

Earth Observing-1



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Section 8

ALI Ground Test & On-Orbit Validation / Performance

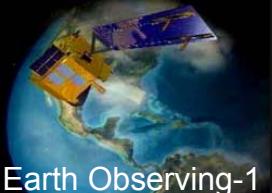
This work was sponsored by NASA Goddard Space flight Center under U.S. Air Force Contract number F19628-00-C-0002. Opinions, interpretations, conclusions and recommendations are those of the author and are not necessarily endorsed by the United States Government.



08/15-16/01

. . . **Jeffrey A. Mendenhall**
Massachusetts Institute of Technology Lincoln Laboratory

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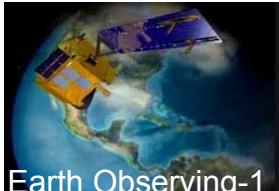
Topics of Discussion



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- ◆ ***Introduction***
- ◆ ***Pre-flight Characterization and Calibration***
 - *Functional*
 - *Spatial*
 - *Radiometric*
- ◆ ***Mission Operations***
 - *Early Checkout*
 - *Nominal Operations*
- ◆ ***Flight Performance Assessment***
 - *Functional*
 - *Spatial*
 - *Radiometric*
- ◆ ***Summary***





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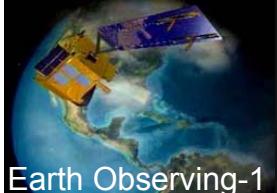
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Introduction



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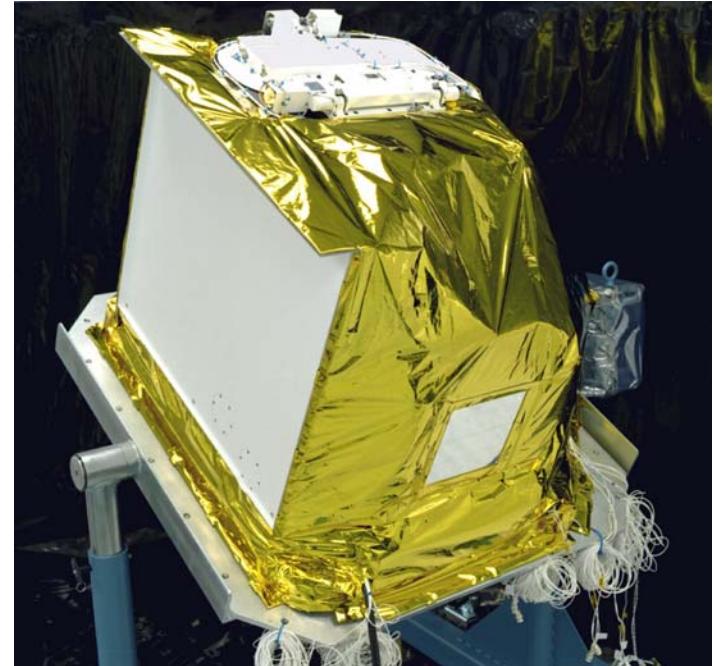
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Introduction

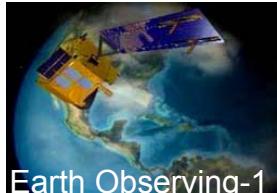


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- ◆ ***Primary instrument on EO-1***
- ◆ ***Validation of New Technologies***
 - *Landsat data continuity, improved performance, and cost reduction*
 - *Innovative approaches to land imaging*
- ◆ ***The ALI was designed, developed, and tested by MIT Lincoln Laboratory with NMP instrument team members***
 - *Raytheon SBRS for the focal plane system*
 - *SSG Inc. for the optical system*



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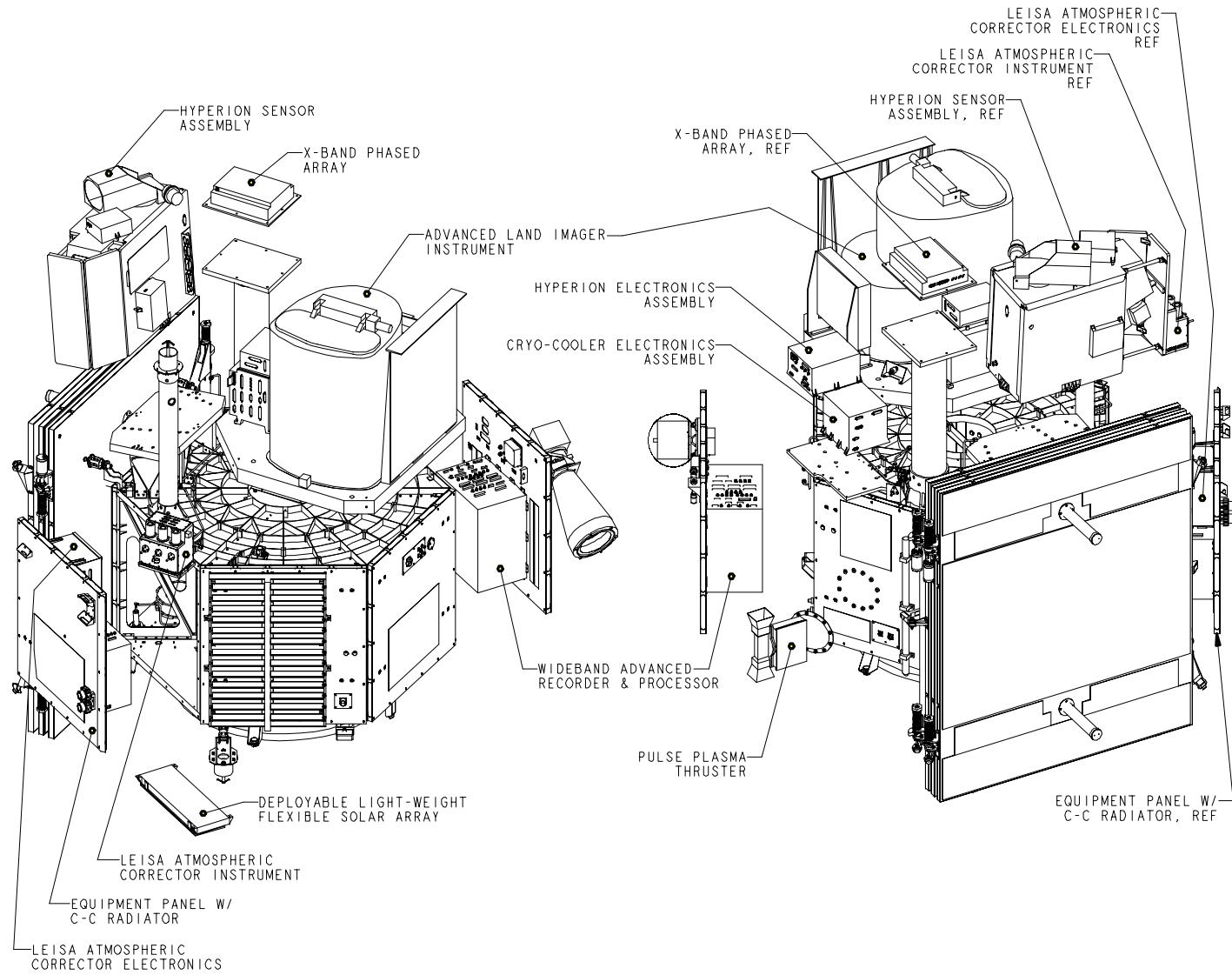


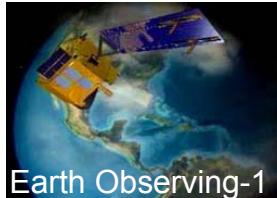
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EO-1 Technology Map



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Earth Observing-1 Spacecraft

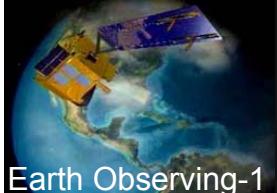


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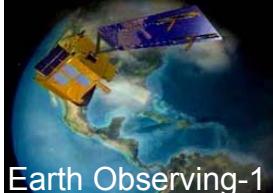


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Pre-Flight Characterization & Calibration

- ◆ *Functional*
- ◆ *Spatial*
- ◆ *Radiometric*
- ◆ *Other Technologies*





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ALI Calibration Matrix



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	Spectral Response Function	Response Coefficient	Zero Signal Offset	Pixel Angular Position	Modulation Transfer Function
Component Tests and Analysis	●	○	○	—	○
Subsystem Tests: Telescope and MS/Pan	○	○	○	○	○
Instrument-Level Laboratory Tests	●	●	○	●	●
On-Orbit Measurements:					
Solar Diffuser	—	●	—	—	—
Closed Aperture Cover	—	—	●	—	—
Internal Sources	—	○	—	—	—
Lunar Scans	—	○	○	—	○
Earth Scenes	—	○	—	○	○

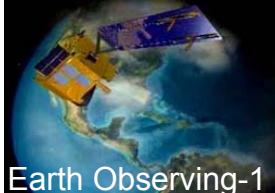


Primary Measurement



Secondary Measurement





ALI Pre-Flight Calibration Table

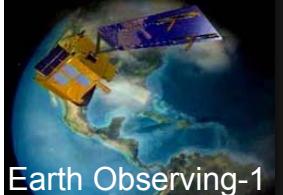


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TASK	OPTICAL TEST CONFIGURATION	STATUS	
		Completed	Comments
	Schmidt sphere imaging collimator		
FPA alignment	Knife edge	X	
Focus verifications	Knife edge	X	May be repeated at GSFC
End-to-end imaging	Scene	X	
MTF measurements	Knife edge	X	
Pixel line-of-sight	Ronchi ruling	X	
Image of filters	CCD camera	X	Plan to repeat after bake-out
Reference cube alignment	Autocollimating theodolite	X	
	Off-axis parabolic collimator		
Spectral calibration	Grating monochromator	X	
Polarization tests	Glan prisms	X	
Solar calibration functional test	1kW Xe arc lamp and Spectralon diffuser	X	
	Integrating sphere and spectroradiometer		
Radiometric calibration	Integrating sphere and spectroradiometer	X	Baseline FPA temperature completed, Temperature excursions in progress
Internal source transfer calibration	Internal source	X	Baseline FPA temperature completed, Temperature excursions in progress
Landsat transfer calibration	GSFC LXR	X	





