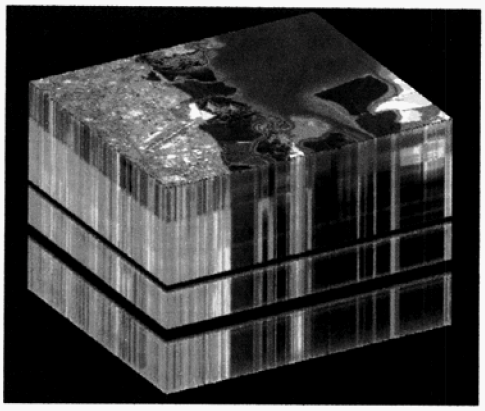
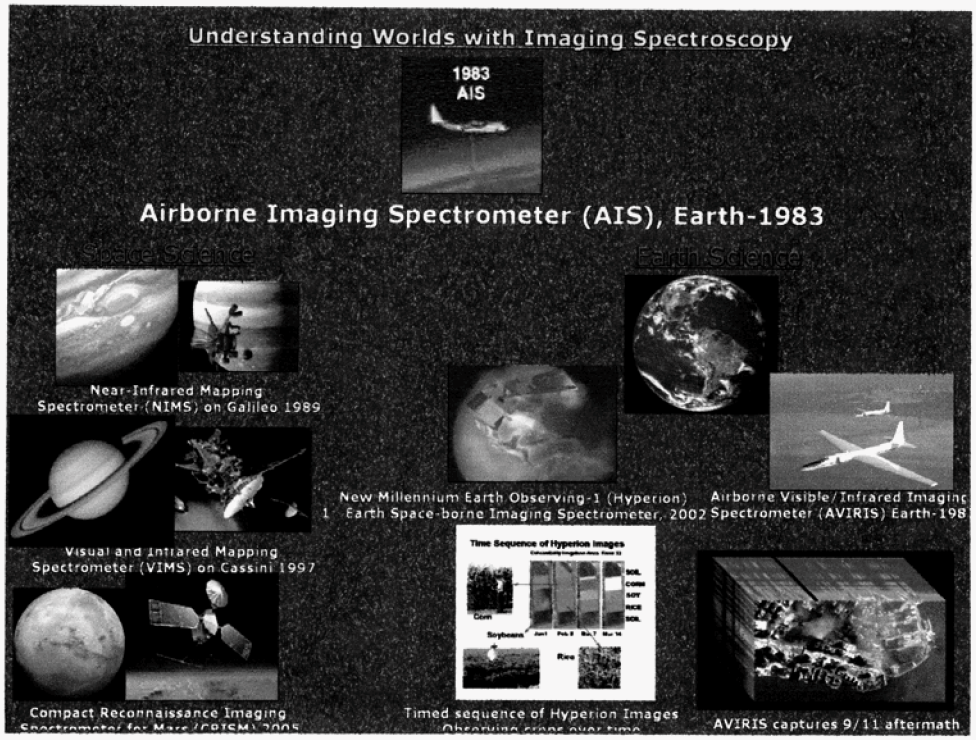
Measuring the Earth System in a Time of Global Environmental Change with Imaging Spectroscopy



Robert O. Green
Jet Propulsion Laboratory / California Institute of Technology

Overview

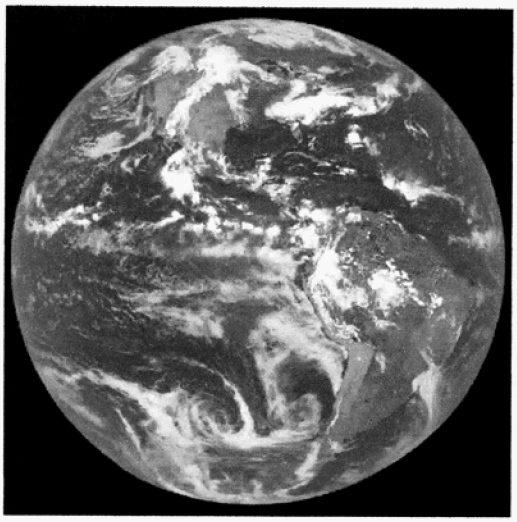
- Objective and Available Signal
- Sensing versus Measurement
- Spectroscopic Approach to Measurement
- Imaging Spectroscopy
- Research and Applications
- Summary and Future


Understanding Worlds with Imaging Spectroscopy
1983
AIS
Airborne Imaging Spectrometer (AIS), Earth-1983
Space Science
Earth Science
Near-Infrared Mapping
Spectrometer (NIMS) on Galileo 1989
Visual and Infrared Mapping
Spectrometer (VIMS) on Cassini 1997
Compact Reconnaissance Imaging
New Millennium Earth Observing-1 (Hyperion)
1 Earth Space-borne Imaging Spectrometer, 2002
Airborne Visible/Infrared Imaging
Spectrometer (AVIRIS) Earth-198
Time Sequence of Hyperion Images
Timed sequence of Hyperion Images
AVIRIS captures 9/11 aftermath

Objective

Components of the Earth System that are Changing

- Atmosphere
  - Clouds
  - Water Vapor
  - Carbon Dioxide
  - etc.
- Surface
  - Land Cover
  - Vegetation
  - Coastal and Inland Water
  - Wild Fires
  - Snow and Ice
  - etc.

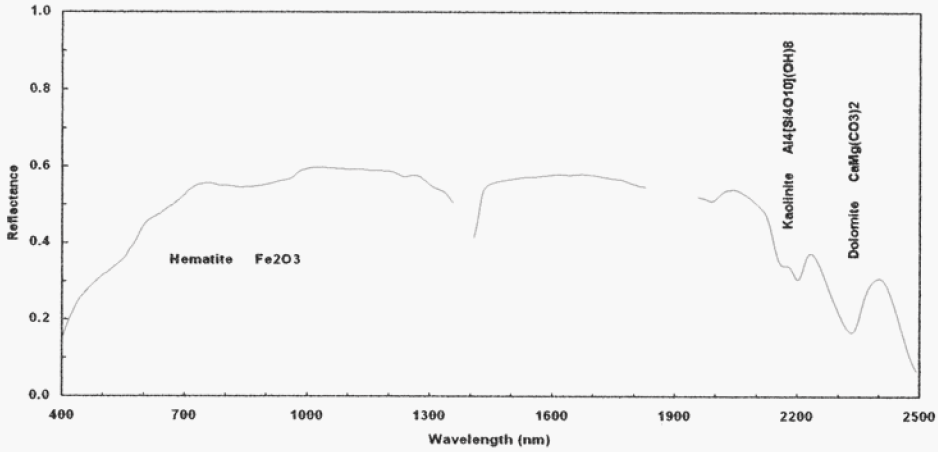


Remote Sensing or Remote Measurement

- Remote Sensing: To get an ideas or sense of what is present.
  - A 20th century approach.
- Remote Measurement: To quantitatively determine properties of the Earth's surface and atmosphere through the physics, chemistry and biology of the interaction of electromagnetic energy with matter.
  - Imaging Spectroscopy a 21st century approach

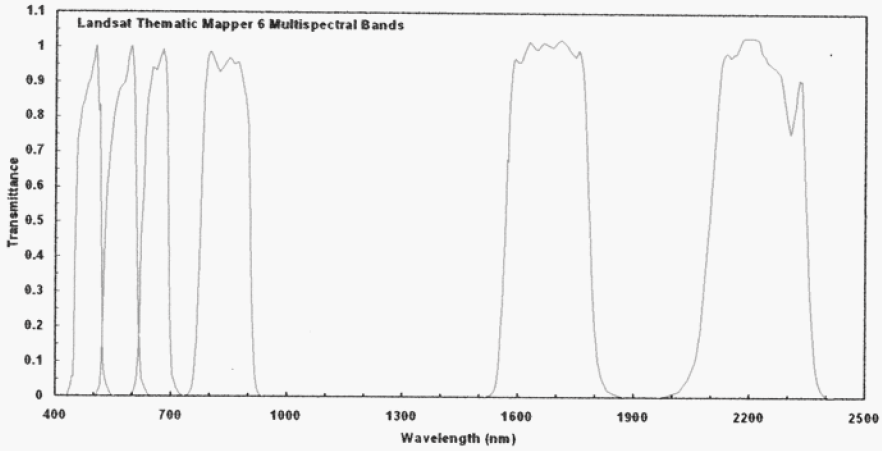
Spectroscopy of the Earth

Spectroscopy: A Reflectance Spectrum Example

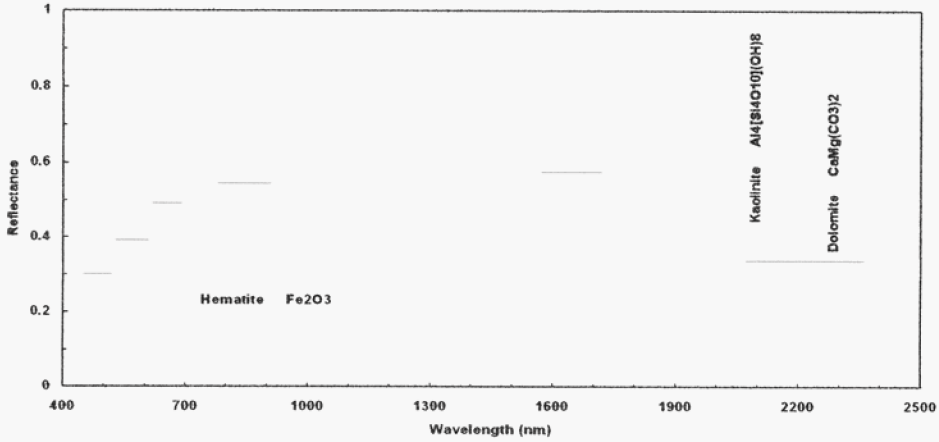


-Three materials are detected
-Three minerals are identified based on molecular absorption characteristics
-The expressed concentration of the three minerals may be derived

Multi Spectral 20th Century Approach
The 6 Solar LandSat TM Bands

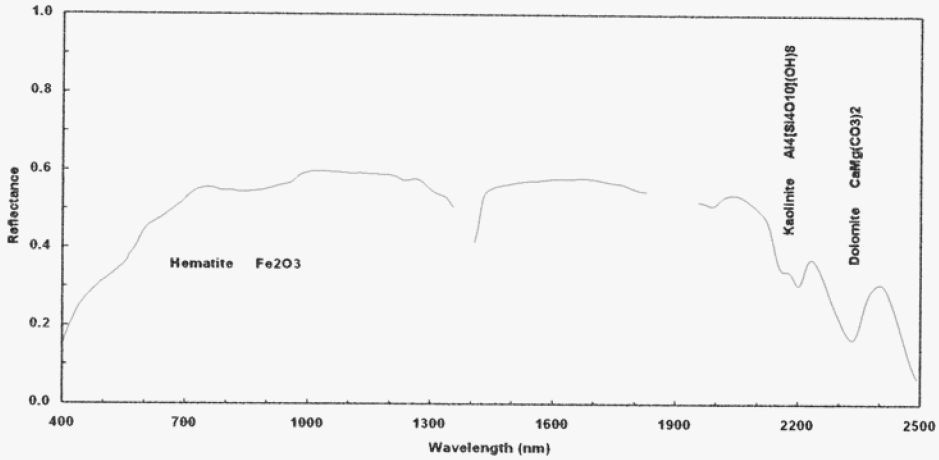


Multi-spectral Observation
20th Century Approach



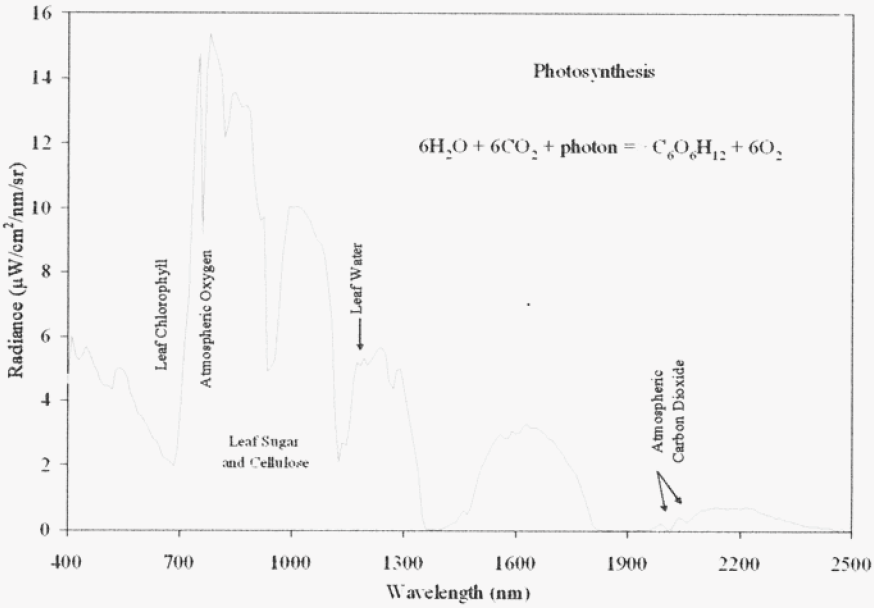
-Three materials are NOT detected
-Three minerals are NOT identified based on molecular absorption characteristics
-The expressed concentration of the three minerals may NOT be derived

