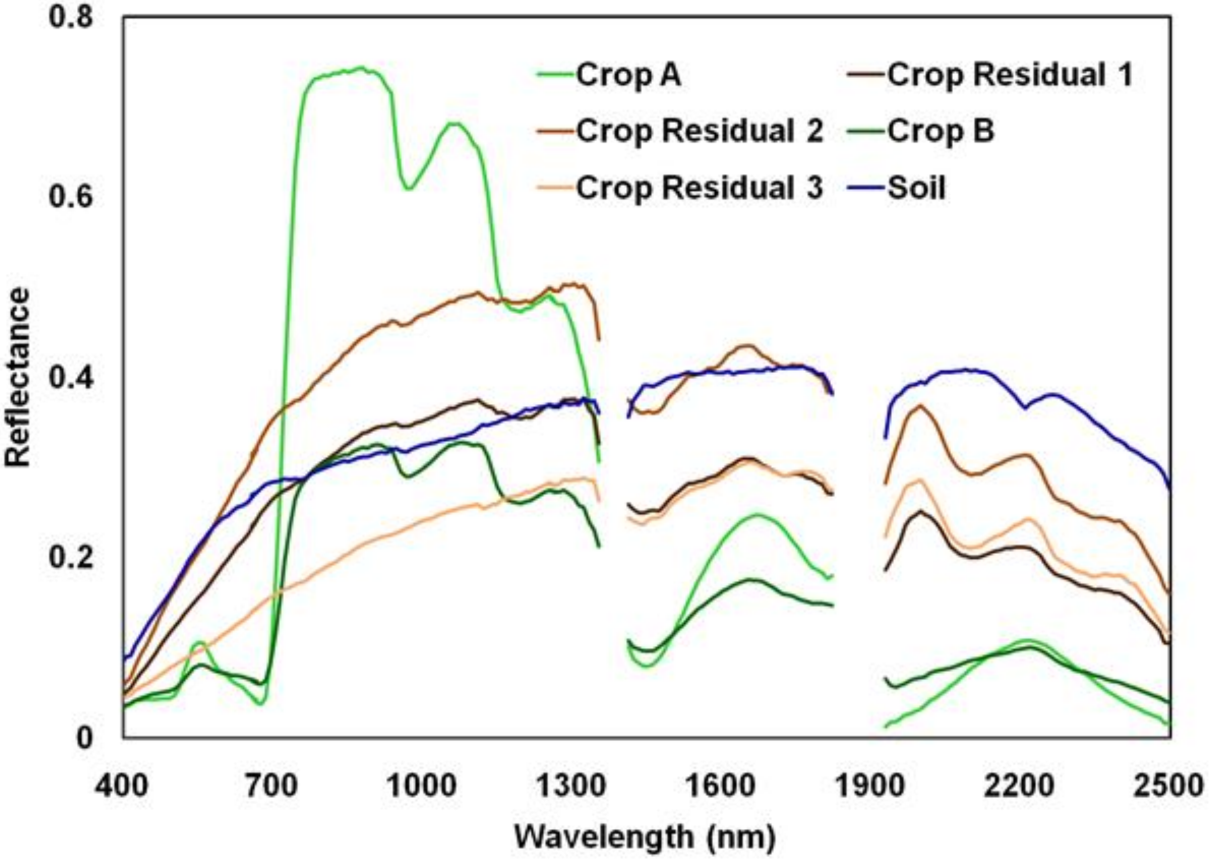
Airborne Imaging Spectroscopy, Santa Barbara, CA

Species/Functional-type Map Shenandoah National Park, USA



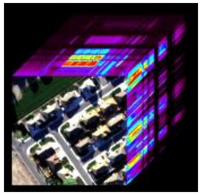
Agriculture

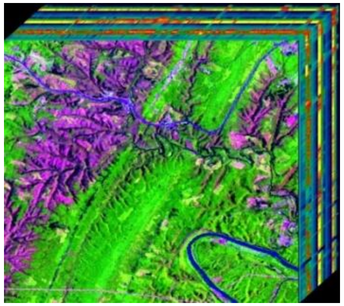


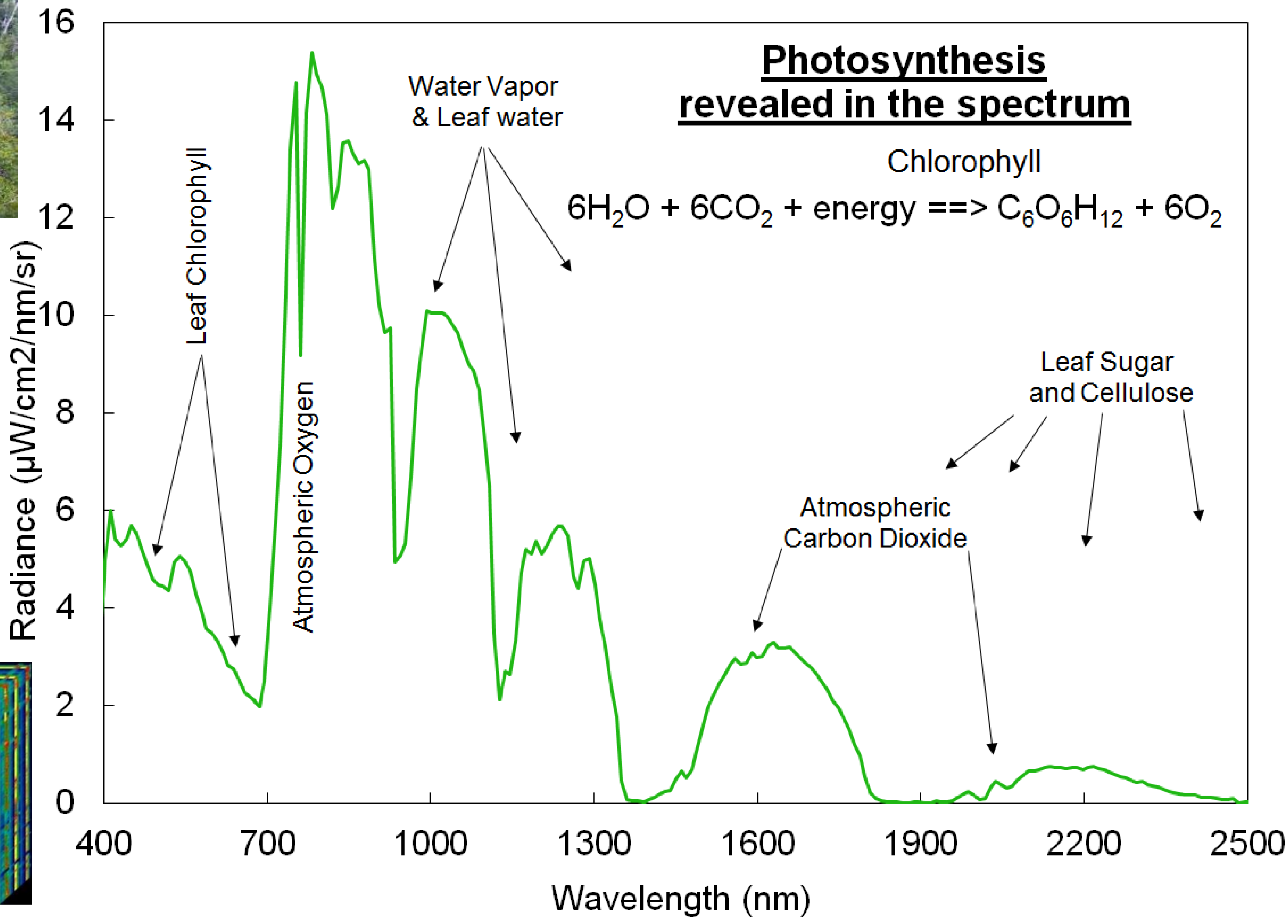


Crop type, Crop health, Nitrogen, Leaf water, Soil Composition, Soil Salinity, Soil Carbon, etc.

Photosynthesis Revealed via Spectroscopy

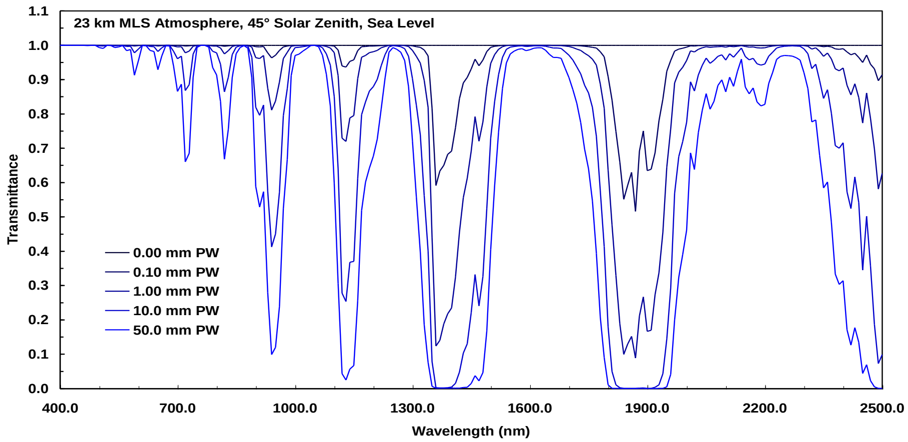




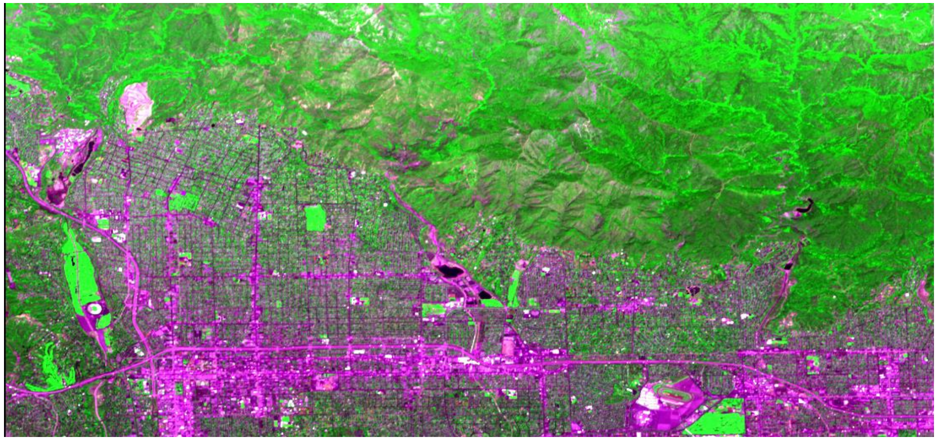


Atmospheric Water Vapor

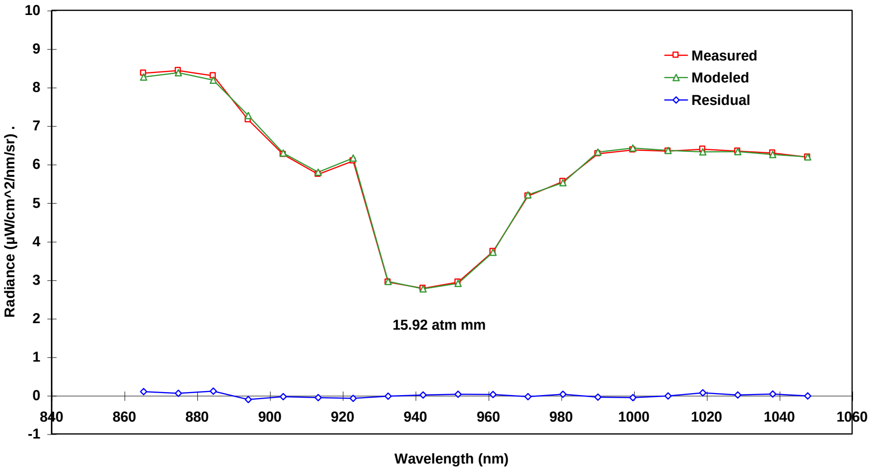
Water Vapor Absorption



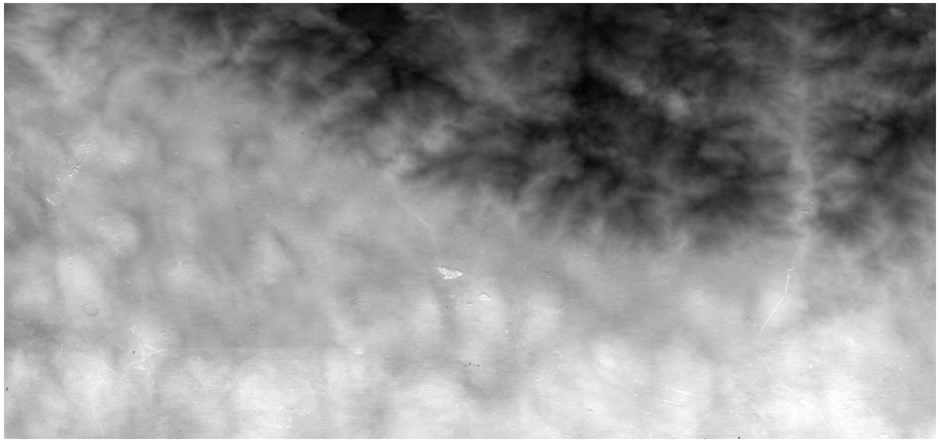
Pasadena Imaging Spectrometer Image



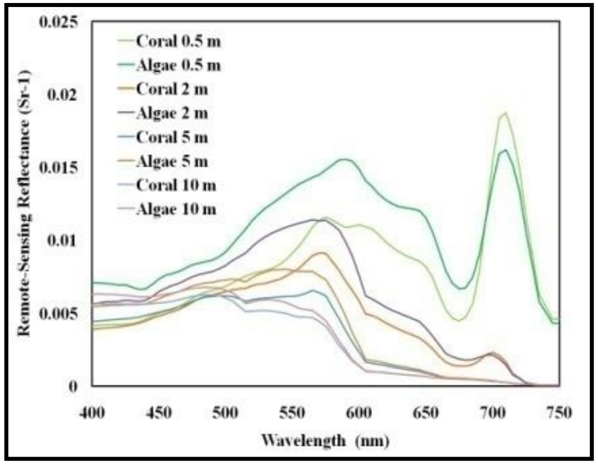
Spectral Fitting 15.92 mm



Water Vapor Map

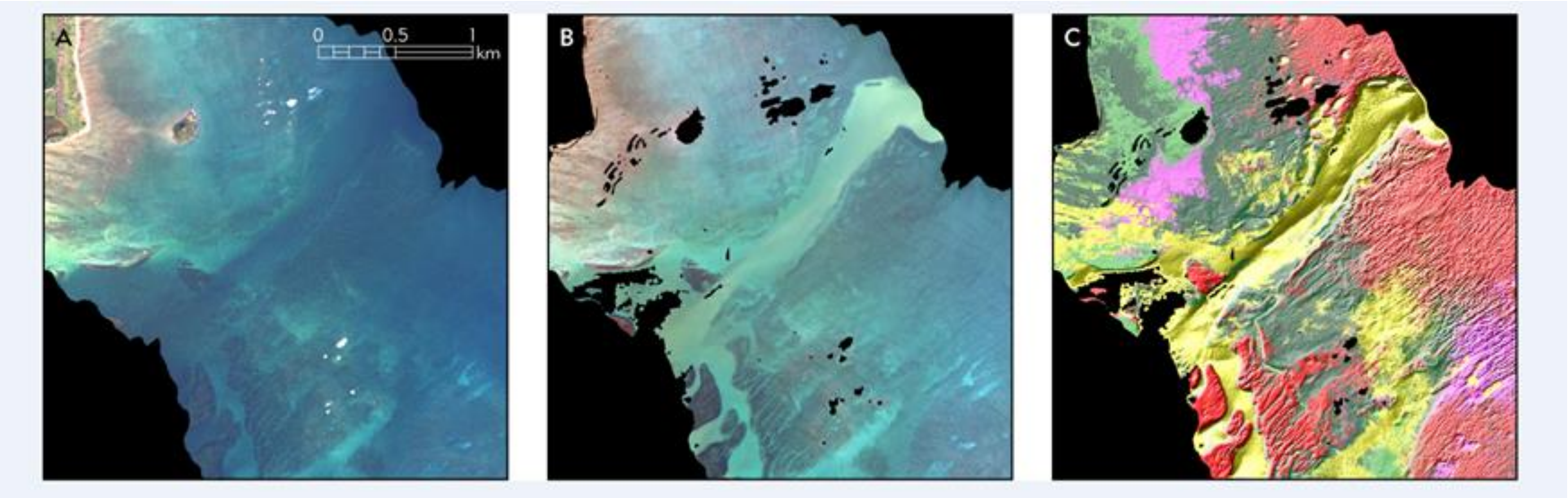


Shallow Water Spectroscopy
Corals



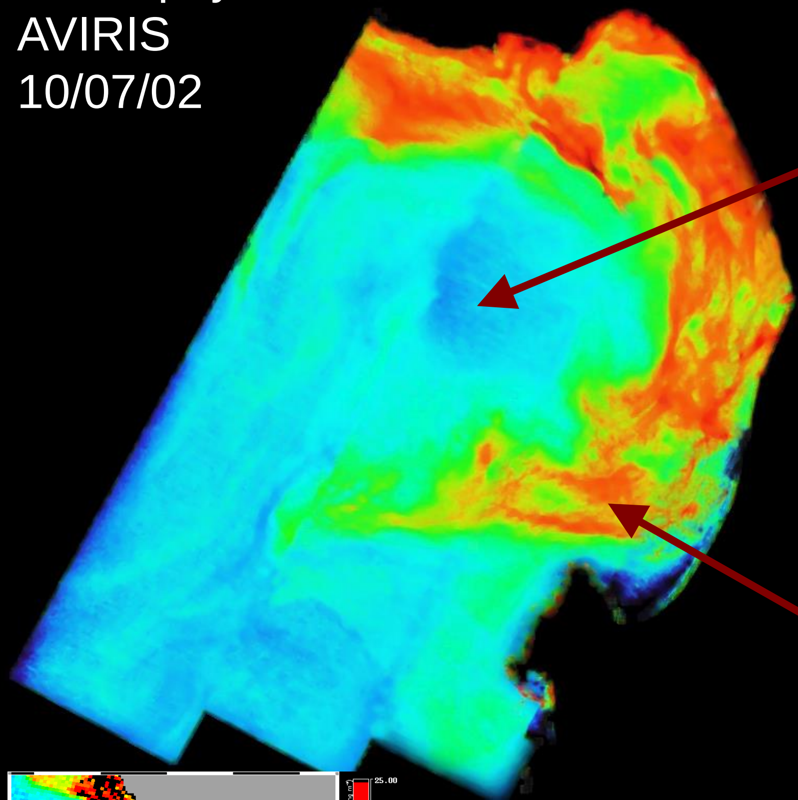
- Composition
- Condition
- Productivity
- Bathymetry
- Water quality