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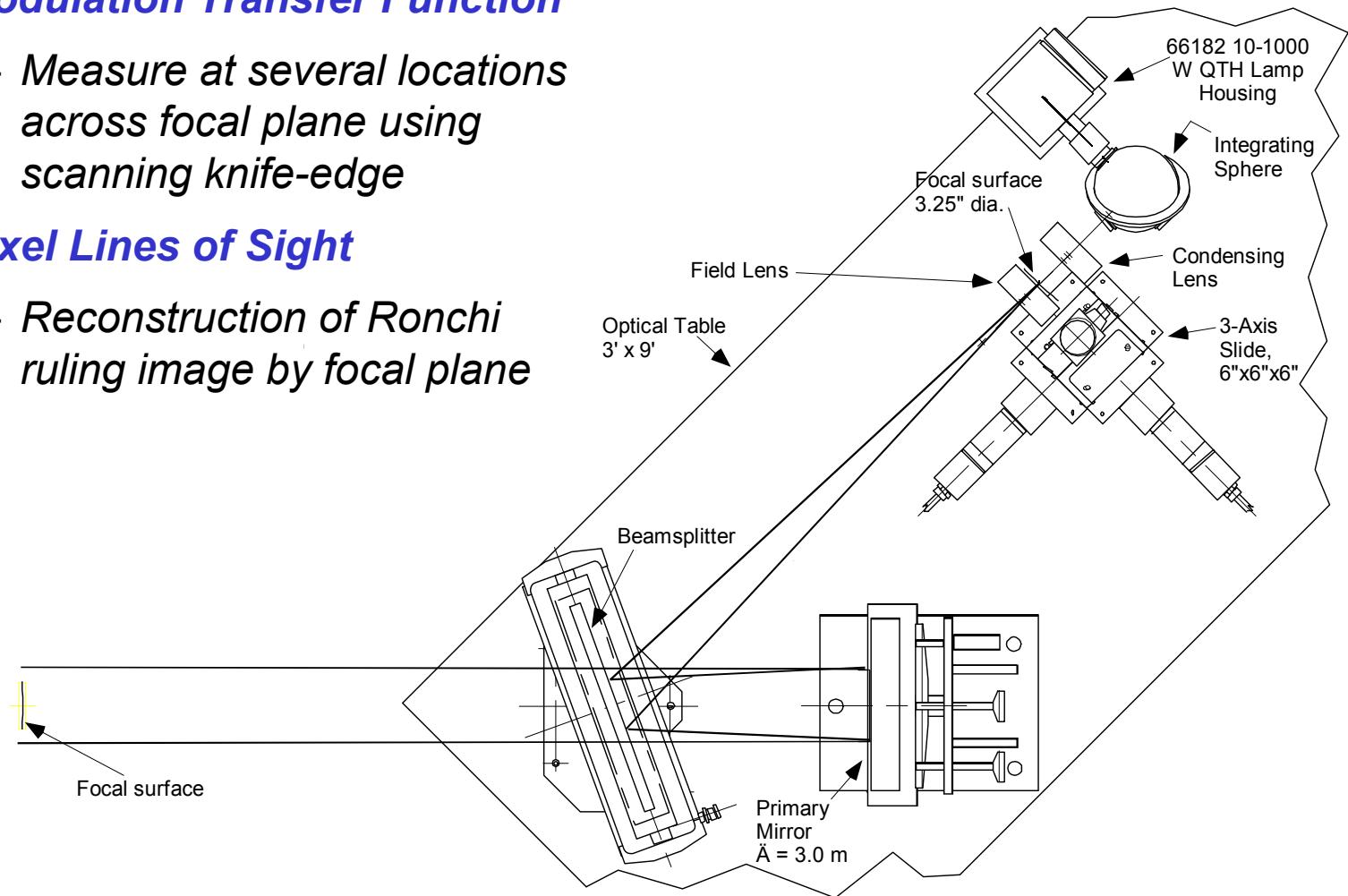
Spatial Performance Assessment

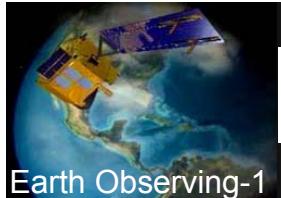


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◆ Pre-Flight Methodology

- **Modulation Transfer Function**
 - Measure at several locations across focal plane using scanning knife-edge
- **Pixel Lines of Sight**
 - Reconstruction of Ronchi ruling image by focal plane



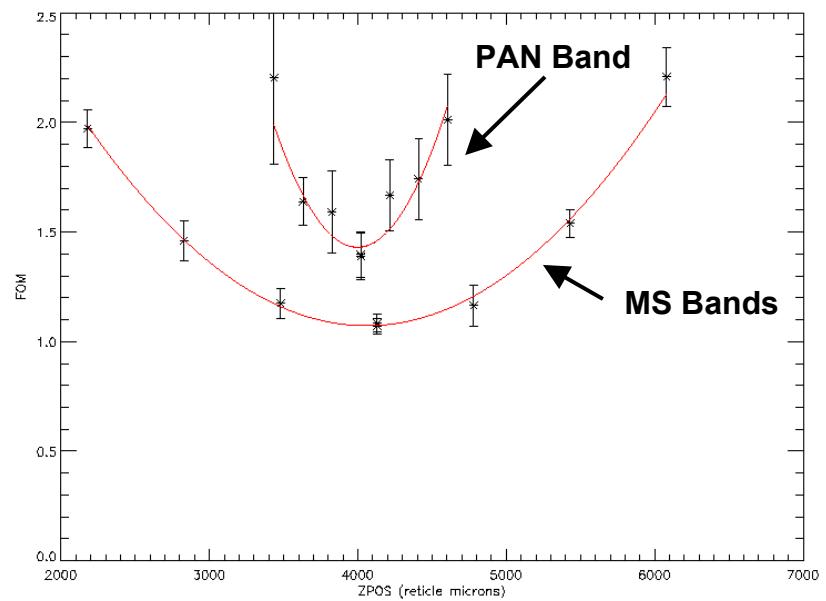
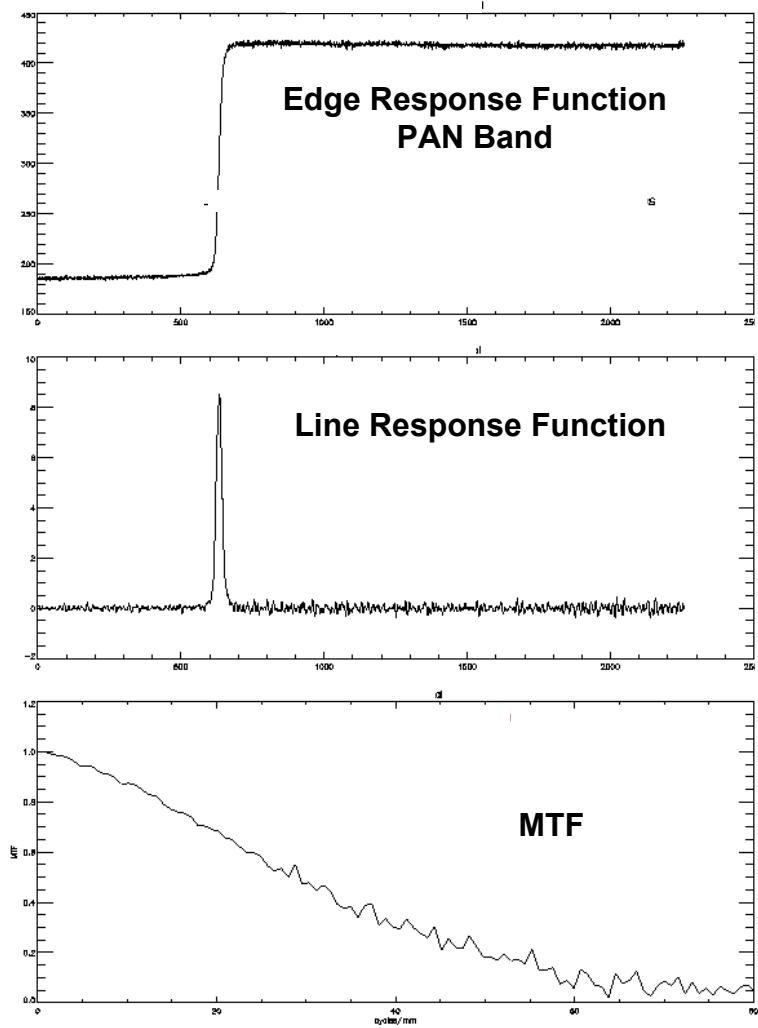


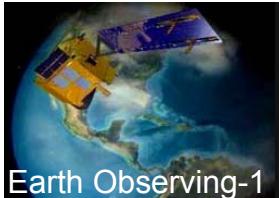
Focus Test & MTF Measurements



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Absolute Radiometry

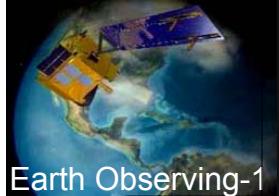


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◆ *Pre-Flight Methodology:*

- *Objective: Calibrate ALI gain, linearity, temperature dependence, repeatability*
- *Flood focal plane with uniform beam from large integrating sphere*
- *Monitor beam with NIST traceable detectors*
- *Spectroradiometer for incident spectrum knowledge*
- *Calibration of integrating sphere output radiance agrees with GSFC measurements within 2% between 440 and 900 nm*