Spectroscopy
21st Century Remote Measurement Approach

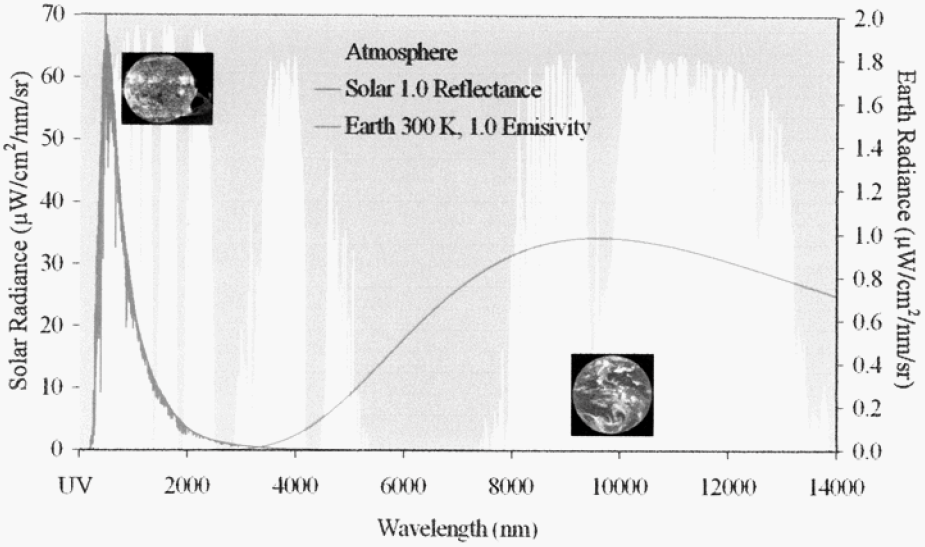


-Three materials are detected
-Three minerals are identified based on molecular absorption characteristics
-The expressed concentration of the three minerals may be derived

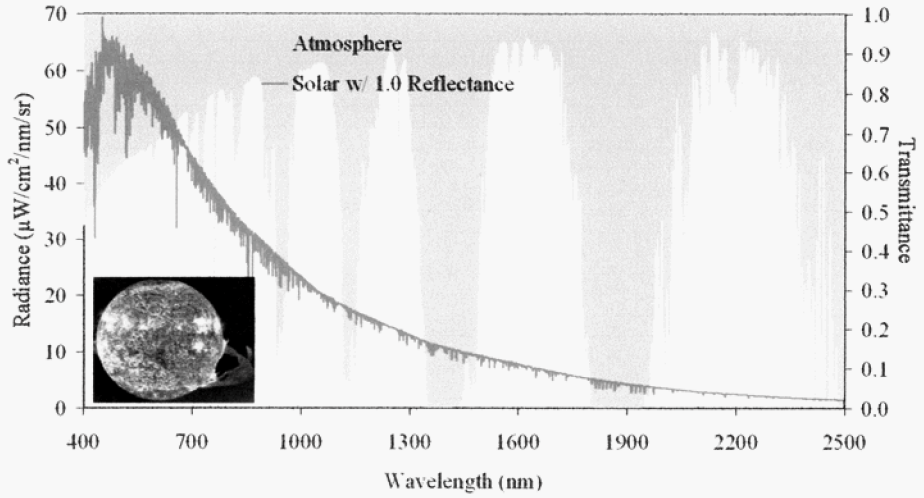
Plant Physiology and Carbon-Water-Nutrients are Directly Expressed in the Reflected Solar Spectrum



Available Signal and Transmittance of the Atmosphere



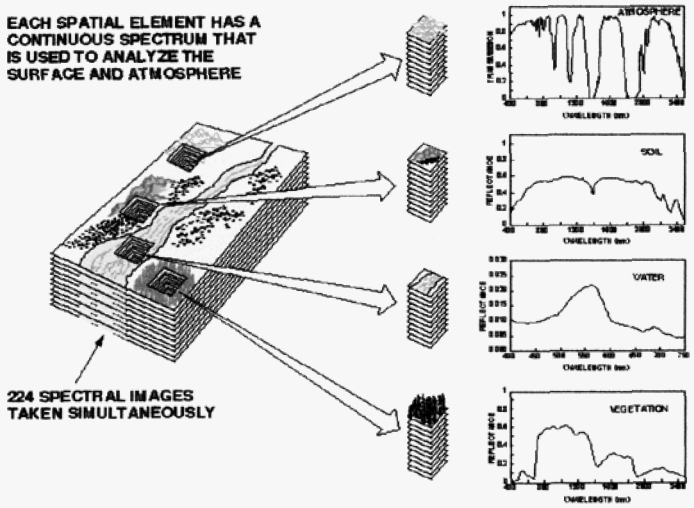
Solar Signal and Transmittance of the Atmosphere



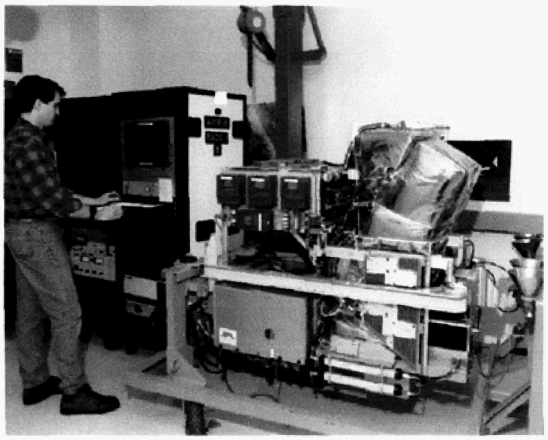
IMAGING SPECTROSCOPY CONCEPT
Scientific Basis

- Determining the composition and inferring processes on the Earth surface by counting photons at the top of the atmosphere is an challenging objective.
- Spectroscopy provides a framework based in physics to achieve this remote measurement (more than sensing) objective in the context of the interaction of photons with matter.
- The physics, chemistry and biology of spectroscopy have been validated through more that 100 years of laboratory and astronomical research and applications. (Fraunhofer 1814)

Imaging Spectroscopy Concept

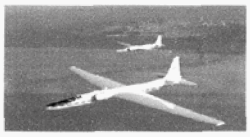


AVIRIS Instrument



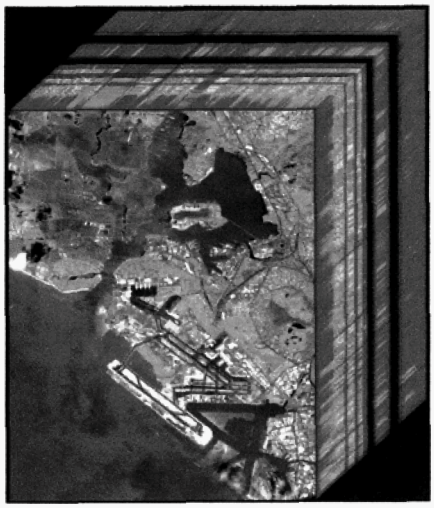
AVIRIS Technology Status

- Thermal control 1997
- Low Altitude 1998
- INU/GPS 1998
- Geo rectification 1998
- Onboard calibrator 1999
- Detector arrays 2000
- Digital signal chain 2001
- Onboard data storage 2001



AVIRIS is designed with 200 μm detectors and F/1 optics.
It is hard to imagine larger detectors or faster optics.
The AVIRIS design is in the advanced technology zone of the physics of spectroscopic measurements

AVIRIS: PEARL HARBOR, HAWAII



Spectral

Range	370 to 2500
Sampling	9.8 nm
Accuracy	0.5 nm

Radiometric

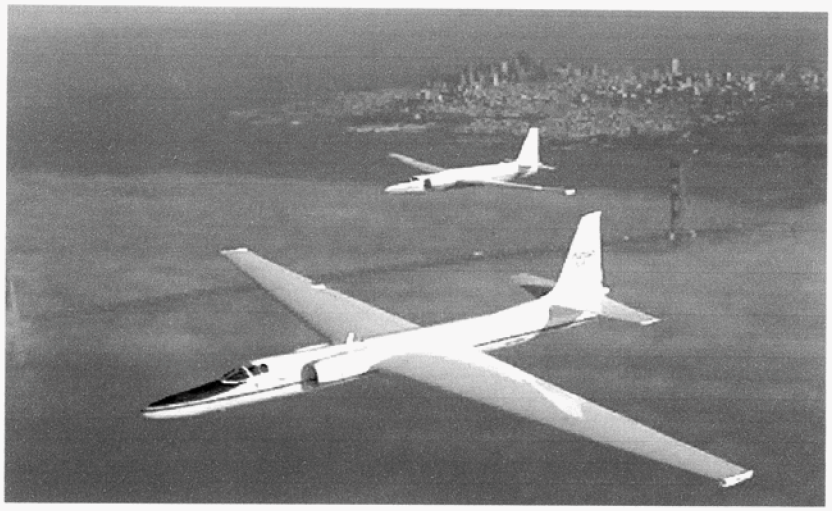
Range	0 to Max Lambertian
Sampling	12 bits
Accuracy	96 percent

Spatial (ER-2 / Twin Otter aircraft)