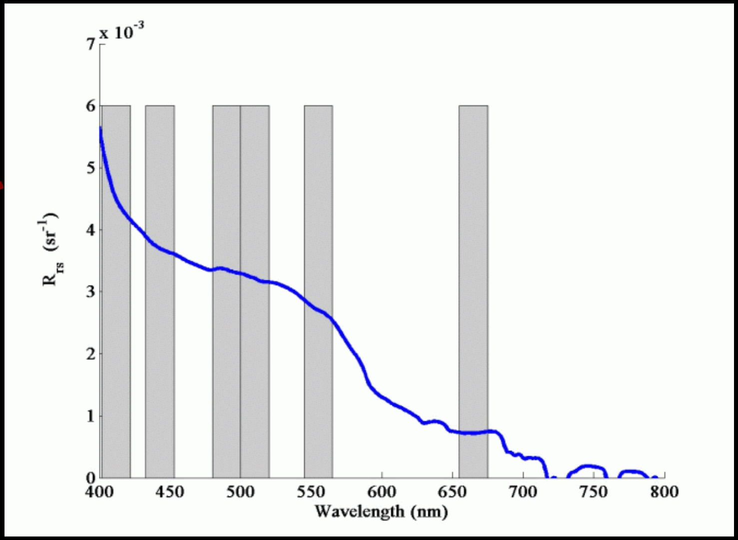
AVIRIS Image of Kaneohe Bay, HI
Classification of the bottom of coastal zones and coral reef types

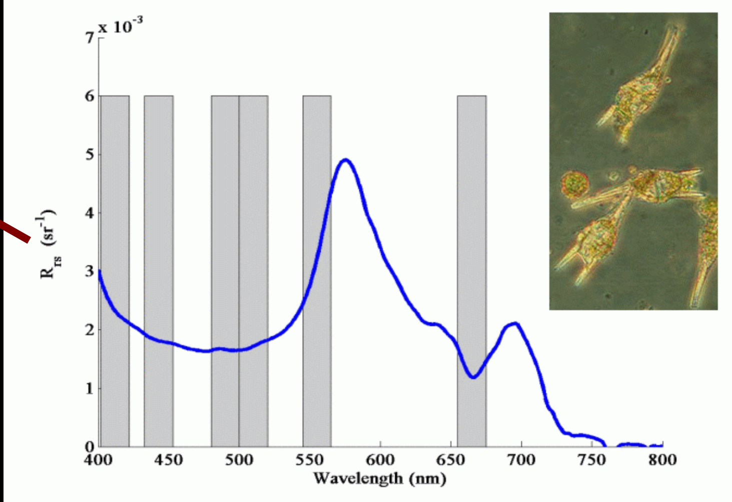


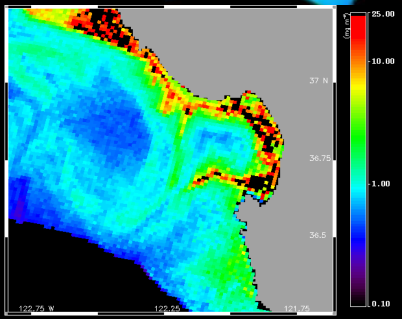
A red-tide bloom in Monterey Bay, CA

Surface Chlorophyll from AVIRIS 10/07/02





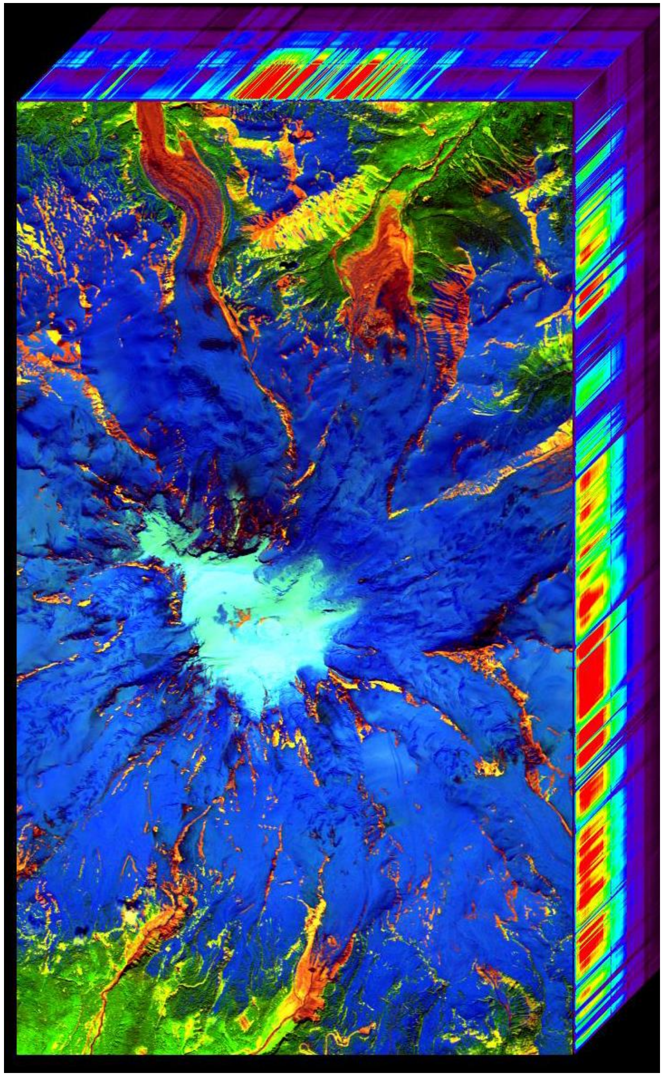


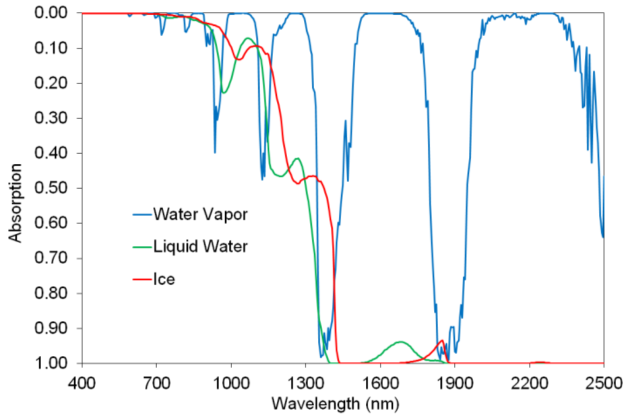


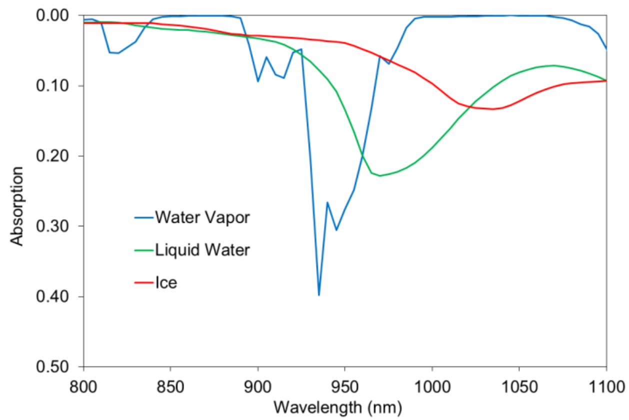
Surface Chl from SeaWiFS 10/08/02

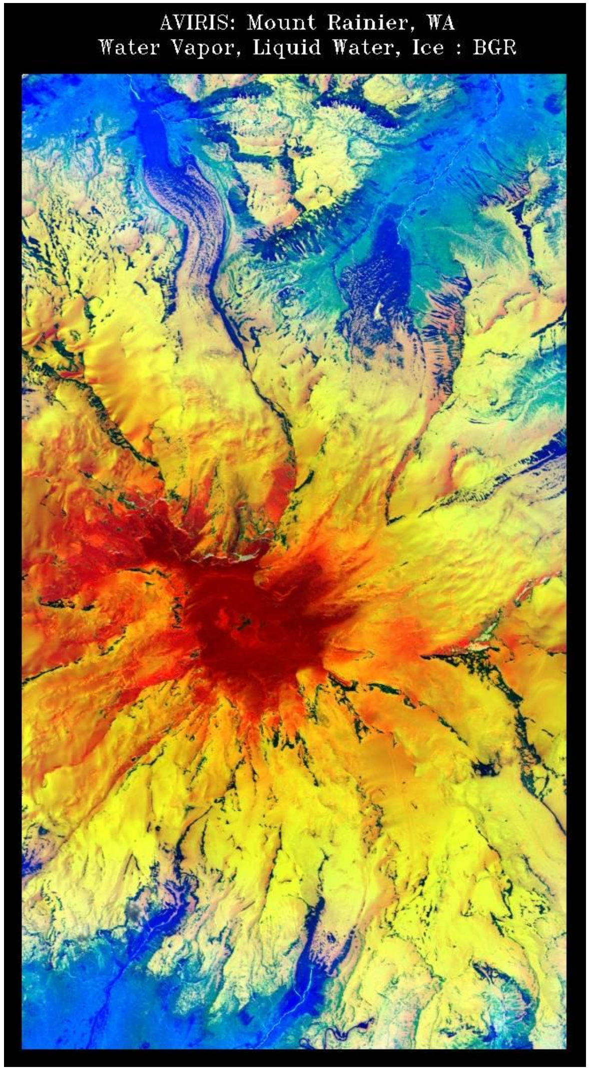
SeaWiFS bands miss signal

Three Phases of Water
Mount Rainier, WA

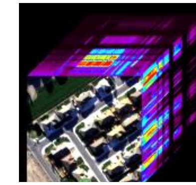






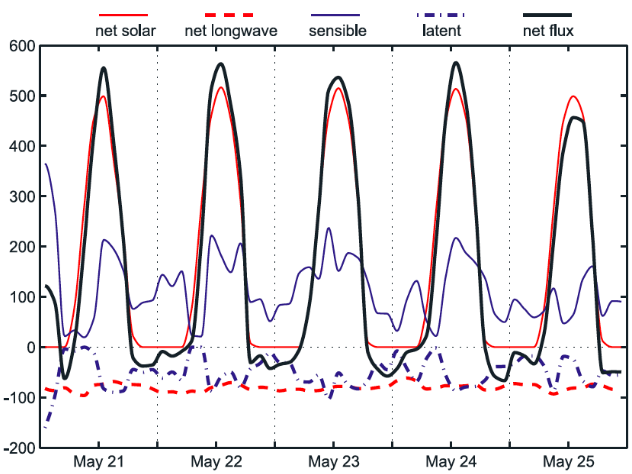


Snow and Ice: Albedo, Dust, Melting

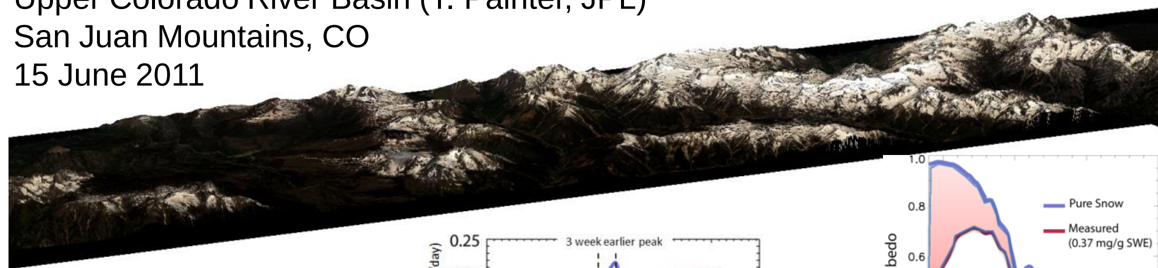


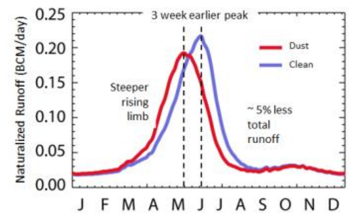
- Water availability
- Melting of the Earth's glaciers.

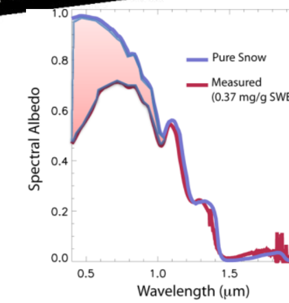
$$\frac{dU}{dt} + Q_m = (1-\alpha)S + L^* + Q_s + Q_v + Q_g + Q_r$$



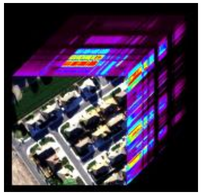
Upper Colorado River Basin (T. Painter, JPL)
San Juan Mountains, CO
15 June 2011



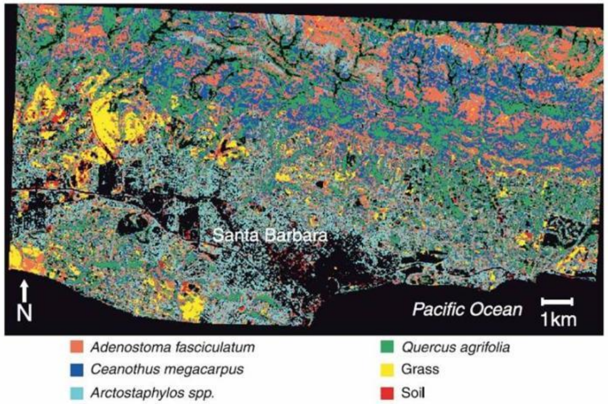




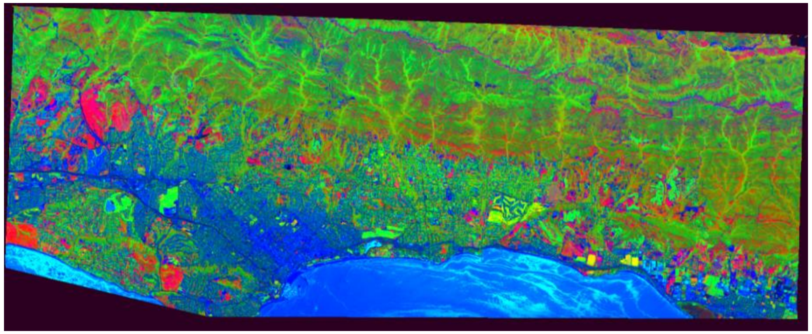
Fire: Risk, Burning, Severity and Recovery



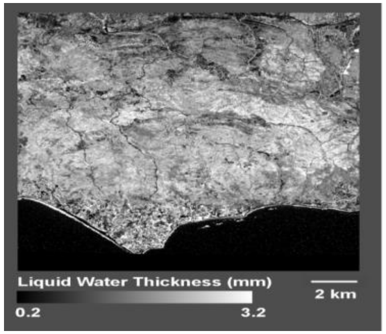
Species Type

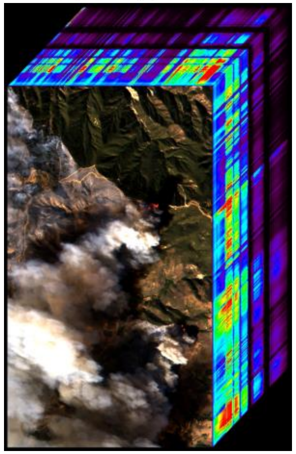


Dry Biomass (Cellulose/Lignin)

