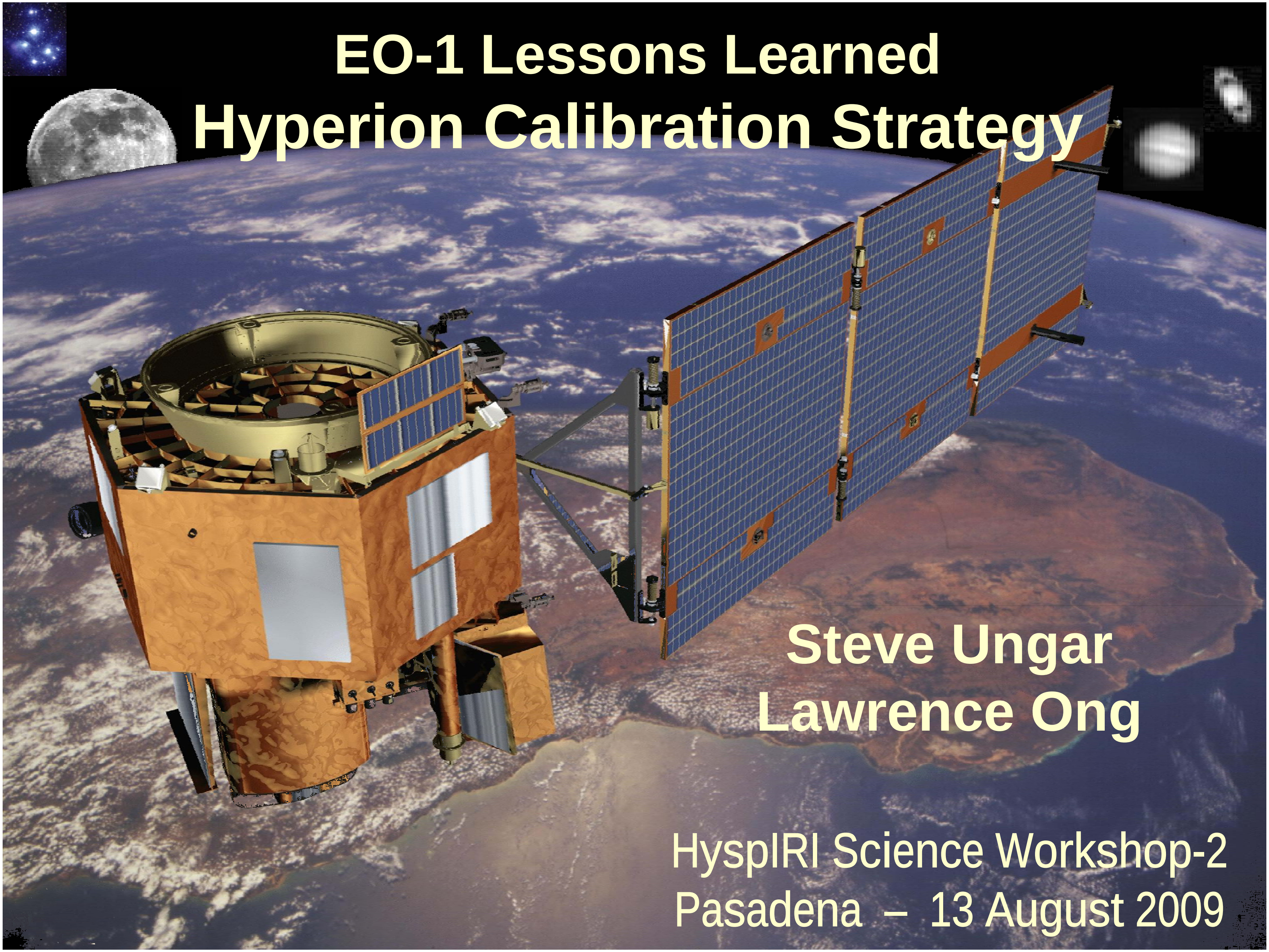
EO-1 Lessons Learned
Hyperion Calibration Strategy



Steve Ungar
Lawrence Ong

HyspIRI Science Workshop-2
Pasadena – 13 August 2009

EO-1 Science Validation Team (SVT)

- Instrument Team
  - Validate/re-establish and refine pre-launch characterizations
  - Provide technology validation
  - Participate on Science Validation Team

- NASA Selected Investigators
  - Conduct scene based instrument performance characterizations
  - Measure ability of instruments to make Landsat-like observations
  - Assess capability for addressing earth remote sensing applications
  - Assist in technology validation
  - Facilitate Commercial Applications (CRSP/SSC)

- International Collaborators
  - Argentina, Australia, Canada, Italy, Japan, Singapore

EO-1 Hyperion Instrument Team

Jay Pearlman	TRW Hyperion Scientist
Pete Jureke	TRW Calibration Lead
Rob Green	Hyperion Calibration Scientist
Tom Chrien	AVIRIS Calibration Guru
Steve Ungar	Mission Scientist
Lawrence Ong	MSO Calibration Lead
Brian Markham	Landsat Transfer Radiometer (LXR)
Jeff Mendehall	ALI Calibration Scientist
Jim Storey	Landsat Geometric Correction

SVT Investigator Research Topics

Southern Hemisphere Campaign: ARGENTINA – AUSTRALIA – ELSEWHERE

Research Topic	Principal Investigator
Forest Logging in Amazonia	Asner, G. P., **University of Colorado**
Desertification	Asner, G. P., **University of Colorado**
Forest Composition/Function	Martin, M., **University of New Hampshire**
Inter-Sensor Calibration	Huete, A. R., **University of Arizona, Tucson**
Arid Vegetation Abundance	Mustard, J. F., **Brown University.**
Tropical Forest Burn Scars	Liew, S. C., **National University of Singapore**
Forest Composition/Structure	Townsend, P. A., **University of Maryland**
Land Cover/Land Use	White, W. A., Crawford, M., **University of Texas at Austin**
Sustainable Forest Development	Goodenough, D. G., **Natural Resources Canada**
Monitoring Forest &	Gong, P., **University of California, Berkeley**
Non-Native Plant Species	McGwire, K. **Desert Research Institute**

SVT Investigator Research Topics (continued)

Research Topic	Principal Investigator
Invasive Plants: Chinese Tallow	Ramsey III, E. W., **USGS, Denver**
Invasive Leafy Spurge	Root, R., **USGS**
Agricultural Monitoring	Liang, S., **USDA, Maryland**
Inter-Satellite Comparison	Moran, M. S. **USDA, Tucson, Arizona**.
Fire Hazard Assessment	Roberts, D. A., **University of California, Santa Barbara**
Geologic Validation of Hyperion	Kruse, F. A., **AIG, Boulder, Colorado**
Volcanic Debris flow Hazards	Crowley, J. K., **USGS, Reno, Nevada**
Analysis of Hot Spots	Flynn, L., Wright, R., **University of Hawaii**
Environmental Monitoring of Coastal/Inland Water in Japan	Matsunaga, T., **Tokyo Institute of Technology.**
Oceanography, Pollution and Urban Mapping	Abrams, M. J., **JPL, California**; R. Bianchi and L. Alberotanza, **NRC, Italy**.
Glaciological Applications	Bindschadler, R., **NASA/GSFC, Maryland**

SVT Investigator Research Topics (continued)

Research Topic	Principal Investigator
Ecological Applications in Yellowstone National Park	Boardman, J. W., AIG, **Colorado**
Commercial Applications	Cassady, P. E., **Boeing, Washington**
Radiometric and Spatial Evaluation of ALI and Hyperion	Biggar, S. F., Thome, K., **University of Arizona**
Atmospheric Correction	Carlson, B. E., **NASA /GISS, New York**
Atmospheric Correction and Sparse Vegetation Mapping	Goetz, A. F. H., **University of Colorado**
Australian Hyperspectral Calibration and Validation Sites	Jupp, D. L. B., **CSRIO, Australia**
Integrated Assessment of EO-1 and Landsat Instrument Suites	Meyer, D. J., **EDC, South Dakota**
Canopy Temperature Estimation	Smith, J. A., **NASA GSFC, Maryland**
Lunar Calibration	Kieffer, H., **USGS, Flagstaff, AZ**

EO-1 Calibration Strategy

- Prelaunch
  - Calibrate and characterize (component and system level)
  - Characterize the calibration and characterization
  - Ensure conformity with, and comparison against, NMI laboratory standards
- Post-launch
  - Lamps
  - **Solar**
  - Lunar (astronomical)
  - Vicarious
  - “Special Targets” (limb scanning, active illumination)
  - Statistical (trending, 90° yaw)
  - Direct comparison against other satellites

CALIBRATION MEASUREMENTS STRATEGY

FOR PASSIVE OPTICAL (0.35-3.5 μm) SYSTEMS

OBSERVING SYSTEM CATEGORY

MS ≡ Multi-Spectral

WIS ≡ Wedge Imaging Spectrometer

GIS ≡ Grating Imaging Spectrometer

OBSERVING SYSTEM PARAMETERS

$F(\lambda)$ ≡ Spectral response function

R_N ≡ Radiometric response for detector N

S_o ≡ Dark response

$(x,y)_N$ ≡ Geometric response (detector pointing vectors)

MTF ≡ Modulation transfer function

CALIBRATION MEASUREMENTS STRATEGY

	PARAMETER														
	$F(\lambda)$			R_N			S_o			$(x, y)_N$			MTF		
	MS	WIS	GIS	MS	WIS	GIS	MS	WIS	GIS	MS	WIS	GIS	MS	WIS	GIS
COMPONENT TESTS AND ANALYSIS	●	○	—	○	○	○	○	○	○	—	—	—	○	○	○
SUBSYSTEM TESTS: TELESCOPE, GIS, WIS AND MS/PAN	○	●	○	○	○	○	○	○	○	●	●	○	○	○	○
INSTRUMENT LEVEL LABORATORY TESTS	○	○	●	●	●	●	○	○	○	○	○	●	●	●	●
ON-ORBIT MEASUREMENTS															
- SOLAR DIFFUSER	—	—	—	●	●	●	○	○	○	—	—	—	—	—	—
- CLOSED APERTURE COVER	—	—	—	—	—	—	●	●	●	—	—	—	—	—	—
- INTERNAL SOURCES	—	—	—	○	○	○	—	—	—	—	—	—	—	—	—
- LUNAR SCANS	—	—	—	○	○	○	○	○	○	—	—	—	○	○	○
- EARTH SCENES	—	○	○	○	○	○	—	—	—	○	○	○	○	○	○

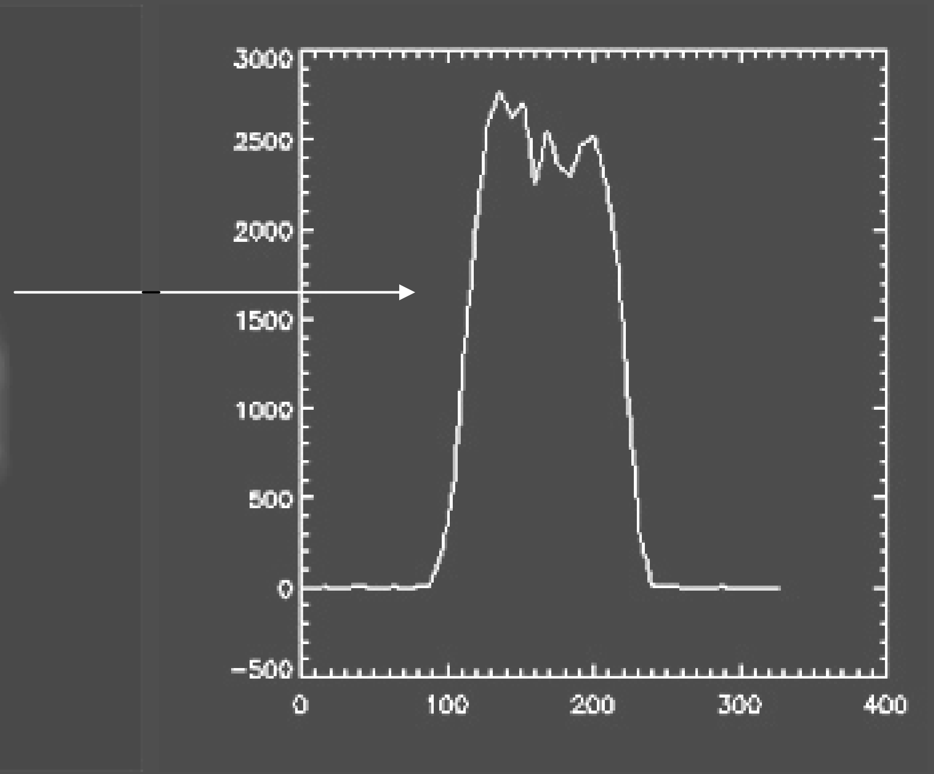
● PRIMARY MEASUREMENT ○ SECONDARY MEASUREMENT

CALIBRATION MEASUREMENTS STRATEGY

	PARAMETER														
	$F(\lambda)$			R_N			S_o			$(x, y)_N$			MTF		
	MS	WIS	GIS	MS	WIS	GIS	MS	WIS	GIS	MS	WIS	GIS	MS	WIS	GIS
COMPONENT TESTS AND ANALYSIS	●	○	—	○	○	○	○	○	○	—	—	—	●	○	○
SUBSYSTEM TESTS: TELESCOPE, GIS, WIS AND MS/PAN	○	●	○	○	○	○	○	○	○	●	●	○	○	○	○
INSTRUMENT LEVEL LABORATORY TESTS	○	○	●	●	●	●	○	○	○	○	○	●	●	●	●
ON-ORBIT MEASUREMENTS															
- SOLAR DIFFUSER	—	—	—	●	●	●	○	○	○	—	—	—	—	—	—
- CLOSED APERTURE COVER	—	—	—	—	—	—	●	●	●	—	—	—	—	—	—
- INTERNAL SOURCES	—	—	—	○	○	○	—	—	—	—	—	—	—	—	—
- LUNAR SCANS	—	—	—	○	○	○	○	○	○	—	—	—	○	○	○
- EARTH SCENES	—	○	○	○	○	○	—	—	—	○	○	○	○	○	○

● PRIMARY MEASUREMENT ○ SECONDARY MEASUREMENT

Image Quality (Edge Sharpness)



Lunar Image Expanded by a Factor of 8

Horizontal Slice Through Expanded Lunar Image Rise and Fall About 1 Pixel in Normal Image.