Swath	11/2.2 km ER-2/TO
Sampling	20/4 m ER-2/TO
Accuracy	20/4 m ER-2/TO

Full INU/GPS geo rectification

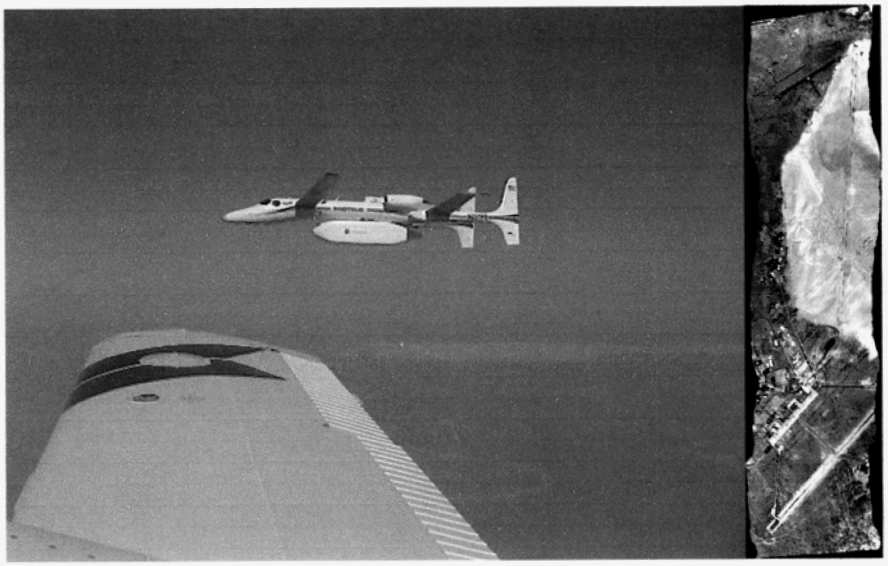
ER-2 Platform 20 km Altitude



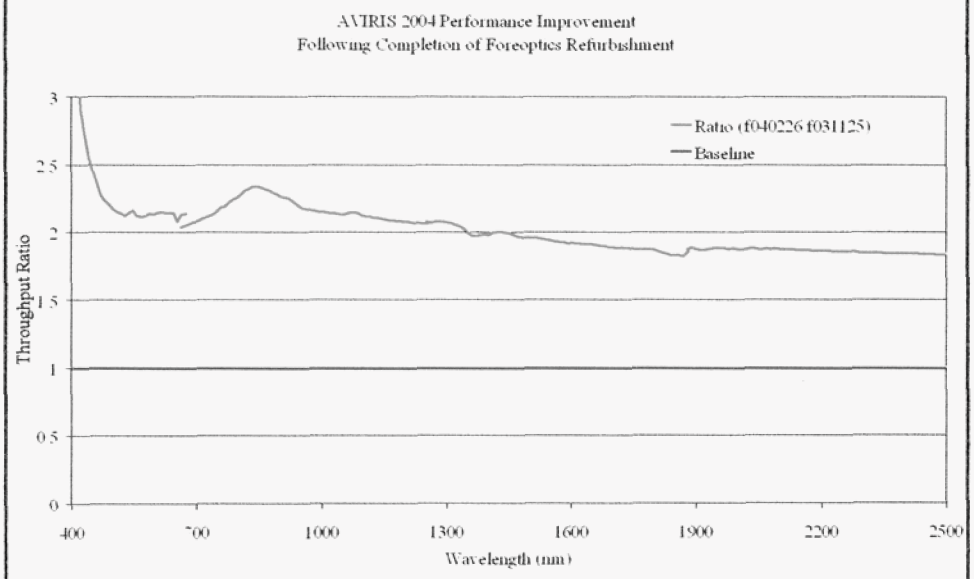
Twin Otter Platform, 4 km Altitude

New Capability, 5 to 8 km Altitude
AVIRIS On Board Proteus 040610

New Capability
AVIRIS On Board Proteus 040611

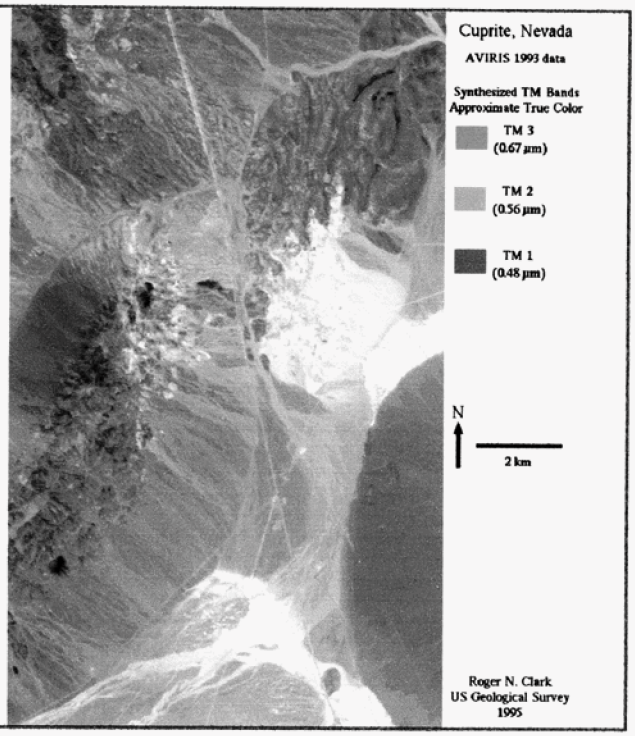


AVIRIS Throughput Increase in 2004



Land Surface Measurement
Geology Example

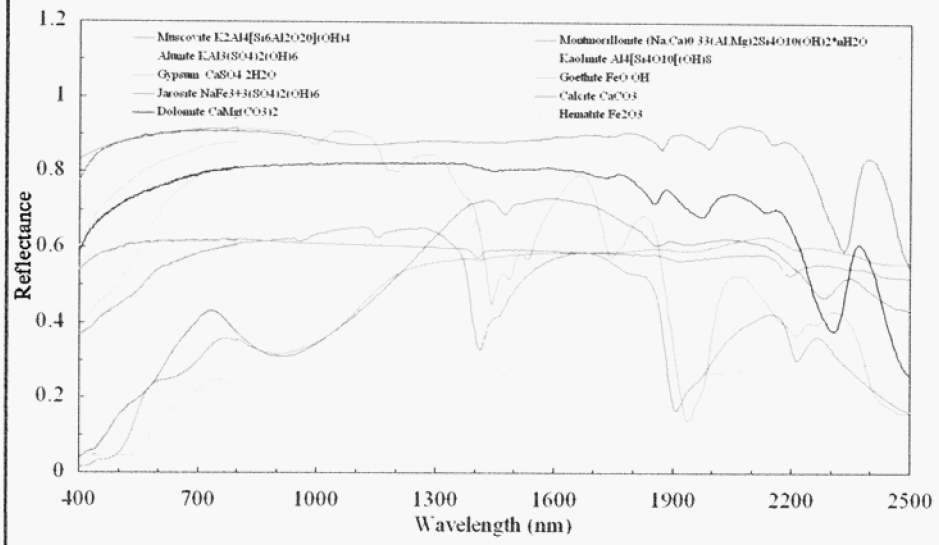
Geology Example:
Imaging Spectroscopy
Remote Measurement

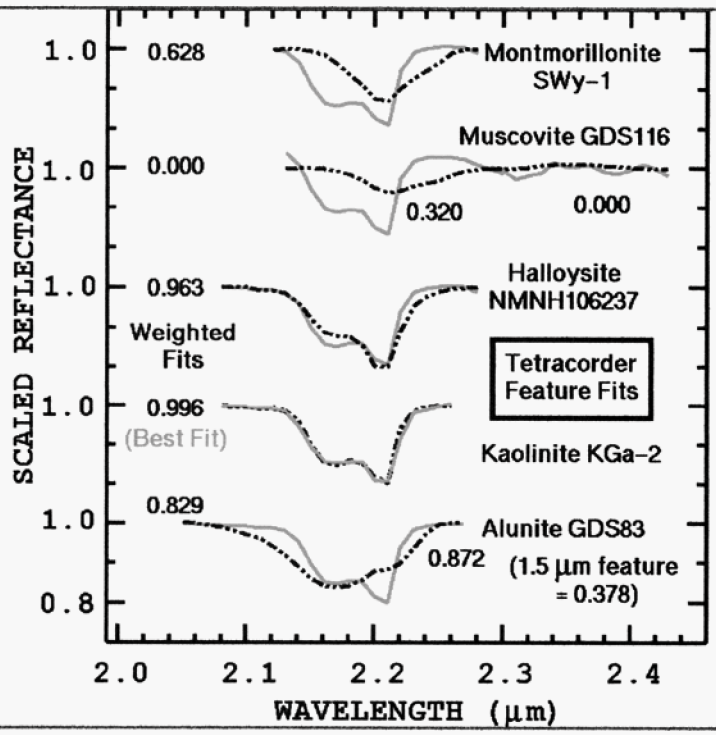


Imaging spectrometer
data det over area of
Interest

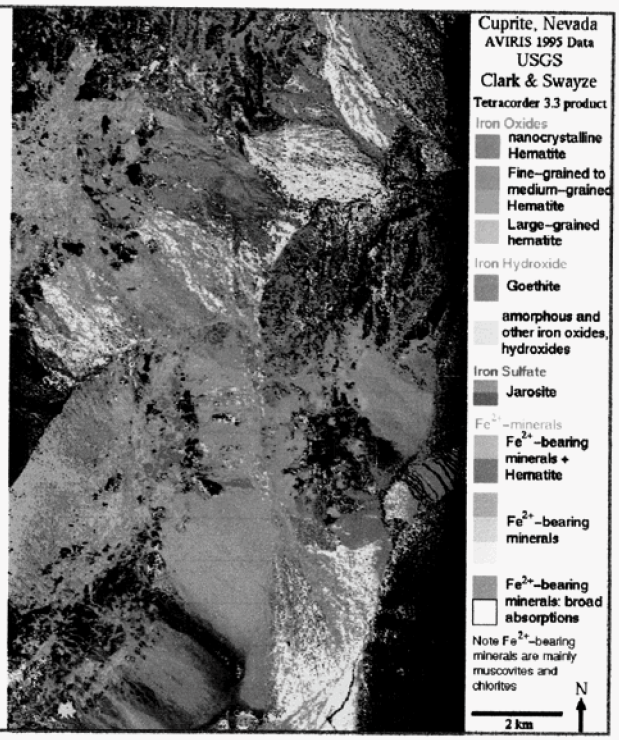
AVIRIS
Cuprite
Nevada

Mineral Spectra

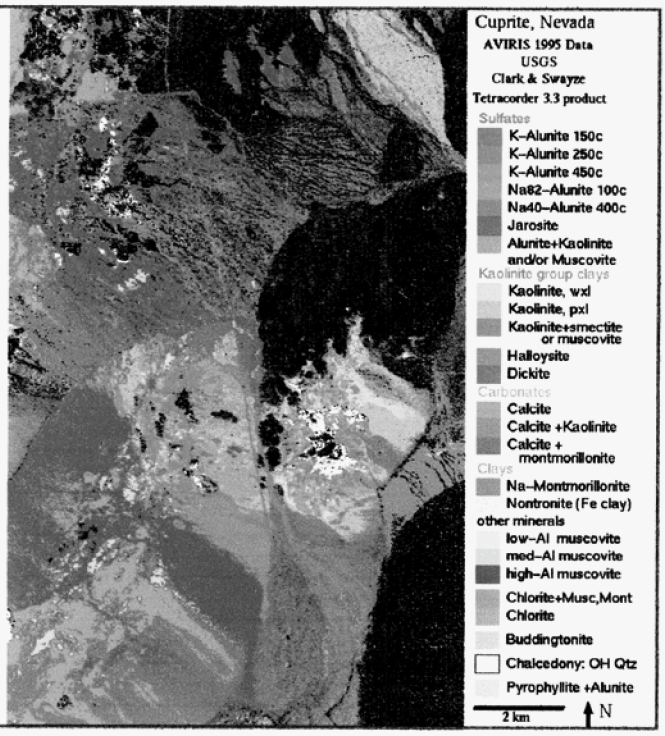




Cuprite, NV
Measured minerals in the 400 to 1500 nm spectral region with imaging spectroscopy

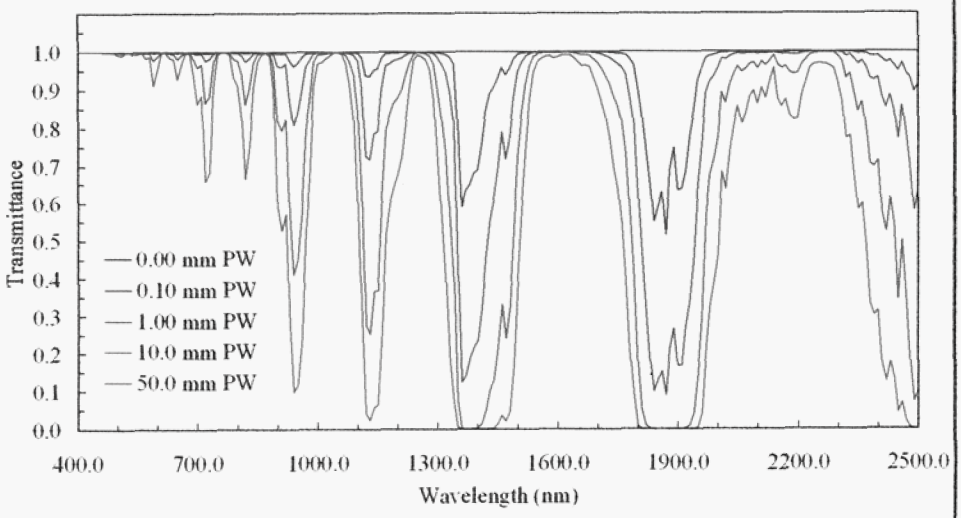


Cuprite, NV
Measured minerals in the 1000 to 2500 nm spectral region with imaging spectroscopy



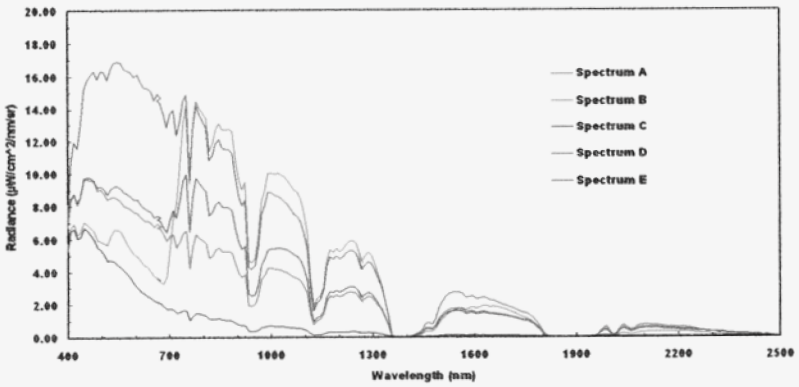
Atmosphere Measurement
Water Vapor
Cirrus Clouds