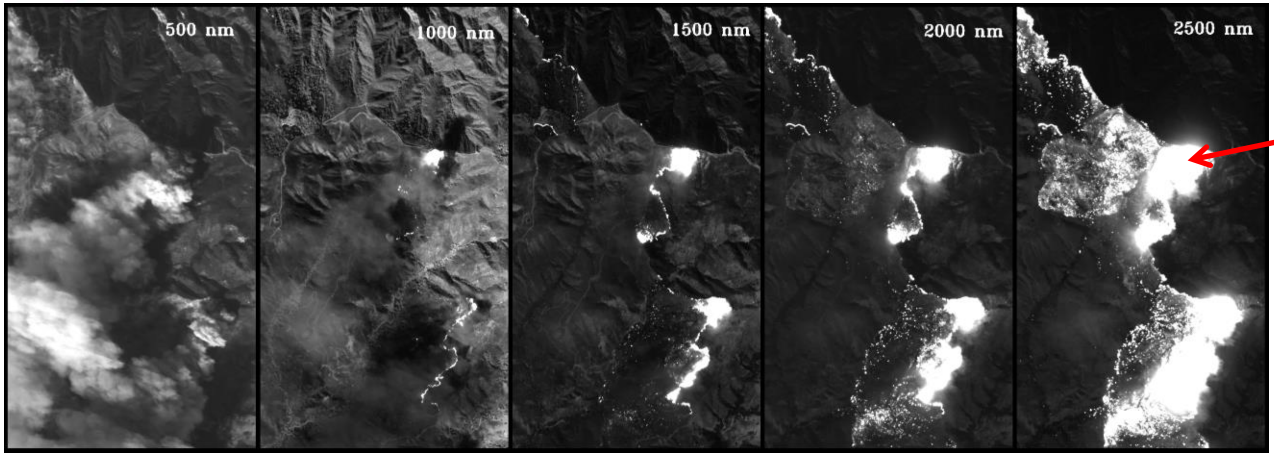


Canopy Water

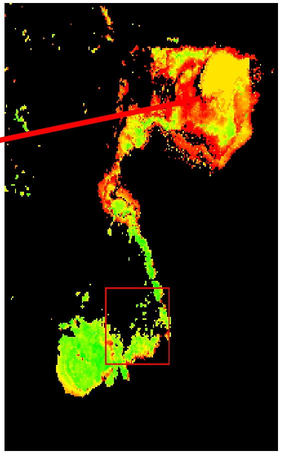




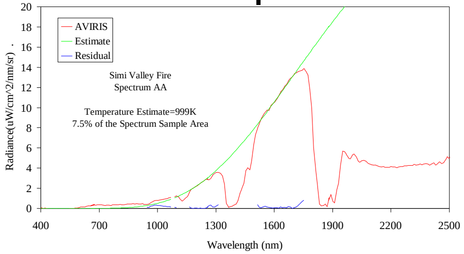
Simi Valley Fire 2003



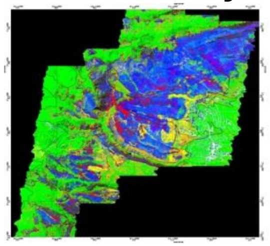
T ~ 1200K



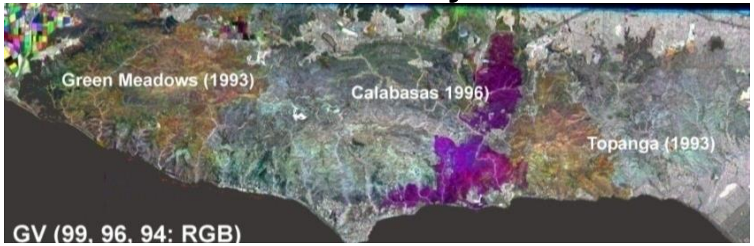
Fire Temperature



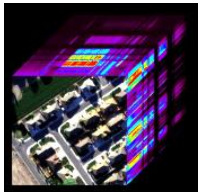
Severity

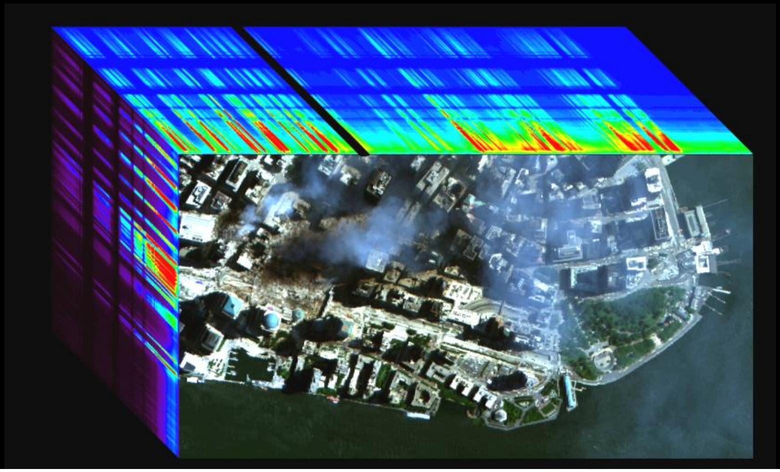


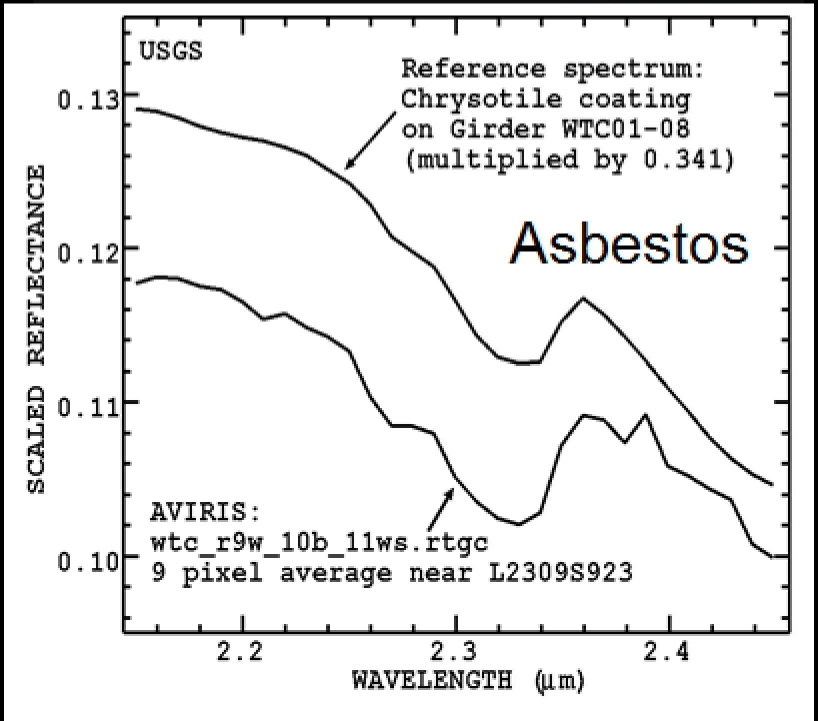
Recovery



2000 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

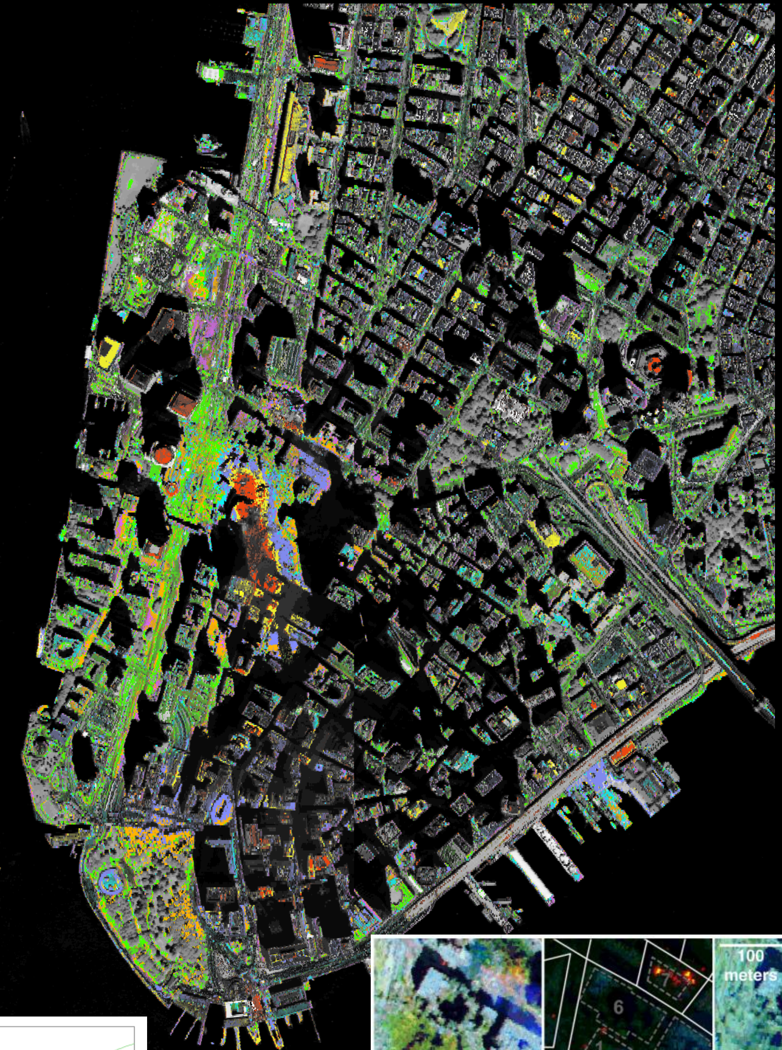
Spectral Shape Map

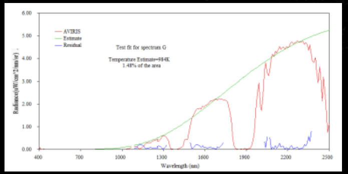
This map shows materials whose spectra are similar to the reference materials below. It is not a map of the identification of these materials. A similarity map is analogous to a map of materials with similar colors viewed with your eyes. The colors may indicate similar compositions.

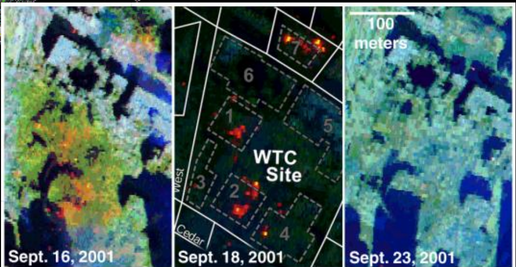
- concrete (WTC01–37B)
- concrete (WTC01–37Am)
- cement (WTC01–37A)
- dust (WTC01–15)
- dust (WTC01–28)
- dust (WTC01_36)
- gypsum wall board

Image sampling:
1.7 meters/pixel

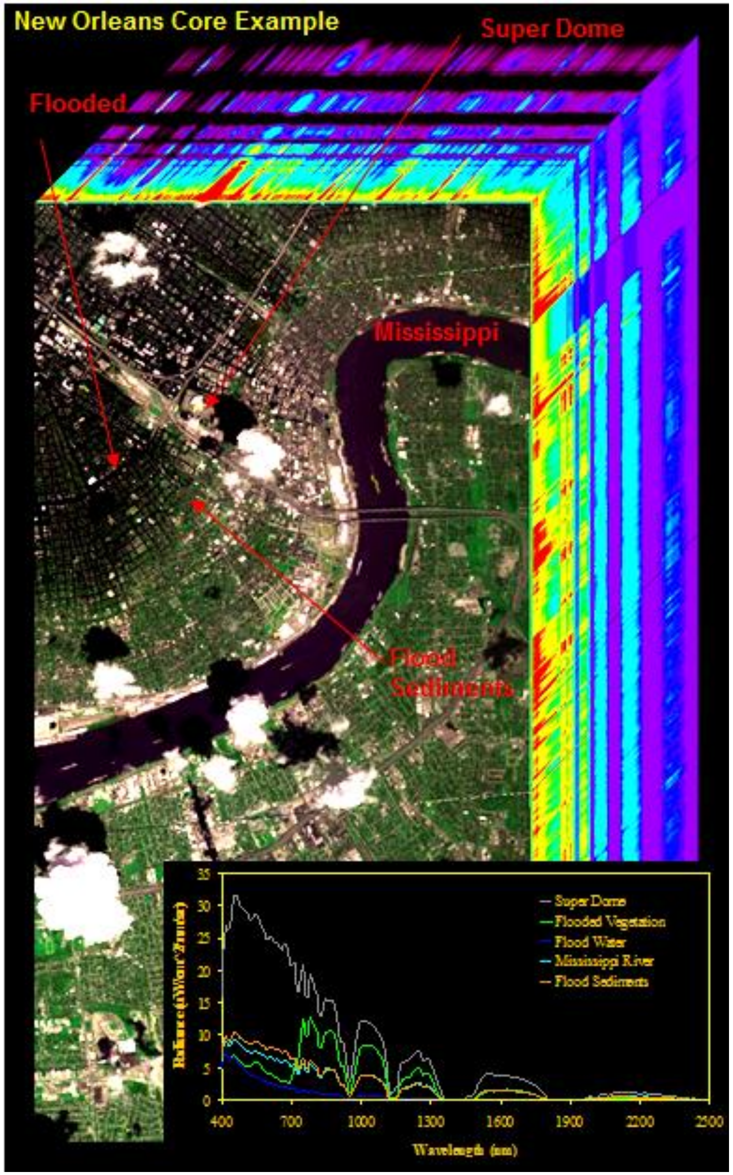
N
200 meters







2005 Hurricane Katrina Response



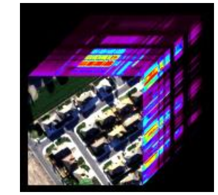
OBJECTIVE

- Assess impact of flood and hazards via imaging spectroscopy

- Examples: Flood water composition, particulate distribution, oil contamination, methane leaks, environmental damage, fires, etc.

COLLABORATORS

- Delivery to FEMA
- Roger Clark, Trude King, et al., USGS
- Prof. Susan Ustin, UC Davis
- Prof. Dar Roberts, UC Santa Barbara
- Prof. Greg Asner, Carnegie (CIW) & Stanford
- Robert Green, JPL
- Joseph Boardman, AIG

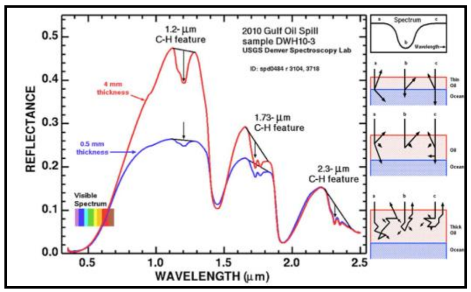


2010 Gulf Oil Spill Response

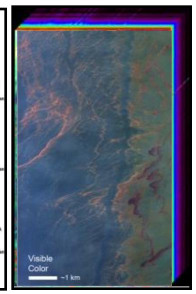
NASA AVIRIS used by USGS, NOAA and NASA science team to estimate the thickness and volume of the surface oil. Example result: High values at 131 liters/pixel*.

Oil Spill

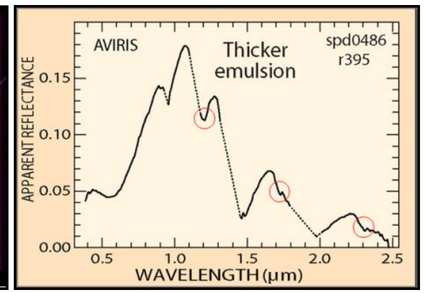
Spectroscopic Basis C-H Bond Absorptions



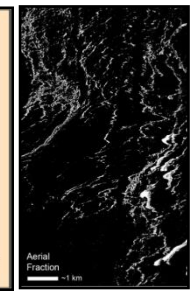
AVIRIS



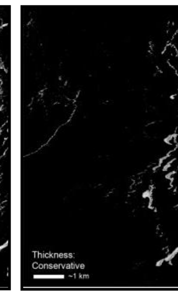
AVIRIS Spectra



Fraction



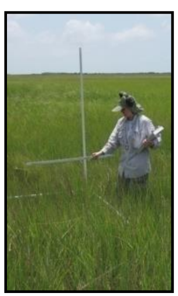
Thickness



Quantitative Volume Estimates

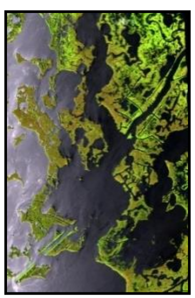
NASA AVIRIS used by a broad government and university science team to map vegetation species and physiological condition (health) before and after oil impact.

Pre Oil

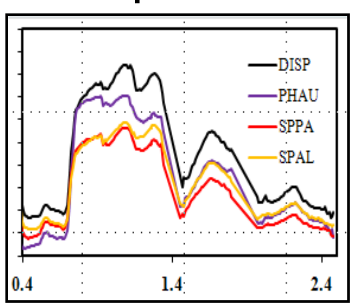


AVIRIS ER-2

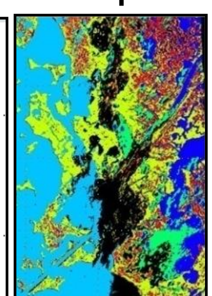
Coastal Data



AVIRIS Vegetation Spectra

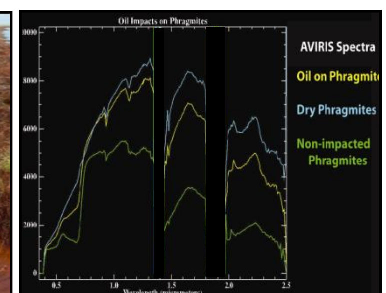


AVIRIS Species Map

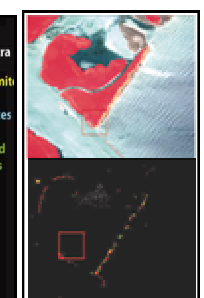


Post Oil

AVIRIS Oil Impacted Vegetation Spectra



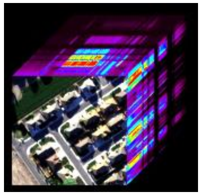
Oil Impact Product

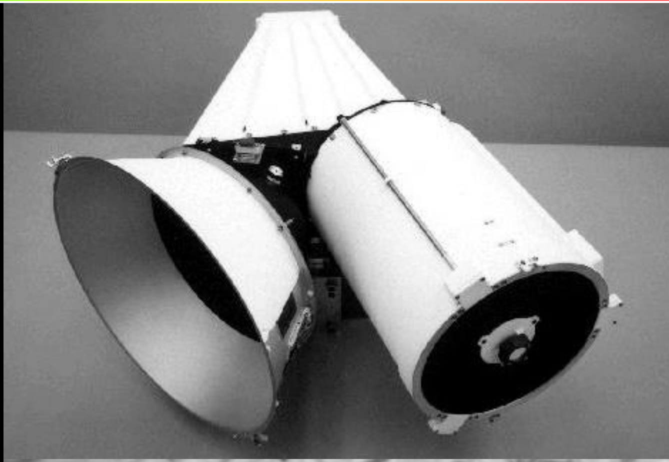


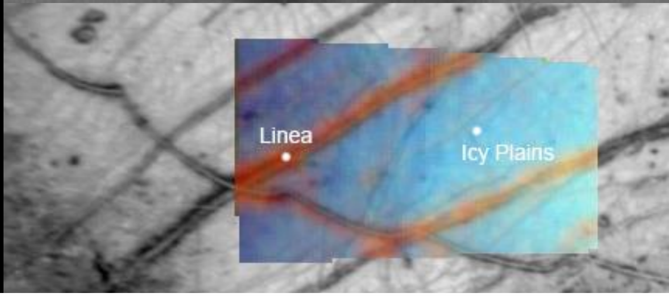
*A Method for Quantitative Mapping of Thick Oil Spills Using HyspIRI; Roger N. Clark[1], Gregg A. Swayze[1], Ira Leifer[2], K. Eric Livo[1], Raymond Kokaly[1], Todd Hoefen[1], Sarah Lundeen[3], Michael Eastwood[3], Robert O. Green[3], Neil Pearson[1], Charles Sarture[3], Ian McCubbin[4] Dar Roberts[3],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