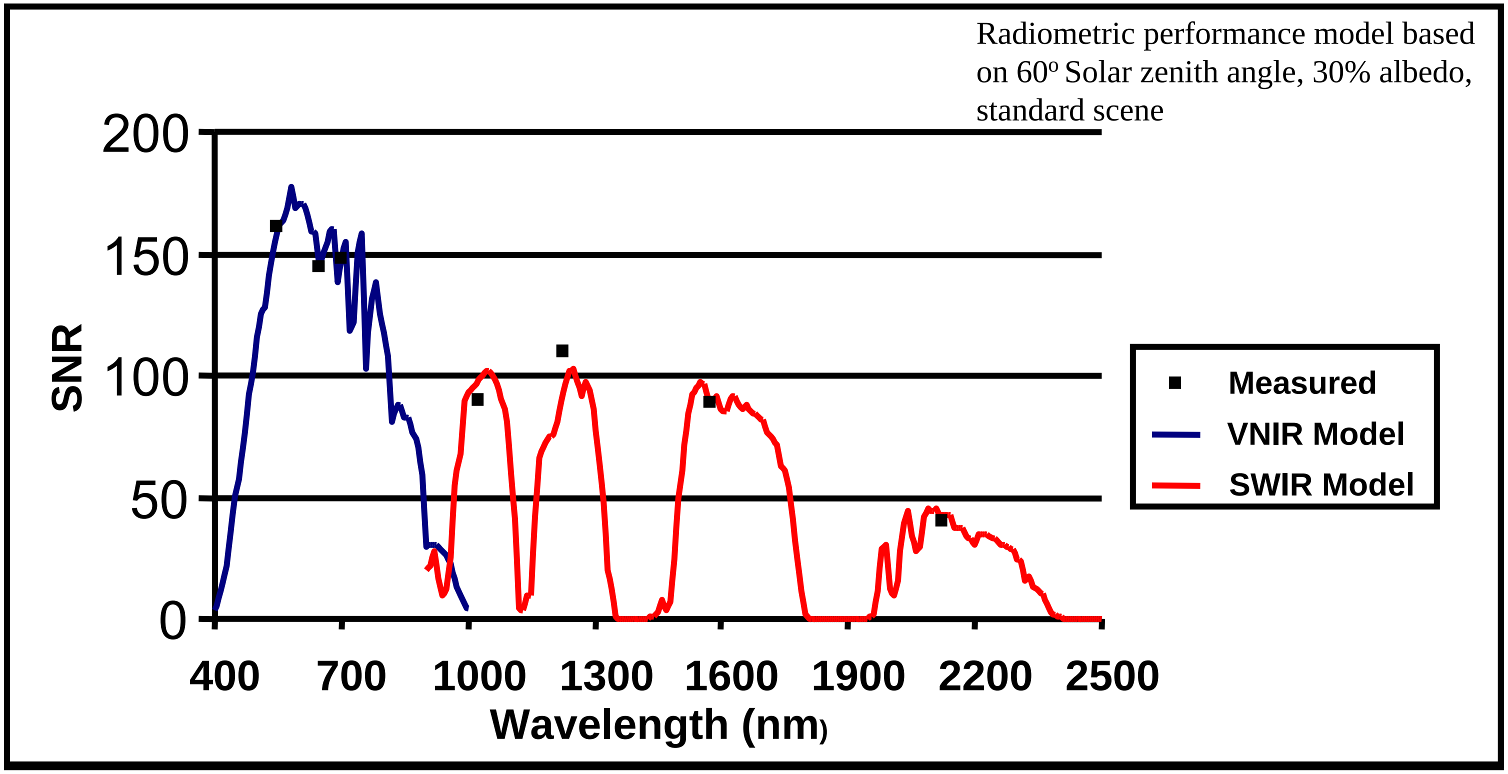
Focus : Lunar Edge

Hyperion Characteristics

Characteristic	Pre-launch Cal	On-orbit Cal
GSD (m)	29.88	30.38
Swath (km)	7.5	7.75
No. of Spectral Channels	220	200 (L1 data)
VNIR SNR (550-700nm)	144-161	140-190
SWIR SNR (~1225nm)	110	96
SWIR SNR (~2125nm)	40	38
VNIR X-trk Spec. Error	2.8nm@655nm	2.2nm
SWIR X-trk Spec. Error	0.6nm@1700nm	0.58
Spatial Co-Reg: VNIR	18% @ Pix #126	*
Spatial Co-Reg: SWIR	21% @ Pix #131	*
Abs. Radiometry(1Sigma)	<6%	3.40%
VNIR MTF @ 630nm	0.22-0.28	0.23-0.27
SWIR MTF @ 1650nm	0.25-0.27	0.28
VNIR Bandwidth (nm)	10.19-10.21	*
SWIR Bandwidth (nm)	10.08-10.09	*

*** Consistent with Pre-Launch Calibration or not measured**

Hyperion SNR



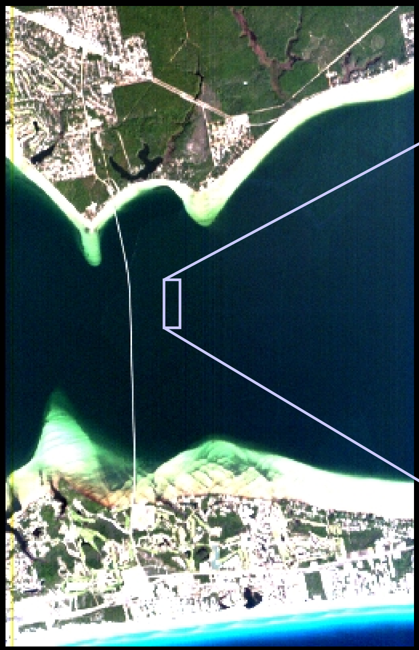
Hyperion Measured SNR						
550 nm	650 nm	700 nm	1025 nm	1225 nm	1575 nm	2125 nm
161	144	147	90	110	89	40

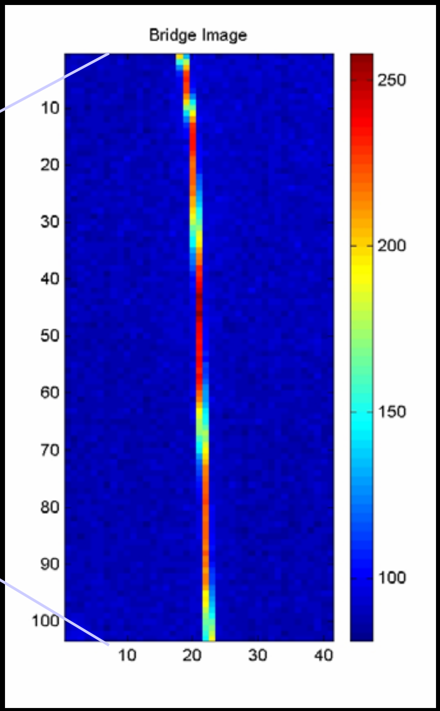
Post Launch MTF Validation Approach

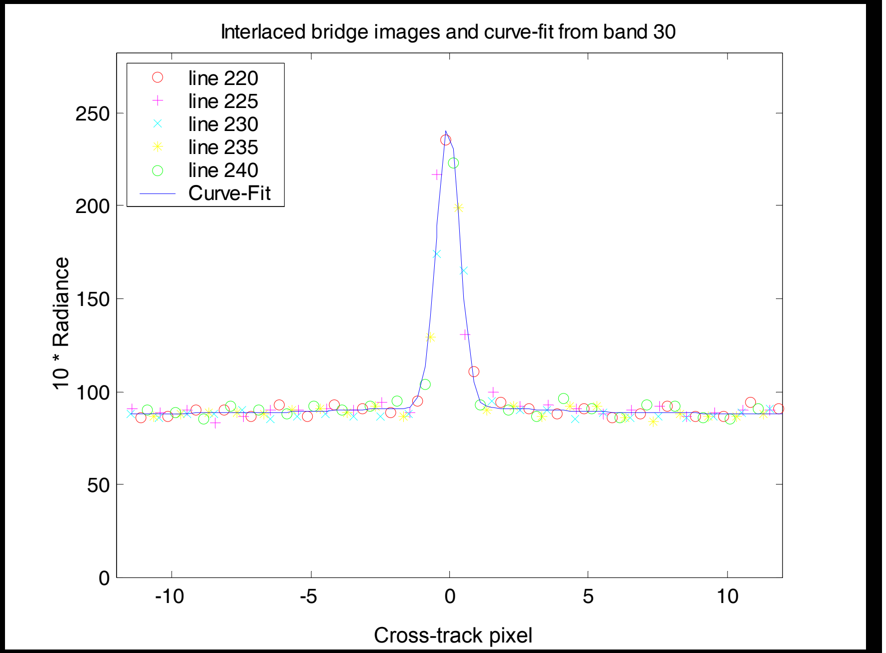
- Calculate cross-track and in-track MTF using a step response and impulse response example
- Results of on-orbit analysis give good agreement with the pre-launch laboratory measurements

Example: Cross-track MTF

- Scene is Port Eglin from Dec 24, 2000. Bridge is the Mid-bay bridge . Bridge width is 13.02 meters.
- Bridge angle to the S/C direction is small so every 5th line is used to develop the high resolution bridge image.
- MTF result at Nyquist is between 0.39 to 0.42 while the pre-flight measurement was 0.42.



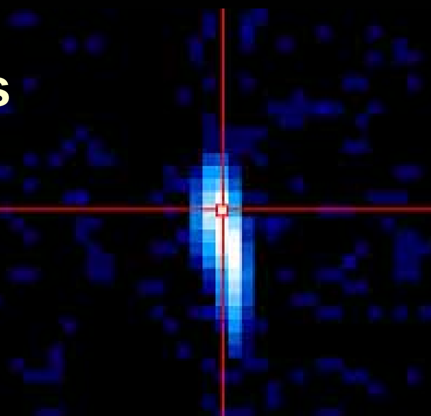




Special targets for characterization

Searchlights
-California

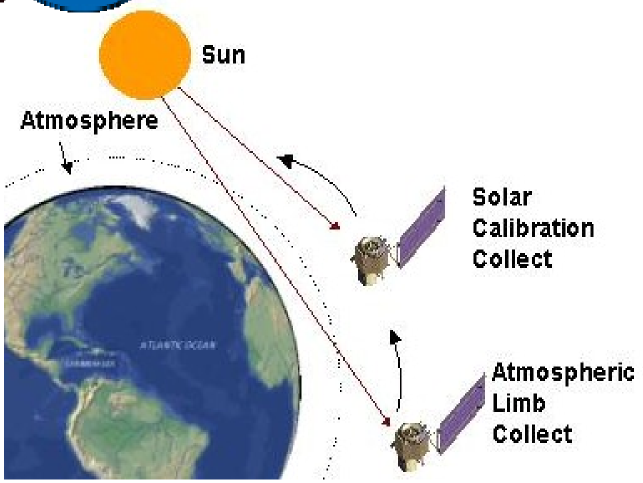
Planets
-Venus



Gas Flares
-Moomba

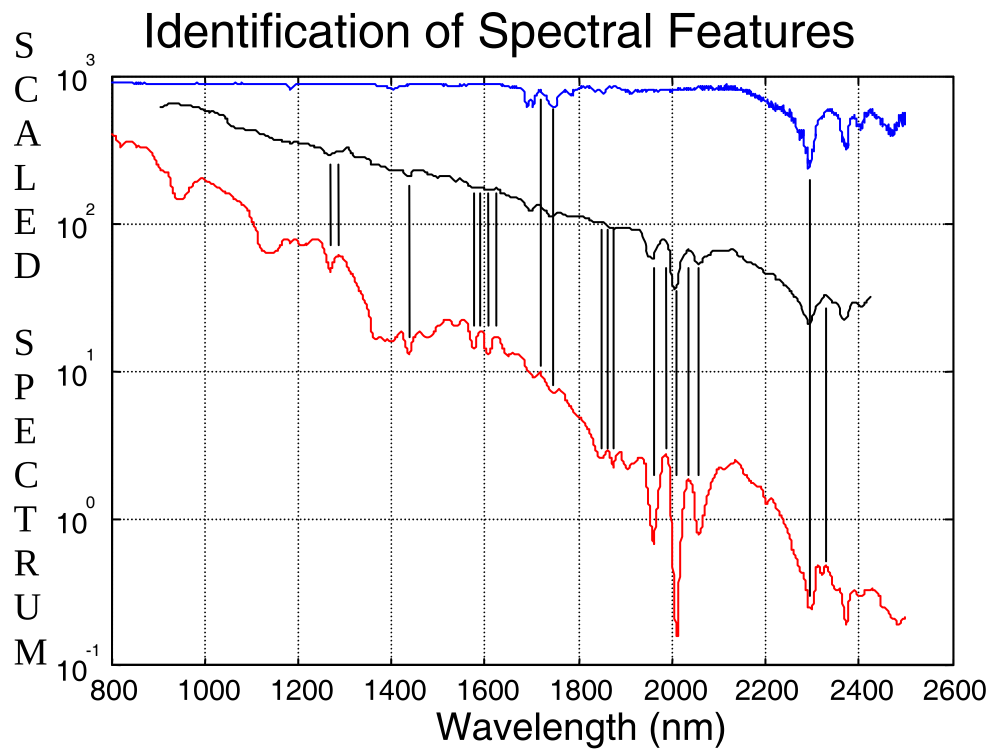
90 deg
Yaw

Spectral Calibration –SWIR



Process:

- Create Pseudo-Hyperion Spectra from reference: Modtran-3 for atmosphere, and Cary 5 & FTS measurements for diffuse reflectance of the cover
- Correlate Spectral Features: band number units of Hyperion max/min correlated with reference wavelength of max/min
- Calculate Band to Wavelength map: apply low order polynomial to fit the data over the entire SWIR regime