Measuring Atmospheric Water Vapor

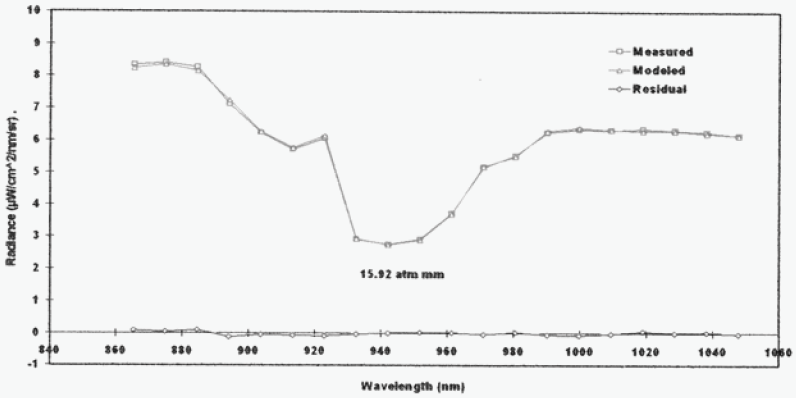


Pasadena, CA

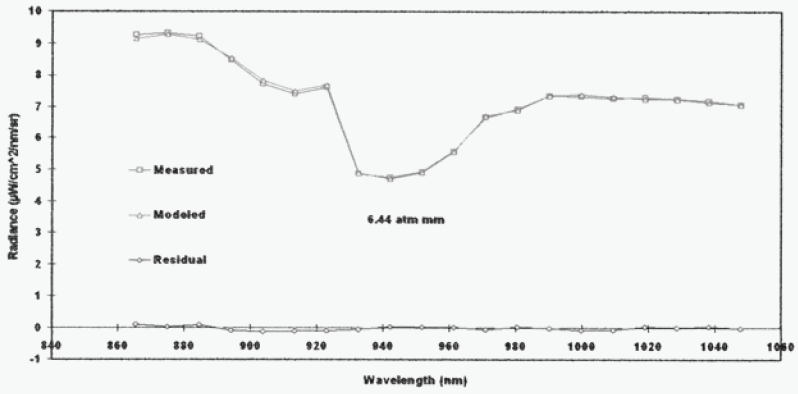
Pasadena Radiance Spectra



Derived Water Vapor at Low Elevation



Derived Water Vapor at High Elevation



Water Vapor at All Spectra

AVIRIS Water Vapor at Rogers Dry Lake, CA

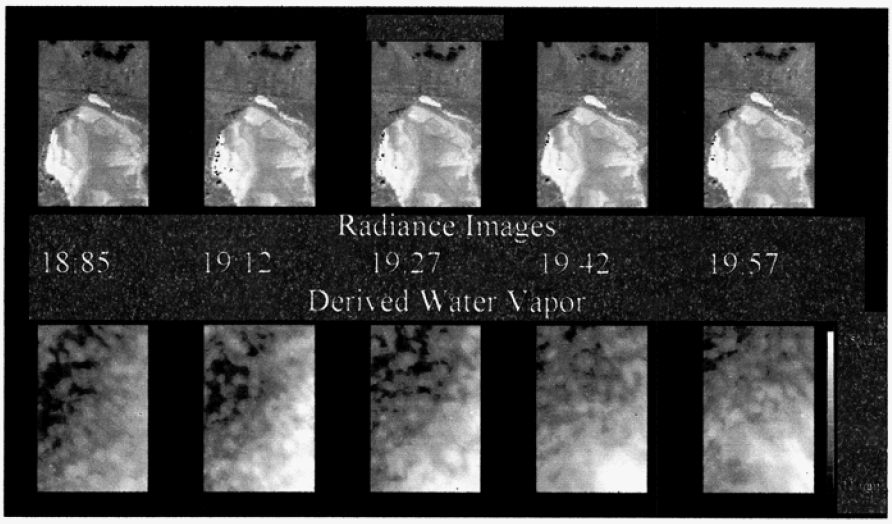


Image of the Mojave Desert, CA

Measuring Cirrus Clouds

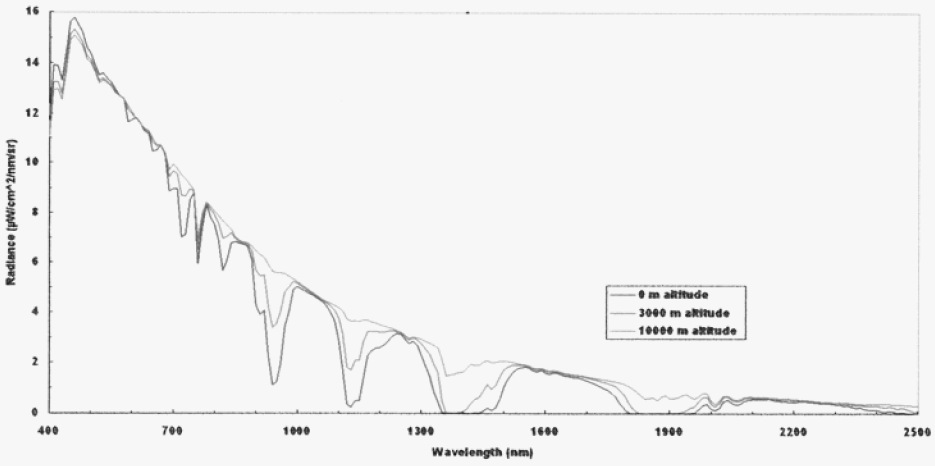
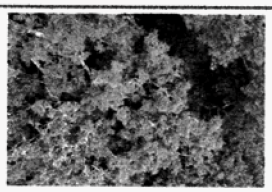
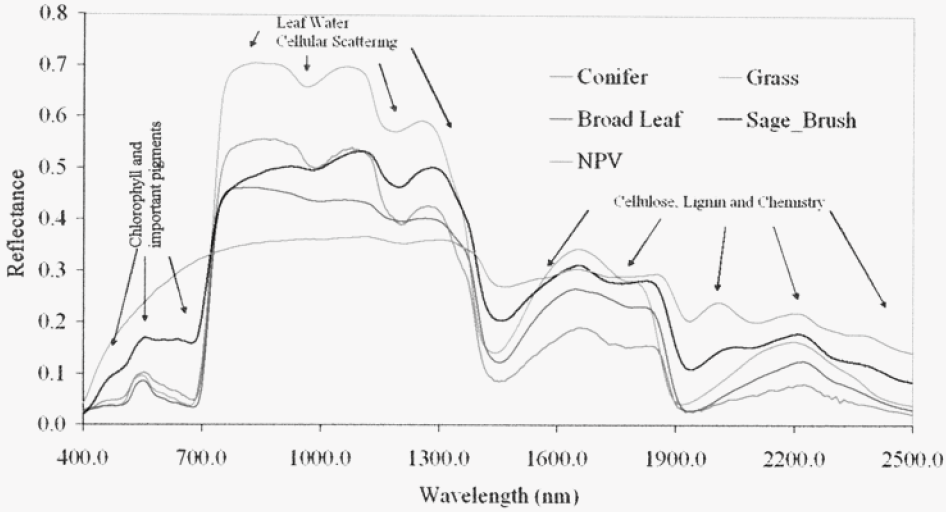


Image of the Mojave Desert, CA at 1380 nm

Vegetation Measurement
Vegetation type
Vegetation Carbon

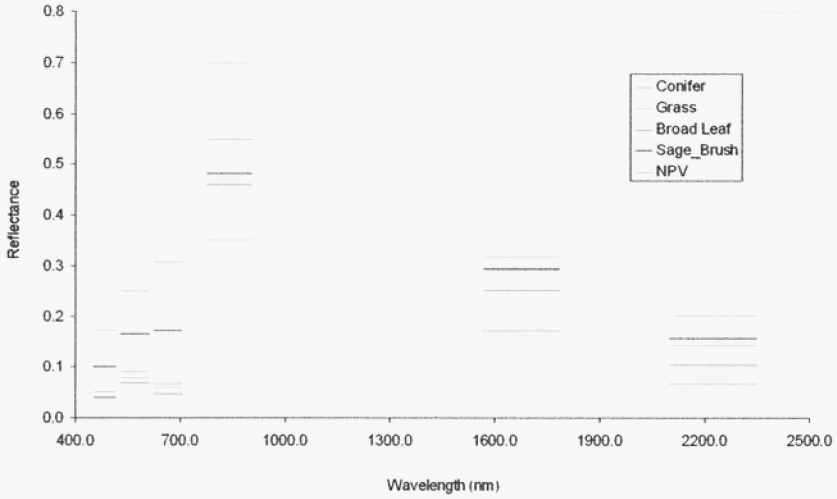


Remote Measurement of Vegetation with Imaging Spectroscopy

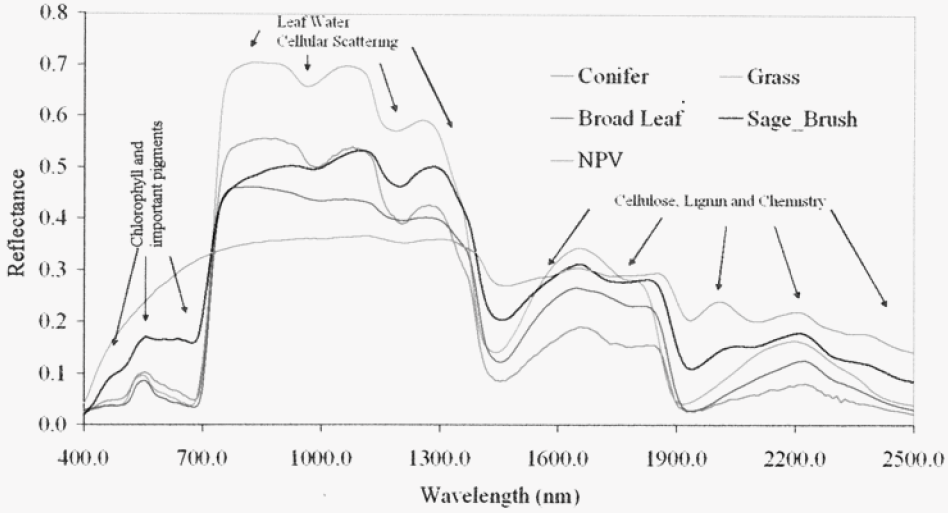


Multi Spectral Remote Sensing of Vegetation the 20th Century Approach

The spectral signatures are missing.

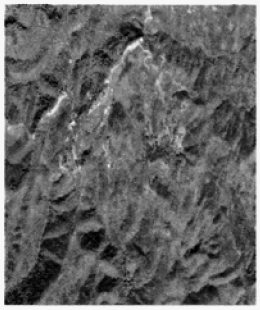


Imaging Spectroscopy is Required for Vegetation Type, Water, Carbon, Cover, Light use, Chemistry, etc



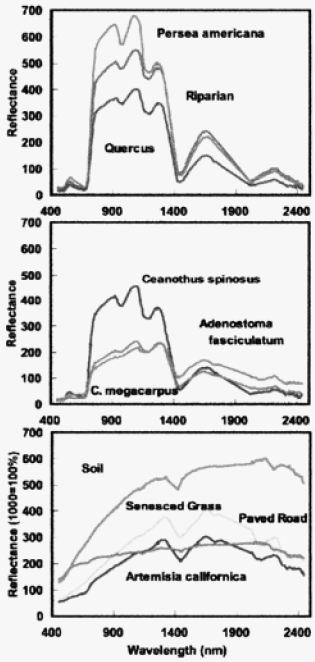
Example High Resolution Spectra

Run 6, Scene 5

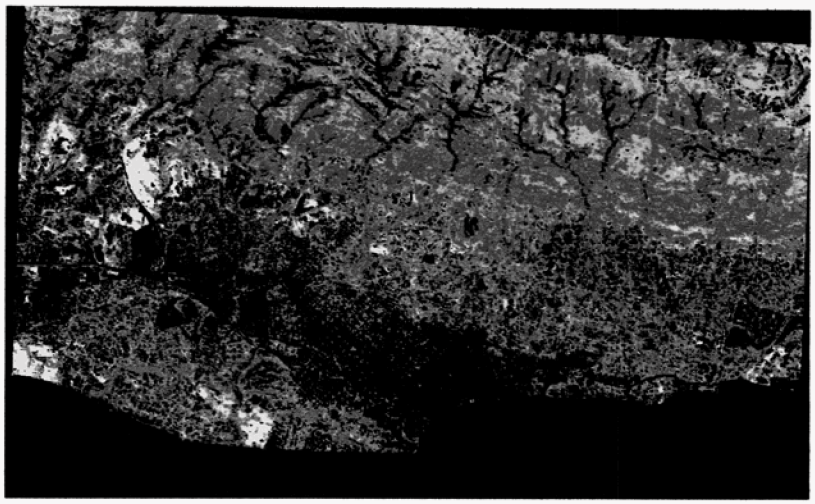


Run 7, Scene 4

1603, 836, 665 nm: RGB



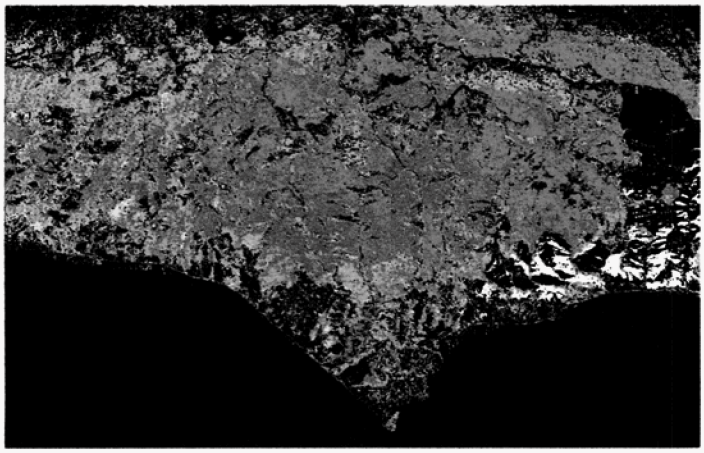
MESMA Vegetation Mapping
Santa Barbara Front Range



- *Adenostoma fasciculatum*
- *Ceanothus megacarpus*
- *Arctostaphylos spp.*
- *Quercus agrifolia*
- Grass
- Soil