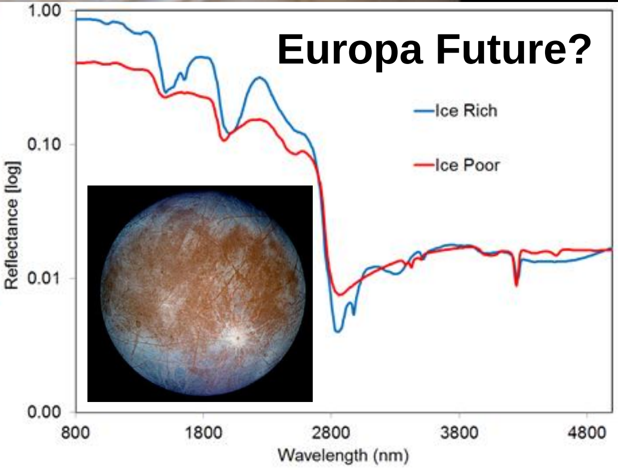
Other Planets and the Moon

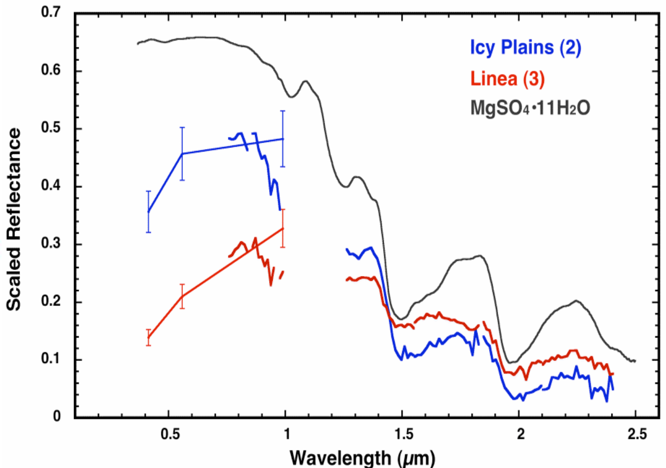
1989 Near Infrared Mapping Spectrometer (NIMS) to Jupiter



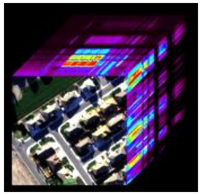


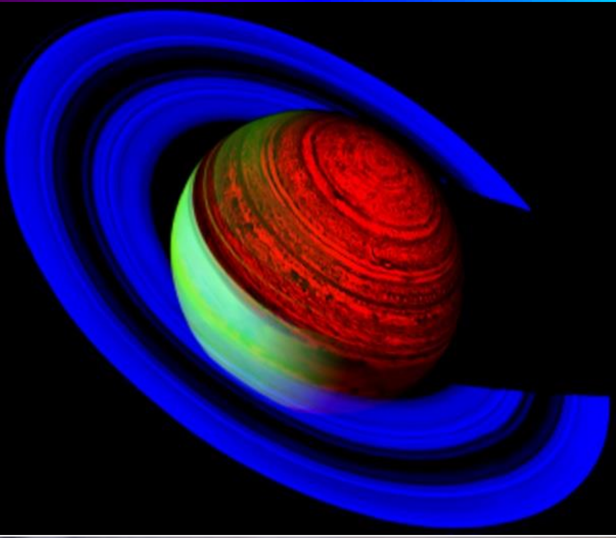


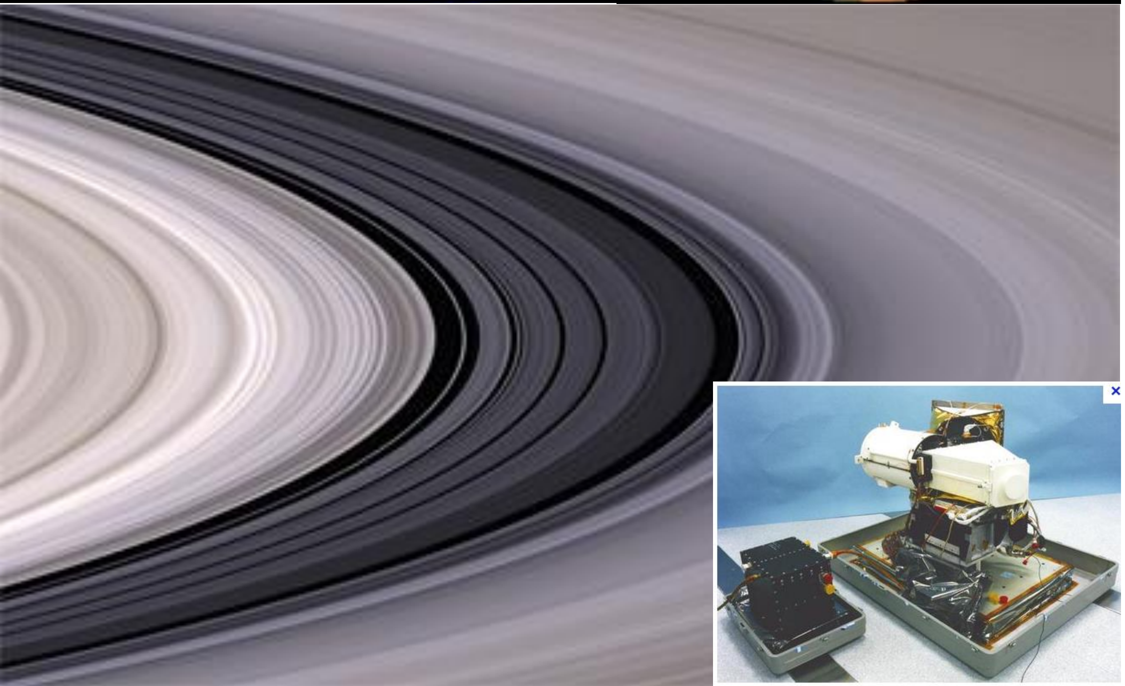


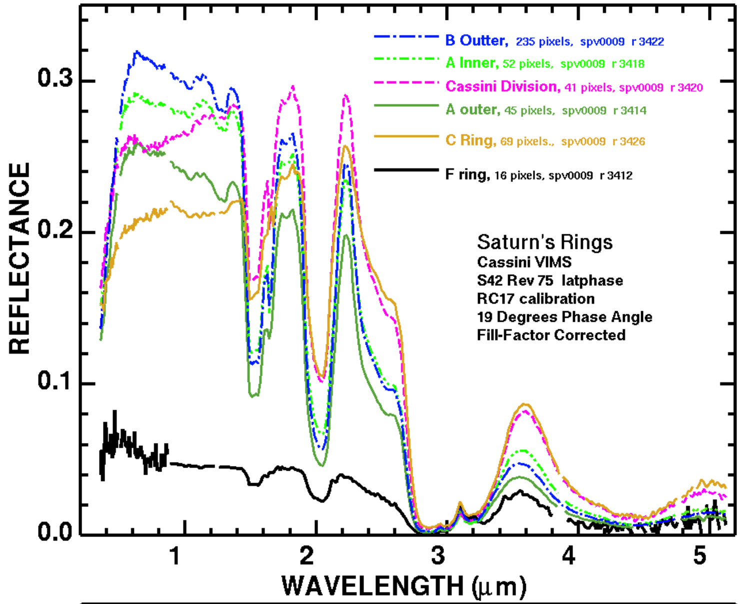


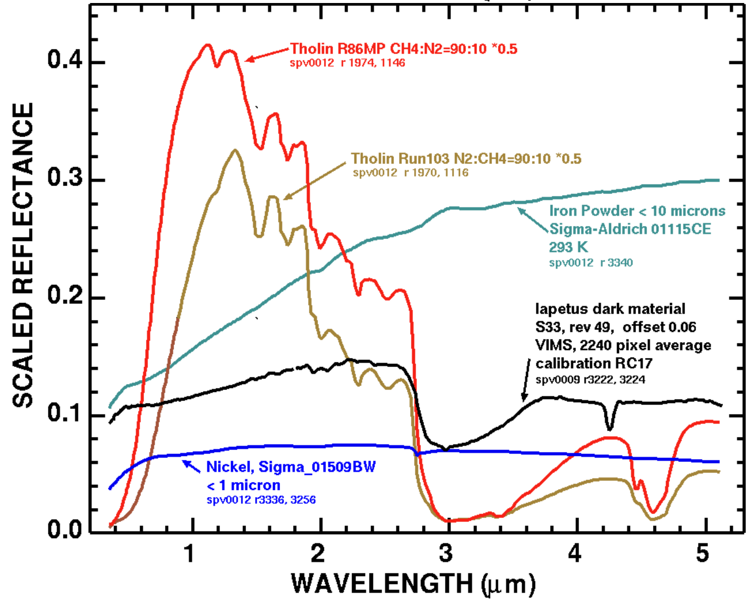
1997 Visual and Infrared Mapping Spectrometer (VIMS) to Saturn





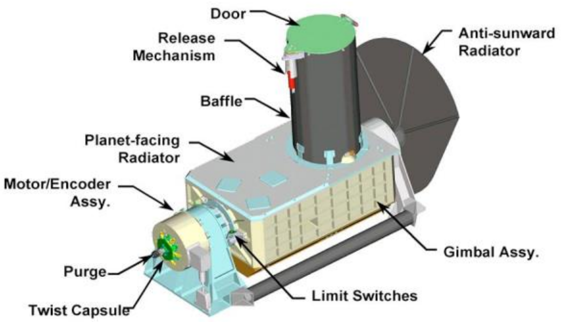


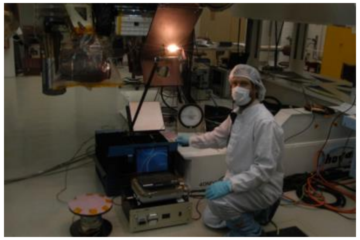




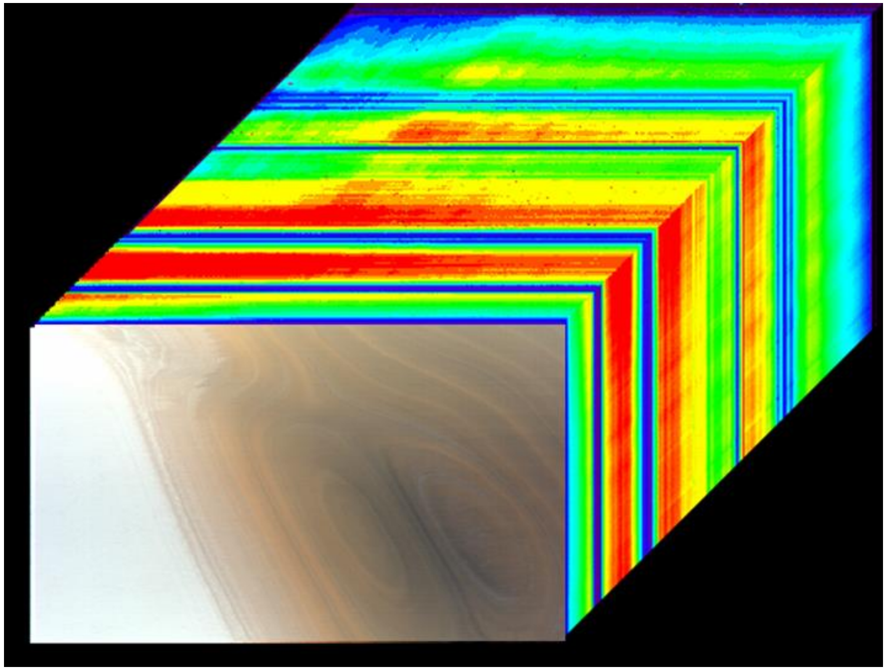
2005 CRISM to Mars

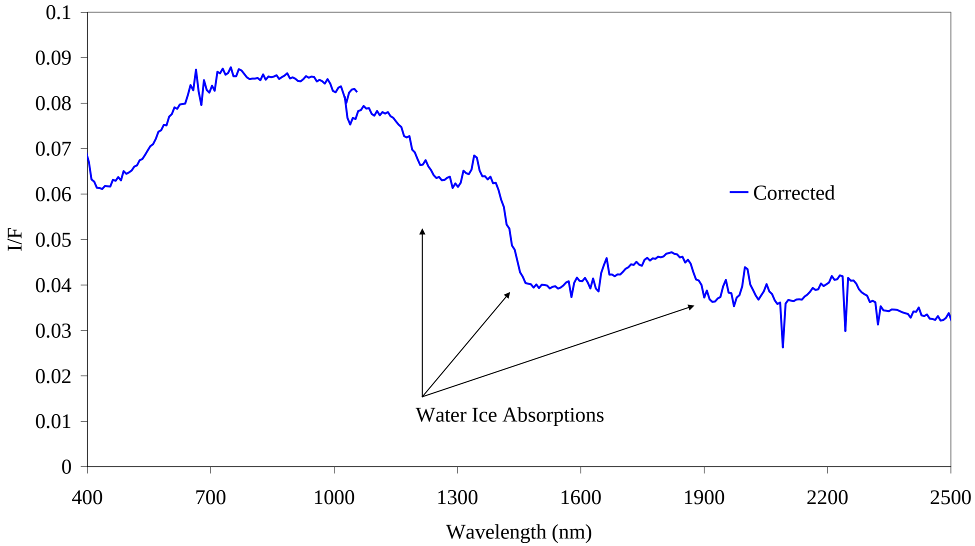
- Spectral: 400 to 4000 nm
- Spatial: 12 by 12 km @24



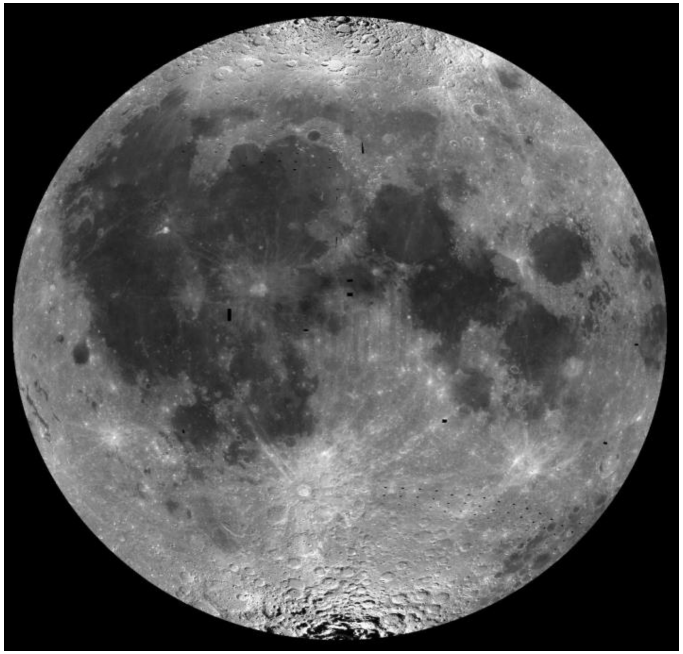


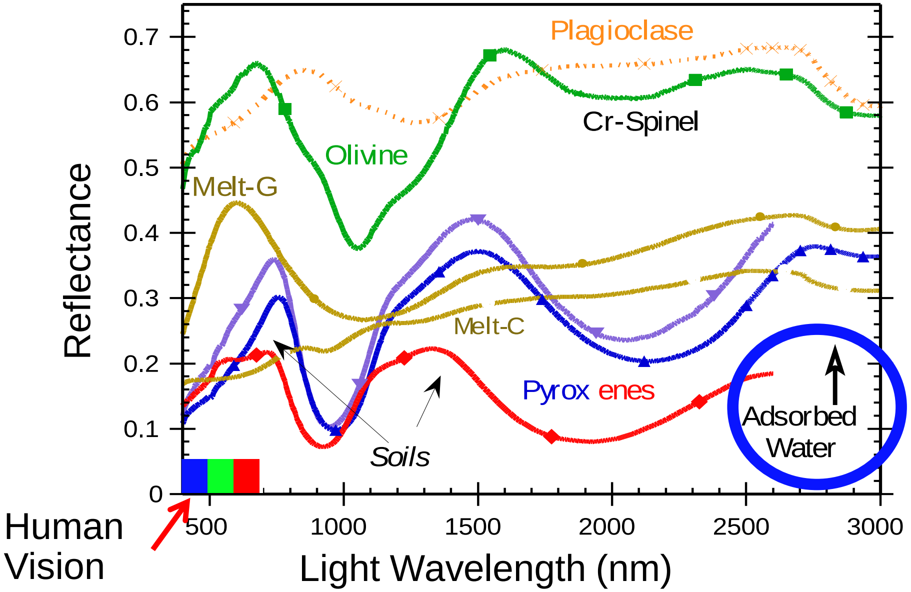
12 Aug 2005

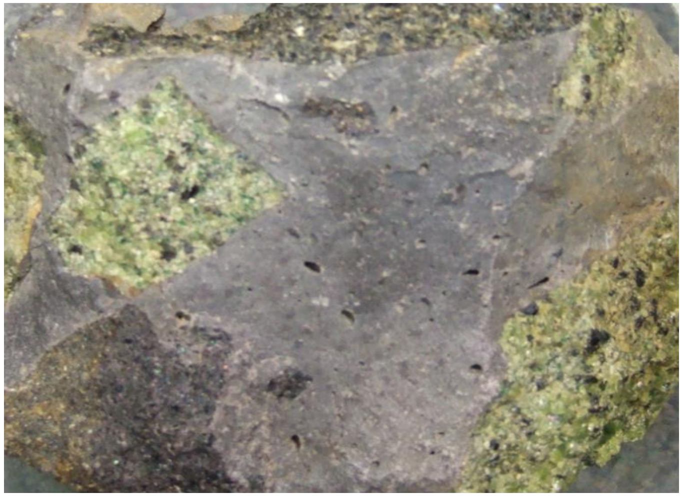


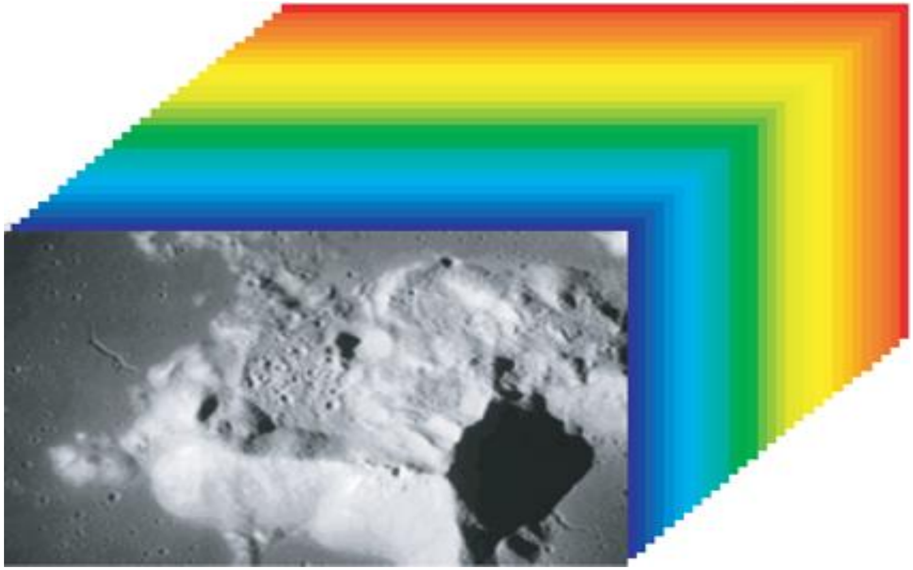


Moon Mineralogy Mapper (M3)