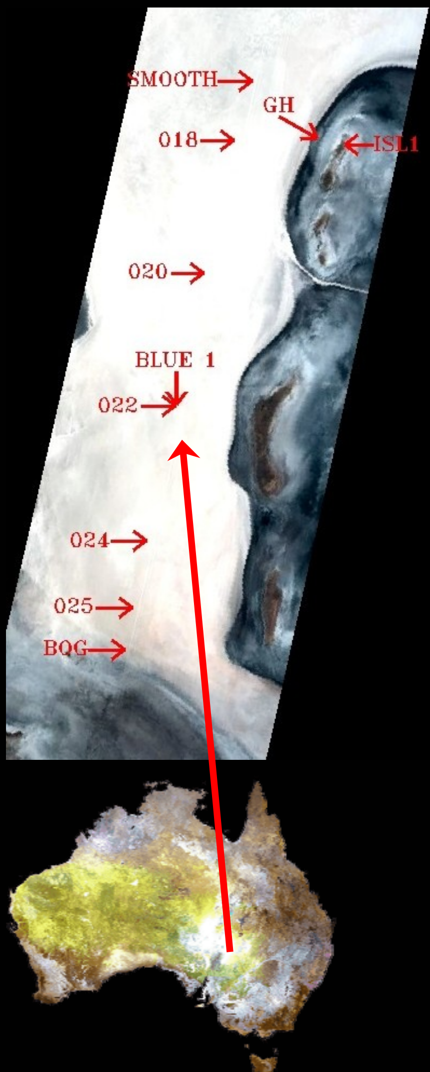
Hyperion Spectra – red

Atmospheric Reference – black

Diffuse Reflectance of cover – blue

Desert Sites used for Vicarious Calibration

Lake Frome

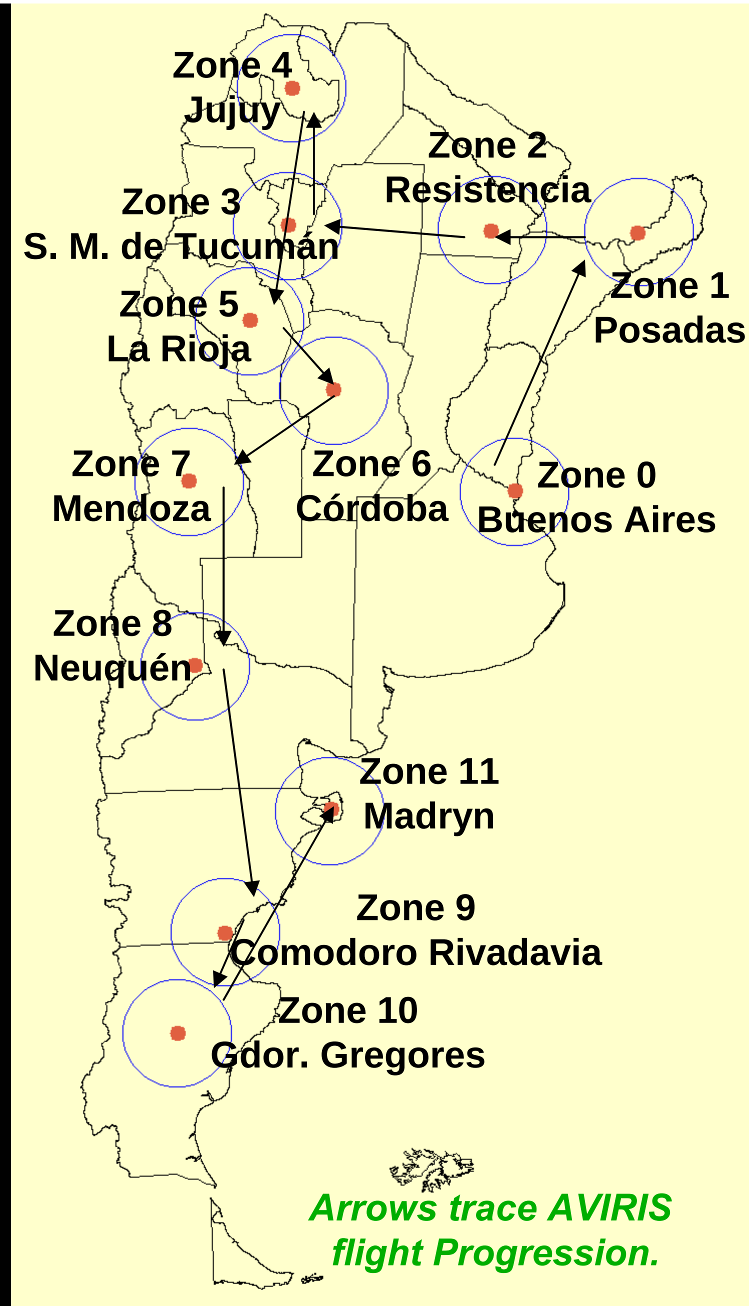


RR Valley

Arizaro/Barreal Blanco

EO-1 Accelerated Mission Southern Hemisphere Field Campaigns

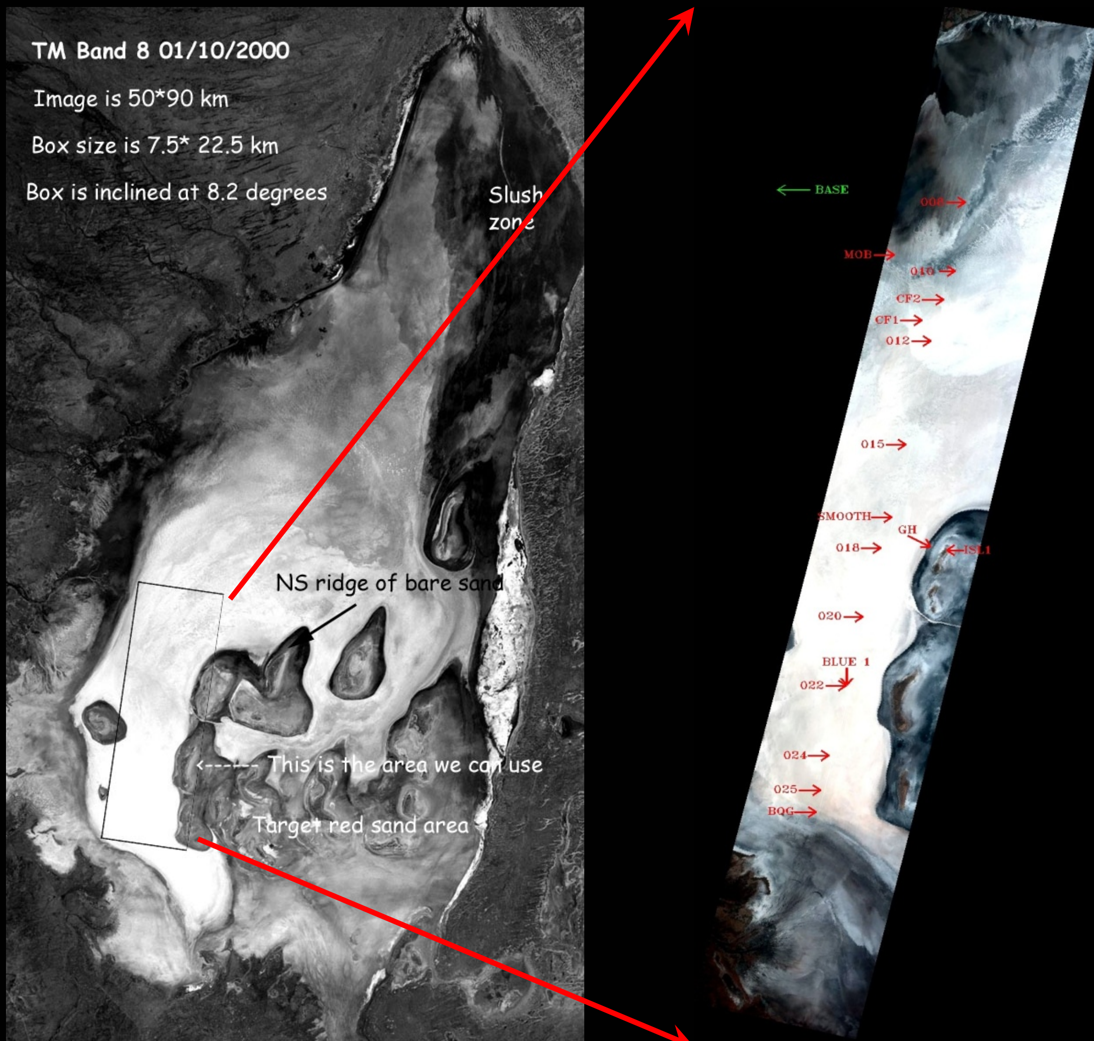
January – February 2001



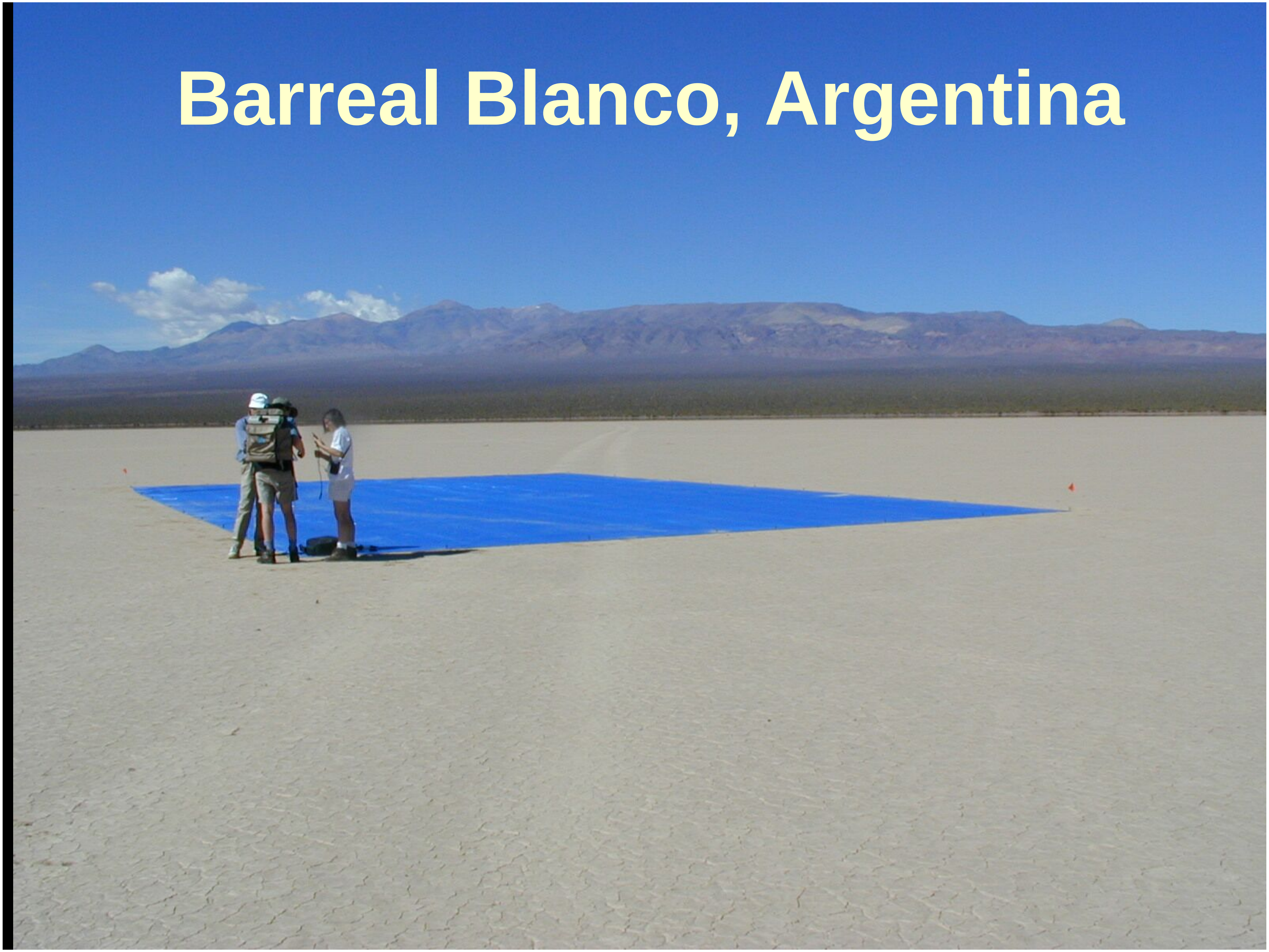
Australian Test Sites

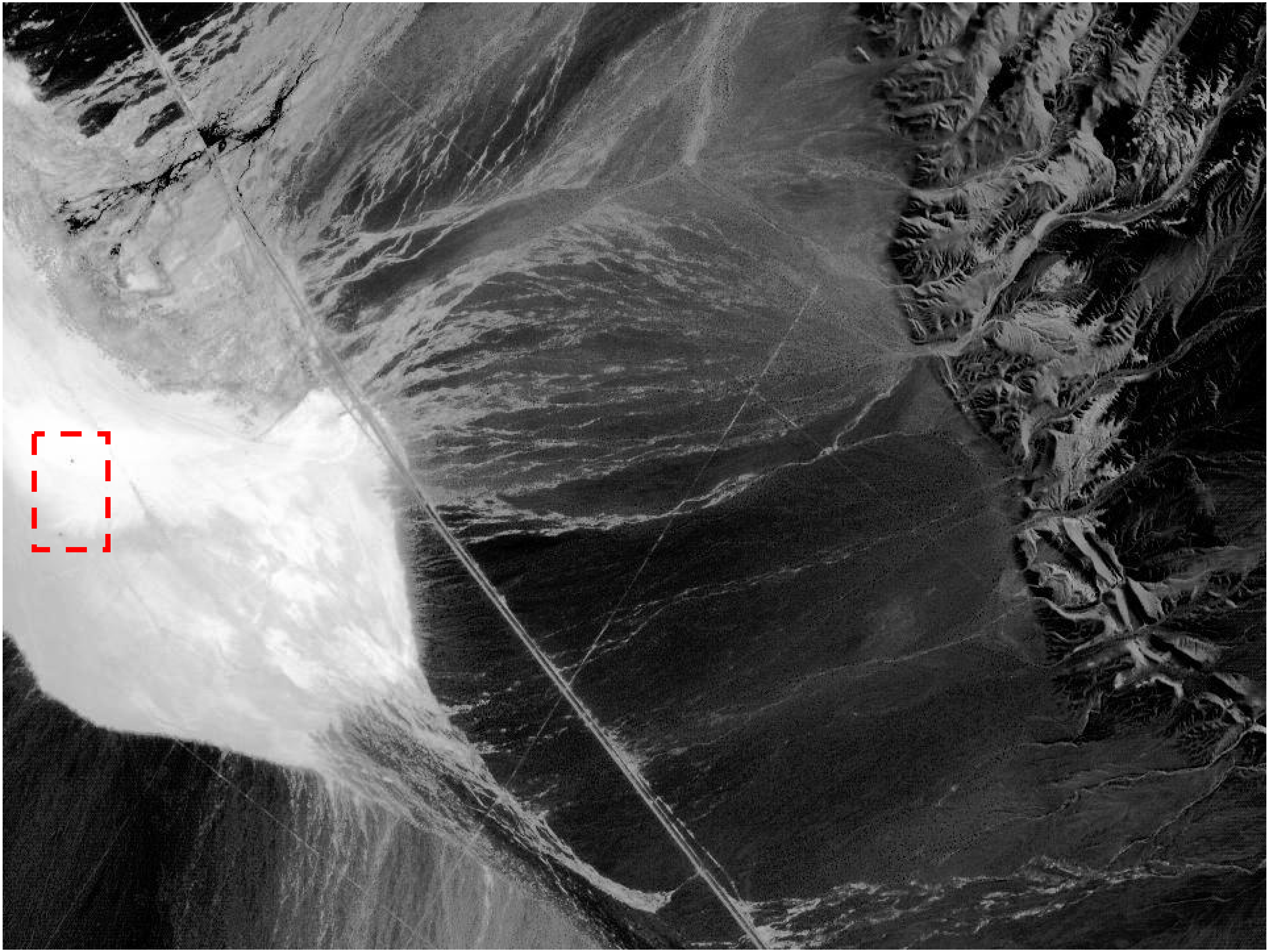
Argentine/AVIRIS Sites

Lake Frome Calibration Site



Barreal Blanco, Argentina





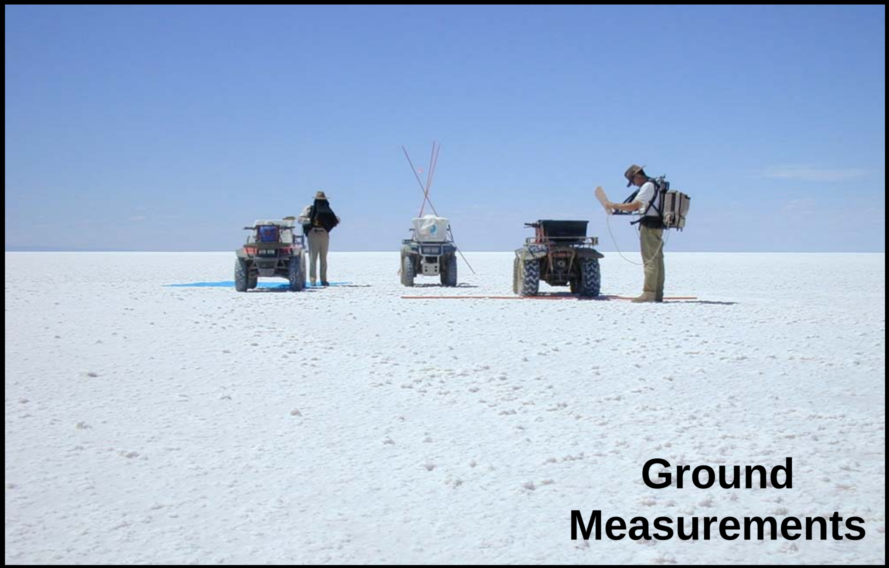

AVIRIS
Twin Otter

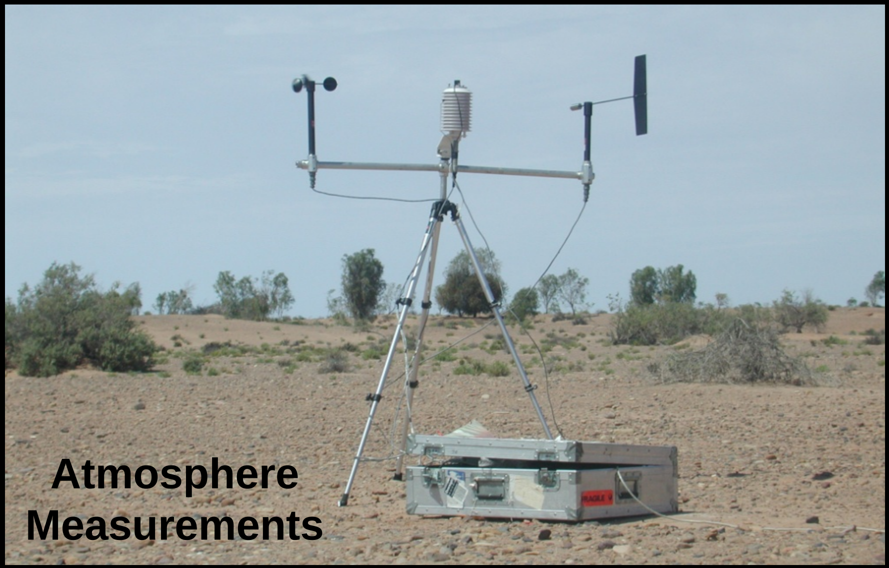
Maricopa, AZ

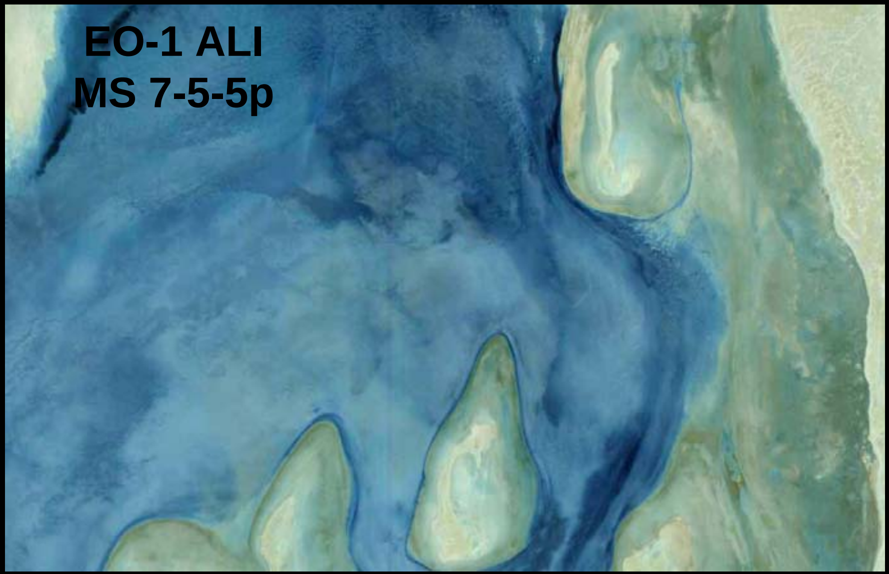
Deployment coincident with EO-1 and L7 ETM+ overpasses