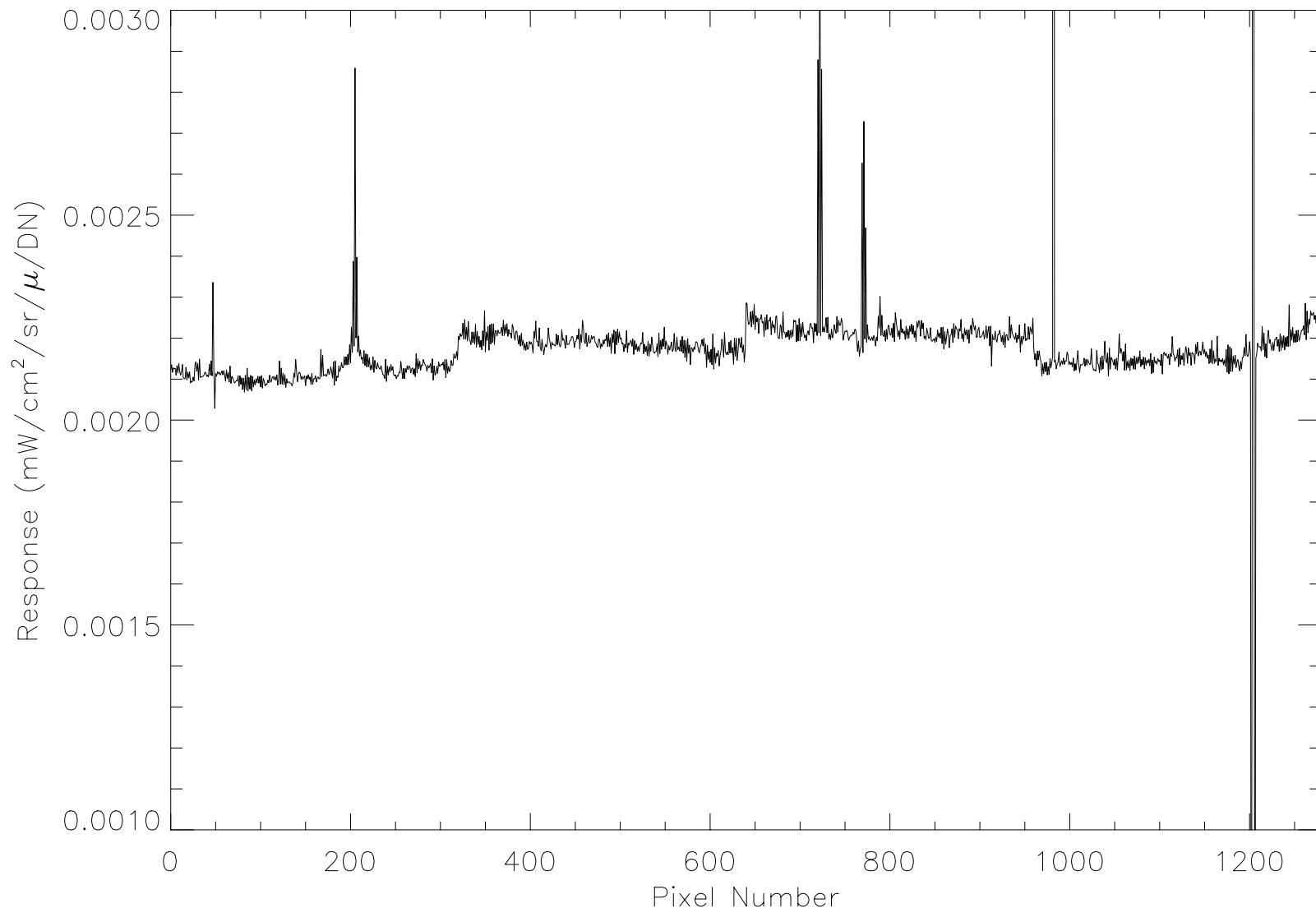




Radiometric Calibration Results: Band 5 Coefficient



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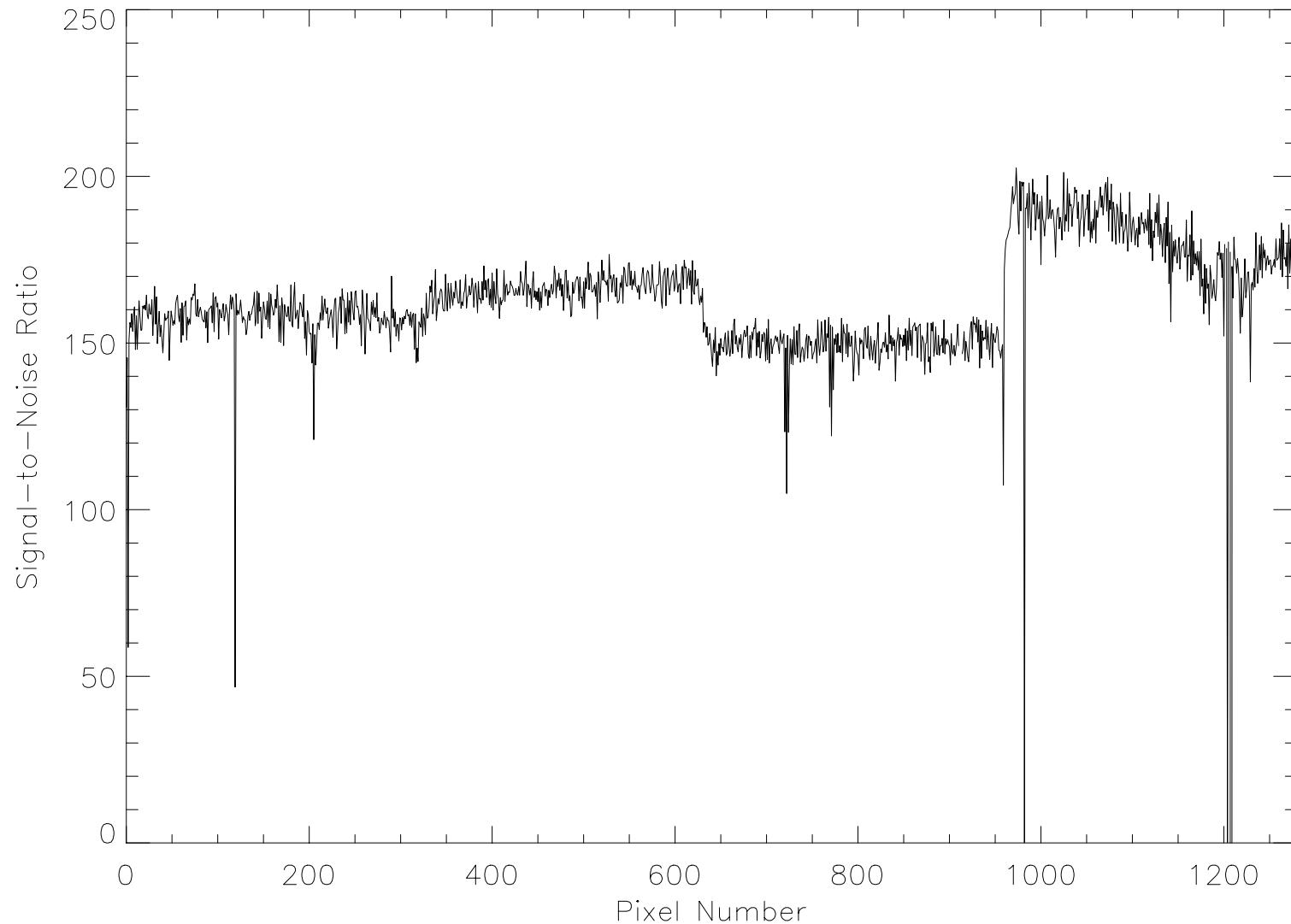
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Radiometric Calibration Results: Band 5 SNR

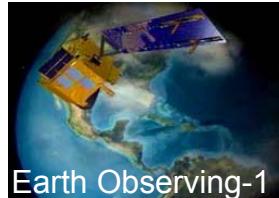


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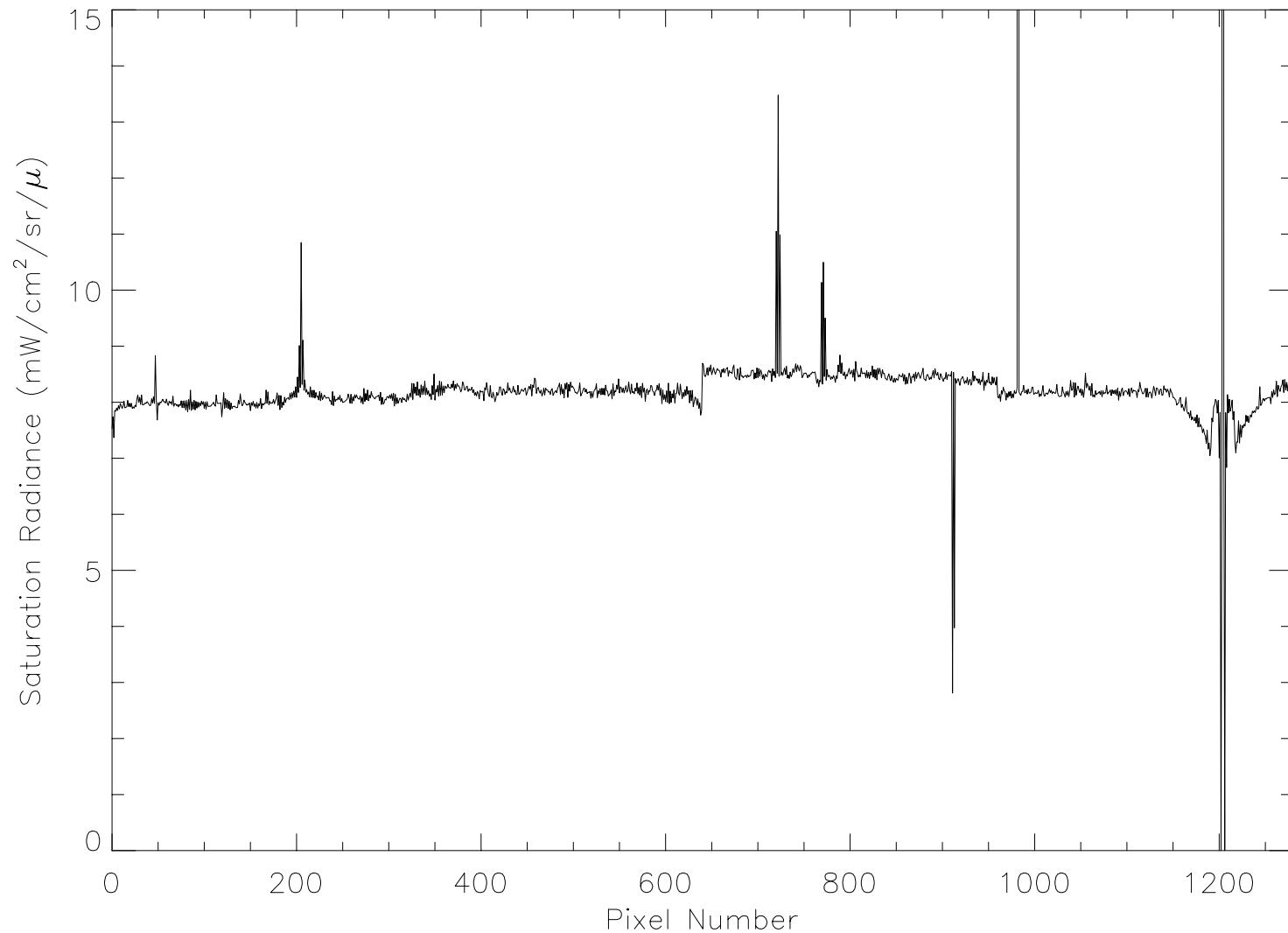