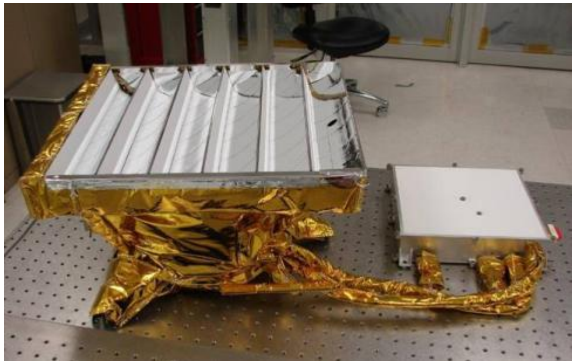






24 Month Build (8 Kg, 15 Watts)

M3 Pre Ship

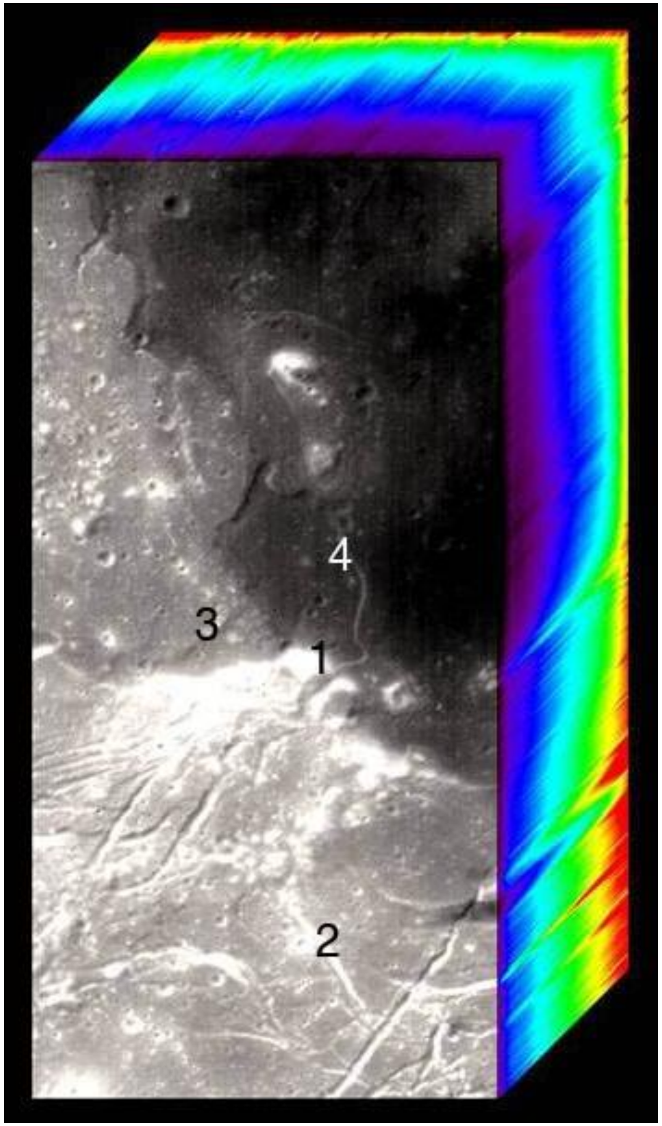


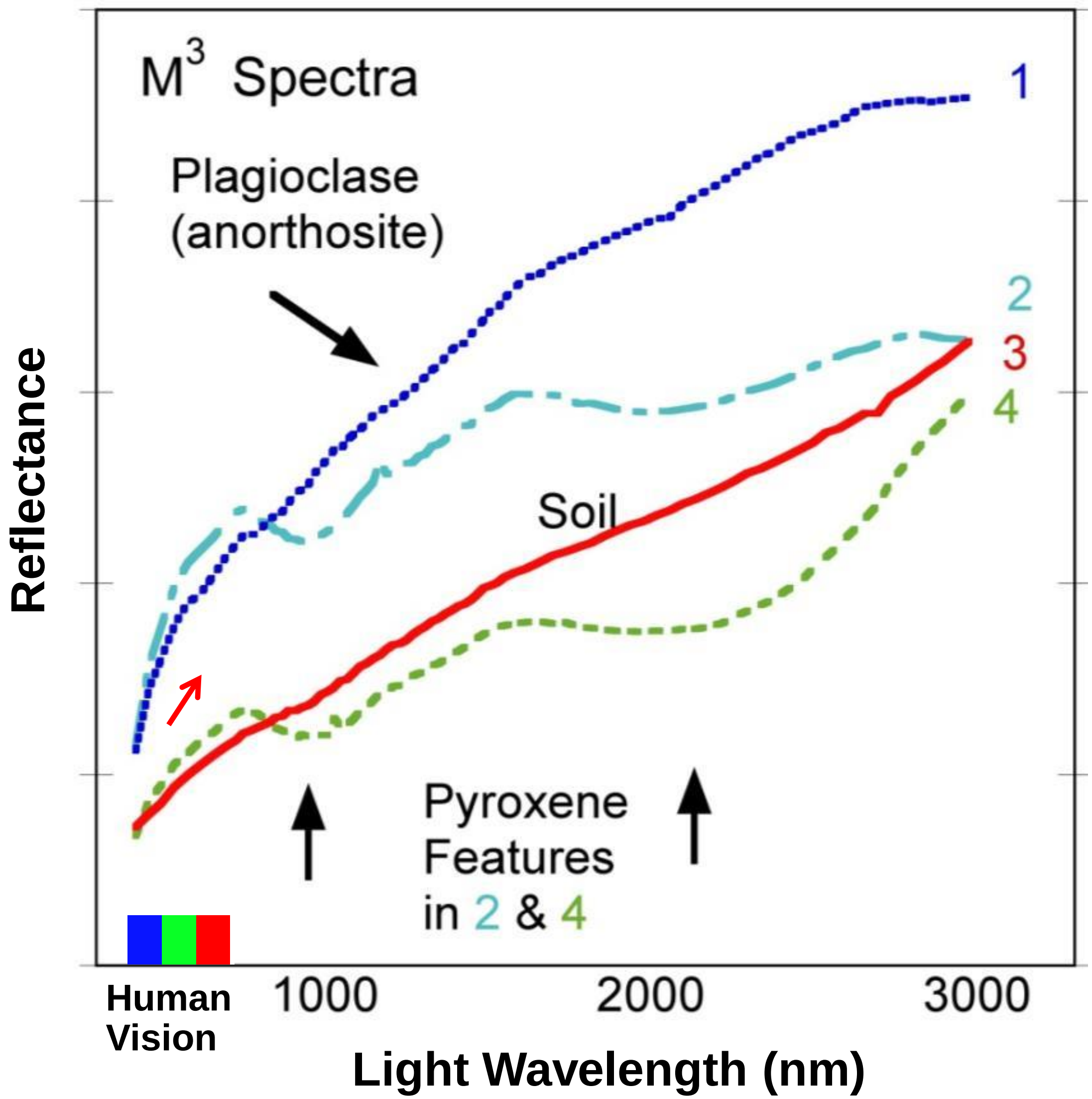
Chandrayaan-1

Launch 22 Oct 2008, India

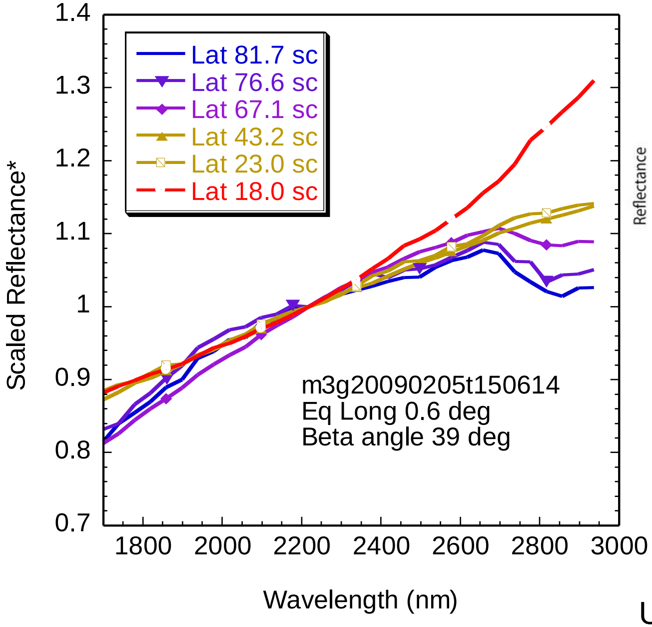
Teledyne 6604a
430 to 3000 nm
Substrate removed

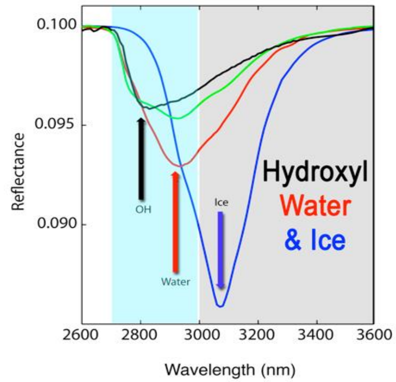
Minerals were mapped within three days of first light