Venice field site

Ground Truth Site: Lake Frome, Au







Radiometric Calibration

- Ground Truth Referencing
  - Lake Frome, Au ground truth collected by CSIRO.
  - Barreal Blanco and Arizario Argentina ground truth collected by U. of Arizona and U. of Colorado
  - Ivanpah Playa ground truth collected by U. of Arizona
  - AVIRIS underflights

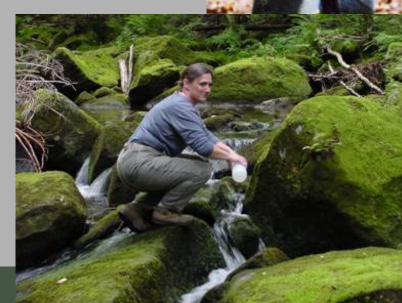
EVEOSD Vegetation Sampling

Field Data Collection

Forest Growth

Leaf & Canopy Chemistry

Canopy Structure



Soil & Water Chemistry

The EO-1 2001 Field Campaign

AVIRIS Overflights

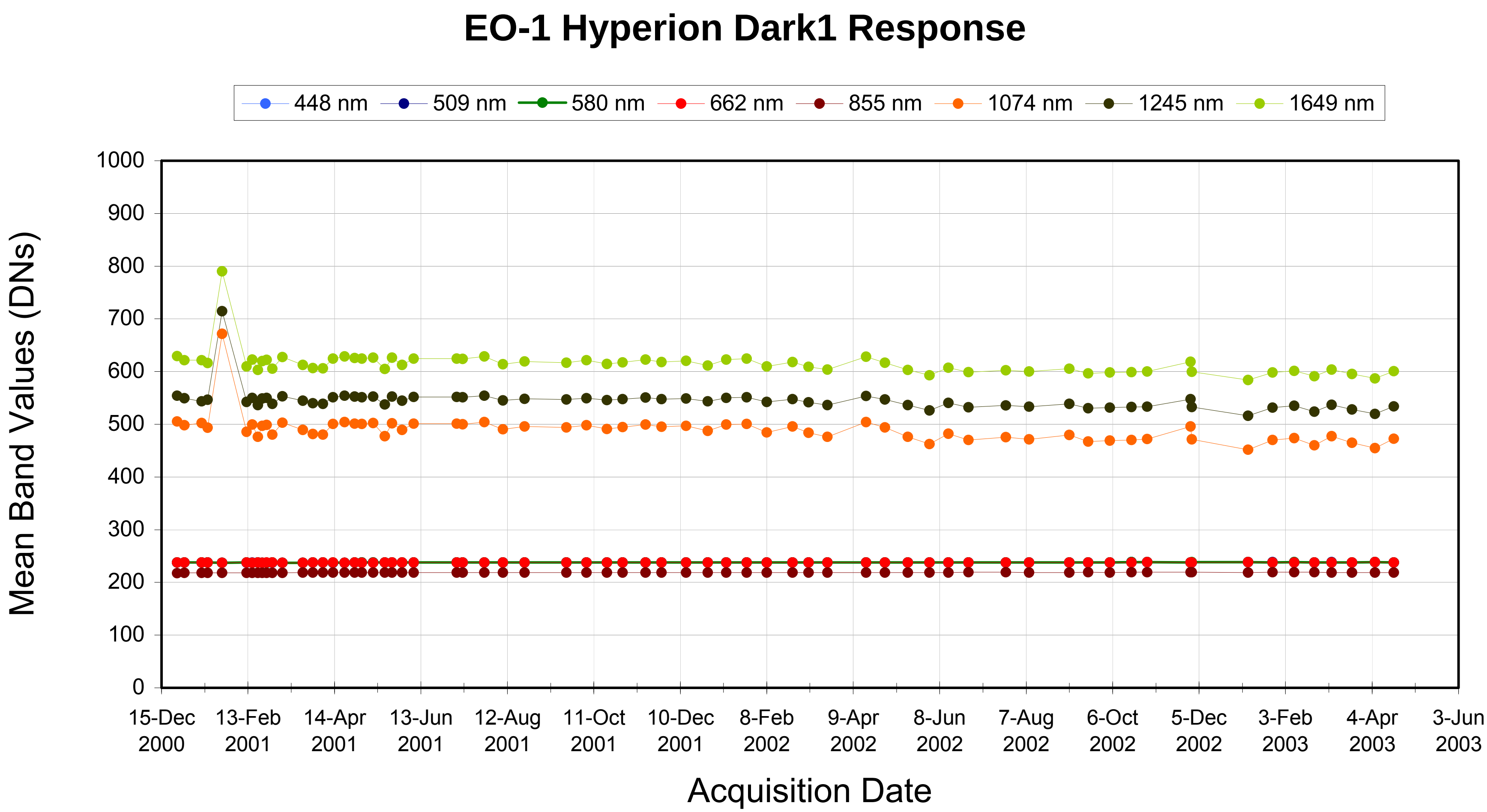
The EO-1 2001 Field Campaign

The EO-1 2001 Field Campaign

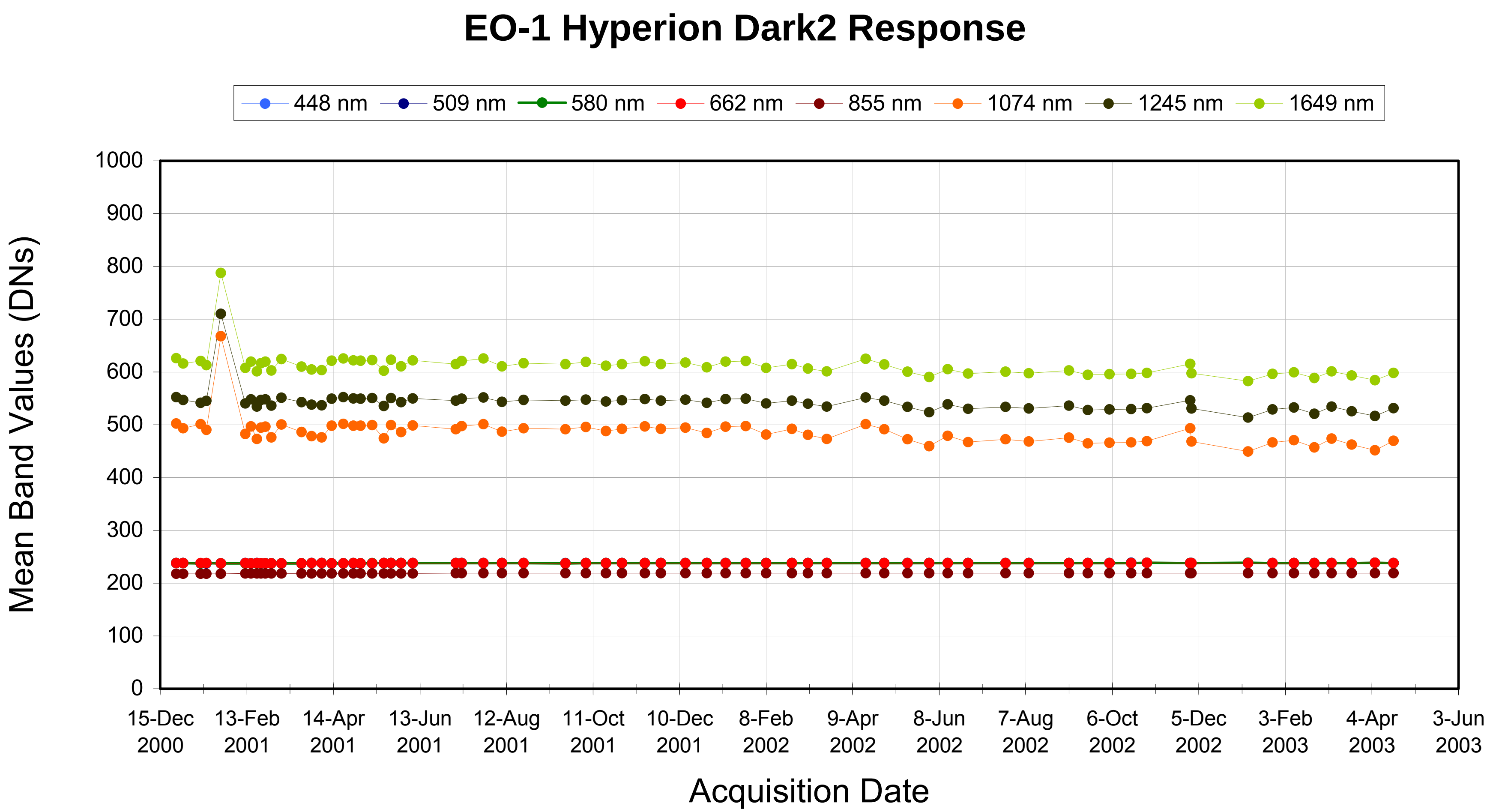
Central Australia

The EO-1 2002 Field Campaign

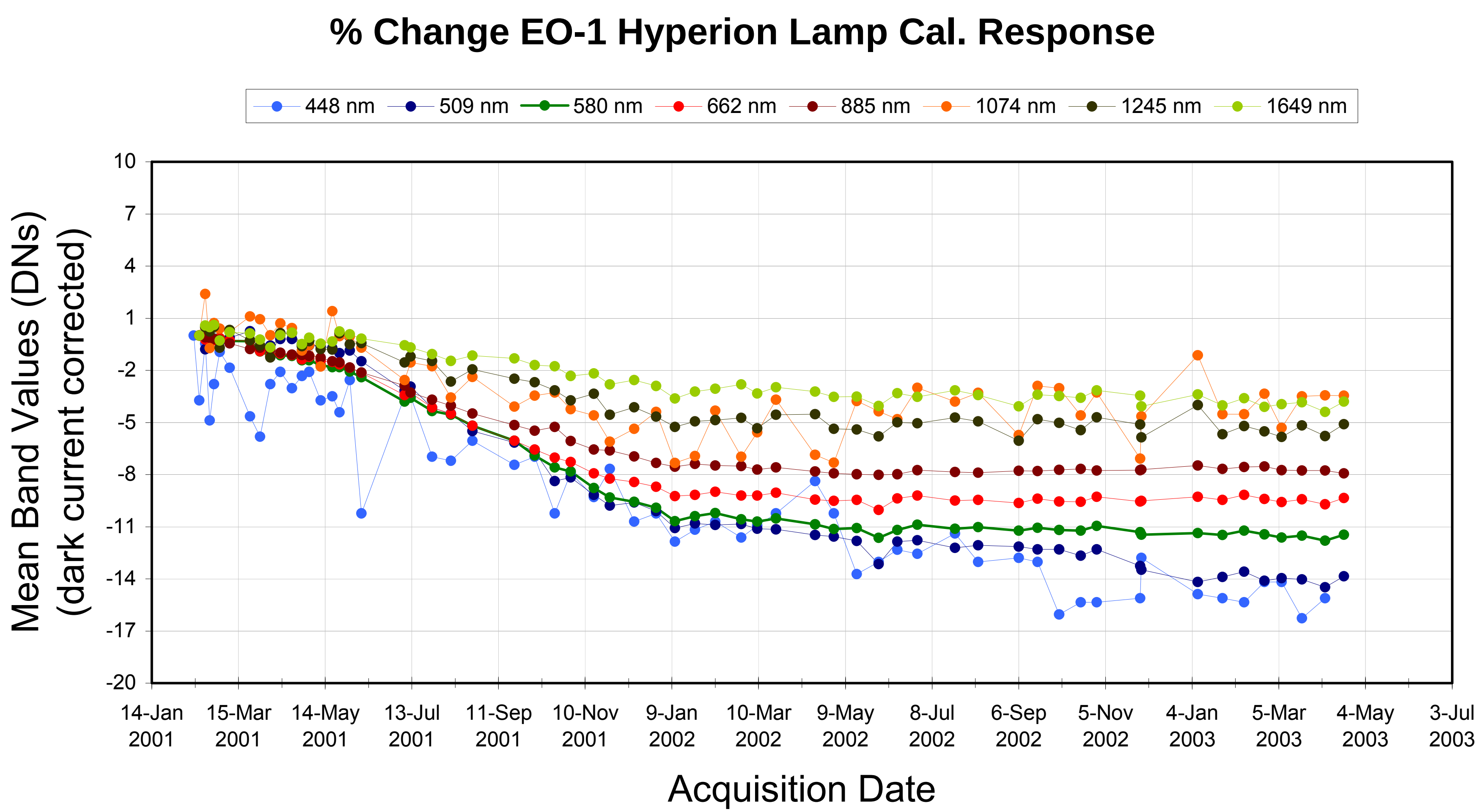
Salar de Arizaro - 11 Dec. 2002



EO-1 Hyperion Dark1 Response
448 nm
509 nm
580 nm
662 nm
855 nm
1074 nm
1245 nm
1649 nm
Mean Band Values (DNs)
1000
900
800
700
600
500
400
300
200
100
0
15-Dec 2000
13-Feb 2001
14-Apr 2001
13-Jun 2001
12-Aug 2001
11-Oct 2001
10-Dec 2001
8-Feb 2002
9-Apr 2002
8-Jun 2002
7-Aug 2002
6-Oct 2002
5-Dec 2002
3-Feb 2003
4-Apr 2003
3-Jun 2003
Acquisition Date