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Radiometric Calibration Results: Band 5 Saturation Radiance

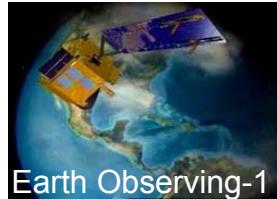


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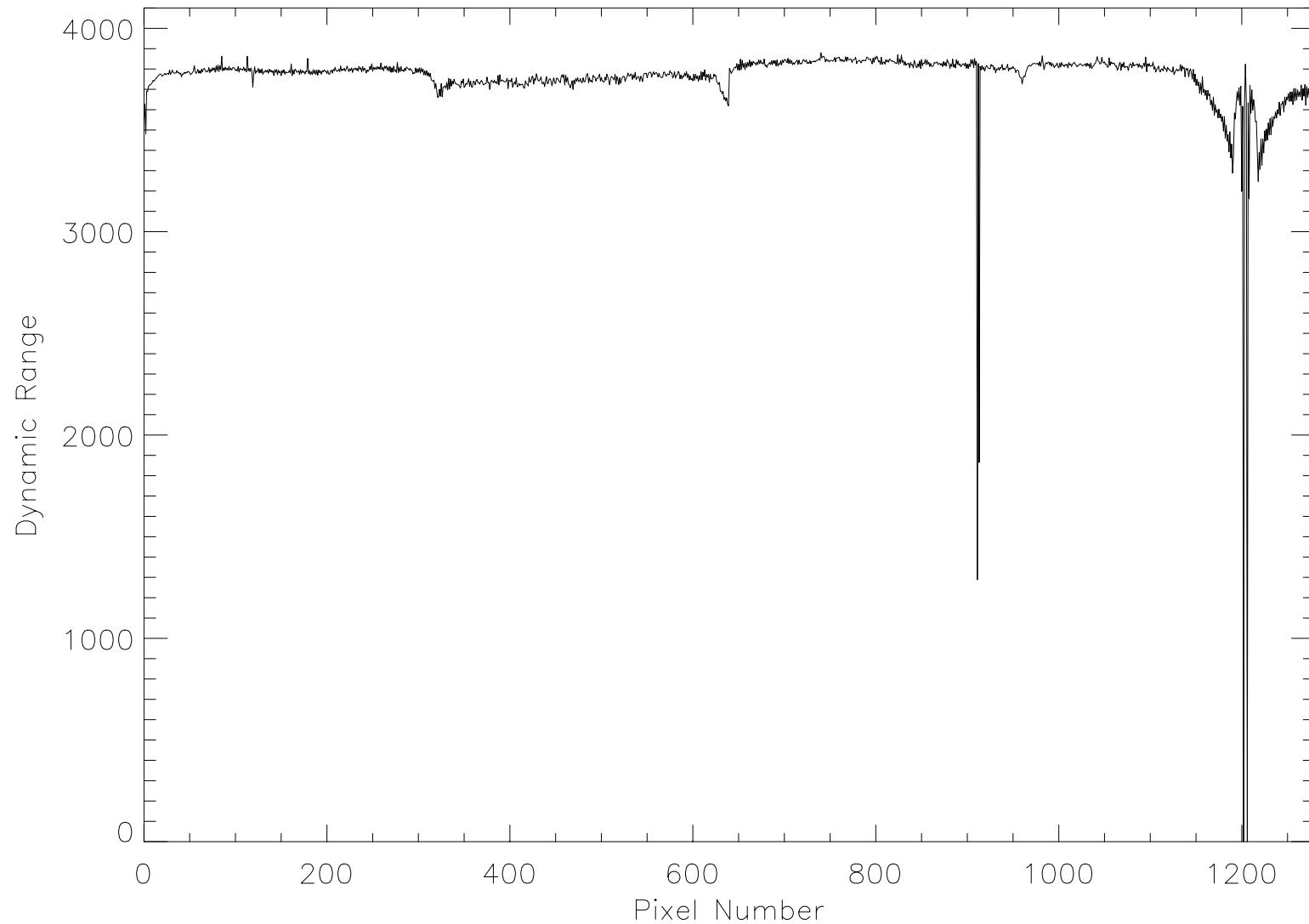


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Radiometric Calibration Results: Band 5 Dynamic Range

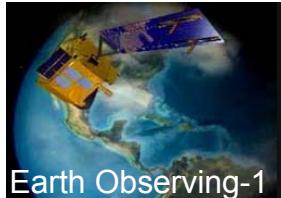


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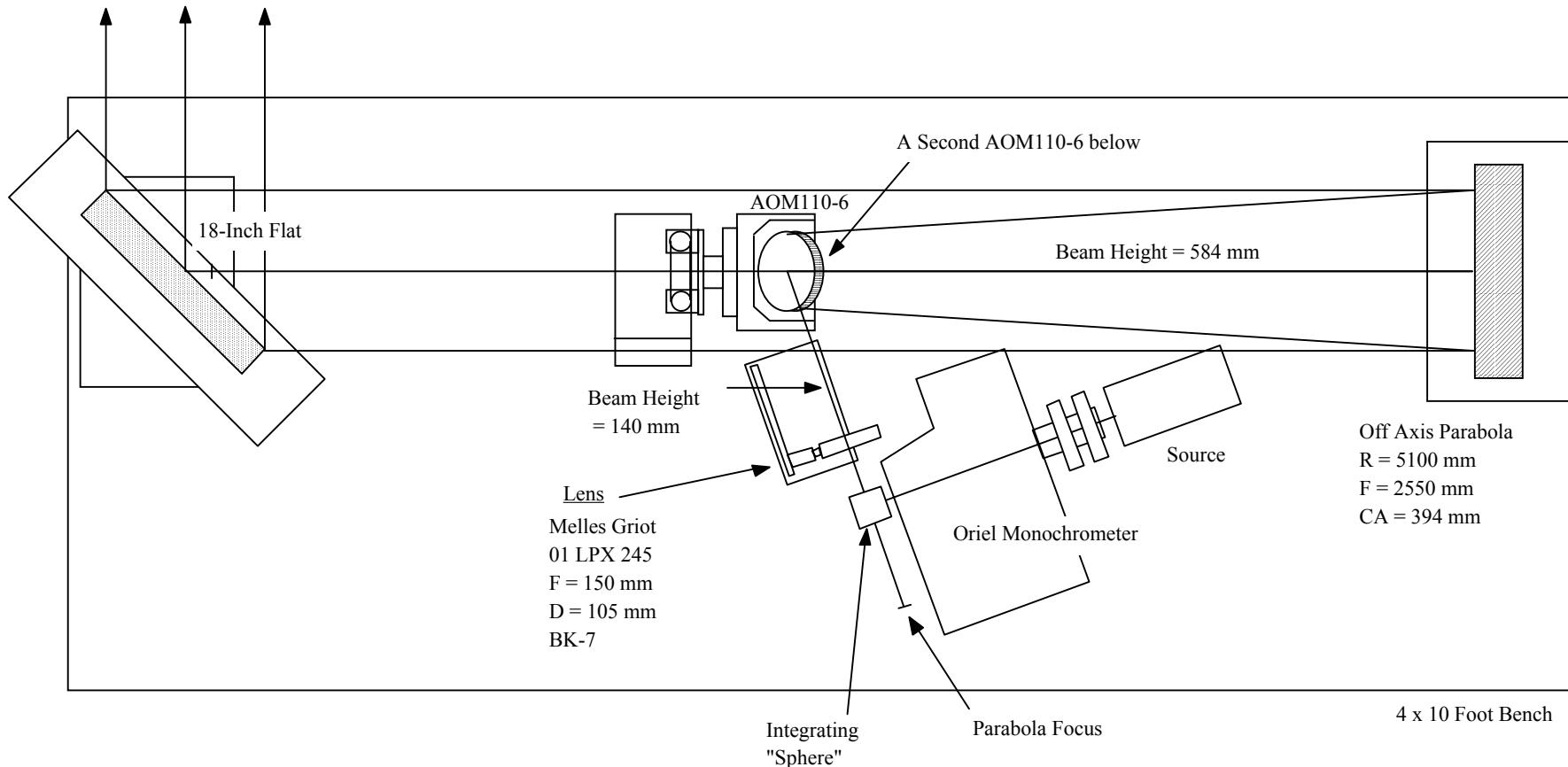
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Spectral Collimator

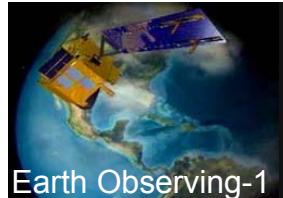


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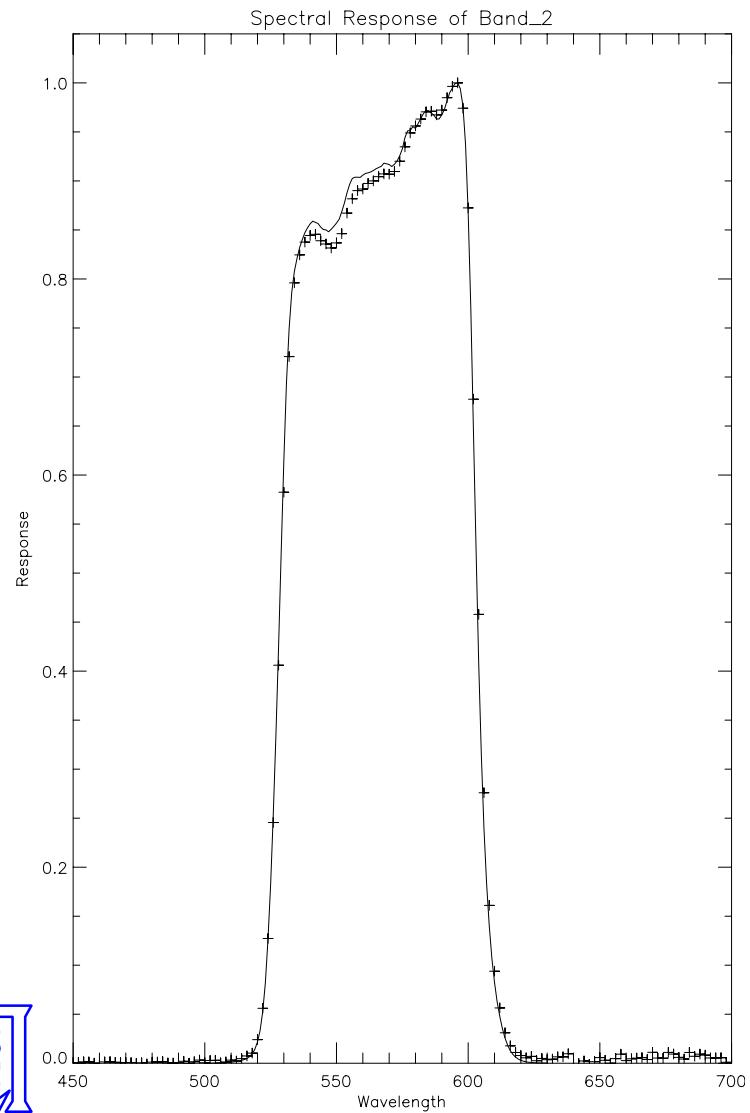