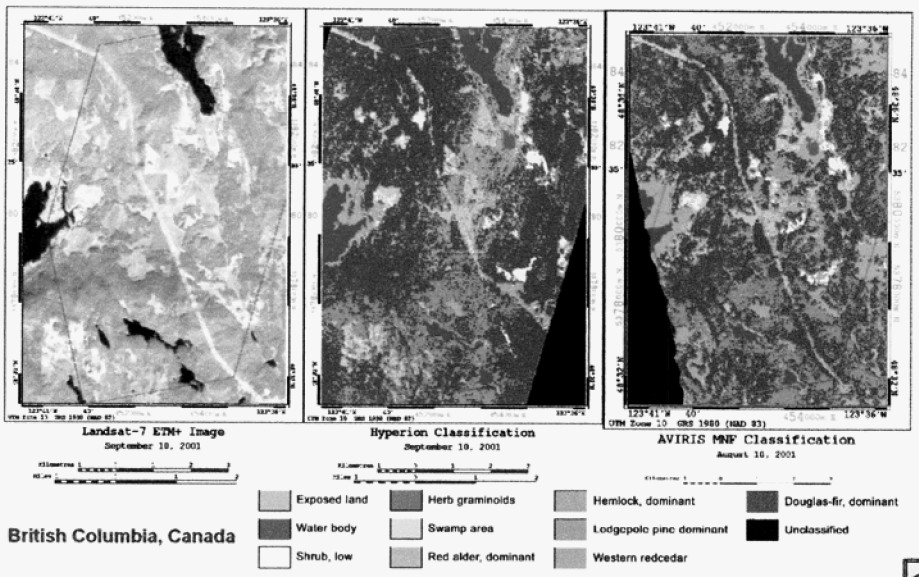
Accuracy: 87%

MESMA Vegetation Species Map
Generated from Oct. 23, 1996 AVIRIS



- Riparian
- Quercus
- Ceanothus spinosus
- Ceanothus megacarpus
- Adenostoma fasciculatun
- Mixed Hard Chaparral
- Artemisia californica
- Eriogonum sp
- Salvia sp
- Mixed Soft Chaparral
- Senesced Grass
- Rock/Soil/Road/Urban
- Persea americana

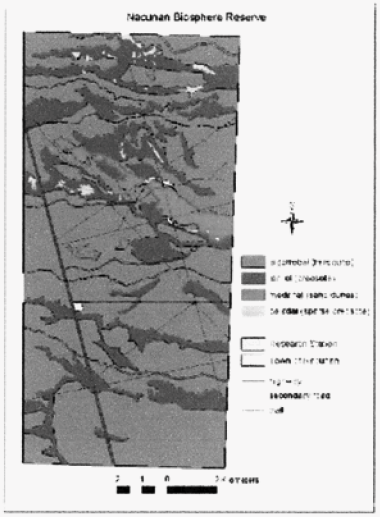
Plant Functional Types from Spectral Unmixing



British Columbia, Canada

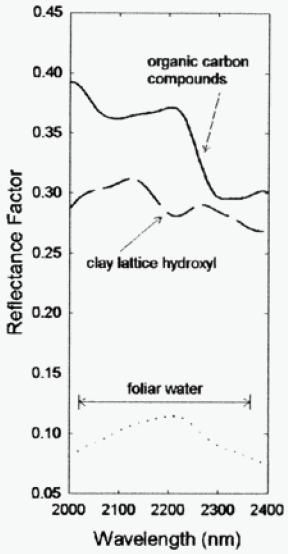
Desertification in Central Argentina

Carbon Impacts Called for by UNEP

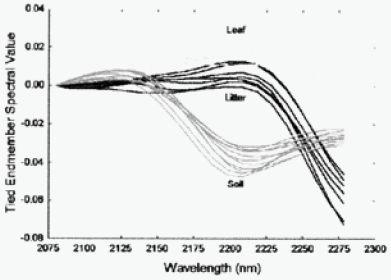


High-Precision Surface Cover Analysis Using VNIR red-edge and SWIR (2000-2400 nm) Spectra

Only SWIR Field Data Shown Here



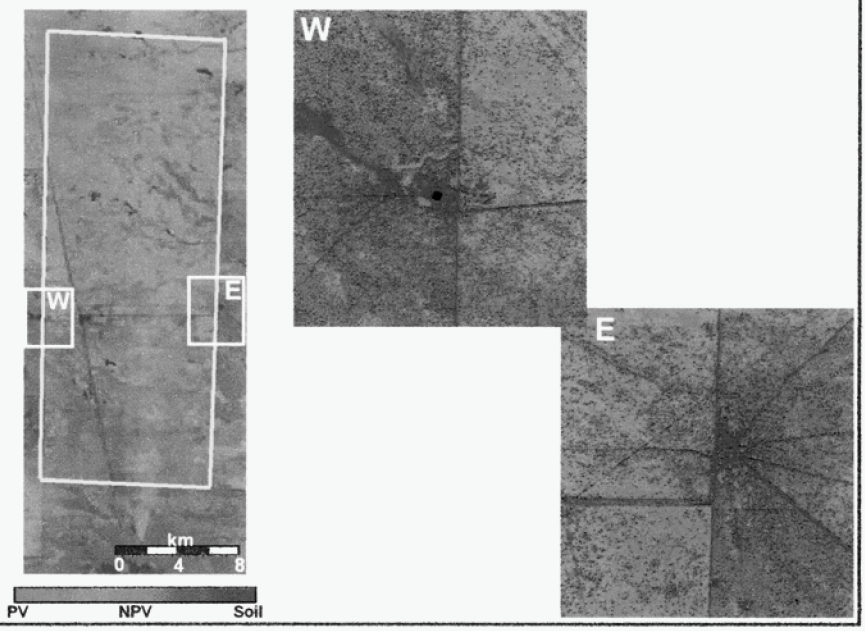
Tied Field Spectra Showing Full Arid/Semi-arid Site Variability

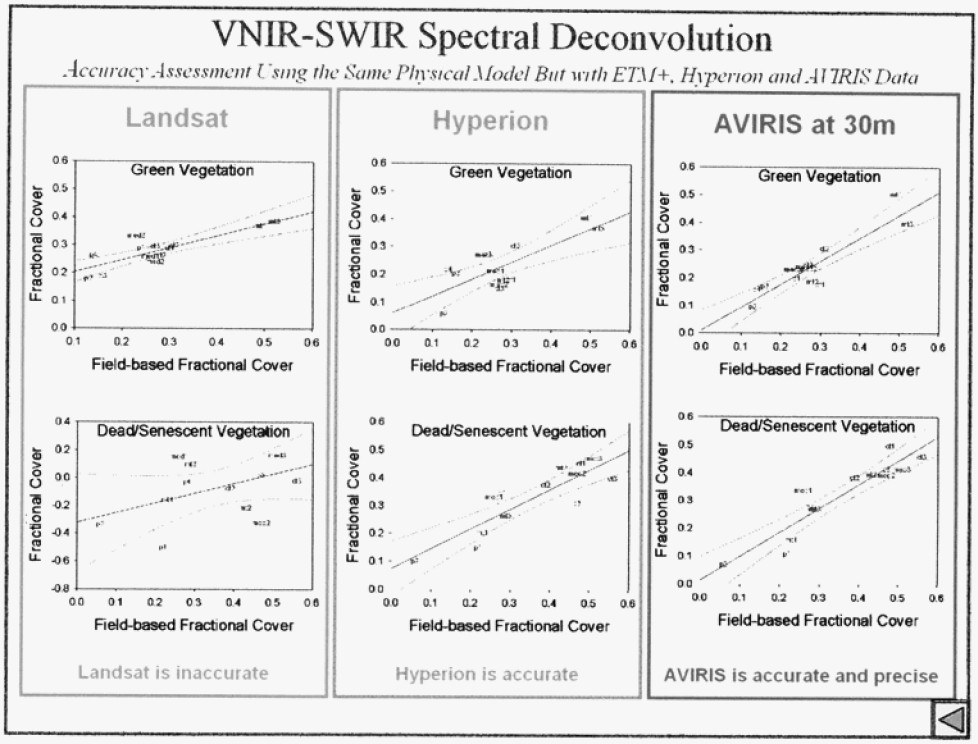


Tied at 2080nm

Tied SWIR Spectra

Desertification in Central Argentina





Measurements for Terrestrial Vegetation for Carbon from Imaging Spectroscopy

- **Fractional Vegetation Cover**
  - Green vegetation (GV)
  - Non-photosynthetic vegetation (NPV)
  - Soil, Water, Snow/ice
- **Plant Functional Types**
  - Grass/forb/shrub/tree
  - Thick/thin leaves
  - Broad/needle leaves
  - Deciduous/evergreen
- **Disturbance and Response of Vegetation Cover**
  - Recovery/change in fractional cover
  - Recovery/change in ecosystem function
  - Spectral signatures of vegetation stress and damage
- **Canopy Physiology and Function**
  - Light use efficiency
  - Canopy liquid water
  - Canopy chemistry

Four Mainstream Land Carbon Models

Where are the satellite constraints?

Major Model Inputs	CENTURY	CASA	SiB3	Ecosystem Demography
Vegetation Type	Prescribed	General Land Cover	General Land Cover	Prescribed
Plant Functional Types	Prescribed	---	Prescribed	---
Fractional Carbon Cover	---	---	---	---
Vegetation Greenness	---	NDVI	NDVI	NDVI
Fractional PAR Absorption	---	NDVI	NDVI	NDVI
Leaf Area Index (0-4 LAI units)	Prescribed	NDVI	NDVI	NDVI
Leaf Area Index (4-10 LAI units)	---	---	---	---
Canopy Gap Frequency and Size	---	---	---	Prescribed
Light-use Efficiency (leaf water, N)	---	---	---	---
Live vs. Senescent Biomass	---	---	---	---
Woody vs. Leaf Biomass	Prescribed	Prescribed	Prescribed	Prescribed
Canopy Allometry	Prescribed	Prescribed	Prescribed	Prescribed
Disturbance Type and Intensity	Prescribed	---, some fire	---	Prescribed

Currently a there is large uncertainty in terrestrial vegetation Carbon storage and change. Not helped with current satellite measurements.

Four Mainstream Land Carbon Models

Where are the satellite constraints?

With proposed Flora Spaceborne imaging spectrometer measurements

Major Model Inputs	CENTURY	CASA	SiB3	Ecosystem Demography
Vegetation Type	FLORA	FLORA	FLORA	FLORA
Plant Functional Types	FLORA	FLORA	FLORA	FLORA
Fractional Carbon Cover	FLORA	FLORA	FLORA	FLORA
Vegetation Greenness	FLORA	FLORA	FLORA	FLORA
Fractional PAR Absorption	FLORA	FLORA	FLORA	FLORA
Leaf Area Index (0-4 LAI units)	FLORA	FLORA	FLORA	FLORA
Leaf Area Index (4-10 LAI units)	FLORA	FLORA	FLORA	FLORA
Canopy Gap Frequency and Size	FLORA	FLORA	FLORA	FLORA
Light-use Efficiency (leaf water, N)	FLORA	FLORA	FLORA	FLORA
Live vs. Senescent Biomass	FLORA-constrained	FLORA-constrained	FLORA-constrained	FLORA-constrained
Woody vs. Leaf Biomass	FLORA-constrained	FLORA-constrained	FLORA-constrained	FLORA-constrained
Canopy Allometry	Prescribed	Prescribed	Prescribed	Prescribed
Disturbance Type and Intensity	FLORA-constrained	FLORA-constrained	FLORA-constrained	FLORA-constrained

Flora will reduce the current large uncertainty in Carbon storage and change in terrestrial vegetation.

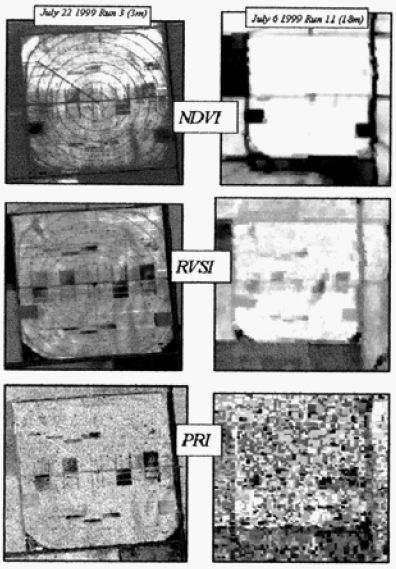
Remote Measurement of Agricultural Vegetation Stress wi

RVSI uses the spectroscopy and is superior in measuring stress.