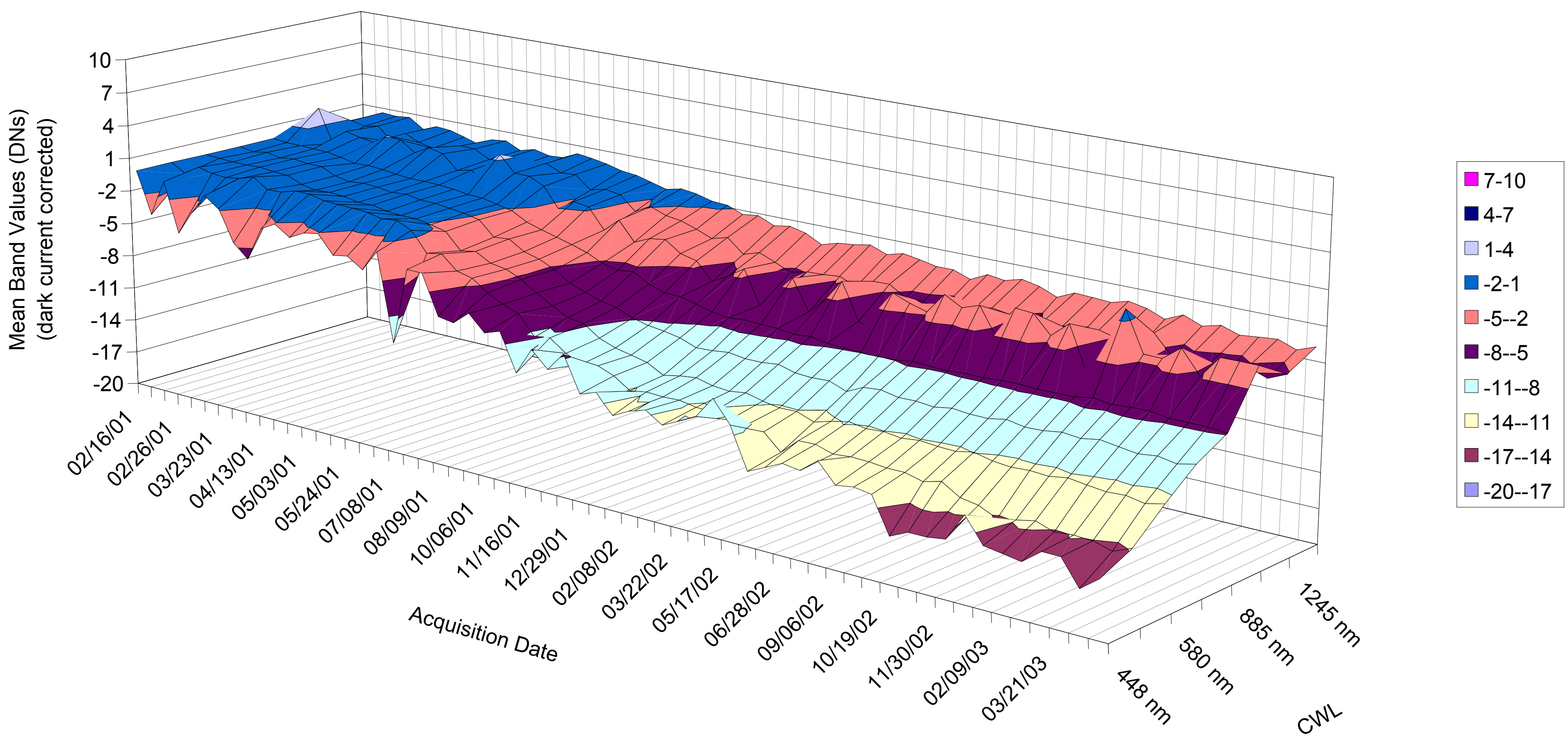


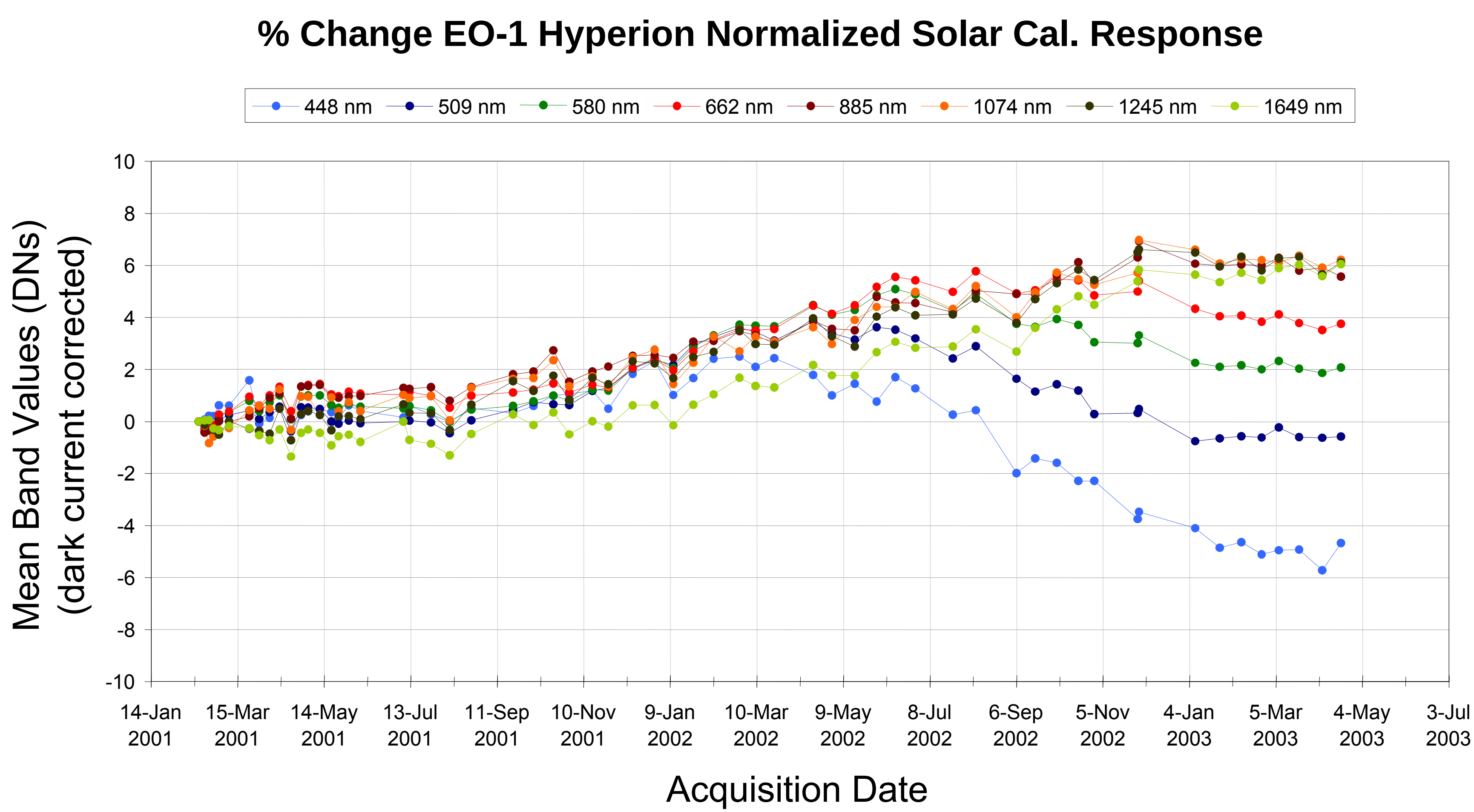
EO-1 Hyperion Dark2 Response
448 nm
509 nm
580 nm
662 nm
855 nm
1074 nm
1245 nm
1649 nm
Mean Band Values (DNs)
1000
900
800
700
600
500
400
300
200
100
0
15-Dec 2000
13-Feb 2001
14-Apr 2001
13-Jun 2001
12-Aug 2001
11-Oct 2001
10-Dec 2001
8-Feb 2002
9-Apr 2002
8-Jun 2002
7-Aug 2002
6-Oct 2002
5-Dec 2002
3-Feb 2003
4-Apr 2003
3-Jun 2003
Acquisition Date



% Change EO-1 Hyperion Lamp Cal. Response
448 nm
509 nm
580 nm
662 nm
885 nm
1074 nm
1245 nm
1649 nm
Mean Band Values (DNs)
(dark current corrected)
10
7
4
1
-2
-5
-8
-11
-14
-17
-20
14-Jan 2001
15-Mar 2001
14-May 2001
13-Jul 2001
11-Sep 2001
10-Nov 2001
9-Jan 2002
10-Mar 2002
9-May 2002
8-Jul 2002
6-Sep 2002
5-Nov 2002
4-Jan 2003
5-Mar 2003
4-May 2003
3-Jul 2003
Acquisition Date

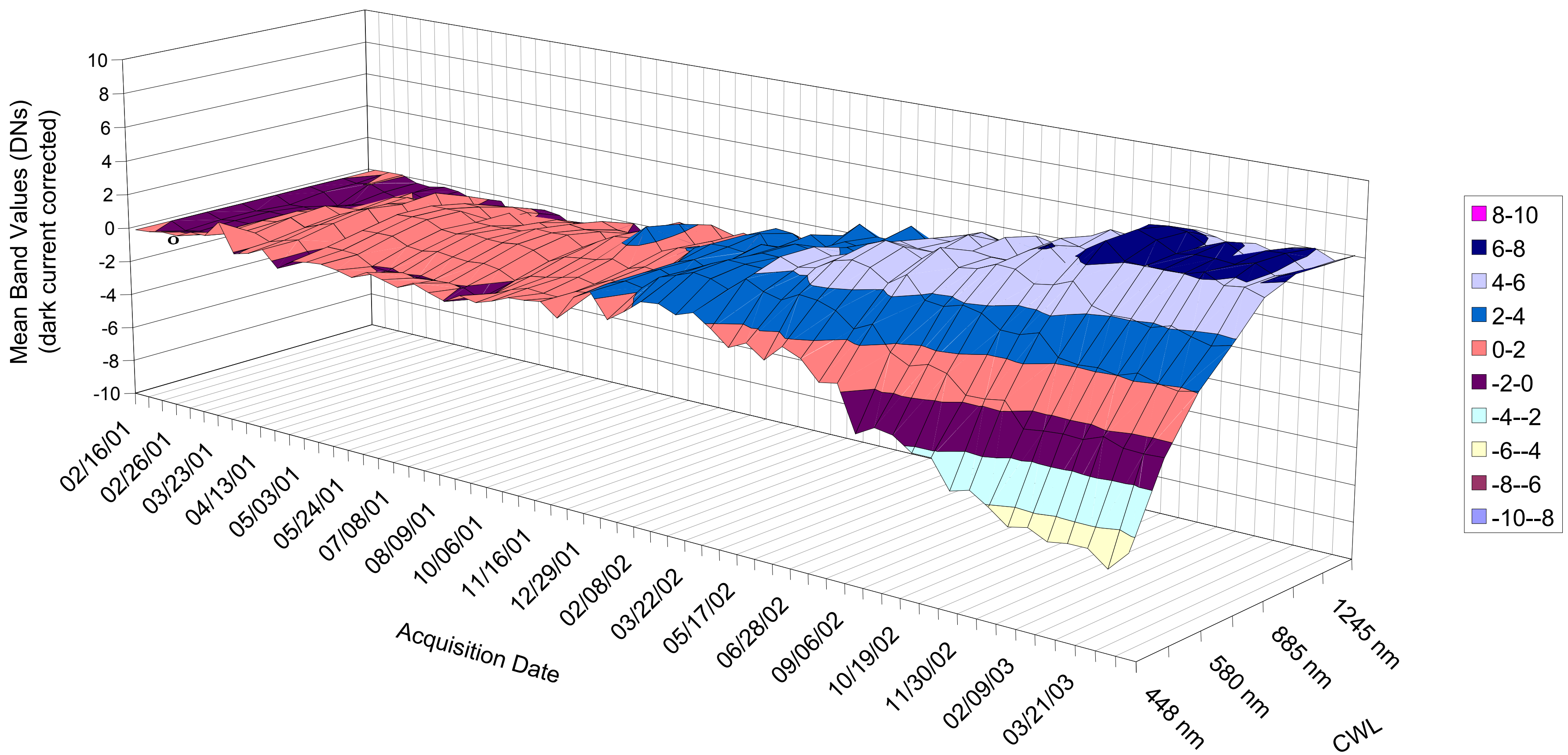
% Change EO-1 Hyperion Lamp Cal. Response

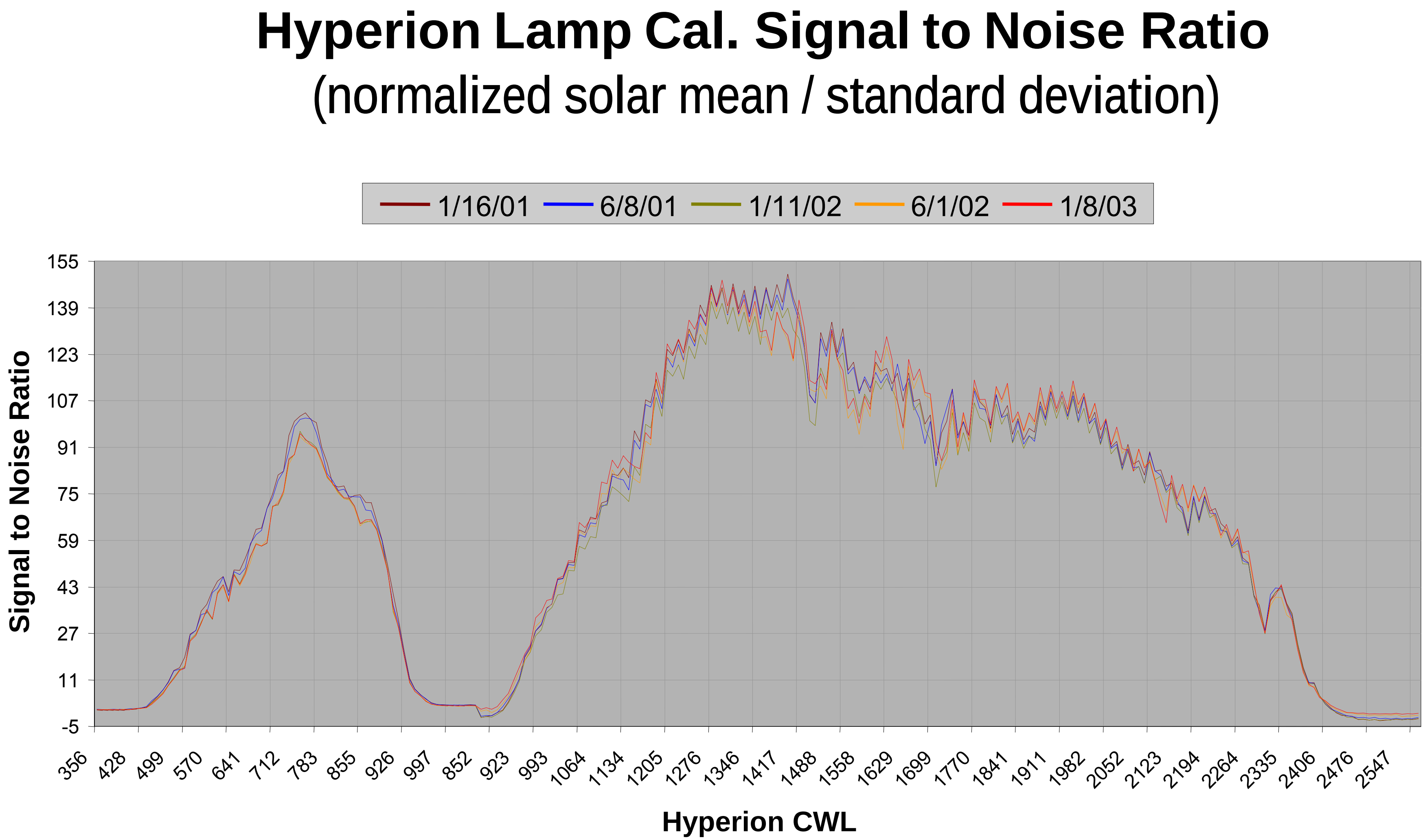




% Change EO-1 Hyperion Normalized Solar Cal. Response
448 nm
509 nm
580 nm
662 nm
885 nm
1074 nm
1245 nm
1649 nm
Mean Band Values (DNs)
(dark current corrected)
10
8
6
4
2
0
-2
-4
-6
-8
-10
14-Jan 2001
15-Mar 2001
14-May 2001
13-Jul 2001
11-Sep 2001
10-Nov 2001
9-Jan 2002
10-Mar 2002
9-May 2002
8-Jul 2002
6-Sep 2002
5-Nov 2002
4-Jan 2003
5-Mar 2003
4-May 2003
3-Jul 2003
Acquisition Date

% Change EO-1 Hyperion Solar Cal. Response (normalized for solar distance)