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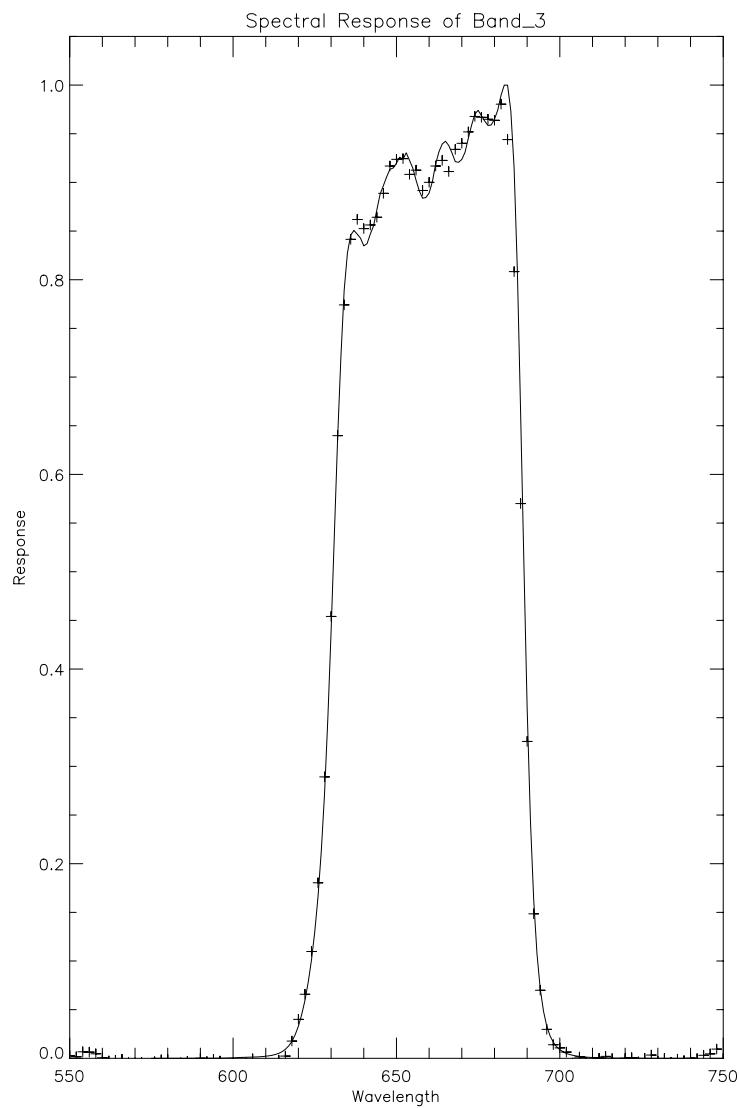
Spectral Calibration Results: Bands 2 and 3

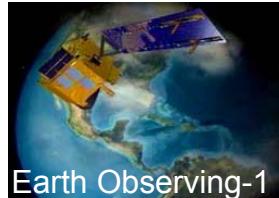


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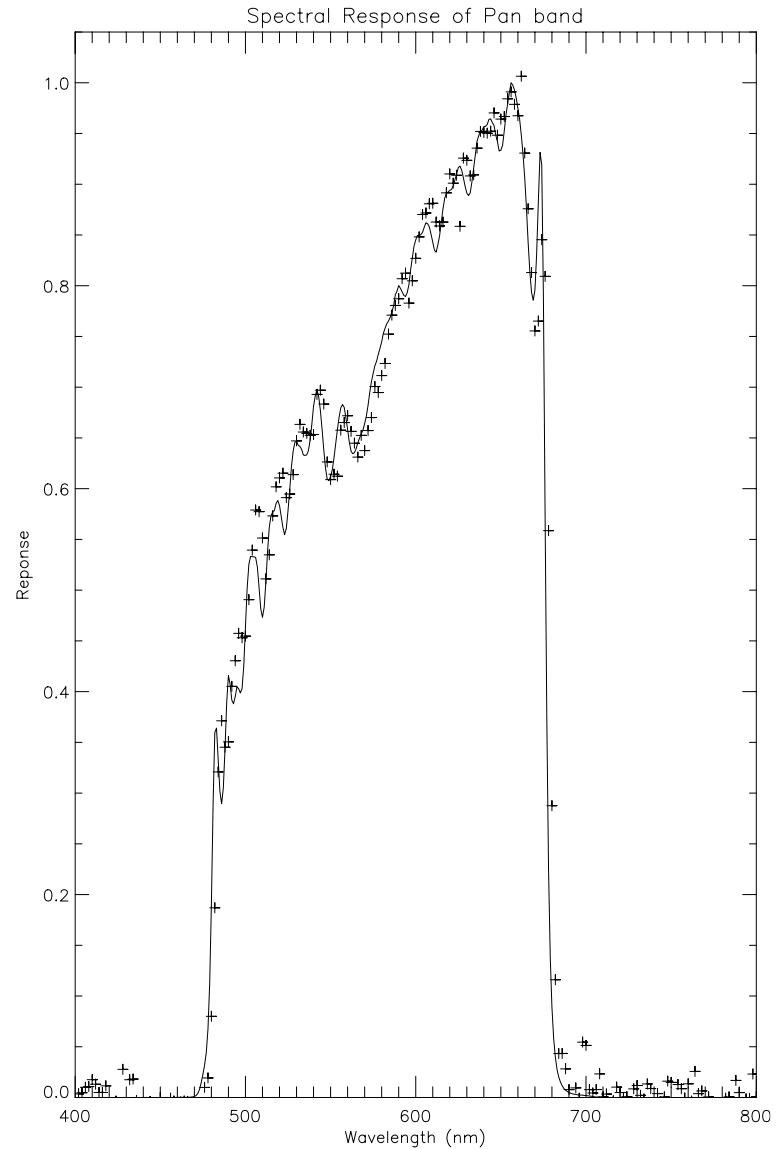


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Spectral Calibration Results: Panchromatic Band

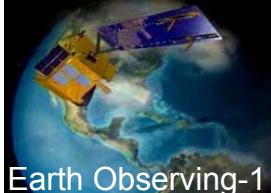


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ALI Calibration Matrix



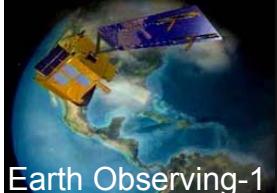
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	Spectral Response Function	Response Coefficient	Zero Signal Offset	Pixel Angular Position	Modulation Transfer Function
Component Tests and Analysis	●✓	○✓	○✓	—	○✓
Subsystem Tests: Telescope and MS/Pan	○✓	○✓	○✓	○✓	○✓
Instrument-Level Laboratory Tests	●✓	●✓	○✓	●✓	●✓
On-Orbit Measurements:					
Solar Diffuser	—	●	—	—	—
Closed Aperture Cover	—	—	●	—	—
Internal Sources	—	○	—	—	—
Lunar Scans	—	○	○	—	○
Earth Scenes	—	○	—	○	○



● Primary Measurement ○ Secondary Measurement ✓ Completed





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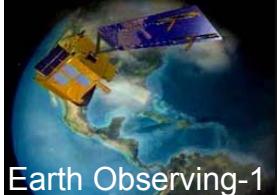
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- ◆ *Early Checkout*
- ◆ *Nominal Operations*



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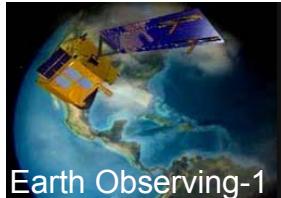
Early Operations



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- ◆ *ALI was turned on on November 25, 2000 (Day 5)*
- ◆ *Comprehensive performance test conducted*
 - *Focal plane* – *Thermal control system*
 - *Heaters* – *High output paraffin actuators*
 - *Internal reference lamps* – *Motors*
- ◆ *Dark current, internal reference lamp, and test pattern data collected*
- ◆ *Launch latches were released*
- ◆ *Obtained four earth scenes with the spacecraft pointing to nadir, i.e., the active part of ALI covering a swath 55 to 92 km east of the S/C ground track.*
 - *Alaska, north-east of Anchorage,*
 - *East Antarctica,*
 - *Marshall Islands,*
 - *North-central Australia.*
- ◆ *Placed in outgassing mode for 5 Days*





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First Image: Sutton, AK

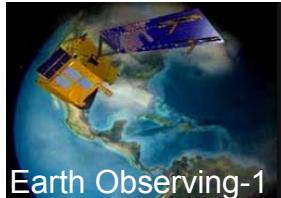


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(2000:330, MS 3-2-1)