Perry et al., 2002

Shelton NE

NASA EOCAP program



Water Vapor at All Spectra

AVIRIS Water Vapor at Rogers Dry Lake, CA

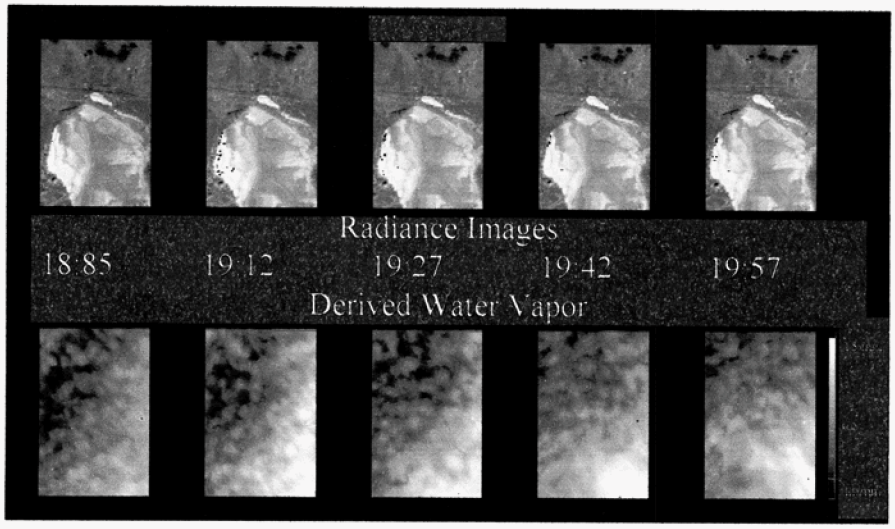


Image of the Mojave Desert, CA

Measuring Cirrus Clouds

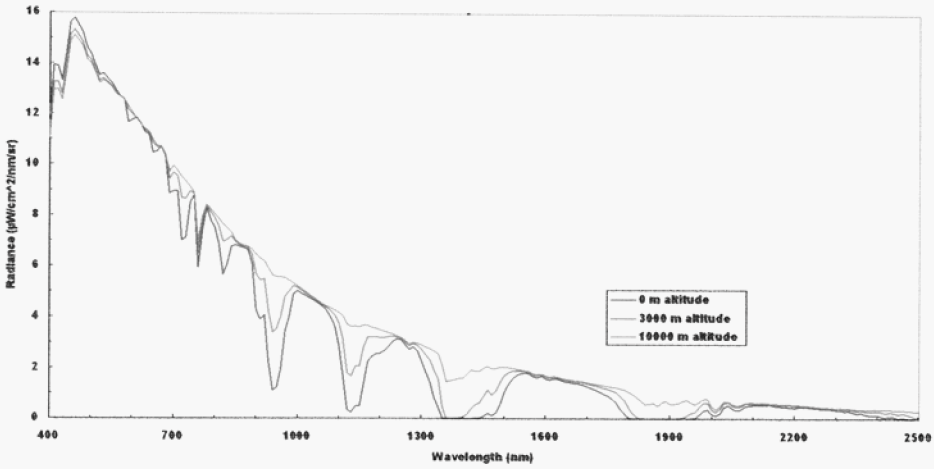


Image of the Mojave Desert, CA

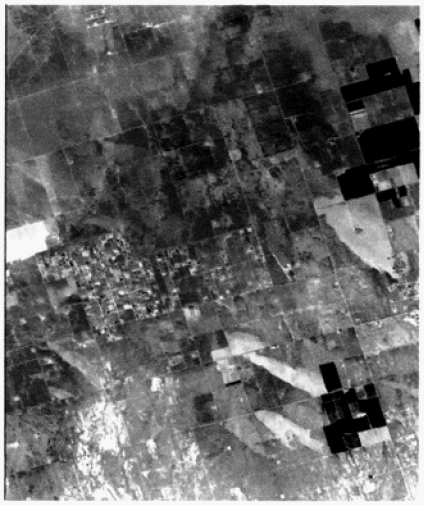
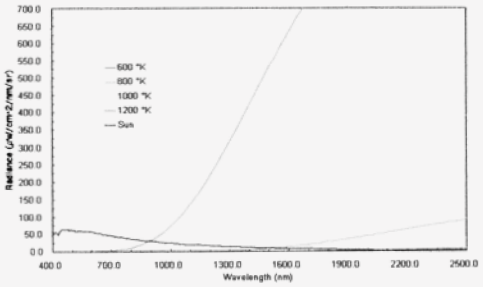


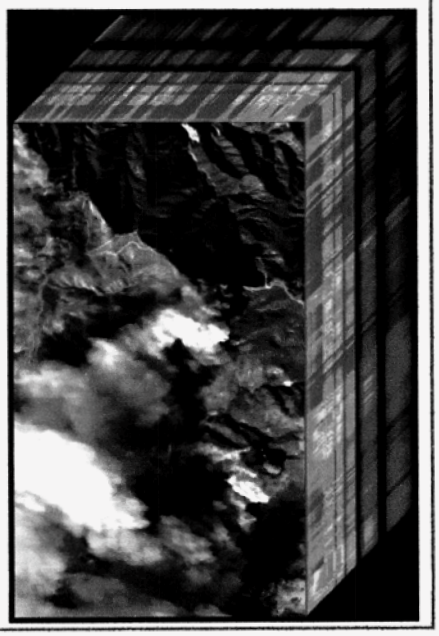
Image of the Mojave Desert, CA at 1380 nm

Wild Fire Measurement

Fire Properties
Vegetation Properties

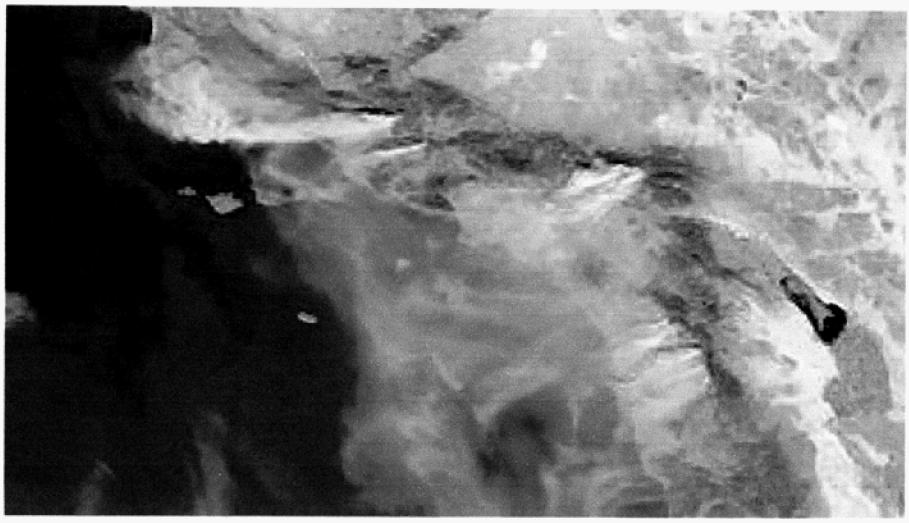
Autumn 2003 California Fires



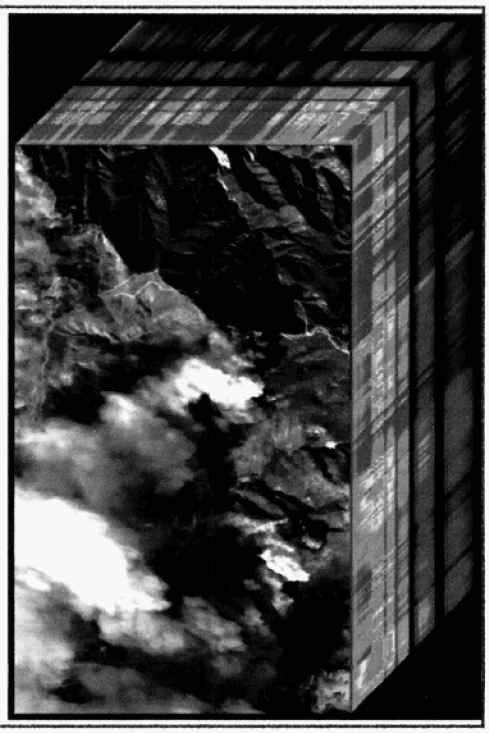


Autumn 2003 California Fires

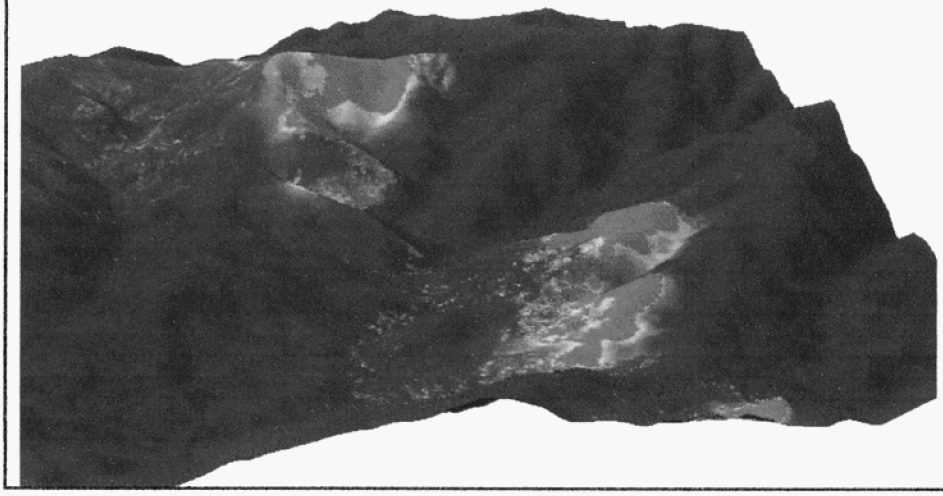
MODIS view 2003 California Fires



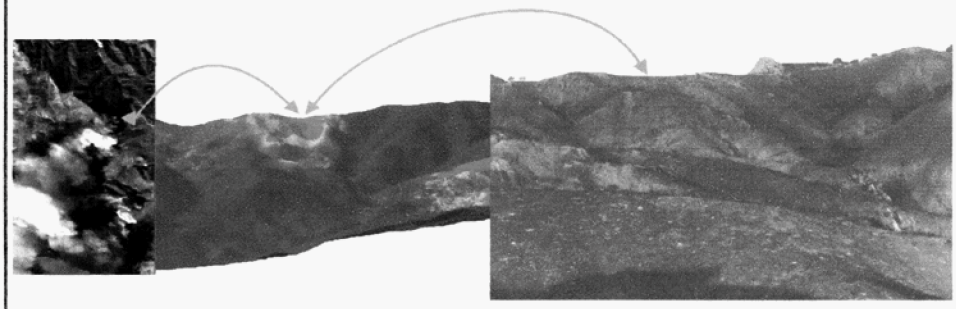
AVIRIS view
2003 California Fires



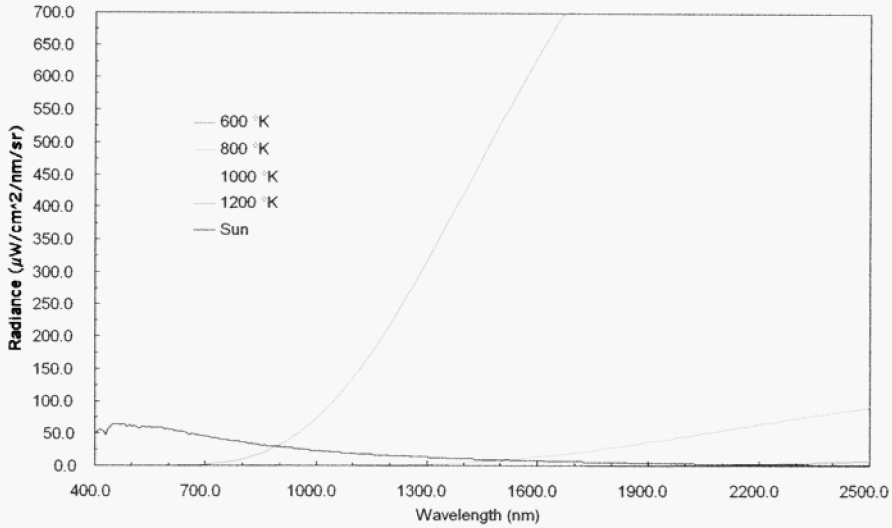
Simi Fire f031027
AVIRIS Radiance on topography



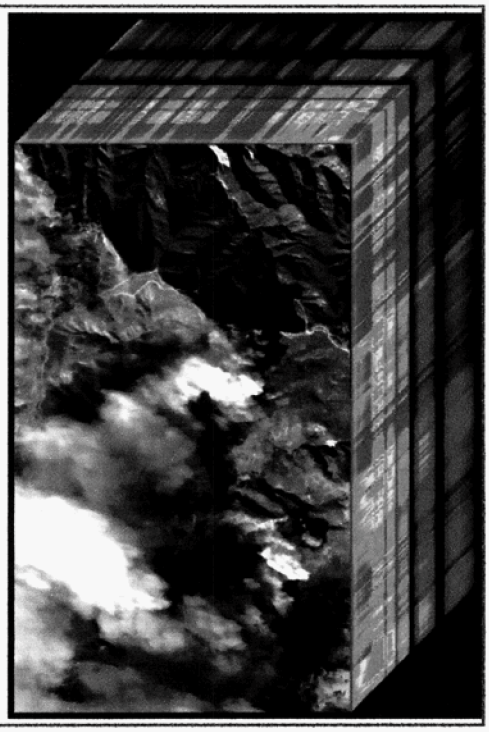
Simi Fire f031027
AVIRIS Radiance, topography and post fire picture



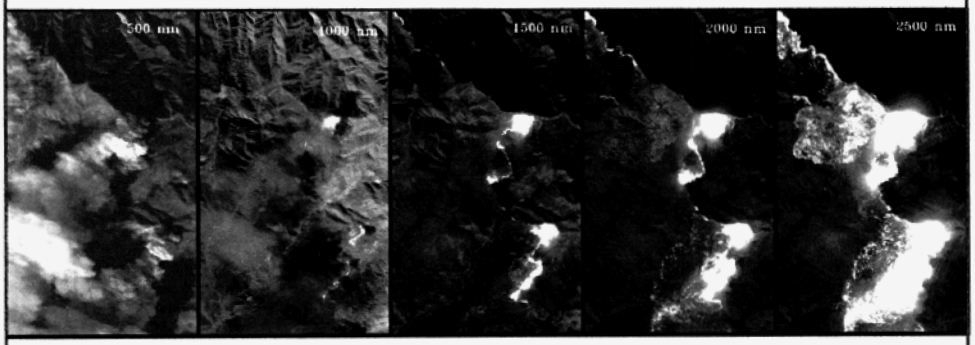
Hot Spot Radiance Modeled with Planck Function