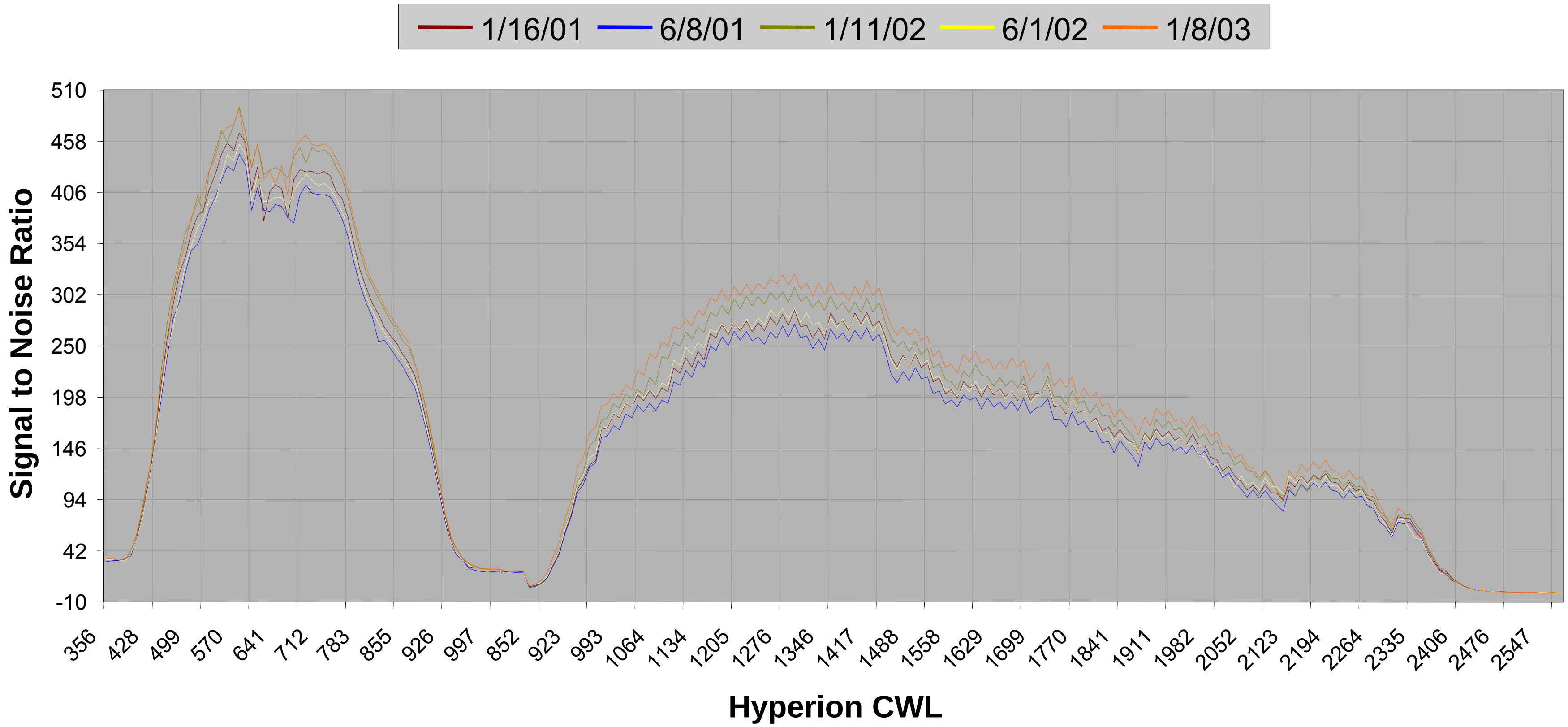




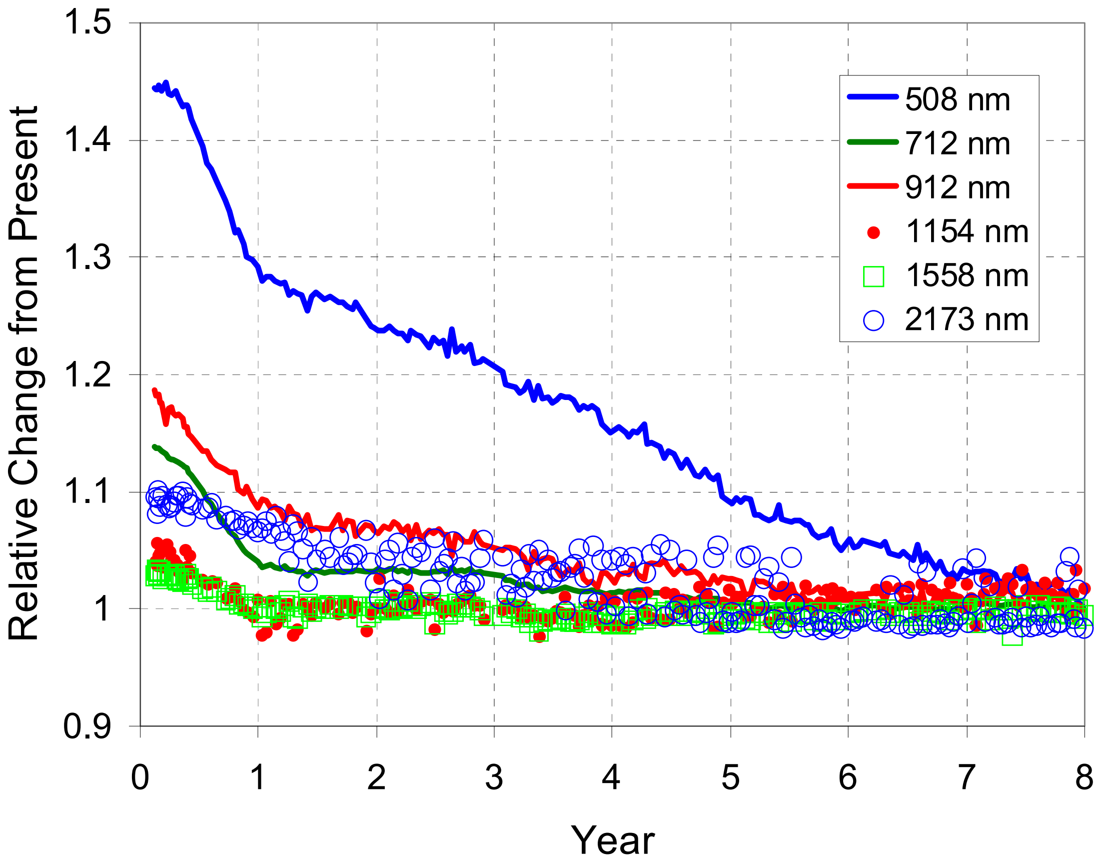
Hyperion Lamp Cal. Signal to Noise Ratio
(normalized solar mean / standard deviation)
1/16/01
6/8/01
1/11/02
6/1/02
1/8/03
Signal to Noise Ratio
155
139
123
107
91
75
59
43
27
11
-5
356
428
499
570
641
712
783
855
926
997
852
923
993
1064
1134
1205
1276
1346
1417
1488
1558
1629
1699
1770
1841
1911
1982
2052
2123
2194
2264
2335
2406
2476
2547
Hyperion CWL

Hyperion Solar Cal. Signal to Noise Ratio

(normalized solar mean / standard deviation)

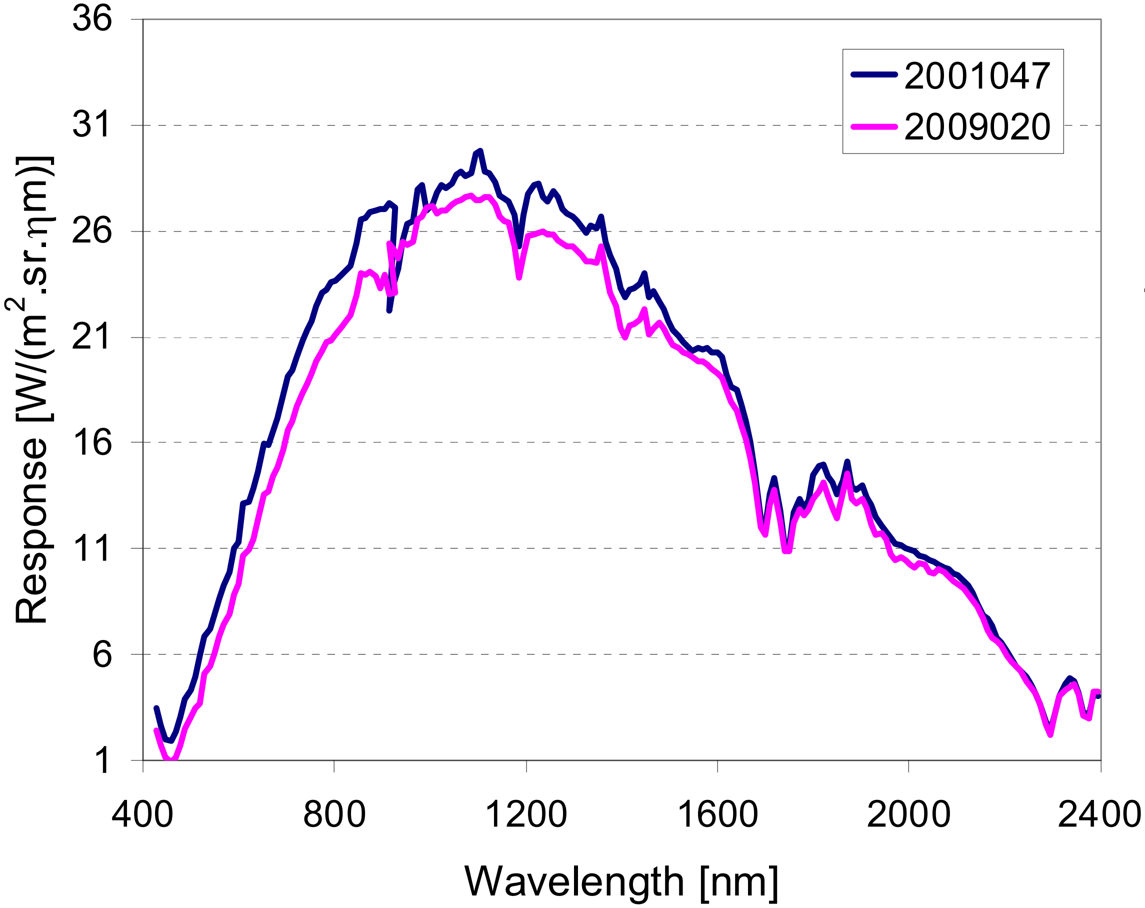


Hyperion Lamp Trends



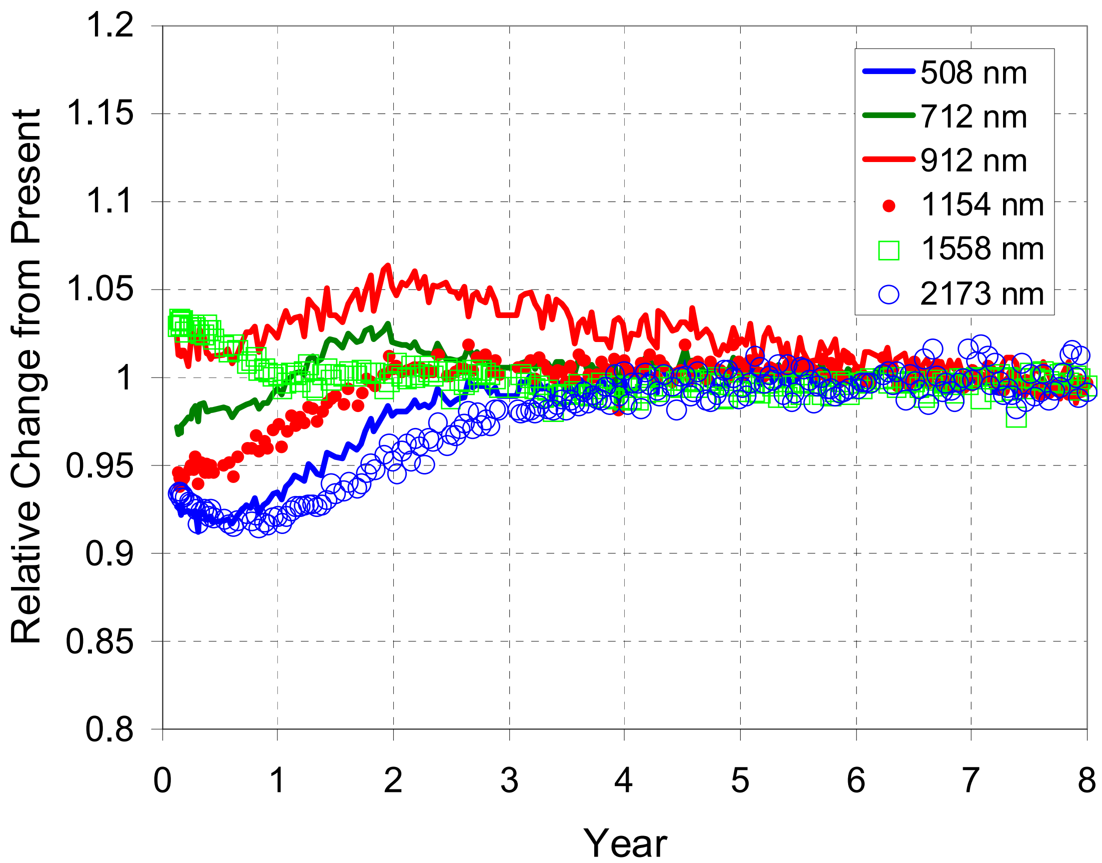
- There is a significant initial decrease in lamp output during the first year of operation.
- The lower wavelength channels (< 500 nm) exhibits the largest change.
- Changes in the SWIR channesl are less than 10%.
- For most bands the lamps appears to achieve some stability after year 4.

Hyperion Lamp Spectra



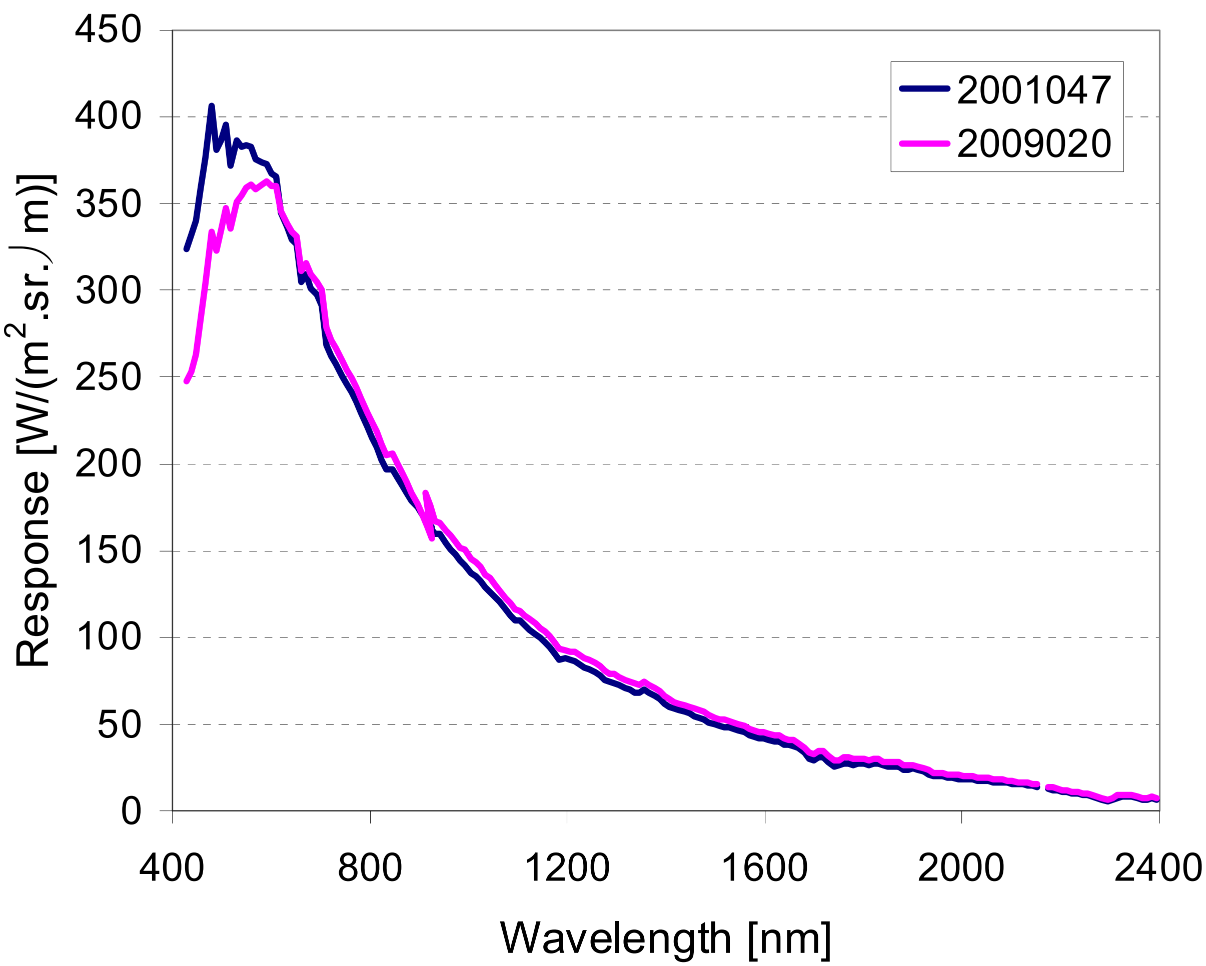
Lamps intensity shows some degradation over the entire spectral range over the 8 years of operation