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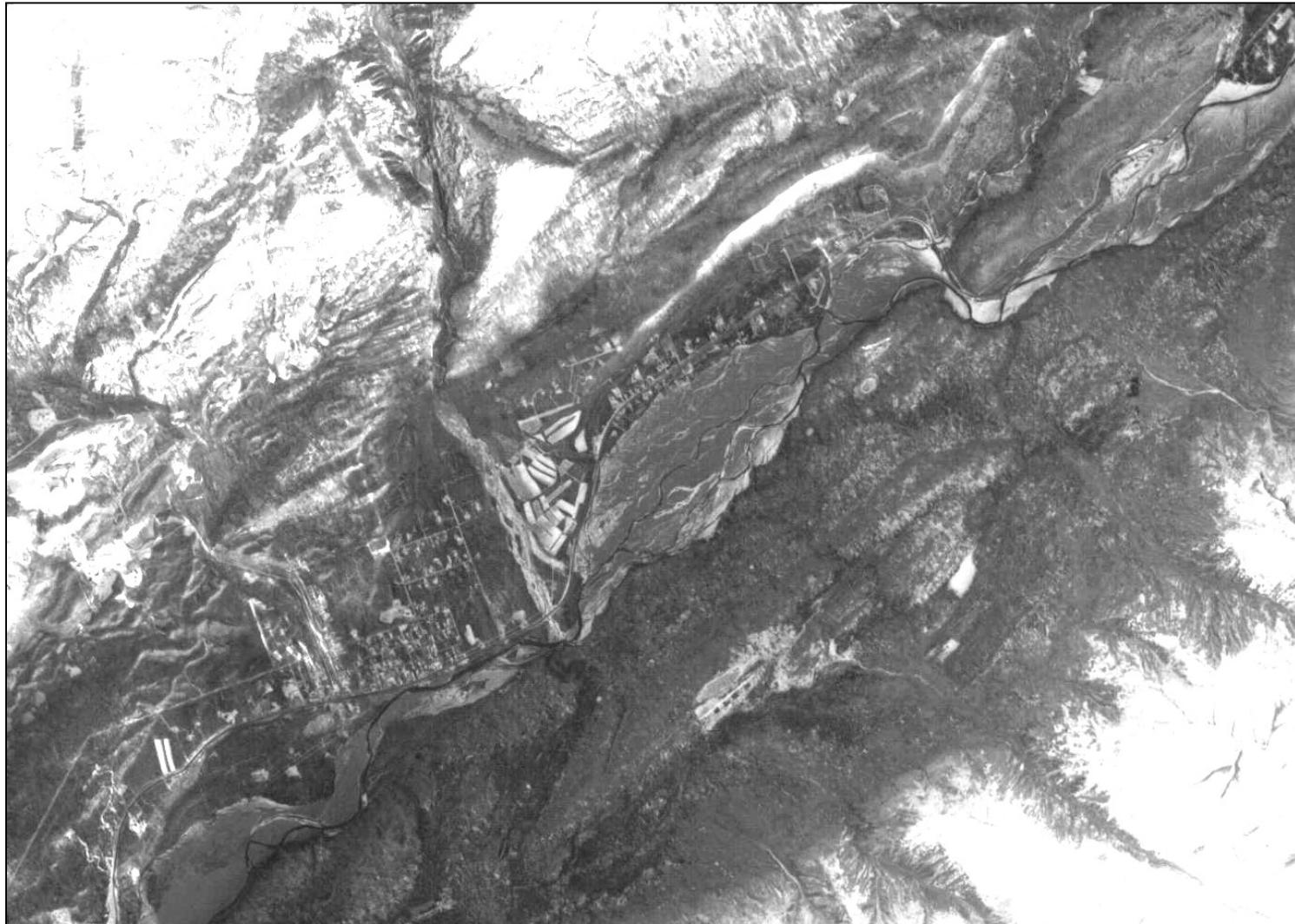
Earth Observing-1

First ALI Image: Sutton, AK

(2000:330, Pan Zoom)

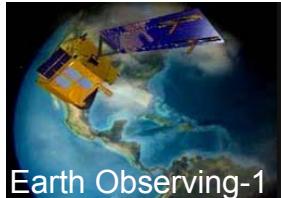


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Landsat-7 & ALI Comparison (Sutton, AK)



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Landsat 7 Panchromatic

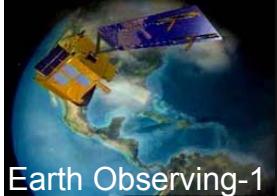


ALI Panchromatic



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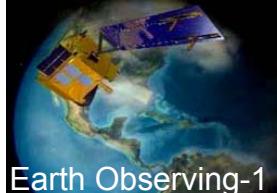
Nominal Operations



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- ◆ *Fly 1-minute behind Landsat 7 on same path*
- ◆ *2-6 all instrument data collection events per day*
- ◆ *Instrument team targets*
 - *Cities* - *Long Dark Collection* - *Mountains*
 - *Solar* - *Limb Scans* - *Shoreline*
 - *Lunar* - *Yaw Steering* - *Ice/Snow*
 - *Stellar* - *Large Flat Regions* - *Low illumination*
- ◆ *Science validation team topics*
 - *Ground truth* - *Tropical forest burn scar mapping*
 - *Forest structure monitoring* - *Coastal and inland water*
 - *Glaciology* - *Fire Hazard*
 - *Deserts* - *Land cover / land use*
 - *Logging* - *Pollution monitoring*
 - *Volcanic debris flow* - *Urban mapping*



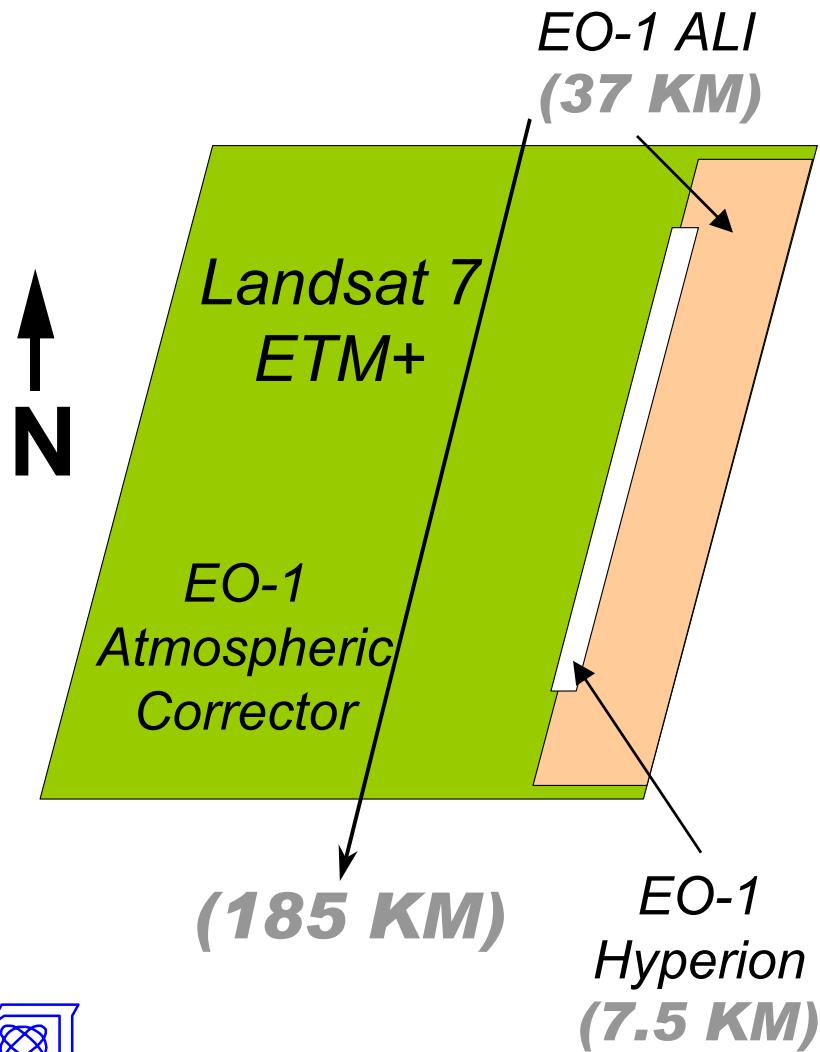


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Morning Constellation



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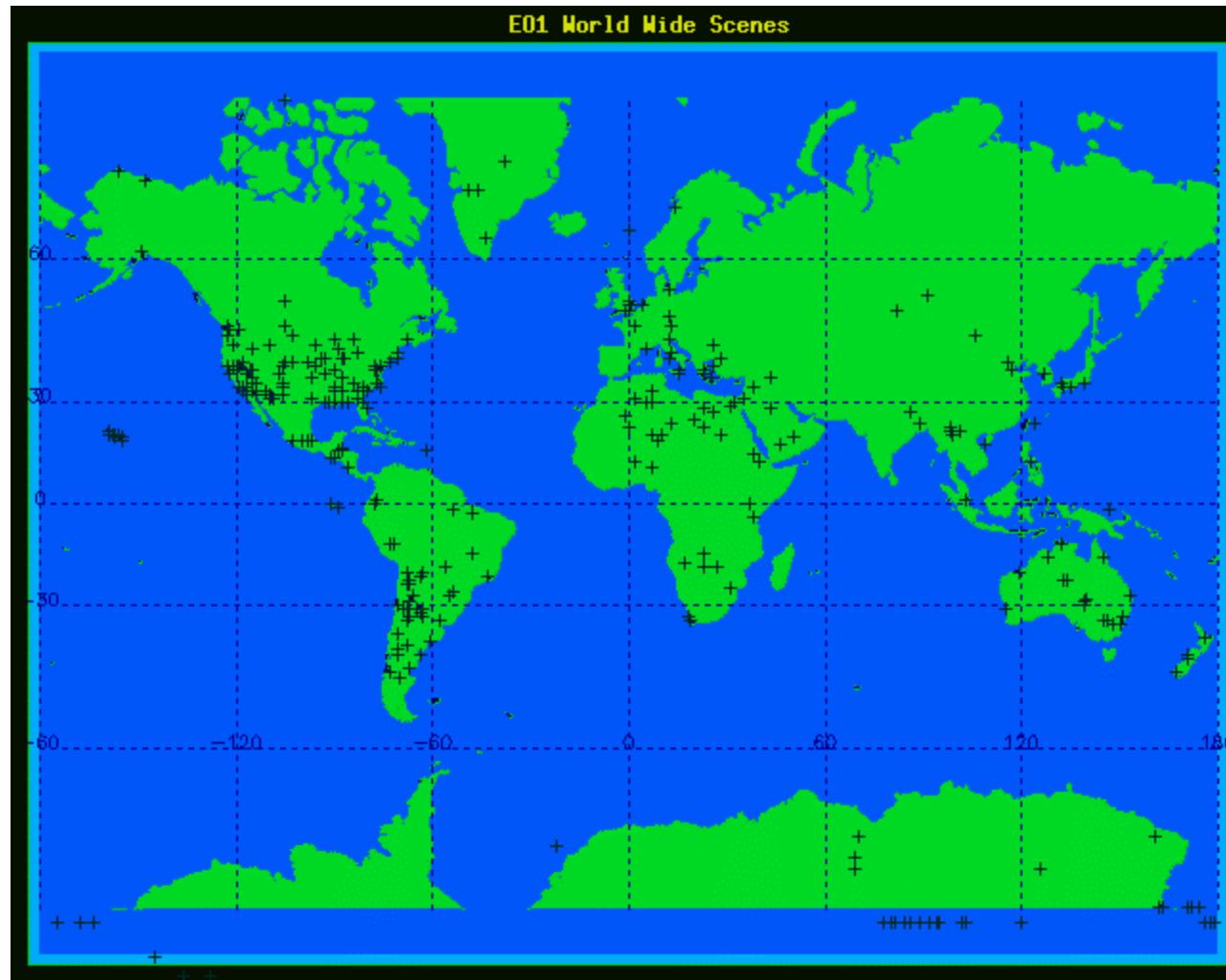