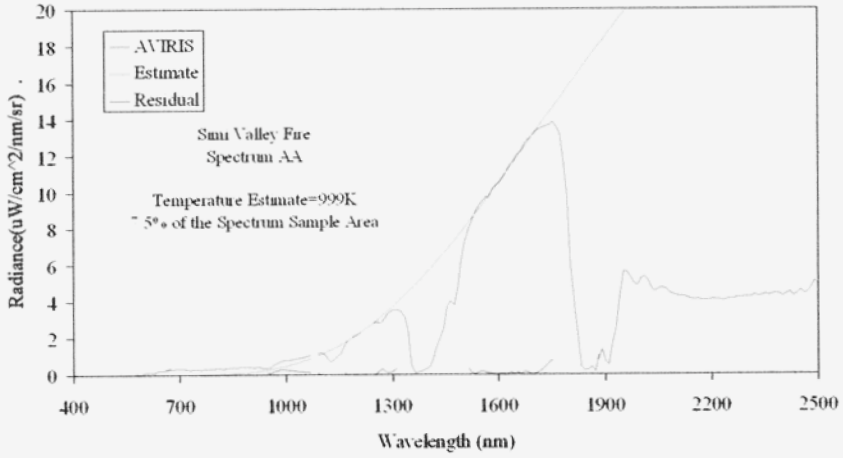
AVIRIS view 2003 California Fires



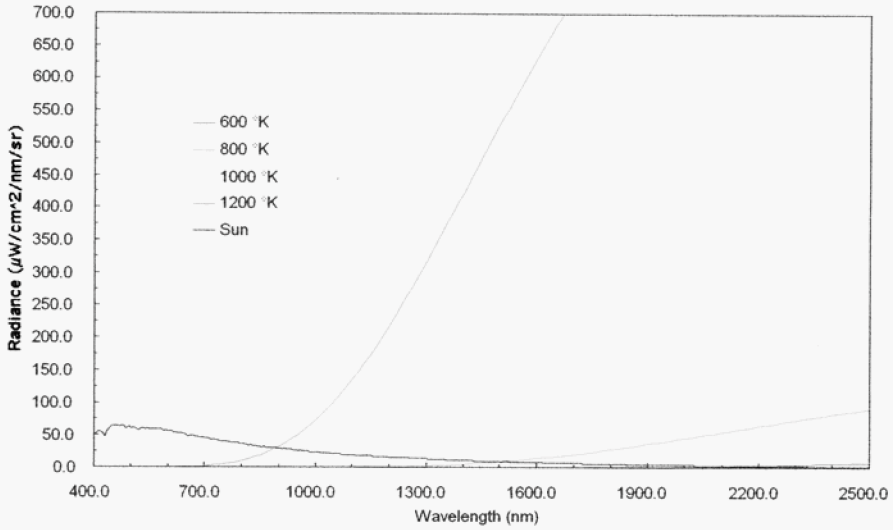
Simi Valley, California
Fire Through the Spectrum



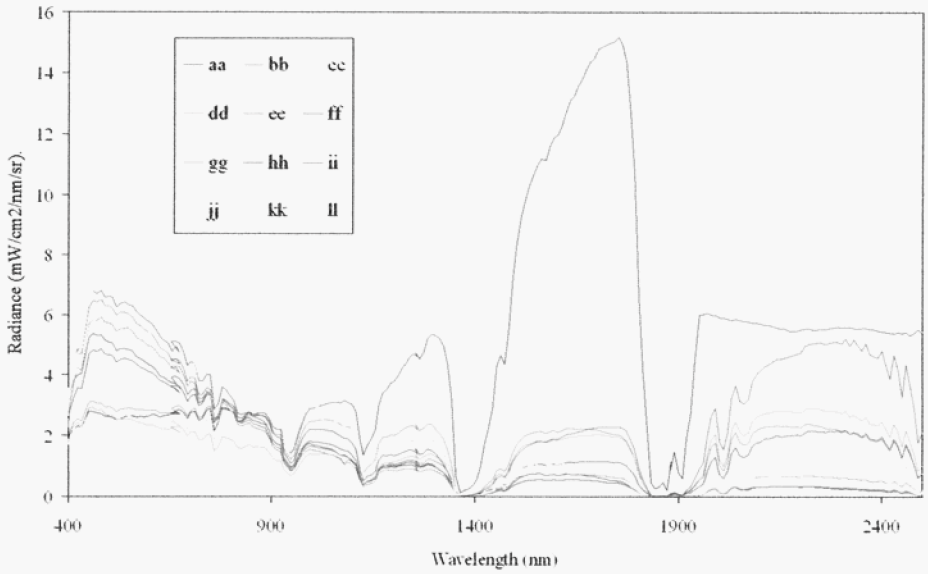
AVIRIS Hot High Fraction Spectrum



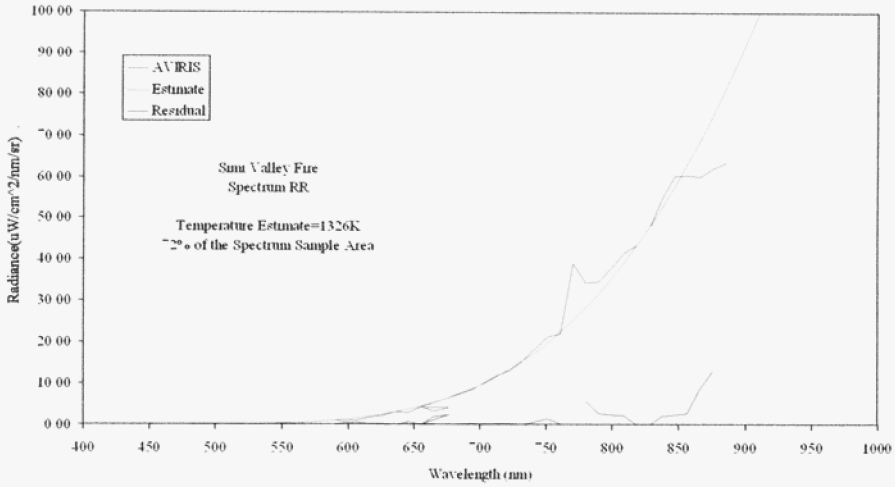
Hot Spot Radiance Modeled with Planck Function



AVIRIS from unburned to burning vegetation

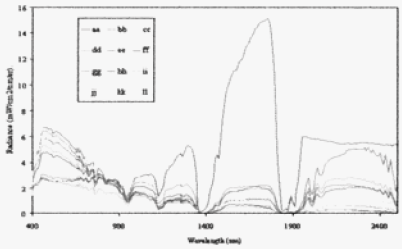


AVIRIS Hot High Fraction Spectrum

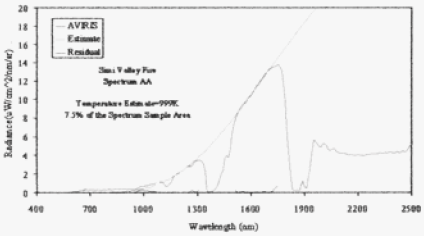


AVIRIS Derived Temperatures

AVIRIS Spectra



Temperature & Area Derivation



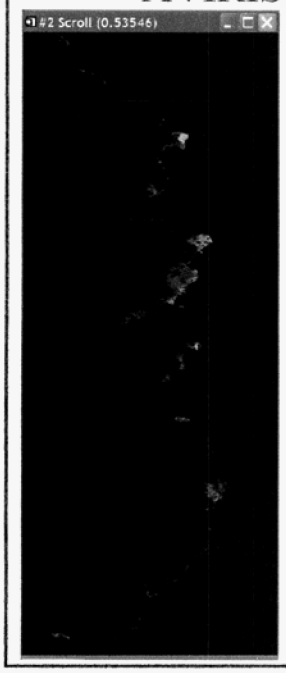
Detailed Fire temperature for structure and research

AVIRIS Derived Temperatures

Temperatures 800 to 1450 K

Detailed structure of fire process

AVIRIS Derived Fire Fractional Areas



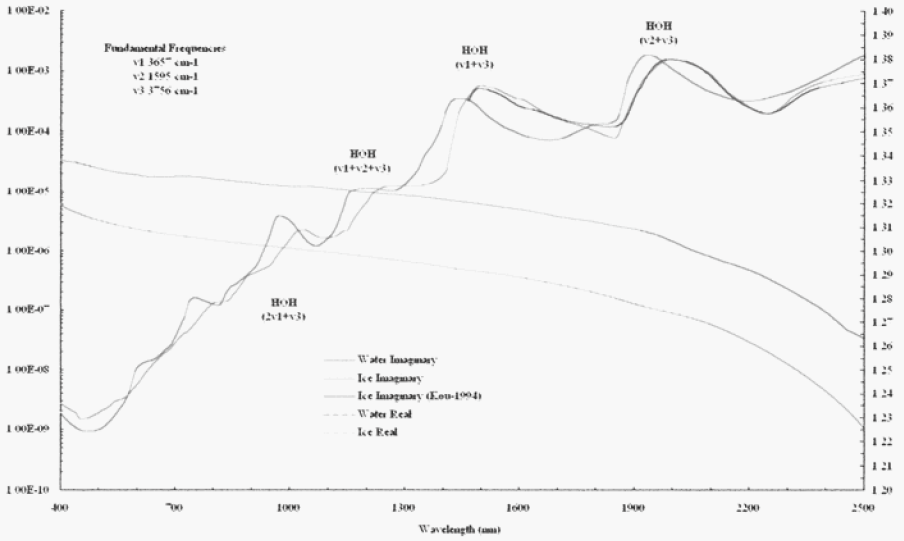
Fractional Areas ~ 1 to13 % and higher

At 4 m spatial scale high fractions at the edges

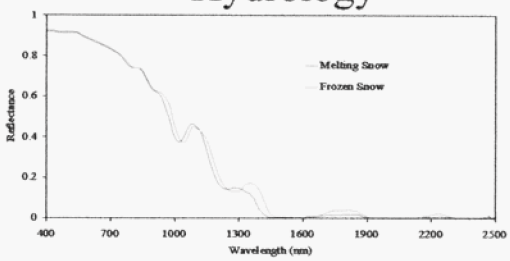
Snow and Ice Measurement
Snow Grain Size
Snow Melting

Snow and ice distribution and properties are changing due to global warming.

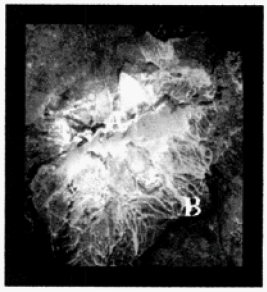
Snow and Ice Measurement via the Optical Constants of Water



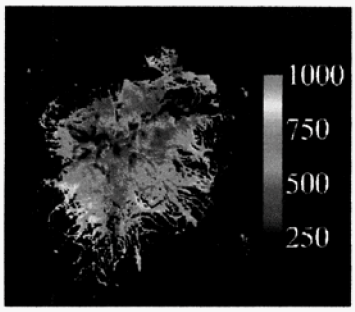
AVIRIS and Snow Hydrology



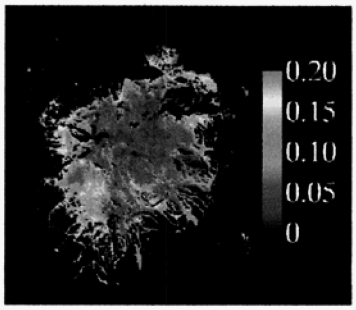
Mammoth Mountain, CA



Surface Grain Size microns



Surface Liquid Water Fraction

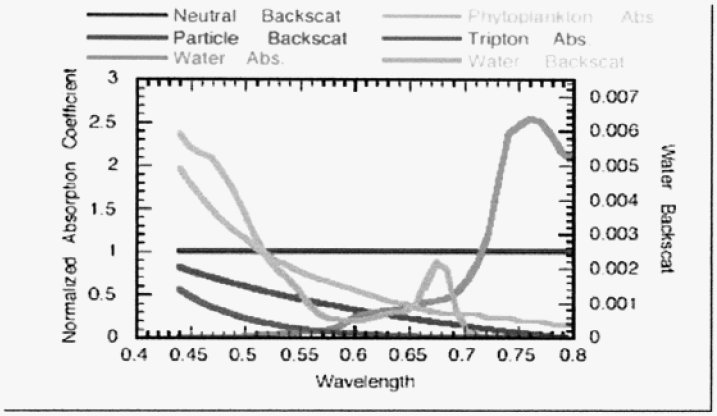


Costal and Inland Water

- Properties to Measure with Imaging Spectroscopy
  - Chlorophyll and other constituent
  - Water depth
  - Aquatic vegetation
  - Coral
  - Pollution