Hyperion Solar Trends



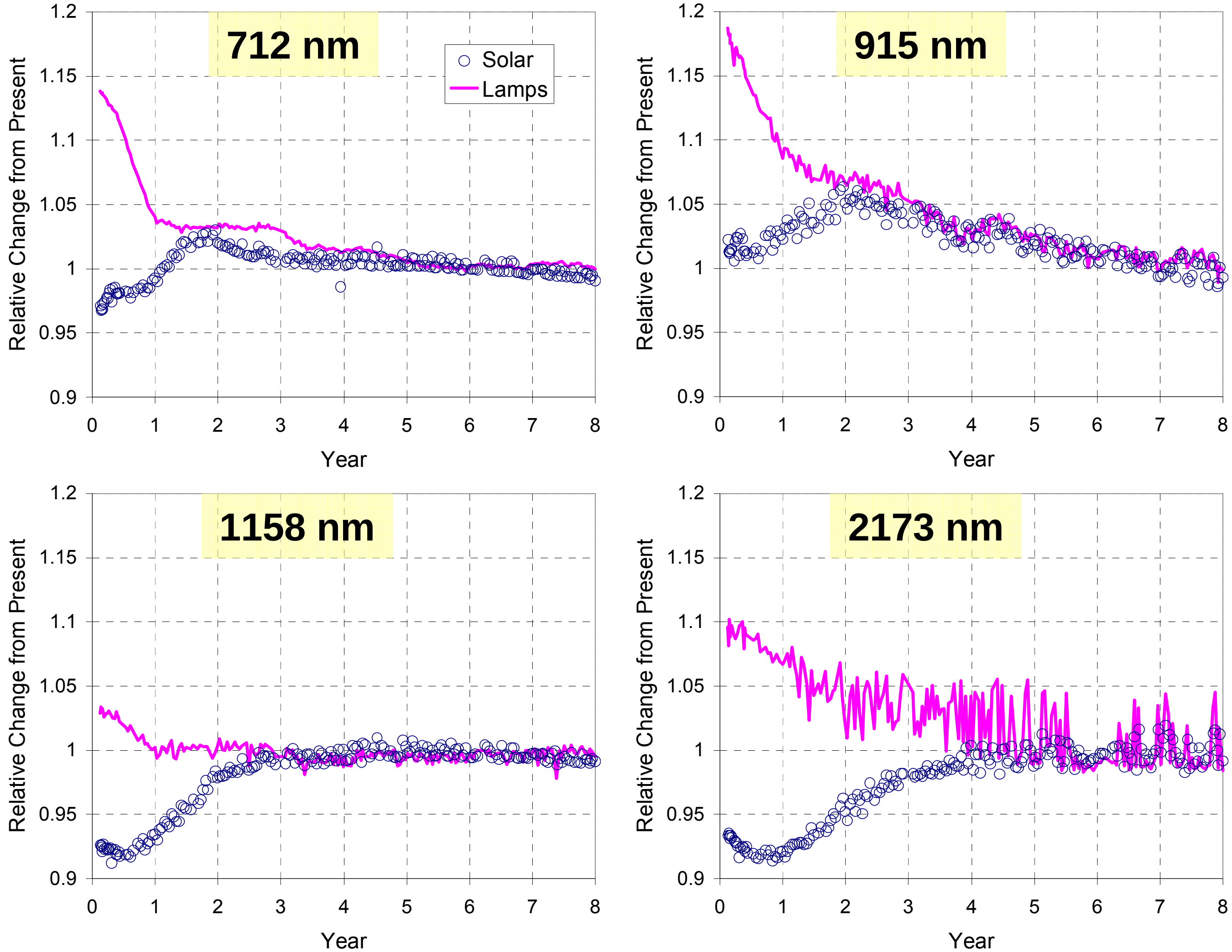
- Changes in the solar panel on orbit are most pronounced during the first 3 years
- Most of the variations are within +/1 5% except for the longer wavelengths.
- For most bands the lamps appears to achieve some stability after year 4.

Solar Panel Spectra



Spectra of the solar panel show large degradation in the shorter wavelengths

Comparing Lamp & Solar Trends



Although inconsistent during early mission life, the solar and Lamp trends agree well after 4 years in orbit

Radiometric Calibration

- Lunar Calibration
  - Calculate Lunar spectral irradiance ($E_M(\lambda)$)
  - Compare to the USGS Robotic Lunar Observatory lunar irradiance model

- Intersatellite Comparison
  - Landsat 7
  - Sites Compared
    - CA Super Site Jan 2001
    - Railroad Valley Jan 2001
    - Lake Frome Jan 2001
  - Compared Bands 1, 2, 3, 5, 7 due to similarity of spectral responses
  - Terra comparisons forthcoming

Typical Lunation (aka Lunar Cycle)

EO-1 Lunar Cal/Val

USGS Robotic Lunar Observatory

ROLO Model

$$I_k = \Omega_p \sum_{i=1}^{N_p} L_{i,k}$$

$$A_k = \frac{\pi \cdot I_k}{\Omega_M E_k}$$

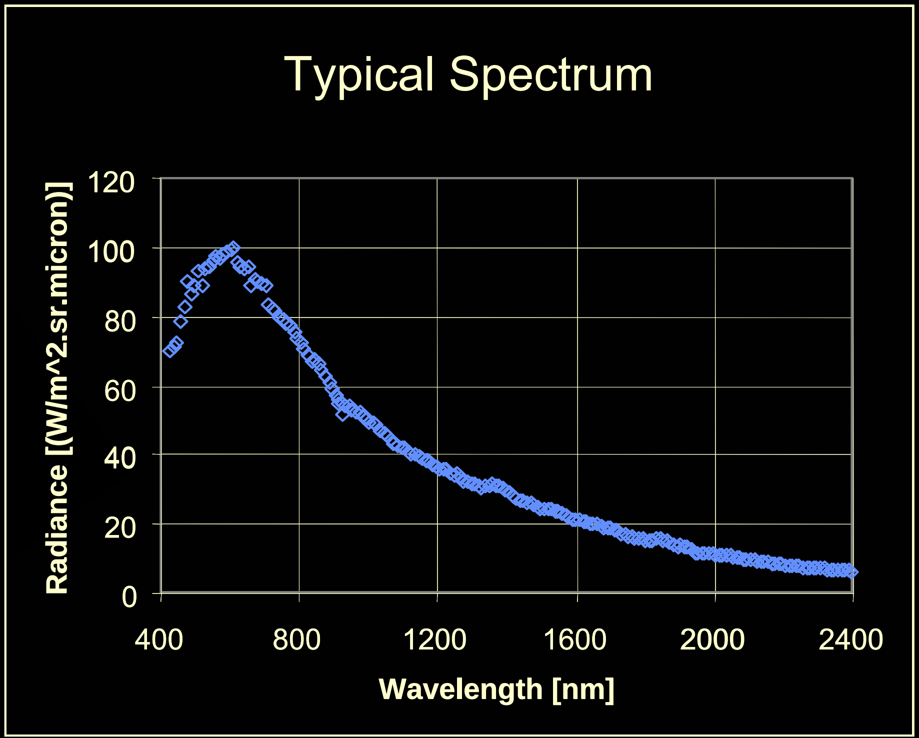
1 total lunation takes ~29.5 days

EO-1 views the moon monthly

(EO-1 ALI Pan band)

Full Moon

(EO-1 Hyperion)



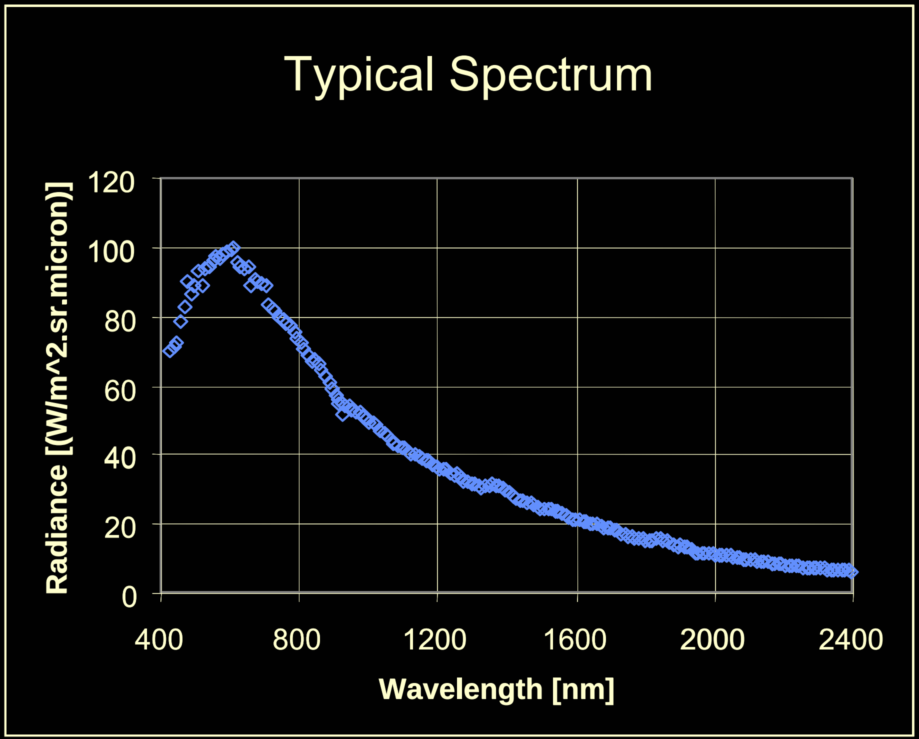
Cumulative Spectral Radiance

EO-1 views the moon monthly

(EO-1 ALI Pan band)

Full Moon

(EO-1 Hyperion)



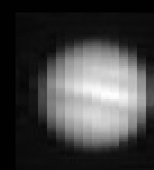
Cumulative Spectral Radiance

Extra-terrestrial calibration!

(Views with the EO-1 ALI Pan band)

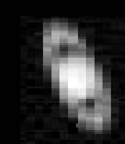
Venus

Full Moon



Jupiter

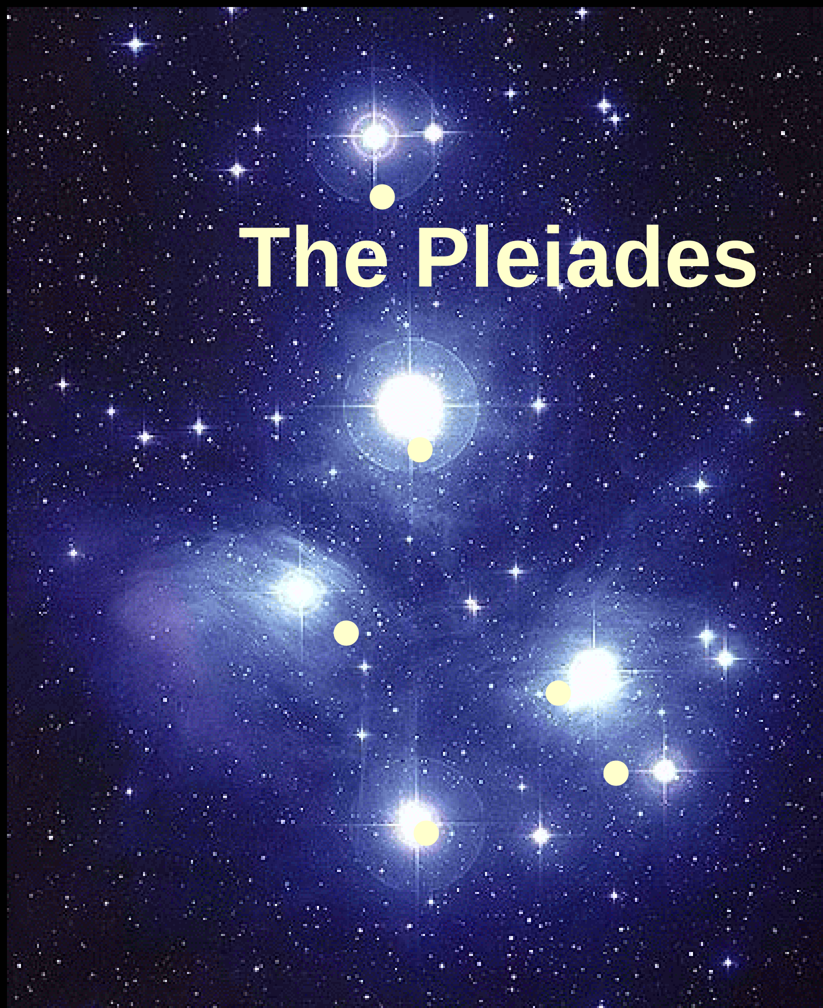
Half Moon



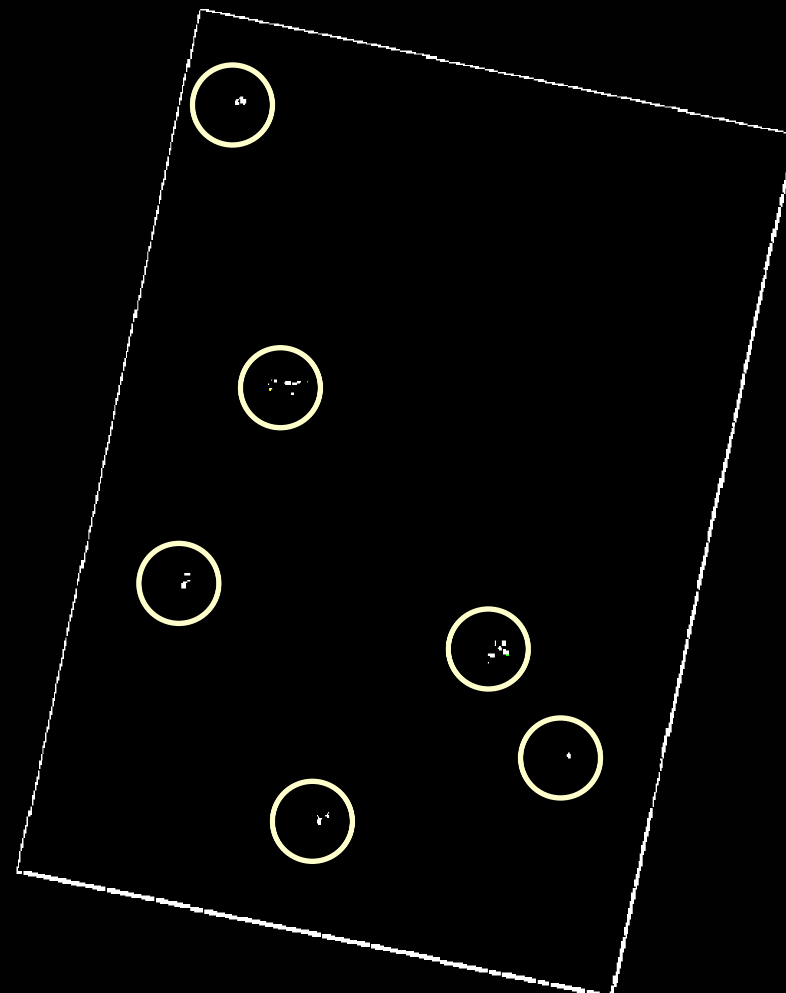
Saturn

Extra-terrestrial calibration!