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Scene Locations



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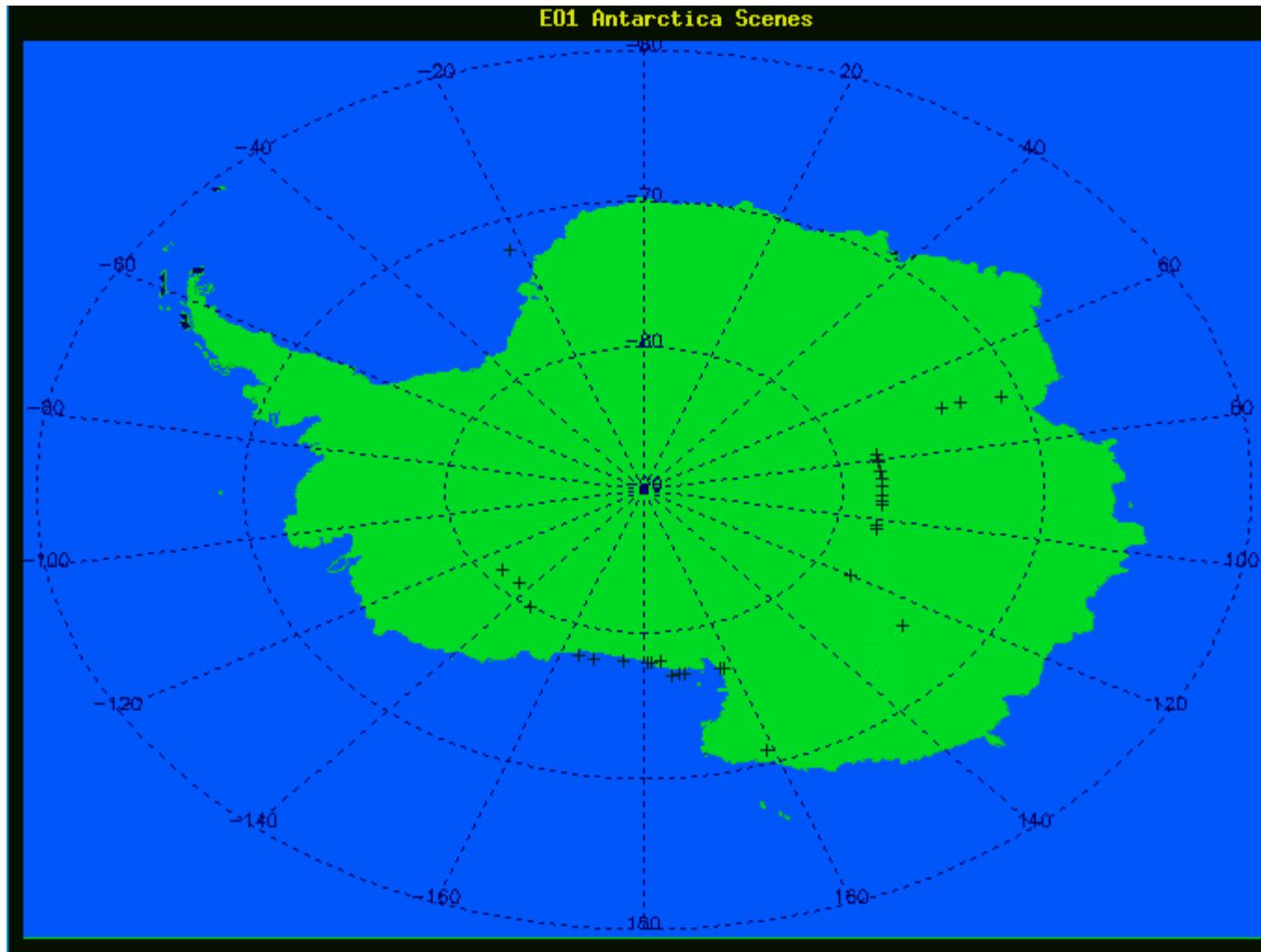


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Scene Locations

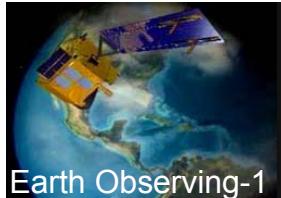


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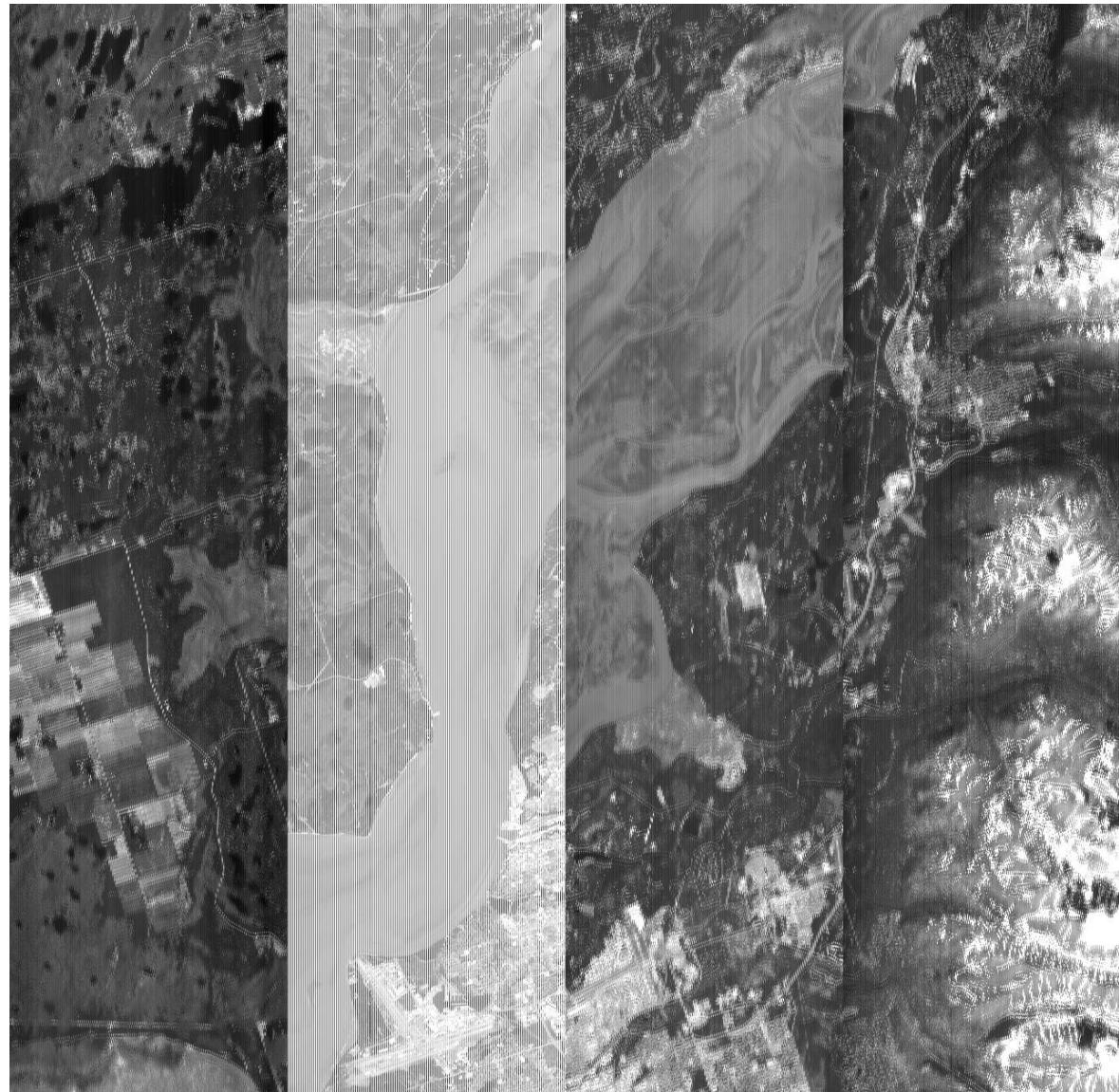
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Image Reconstruction

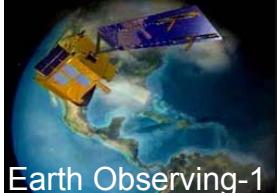


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- ◆ *Raw Image*



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Image Reconstruction

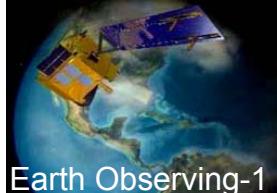


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- ◆ *Raw Image*
- ◆ *Shift odd pixels*



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Image Reconstruction

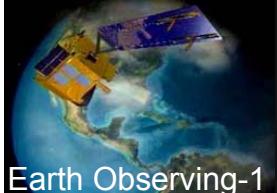


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- ◆ *Raw Image*
- ◆ *Shift odd pixels*
- ◆ *Subtract dark current*



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Image Reconstruction

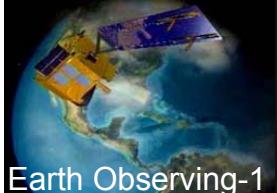


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- ◆ *Raw Image*
- ◆ *Shift odd pixels*
- ◆ *Subtract dark current*
- ◆ *Calibrate radiometrically*



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Image Reconstruction

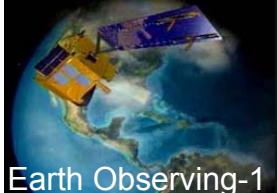


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- ◆ ***Raw Image***
- ◆ ***Shift odd pixels***
- ◆ ***Subtract dark current***
- ◆ ***Calibrate radiometrically***
- ◆ ***Correct for cross talk***