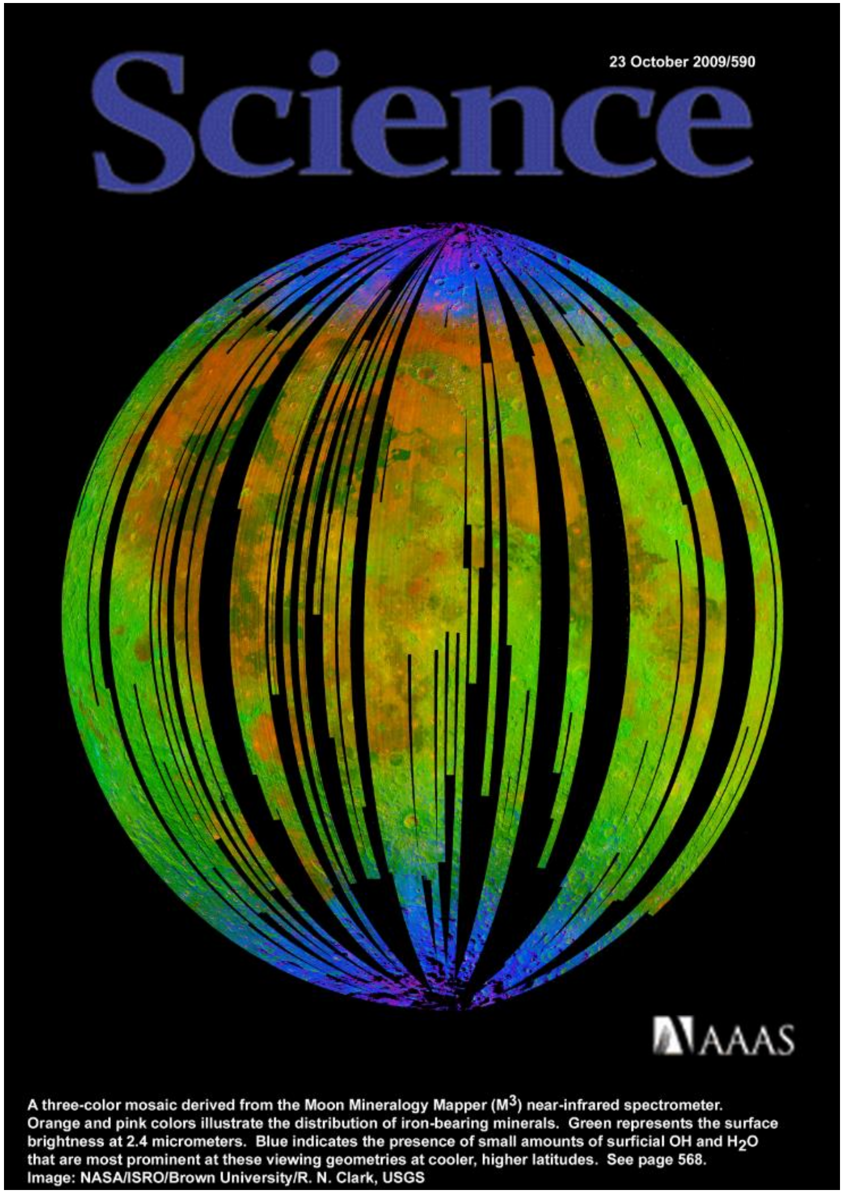


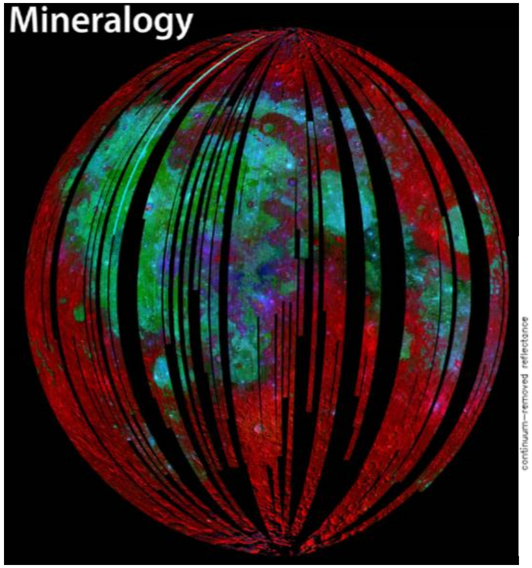


M3 Hydroxyl/Water on the Moon

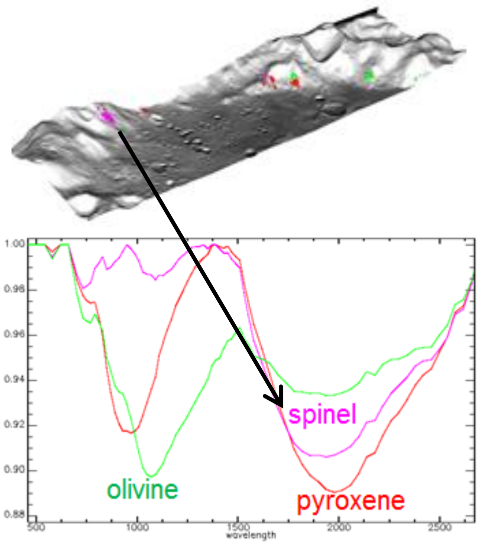




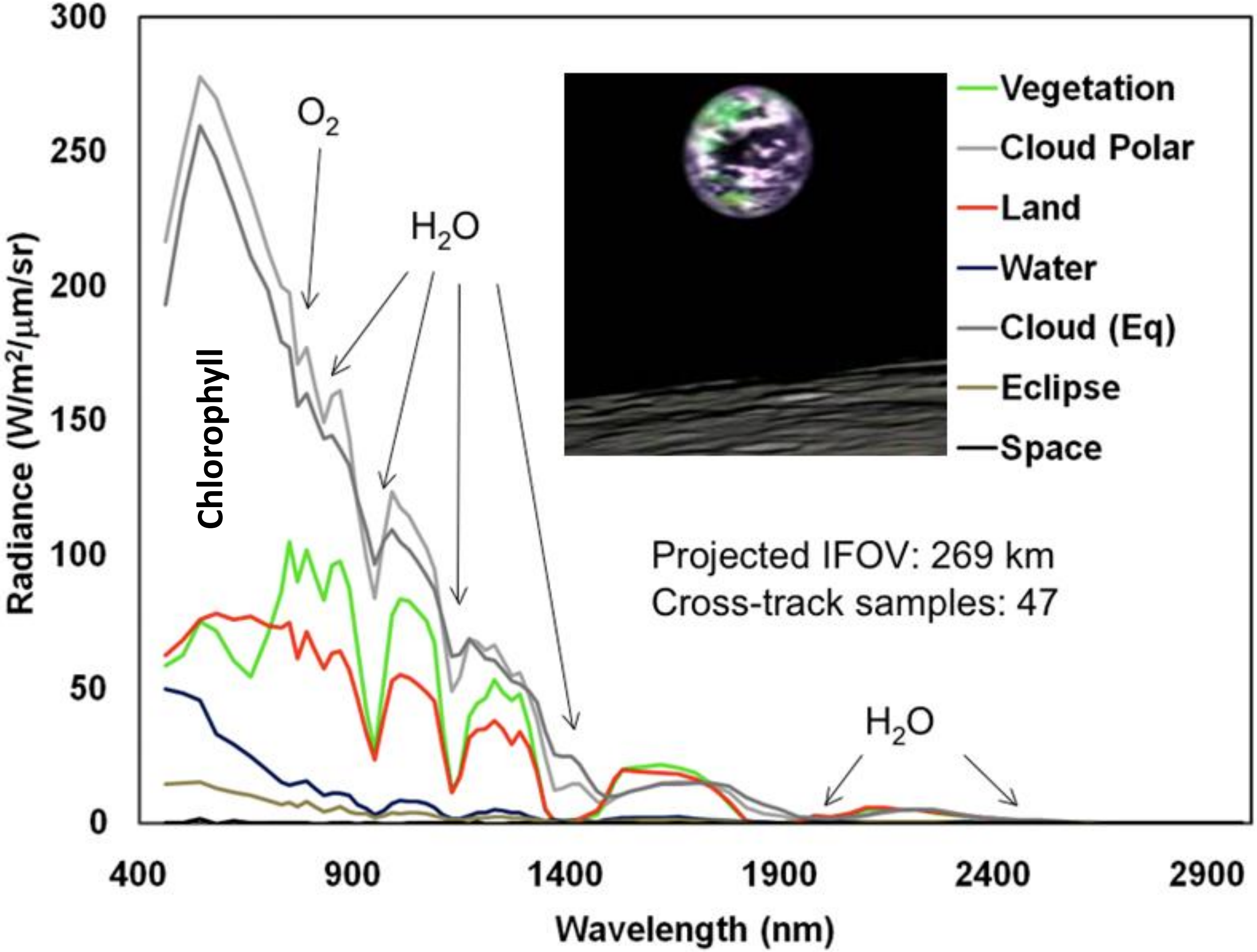


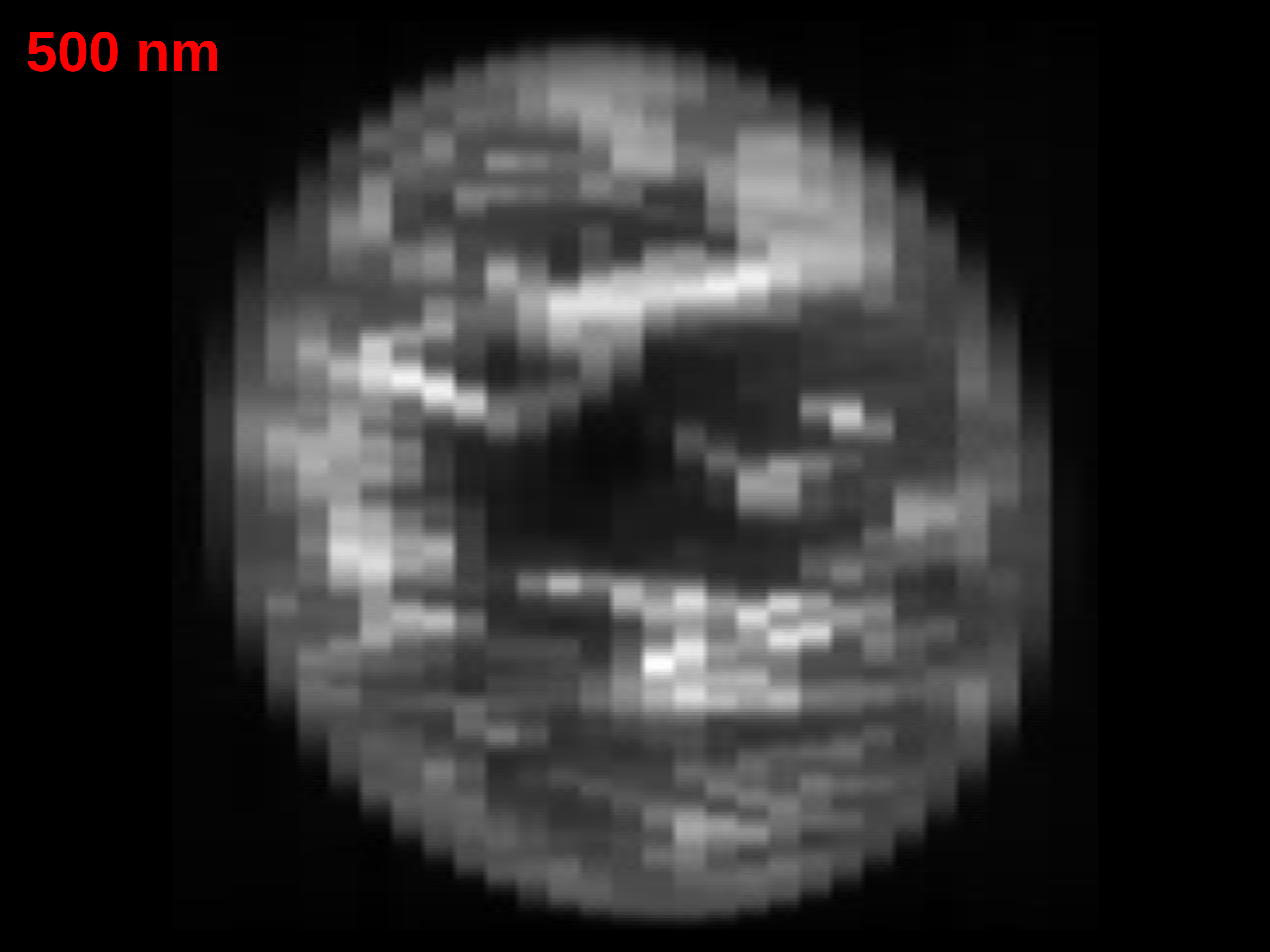


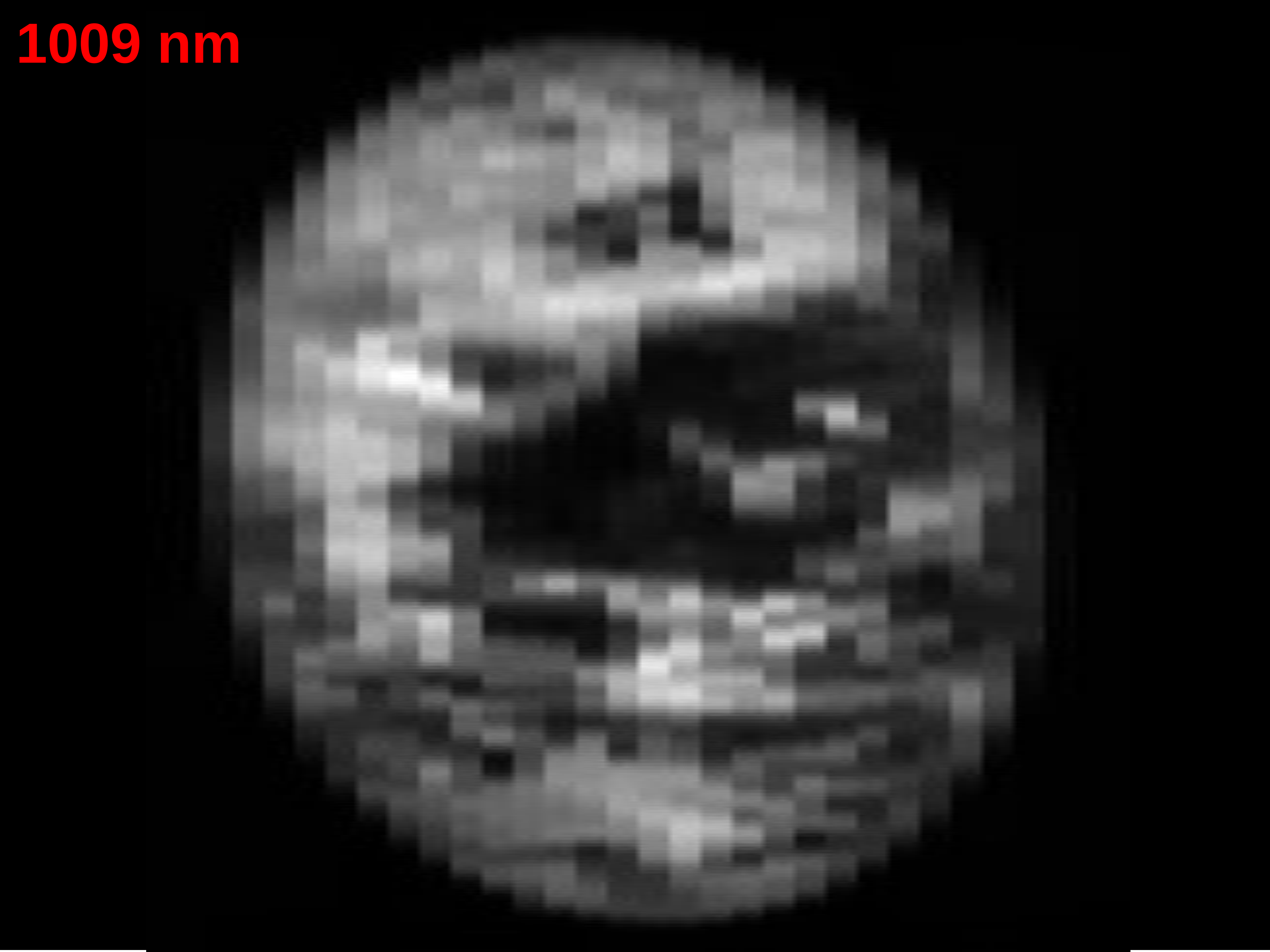
Unexpected Minerals

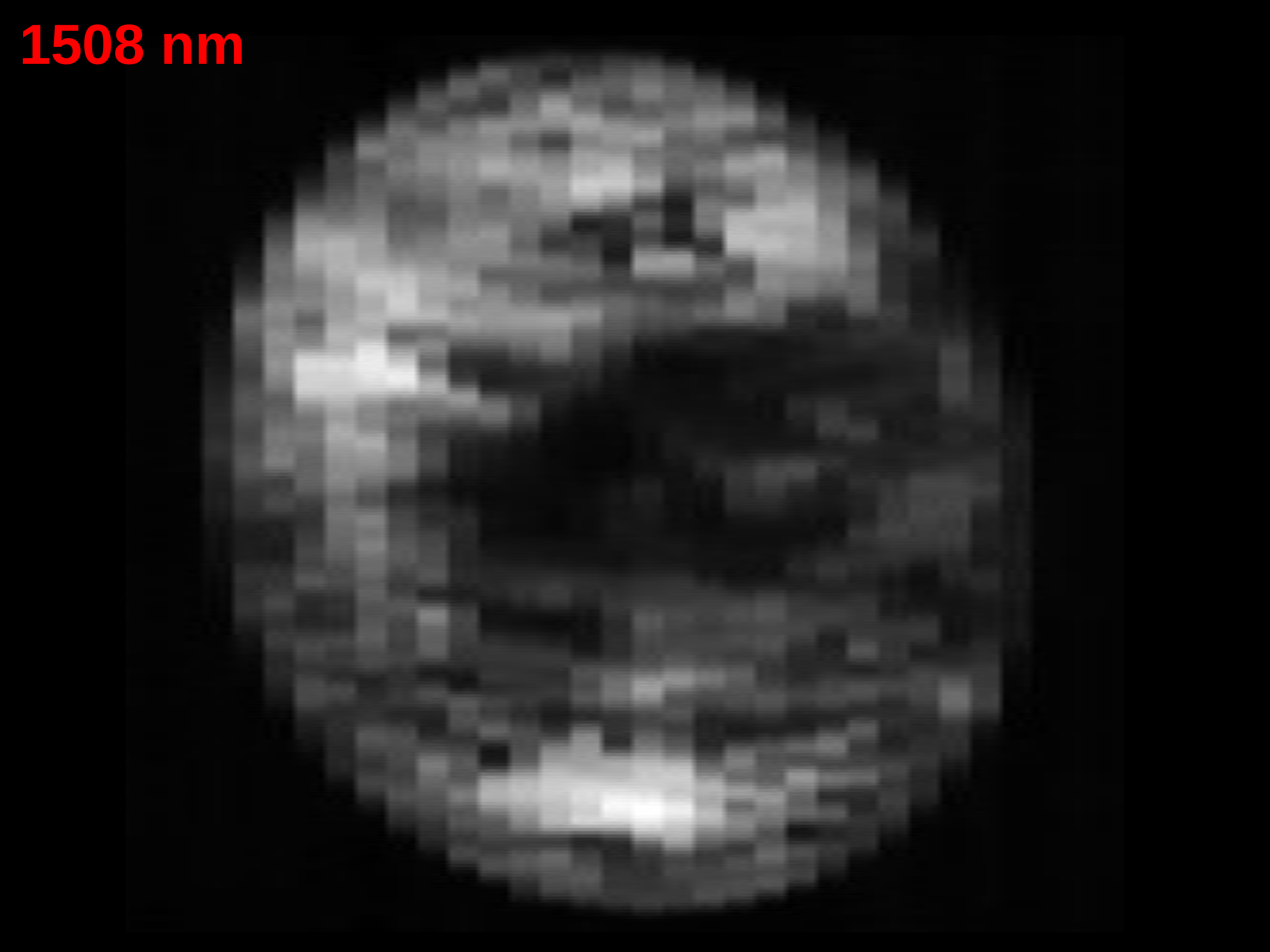


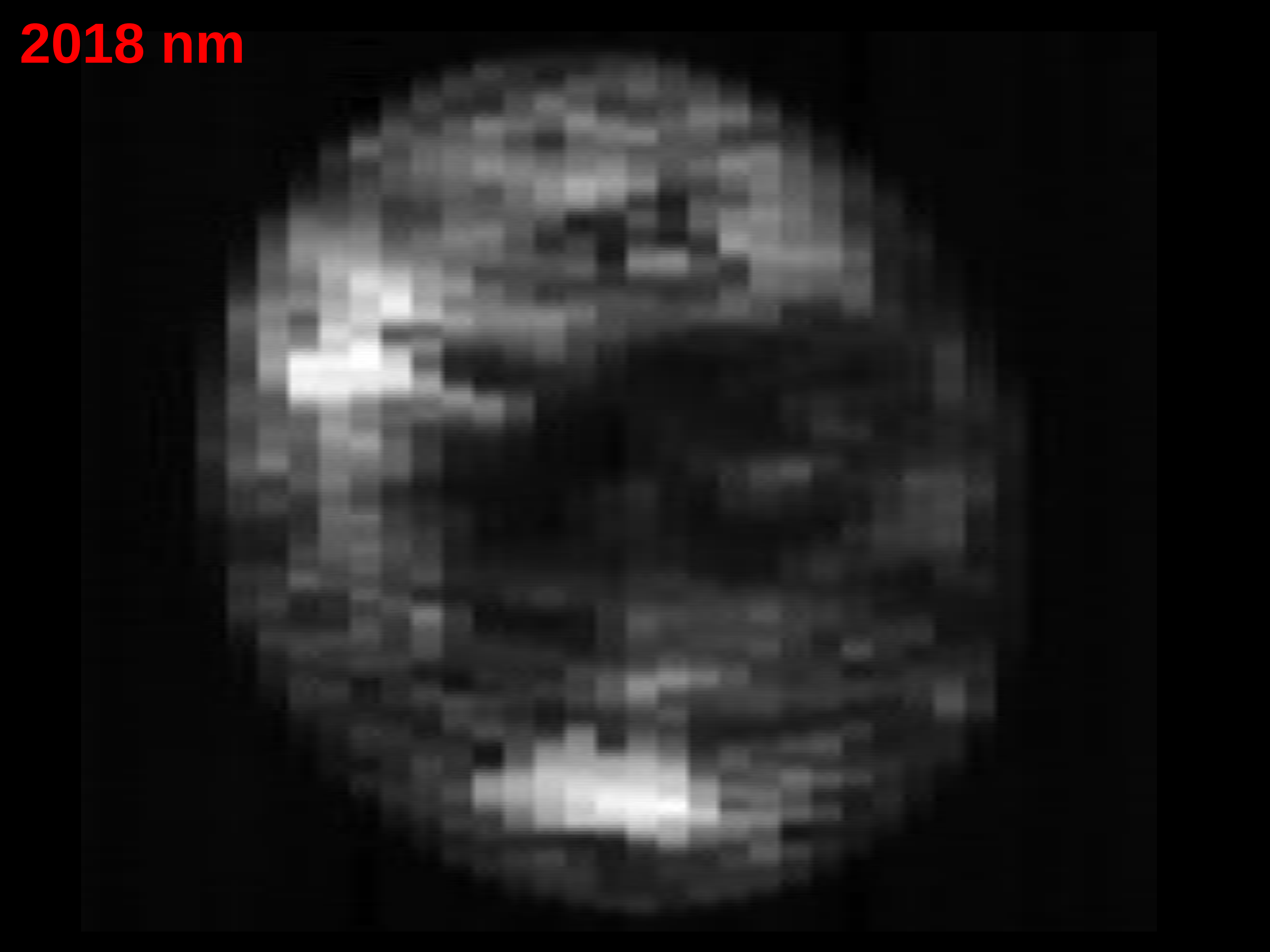
M3 Looking Back at Earth 2009

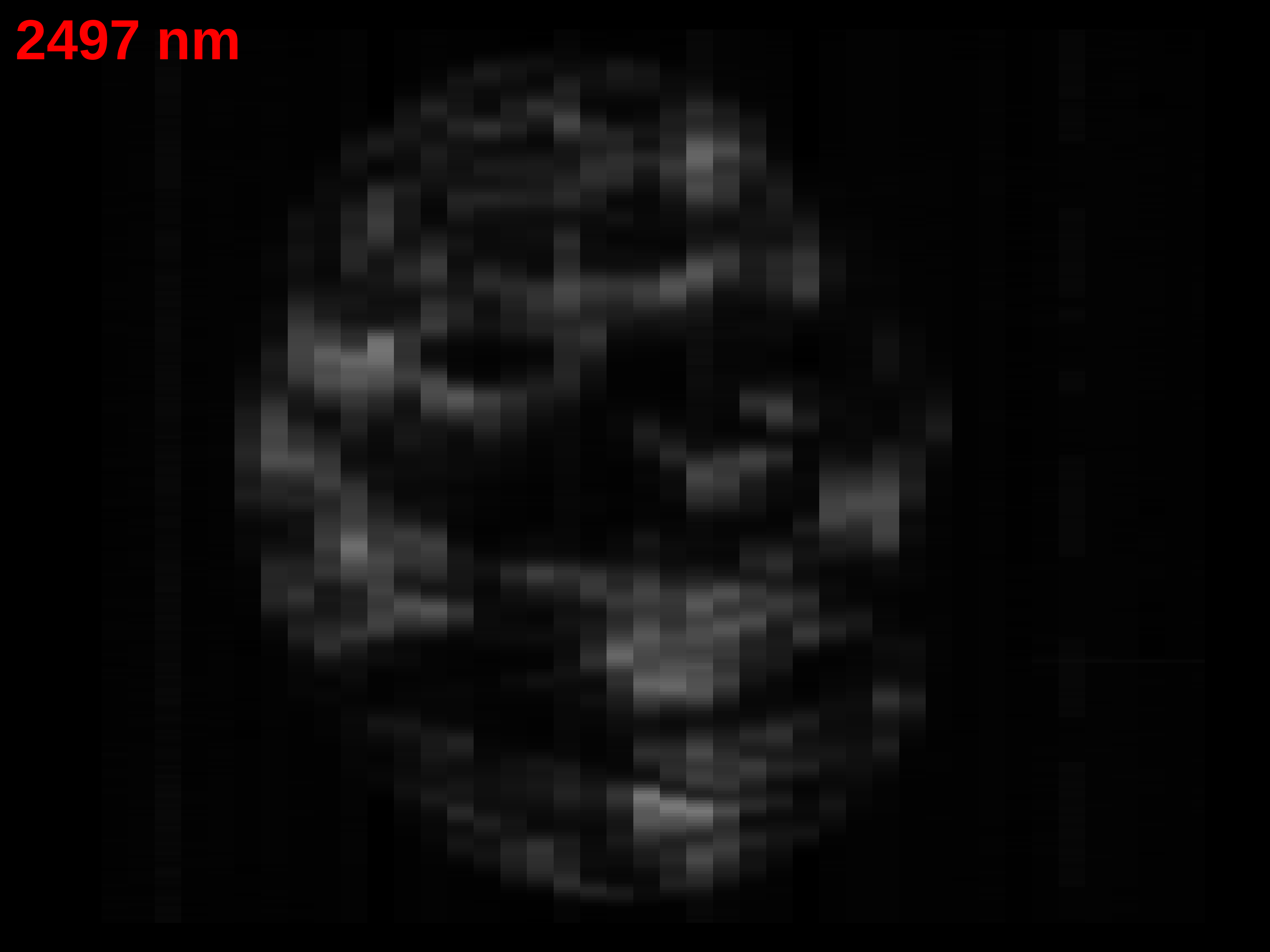



500 nm

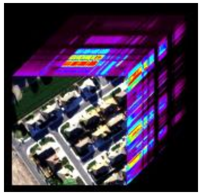

1009 nm


1508 nm


2018 nm

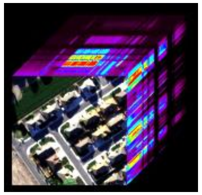

2497 nm

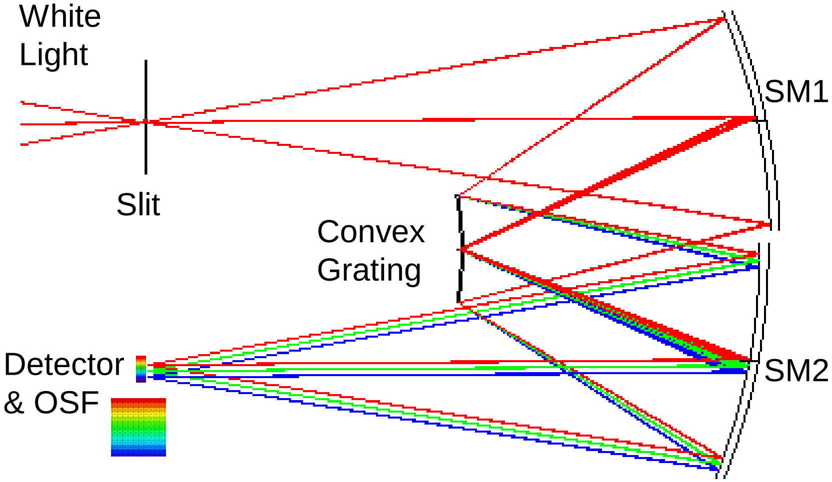
2816 nm



Instrument Evolution and Next Generation Measurements

Imaging Spectrometer Optical Advances

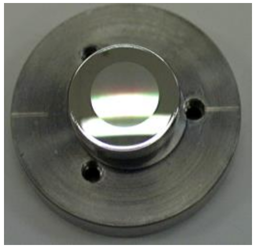




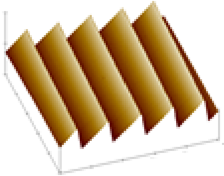
- An Offner spectrometer enables uniform spectroscopy using a slit, two spherical mirrors, a convex grating, order sorting filter (OSF) and detector array.
- **The grating on a convex surface is the key.** The slit, optical component mounts, OSF and detector also have critical requirements.

Mouroulis P., Green R. O., Chrien T. G., "**Design of pushbroom imaging spectrometers for optimum recovery of spectroscopic and spatial information**," APPL OPTICS 39: (13) 2210-2220 MAY 1 2000

Single Blaze Hyperion