(Views with the EO-1 ALI Pan band)



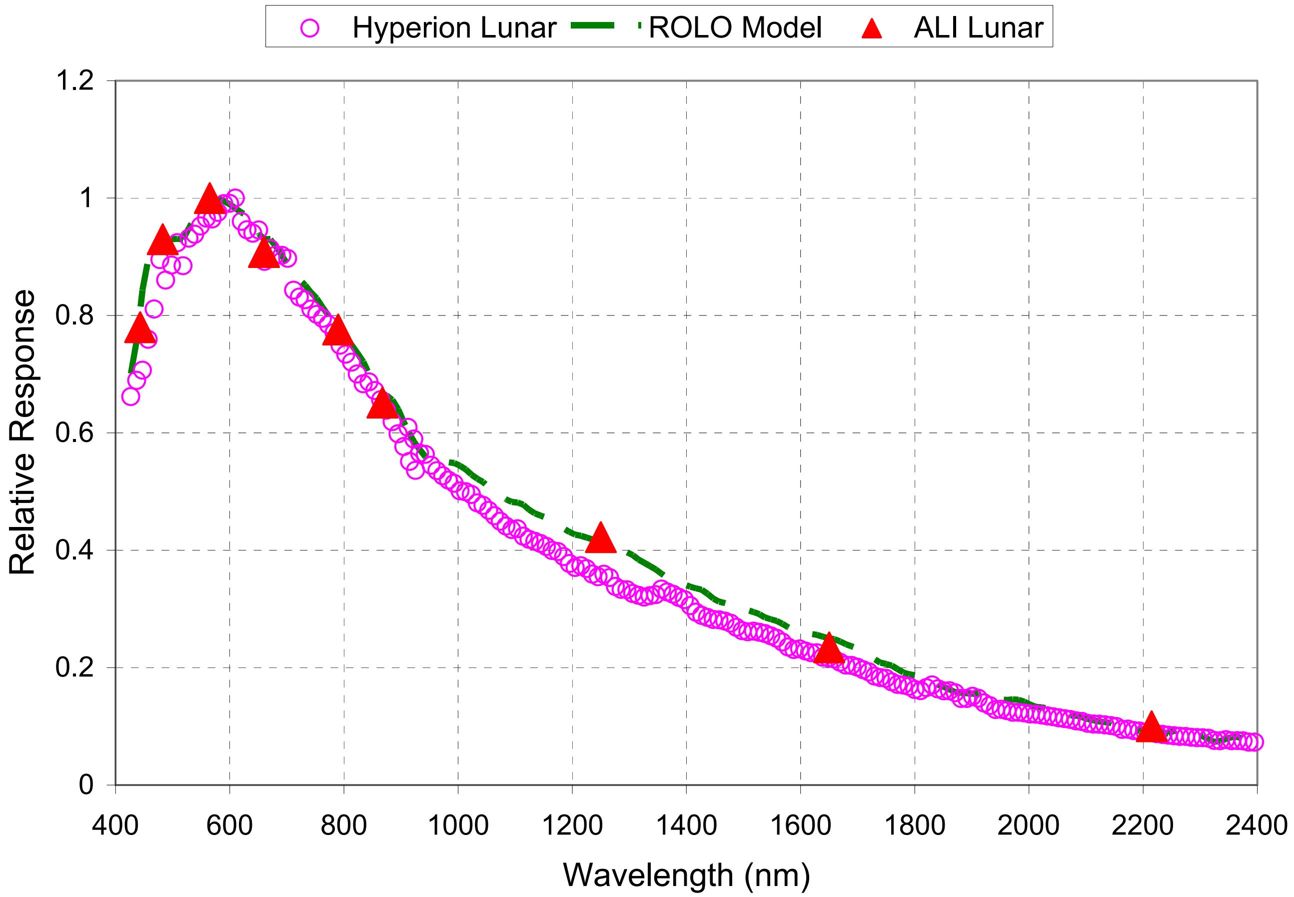
Photograph



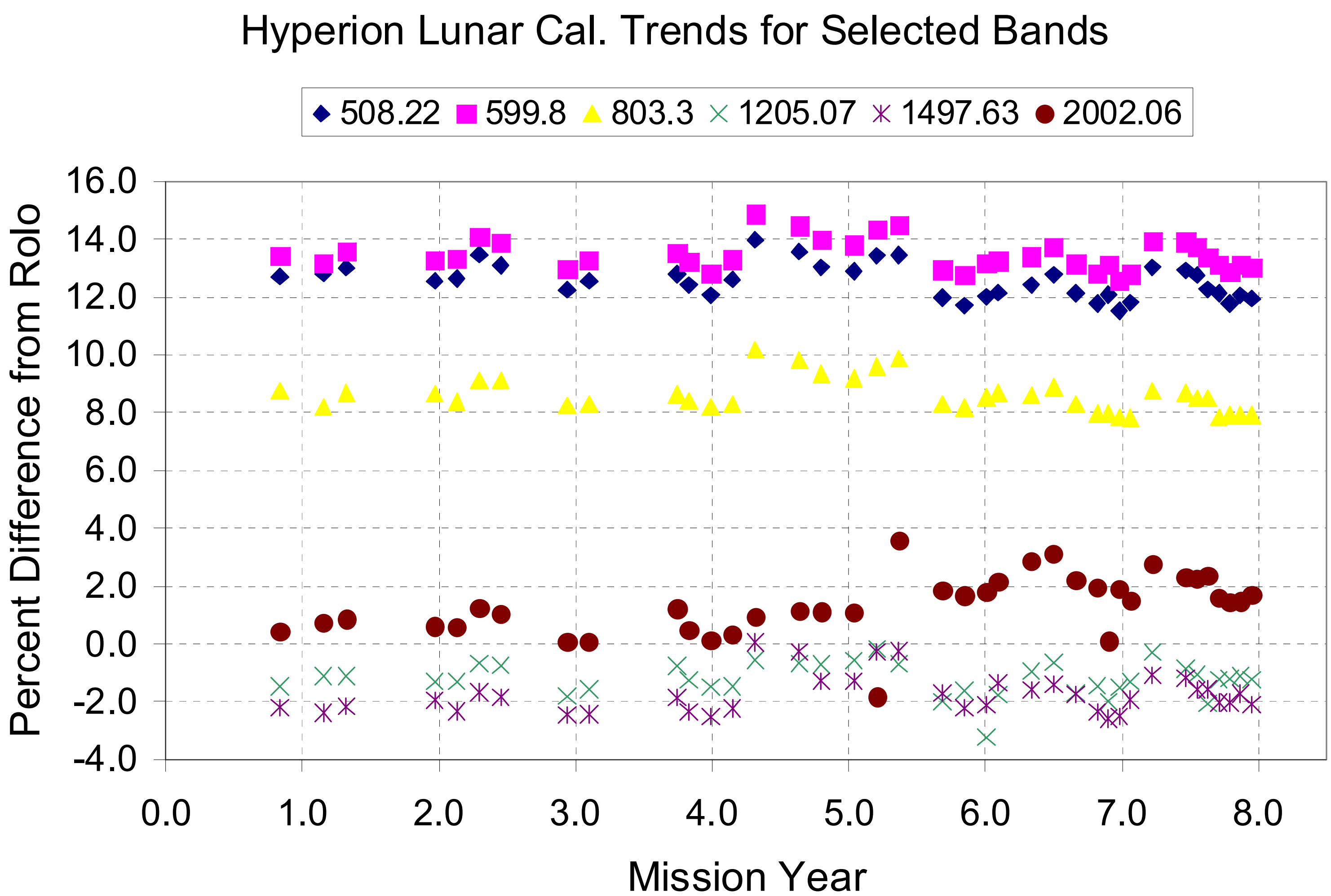
ALI detections

Hyperion Lunar Spectra

The pitch rate across the moon is the same as that used for earth imaging. This results in a 8X oversampling of the moon.

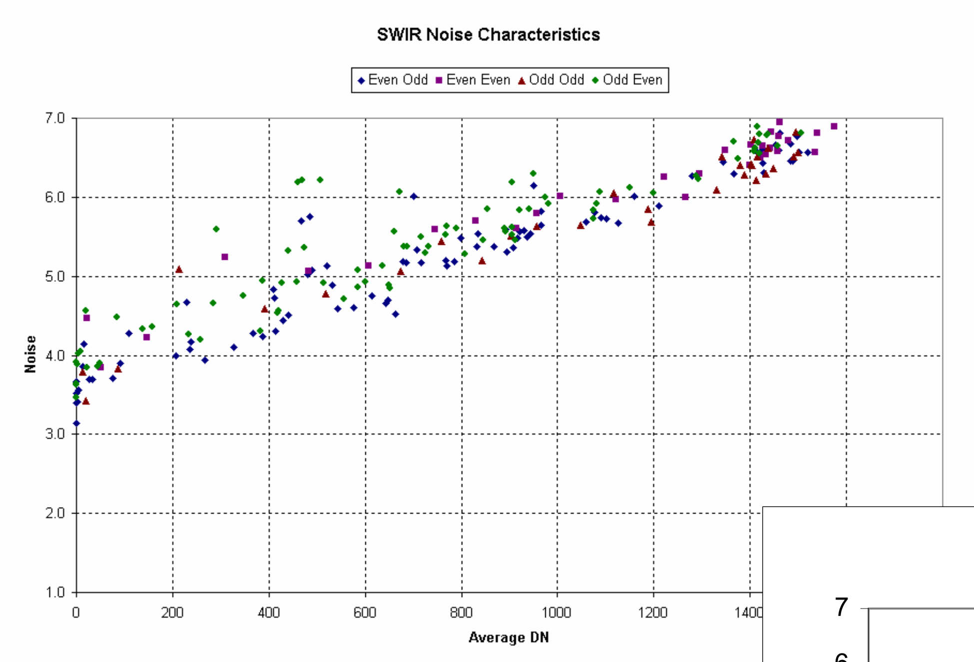


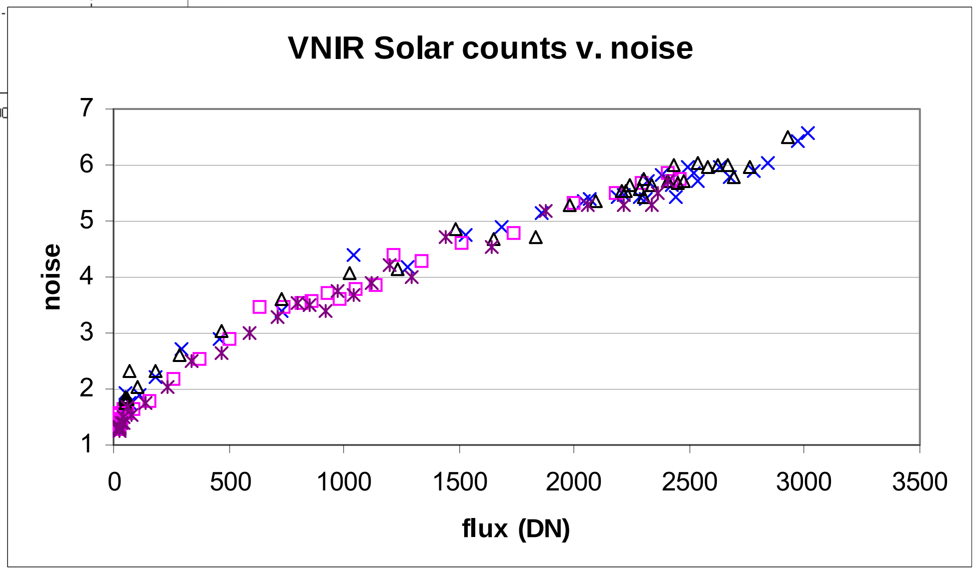
Lunar Calibration Results



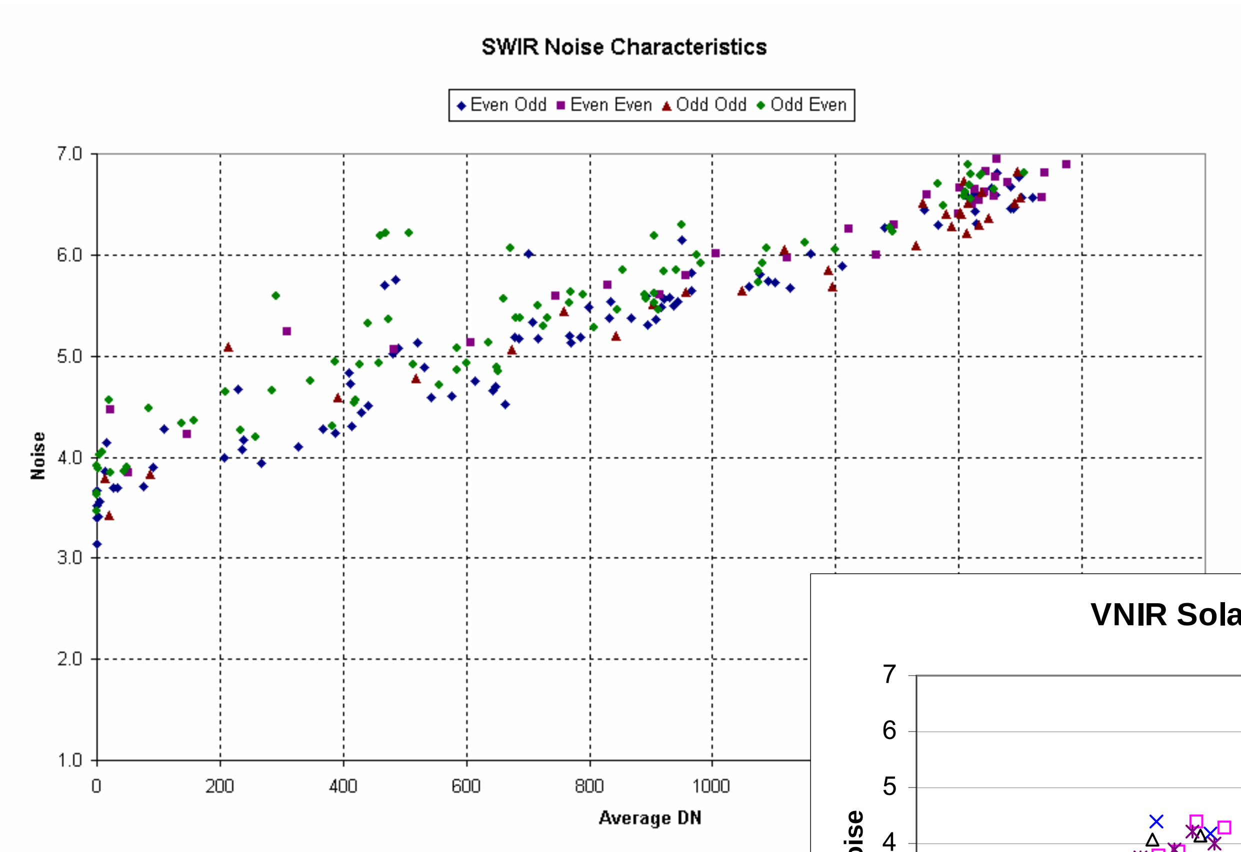
Why does Steve wear a hat?

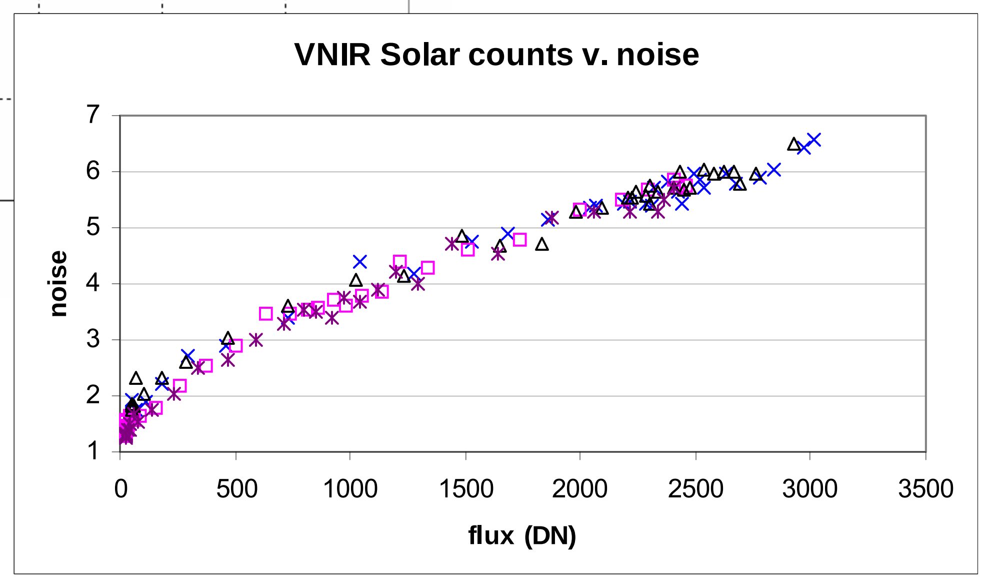
SNR Calculated From Solar Calibration Data





SNR Calculated From Solar Calibration Data





Scene Based Estimate of Hyperion SNR
(Source JPL AVIRIS LAB)