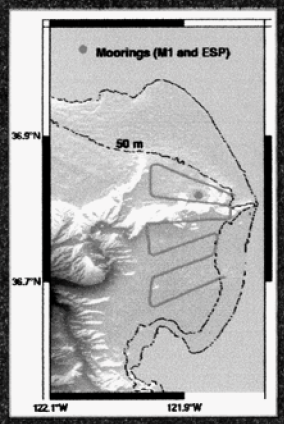
Costal and Inland Waters
Spectral Signatures of Water Constituents

(from John Mustard)



Model Based Inversion for Chlorophyll

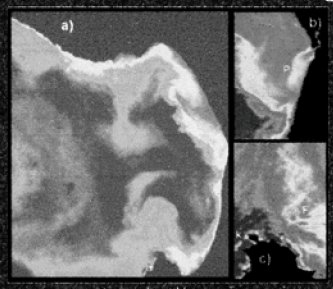
Five-week *Acrobat* towfish volume time-series from *R/V Zephyr*



September - October 2002

- Towed-undulating surveys
- Surface underway mapping
- bottle samples

Airborne Remote Sensing



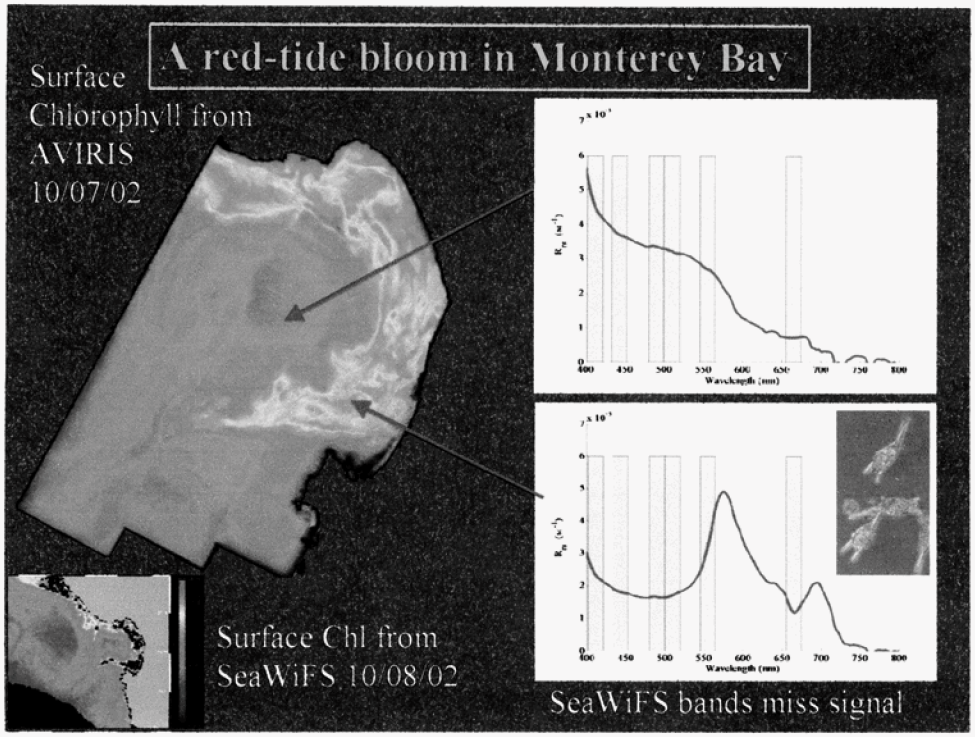
two overflights in October

2500 x spatial resolution of satellite

far greater spectral resolution and coverage

ground-truth optics

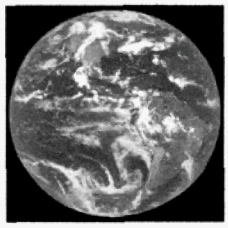
In collaboration with labs of Johnson, Chavez, Schofield (MBARI) and Kudela (UCSC)



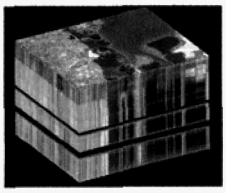
Research and Applications

- Atmosphere: water vapor, clouds properties, aerosols, absorbing gases…
- Ecology: chlorophyll, leaf water, lignin, cellulose, pigments, structure, nonphotosynthetic constituents…
- Geology and soils: mineralogy, soil type…
- Coastal and Inland waters: chlorophyll, plankton, dissolved organics, sediments, bottom composition, bathymetry…
- Snow and Ice Hydrology: snow cover fraction, grainsize, impurities, melting…
- Biomass Burning: subpixel temperatures and extent, smoke, combustion products…
- Environmental hazards: contaminants directly and indirectly, geological substrate…
- Calibration: aircraft and satellite sensors, sensor simulation, standard validation..
- Modeling: radiative transfer model validation and constraint…
- Commercial: mineral exploration, agriculture and forest status…
- Algorithms: autonomous atmospheric correction, advance spectra derivation…
- Other: human infrastructure...

Summary



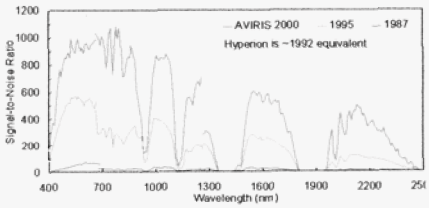
- Measuring the Earth system in a time of global environmental change
- Imaging Spectroscopy enables remote measurement
- Remote Measurement determination of the properties of the Earth's surface and atmosphere through the physics, chemistry and biology of the interaction of electromagnetic energy with matter.
- Imaging spectroscopy a 21st century approach



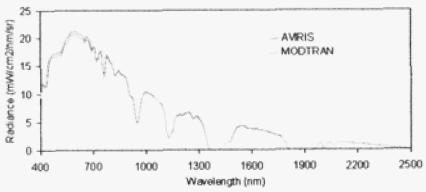
Future Vision

What is needed: High Fidelity Imaging Spectroscopy

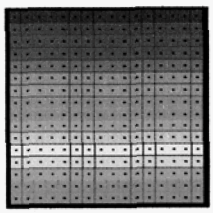
- High Signal-to-noise ratio required for molecular spectroscopy



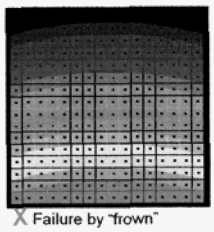
- Excellent calibration for quantitative results (spectral, radiometric, spatial)



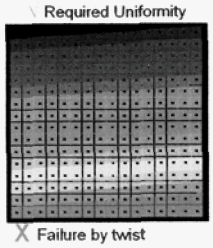
- Uniformity is required for spectroscopy in the image domain



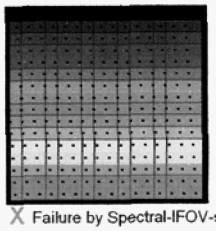
Required Uniformity



X Failure by "frown"

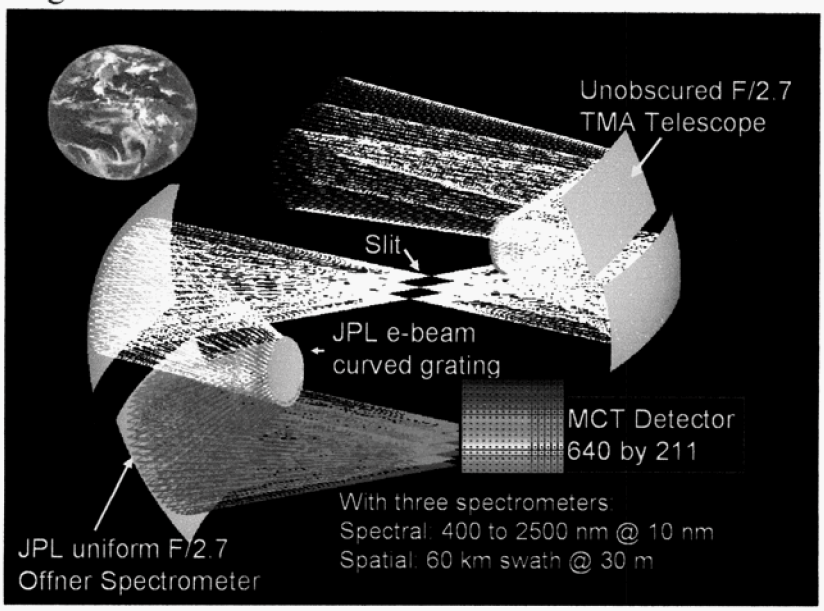


X Failure by twist

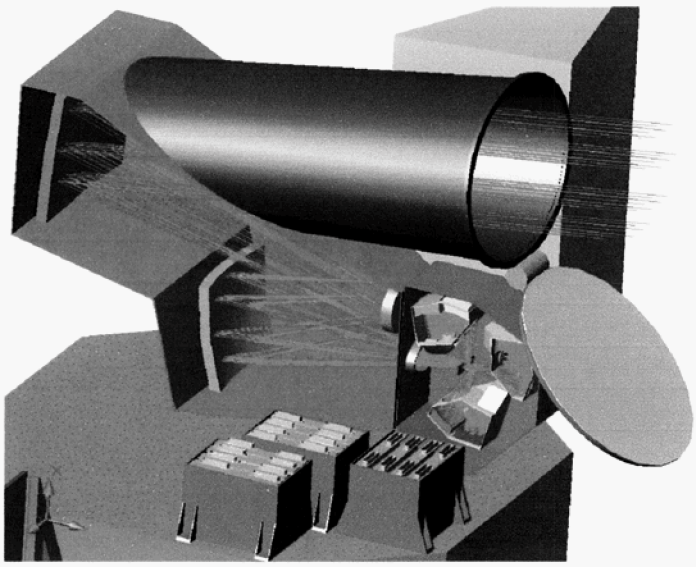


X Failure by Spectral-IFOV-shift

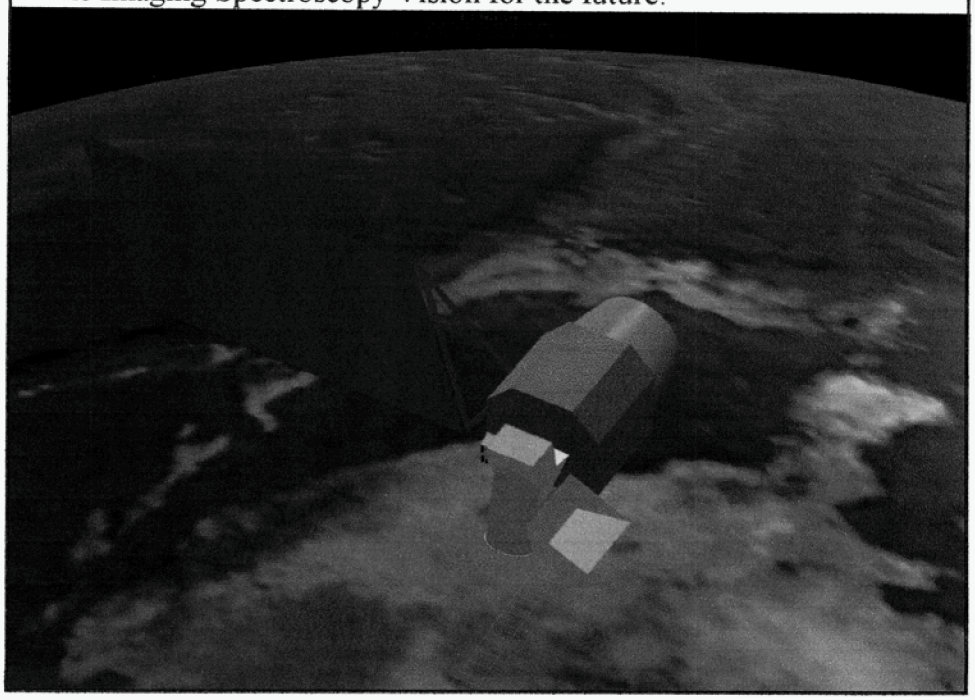
Future: Advanced high throughput and high uniformity designs



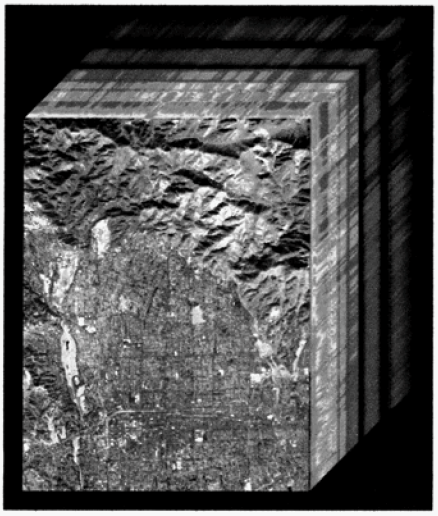
A possible design: 30 meter spatial resolution and 60 km swath



The Imaging Spectroscopy Vision for the future:



Thank You



- AVIRIS website: http://aviris.jpl.nasa.gov
- Email: rog@jpl.nasa.gov
- AVIRIS Workshop Proceedings: On-line at website
- AVIRIS Workshop: May 2005