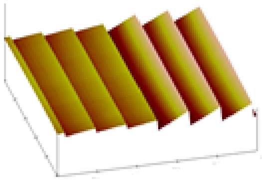


2000



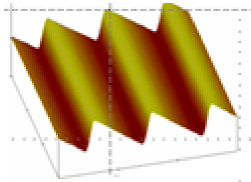
Area Weighted Blaze, CRISM

2005



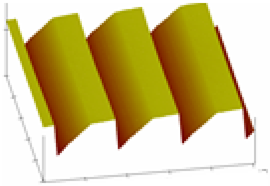
Concentric Blaze MaRS

2005

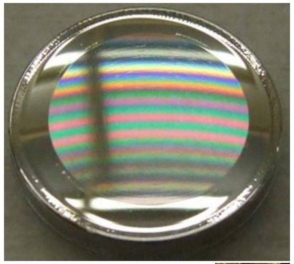


Uniform Facet Blaze M3, ARTEMIS

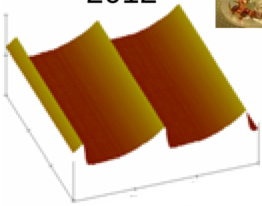
2008



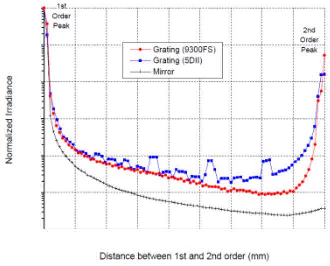
Structured Groove Blaze, UCIS



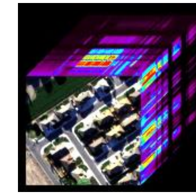
2012

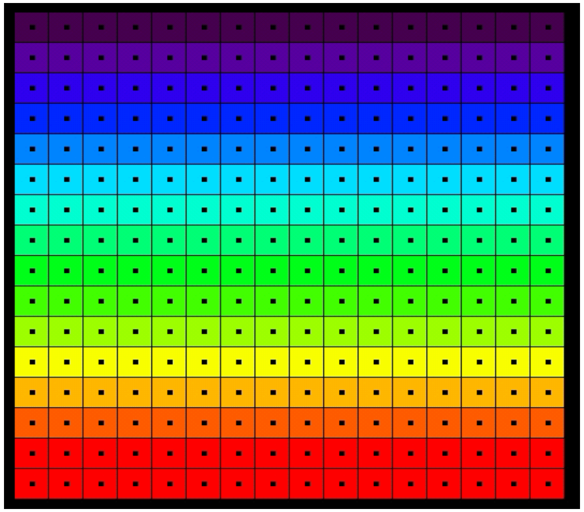


Tuned efficiency, low scatter, low polarization sensitivity structured groove blaze

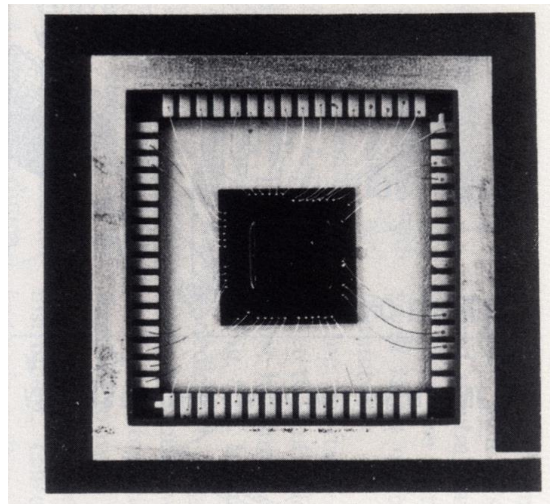


Detectors Advances: Increase in Array Size and Spectral Range

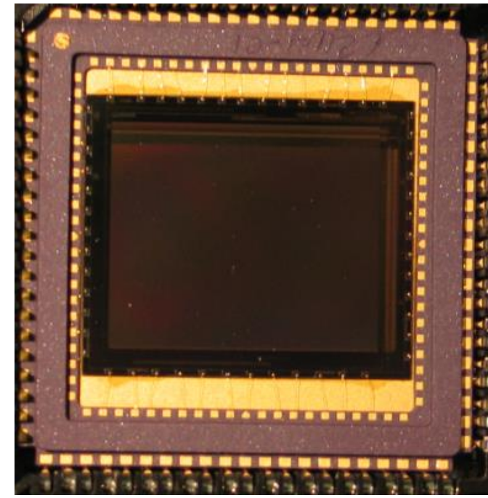




32 x 32

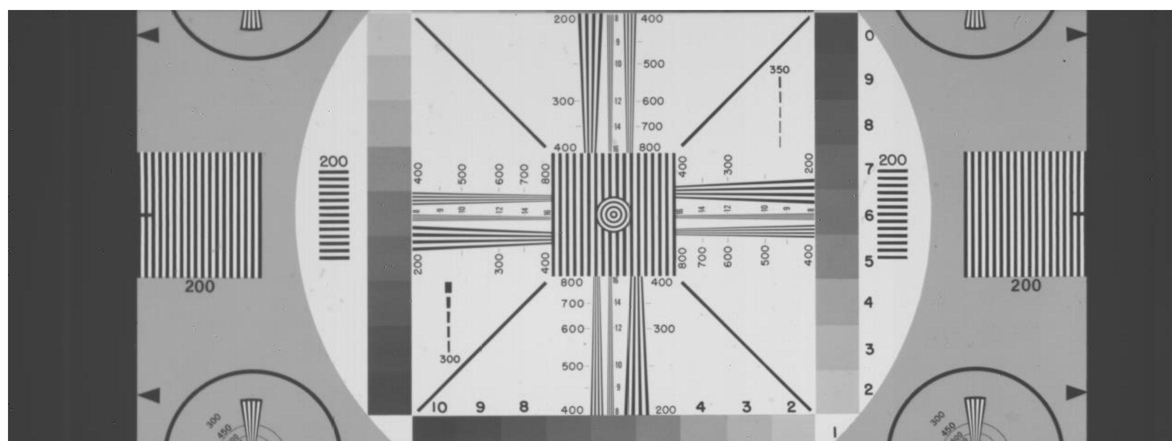


640 x 480



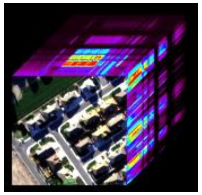
2048 x 2048

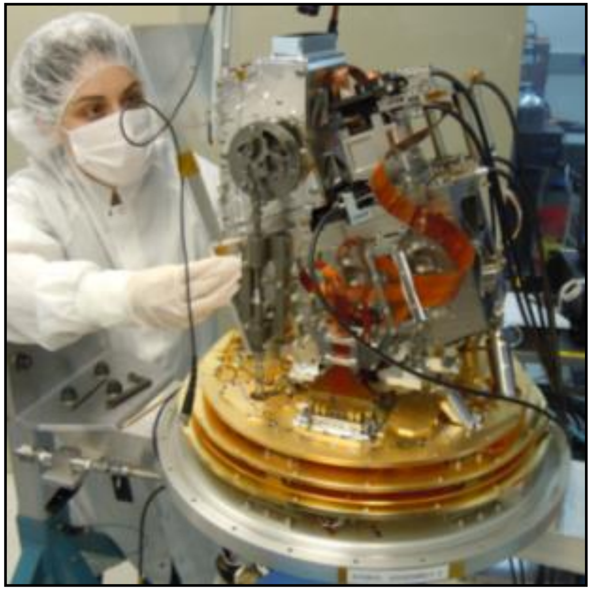
1280 x 480… Larger

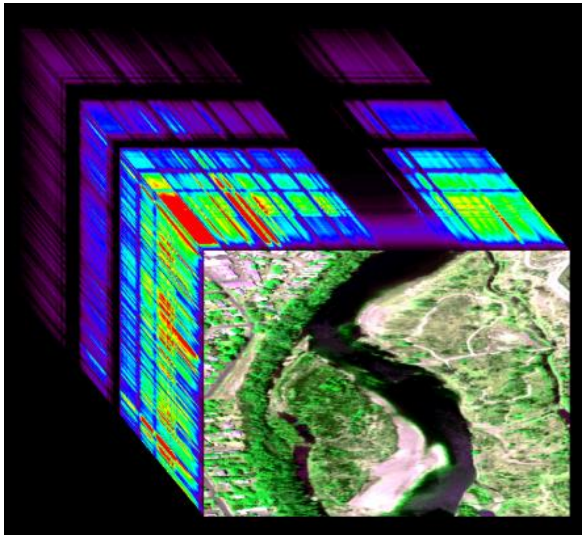


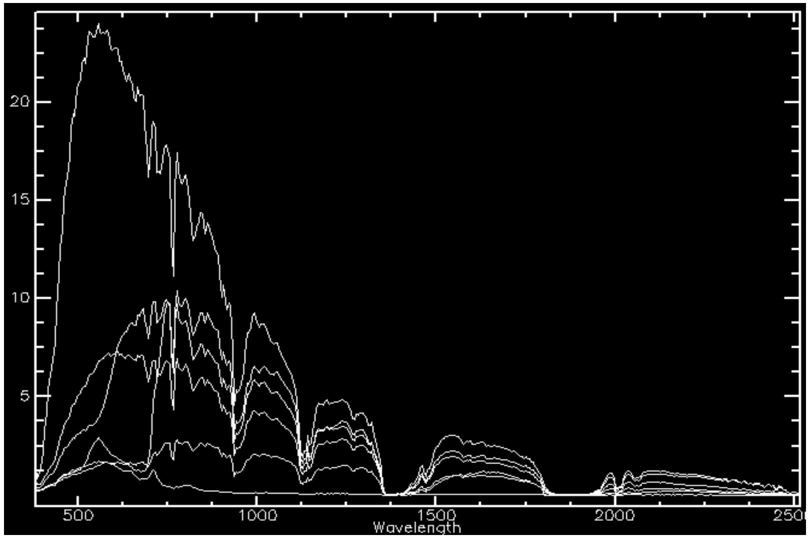
2012 AVIRIS-Next Generation

Substrate removed MCT 380 to 2510 nm

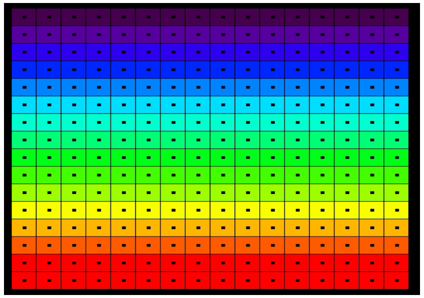




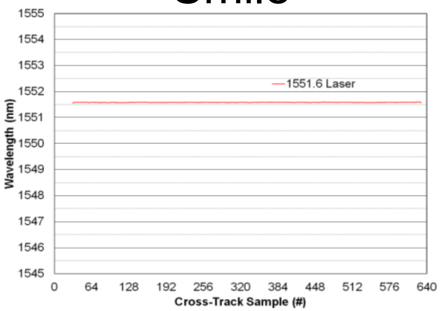




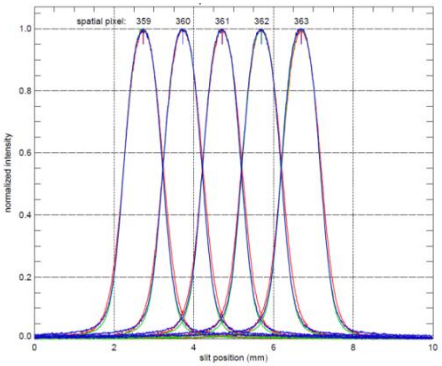
>95% cross-track and IFOV uniformity



“Smile”

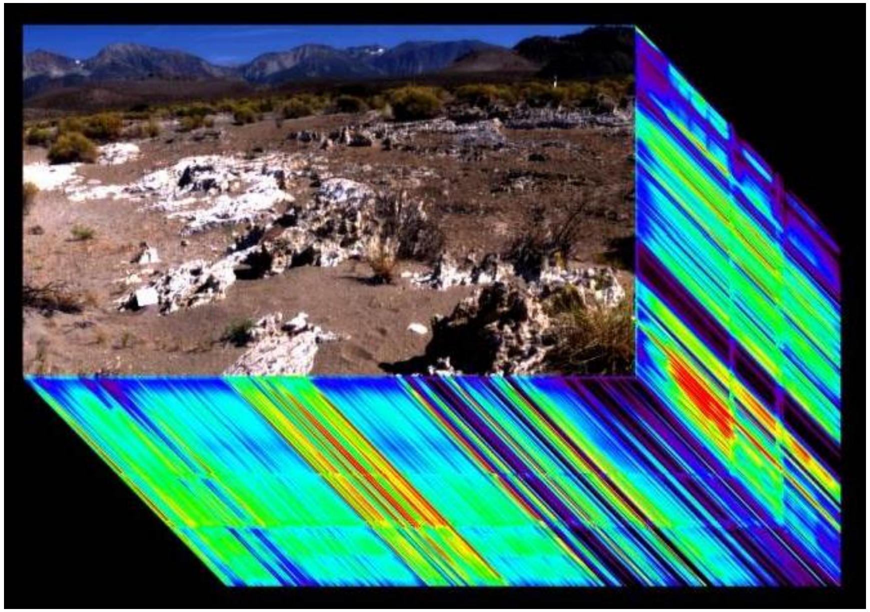


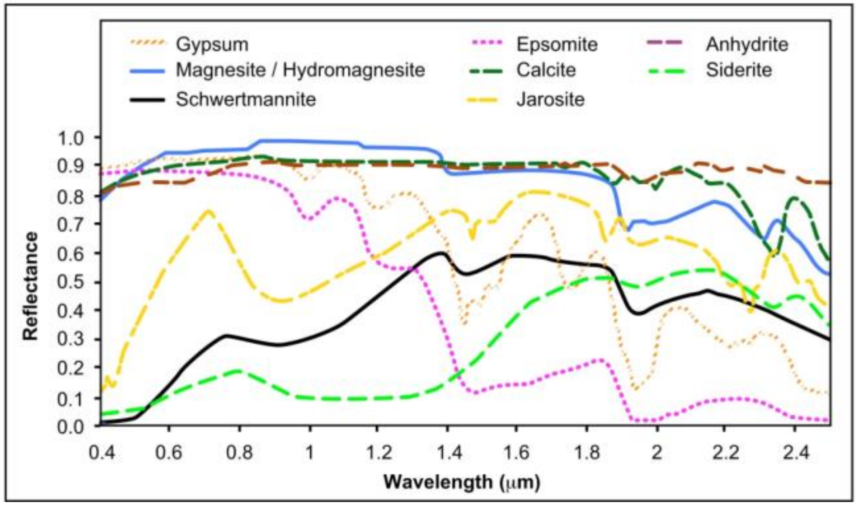
“Keystone”



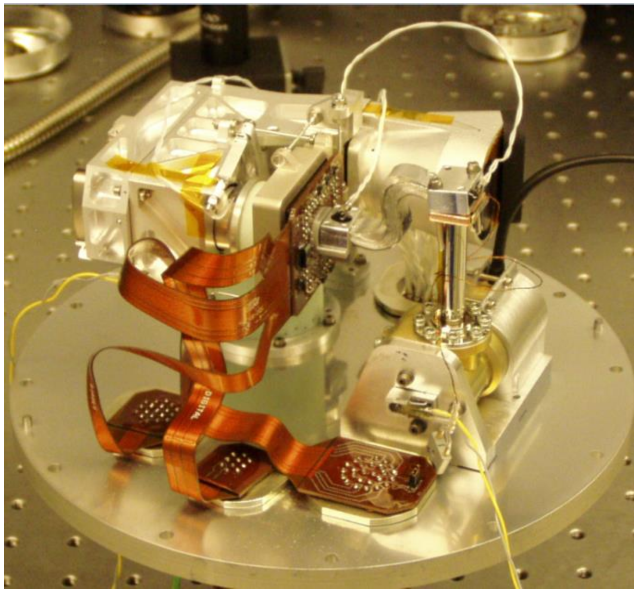
2012 Ultra Compact Imaging Spectrometer (UCIS) <3kg < 3W

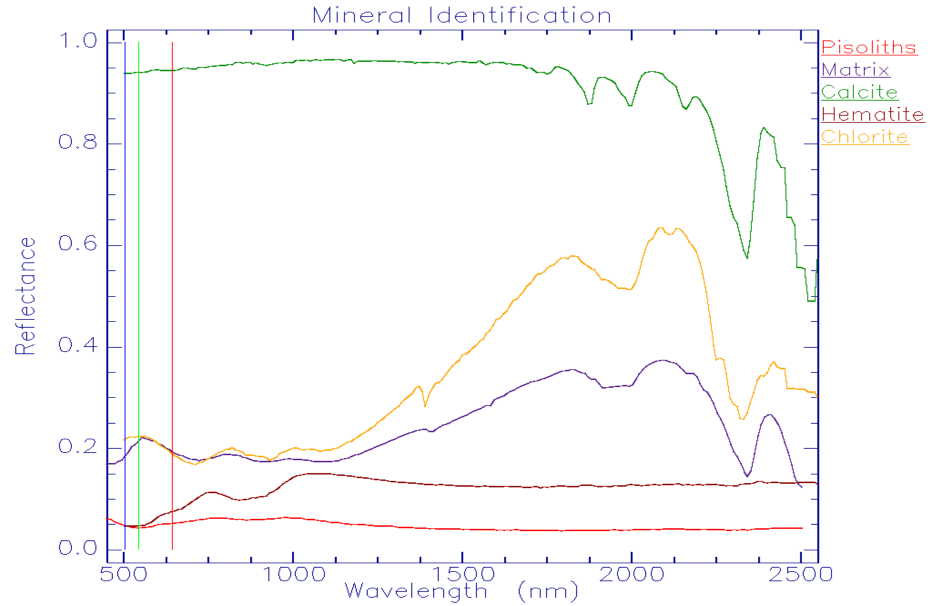
Substrate removed MCT 500 to 2550 nm



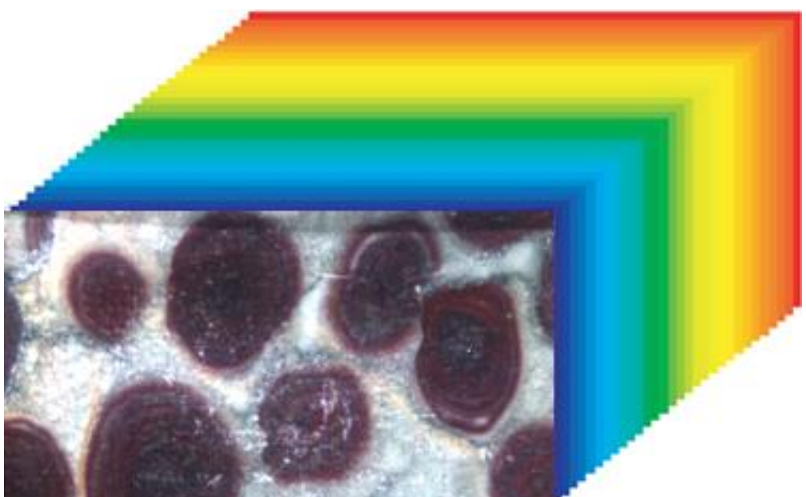


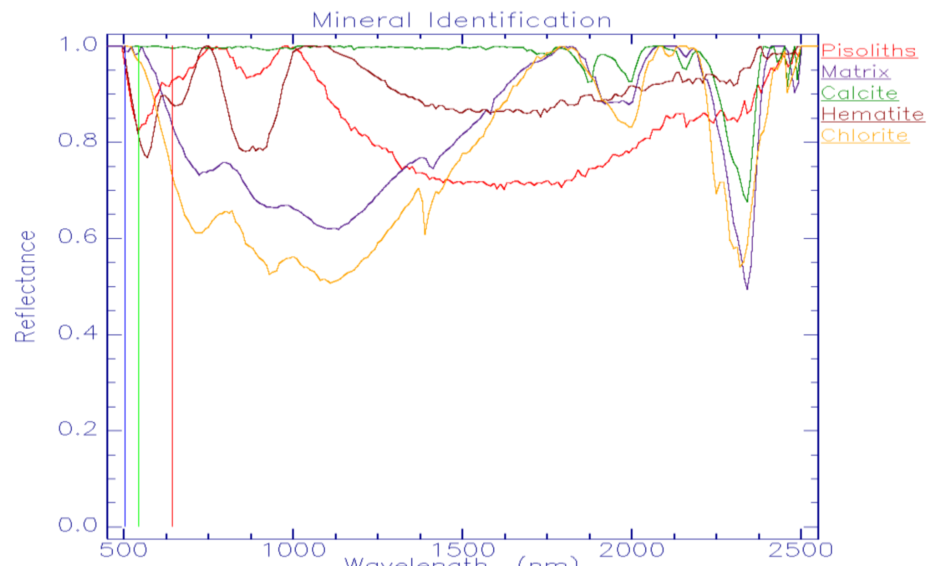
2012 Micro Scale Imaging Spectroscopy with UCIS





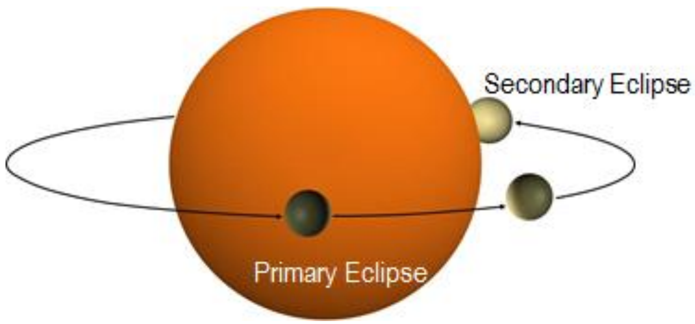
Pisolithic Ironstone with <100 µm spot

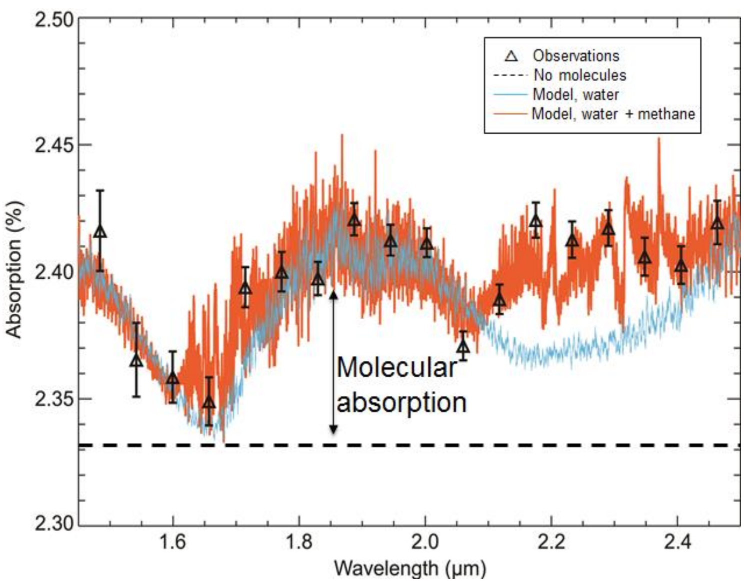




Exoplanet Worlds

Transit spectroscopy





From "The Presence of Methane in the Atmosphere of an Extrasolar Planet,"Swain, Vasisht & Tinetti, ***Nature***, Volume 452, pp. 329-331 (2008)

Spectroscopy of Exoplanets

- Provides access to information about molecules, atmospheric conditions, composition

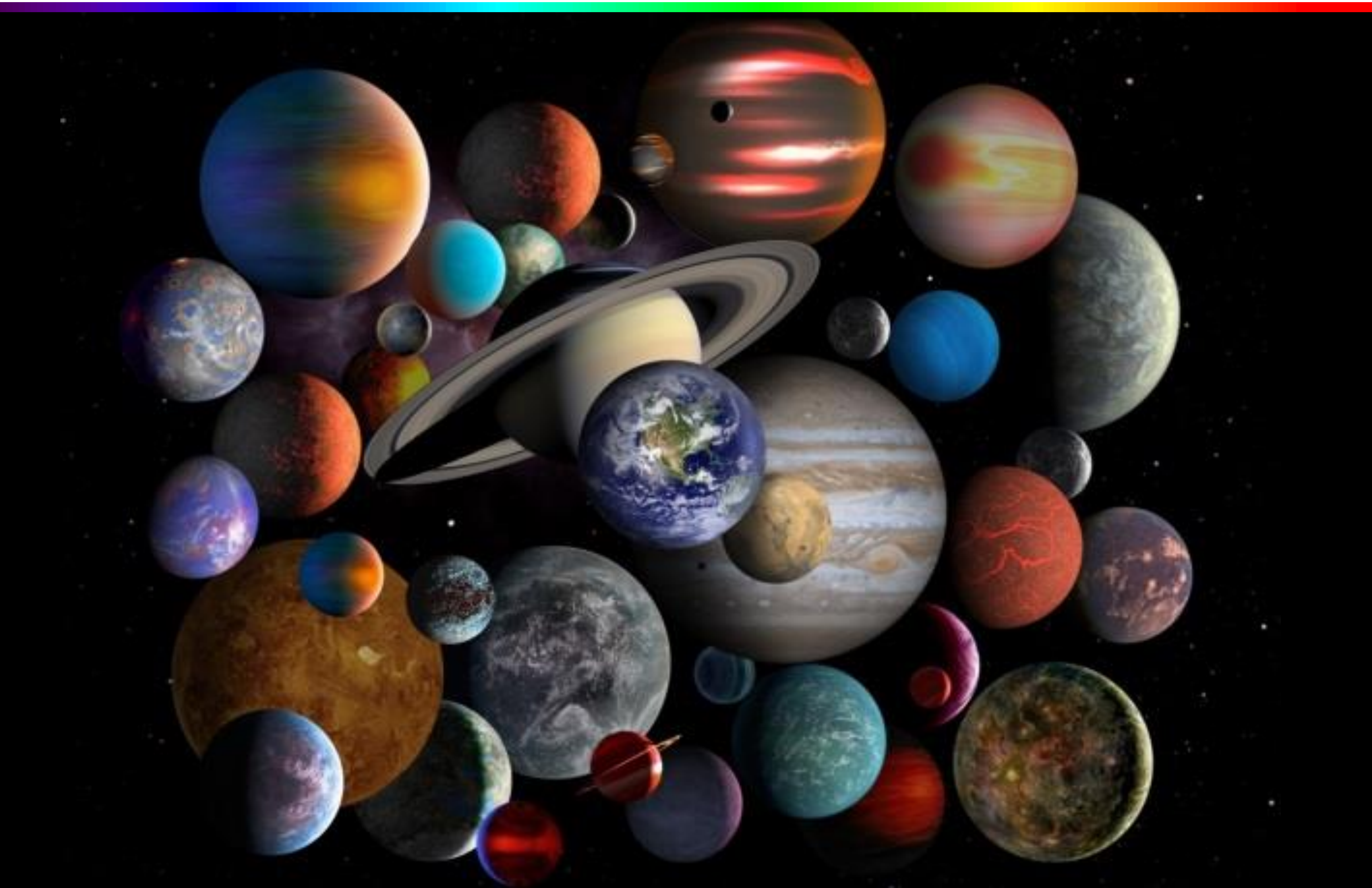
Imaging strategies exist

Disequilibrium chemistry

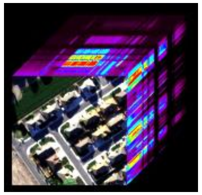
- Spectroscopy could provide the first evidence for life beyond Earth

Accessible Molecules
H_2O
CH_4
CO_2
CO
C_2H_2
HCN
O_3
O_2
NH_3
C_2H_4
C_2H_6
H_2S
SO_2
+ others

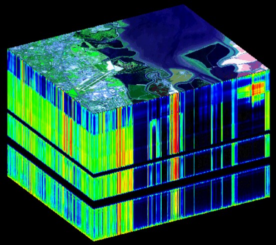
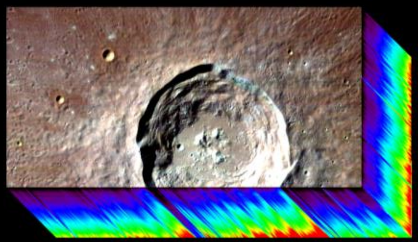
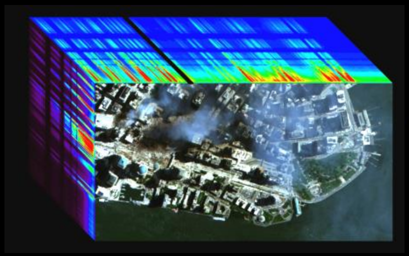
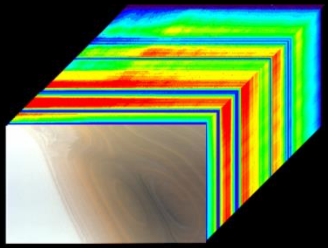
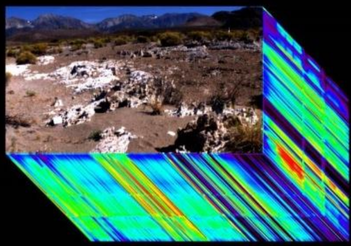
Understanding Worlds with Imaging Spectroscopy



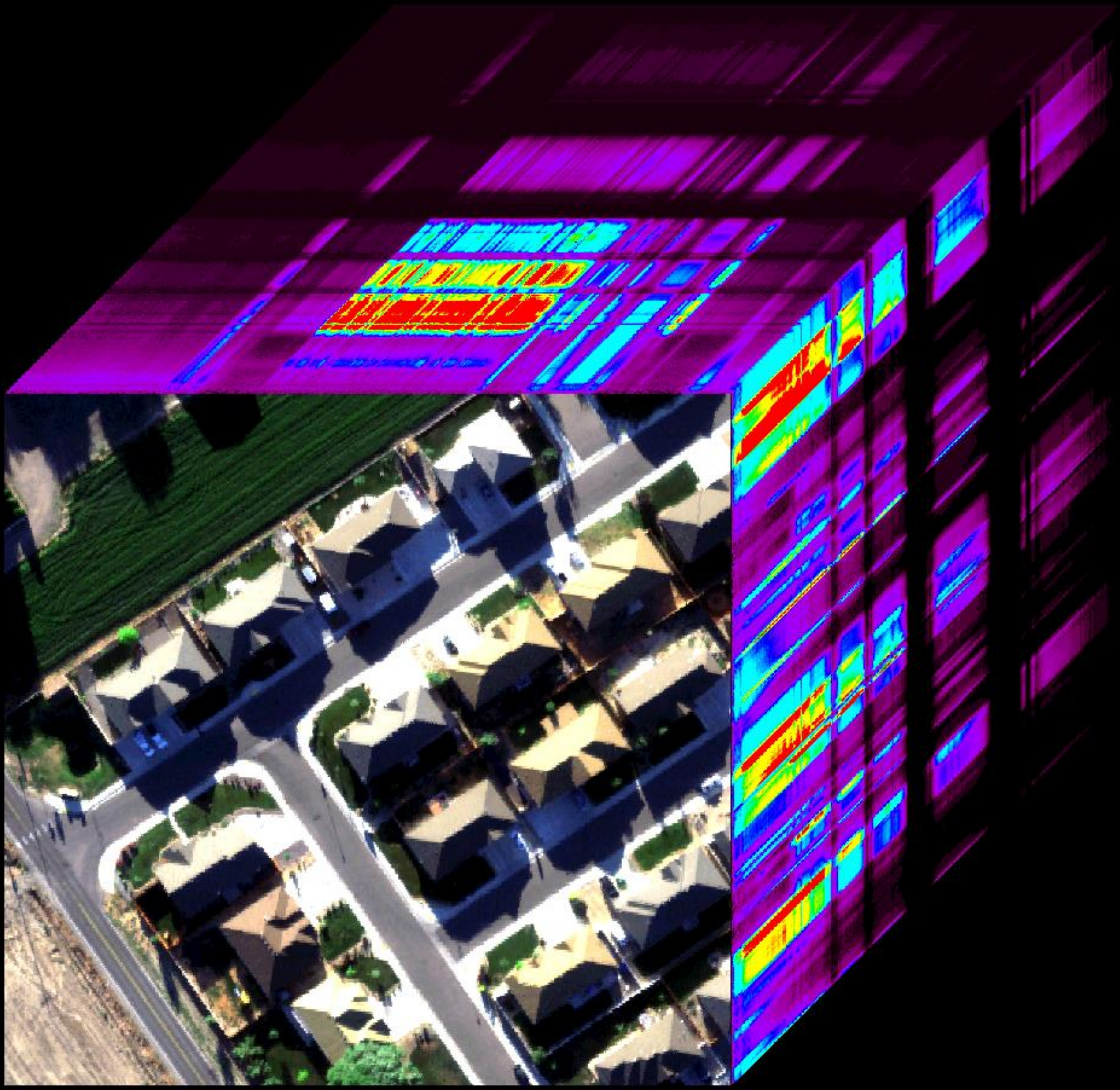
Conclusions



- 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 (AIS)
- Since its inception, the use of imaging spectroscopy on Earth and throughout the solar system has been proven and expanded extraordinarily
- There are now a suite of compelling science research examples for understanding worlds from the micron scale to exoplanet distances
- Imaging spectroscopy enables remote measurement for the 21st Century

Thank You!



Images raise questions and spectra answer them!