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Image Reconstruction

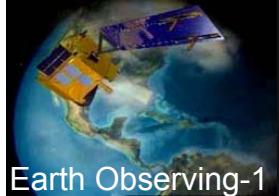


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- ◆ ***Raw Image***
- ◆ ***Shift odd pixels***
- ◆ ***Subtract dark current***
- ◆ ***Calibrate radiometrically***
- ◆ ***Correct for cross talk***
- ◆ ***Shift odd SCAs***



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Earth Observing-1

Image Reconstruction

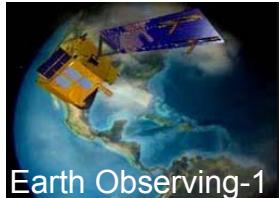


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- ◆ ***Raw Image***
- ◆ ***Shift odd pixels***
- ◆ ***Subtract dark current***
- ◆ ***Calibrate radiometrically***
- ◆ ***Correct for cross talk***
- ◆ ***Shift odd SCAs***
- ◆ ***Overlay different bands***



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Washington, DC (2000:336, Pan)

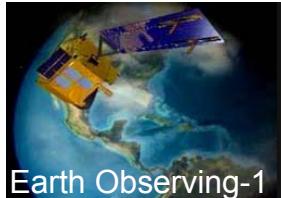


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Boston 2001:042, Pan)

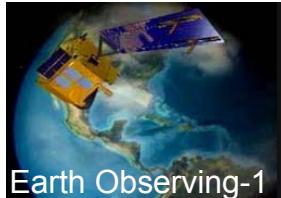


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Cape Canaveral (2001:013, MS 4-3-2)

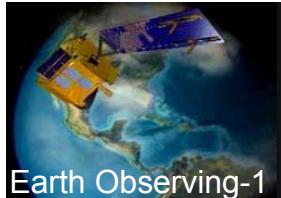


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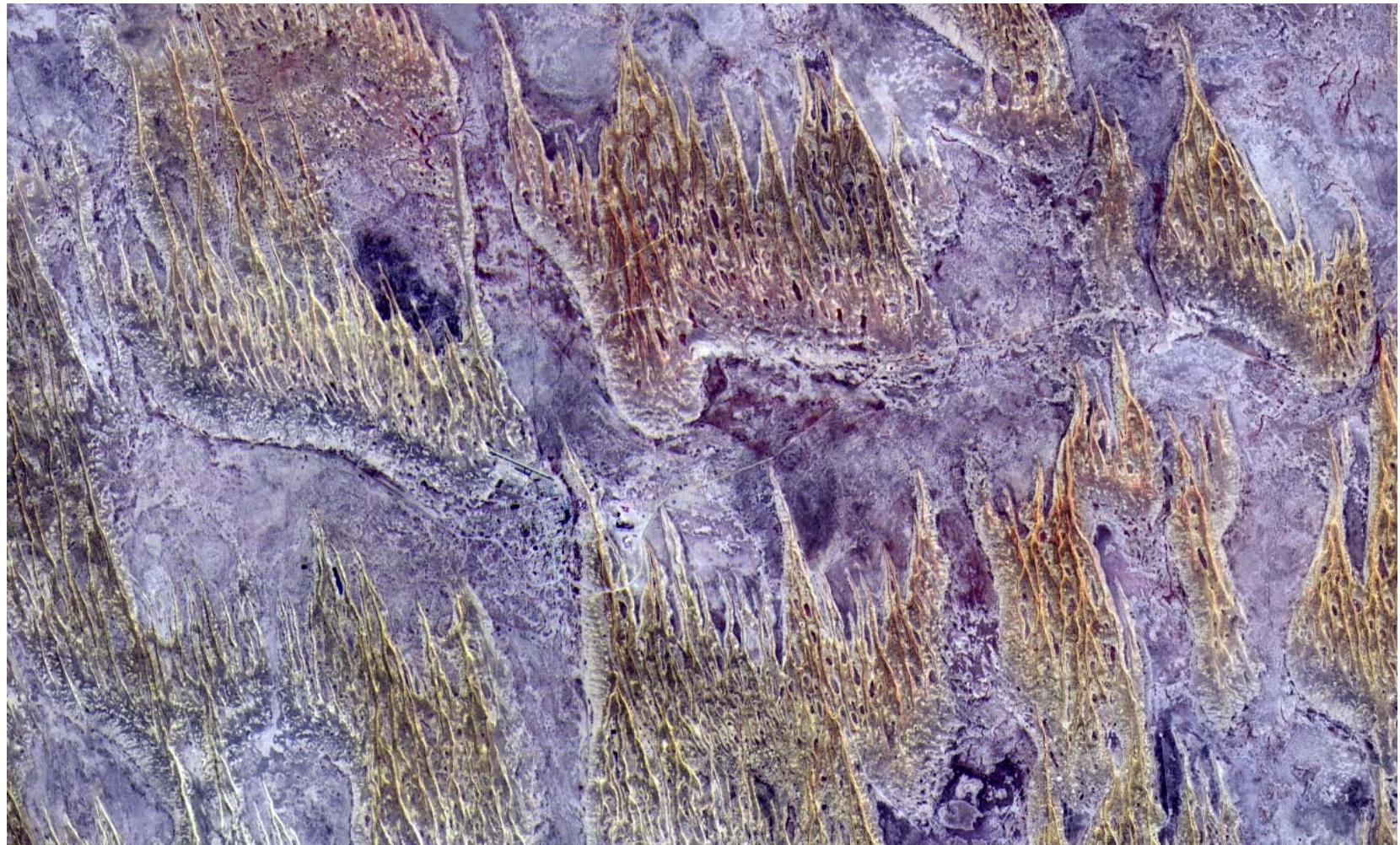


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Tinga, Tingana
(-29°, 139.8°)
(2001:149, MS 4-3-2)

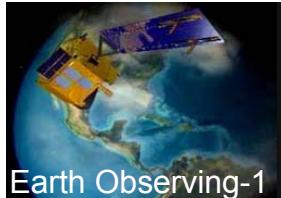


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Earth Observing-1

Oahu, Hawaii



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MS 3-2-1

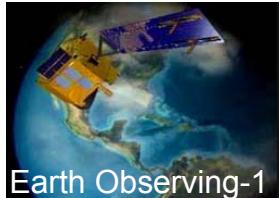


Pan



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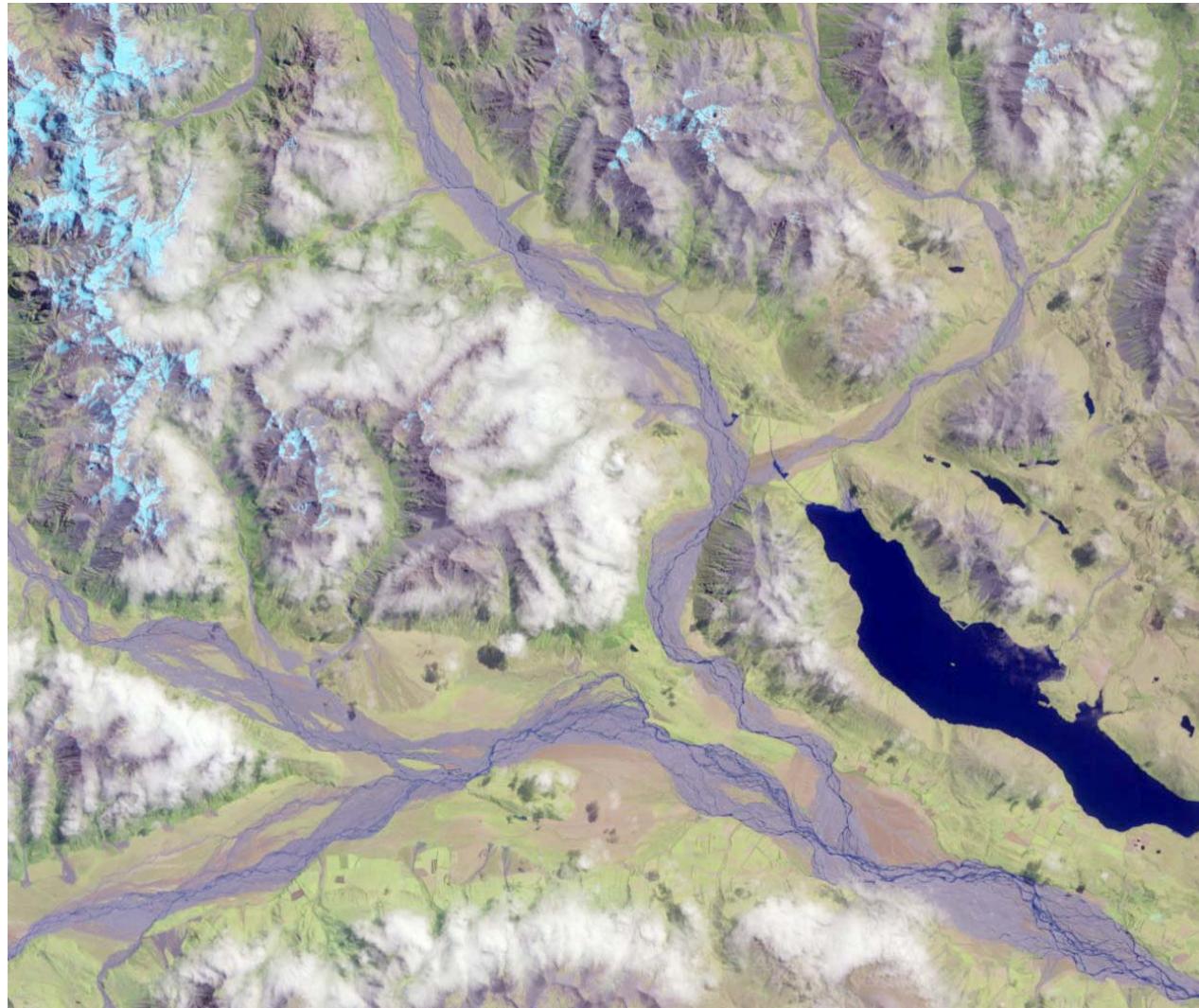


Earth Observing-1

New Zealand 2001:049, MS 7,4,2

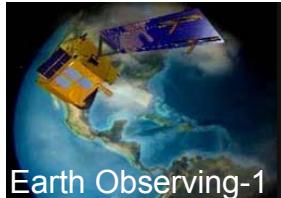


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Earth Observing-1

East Antarctica



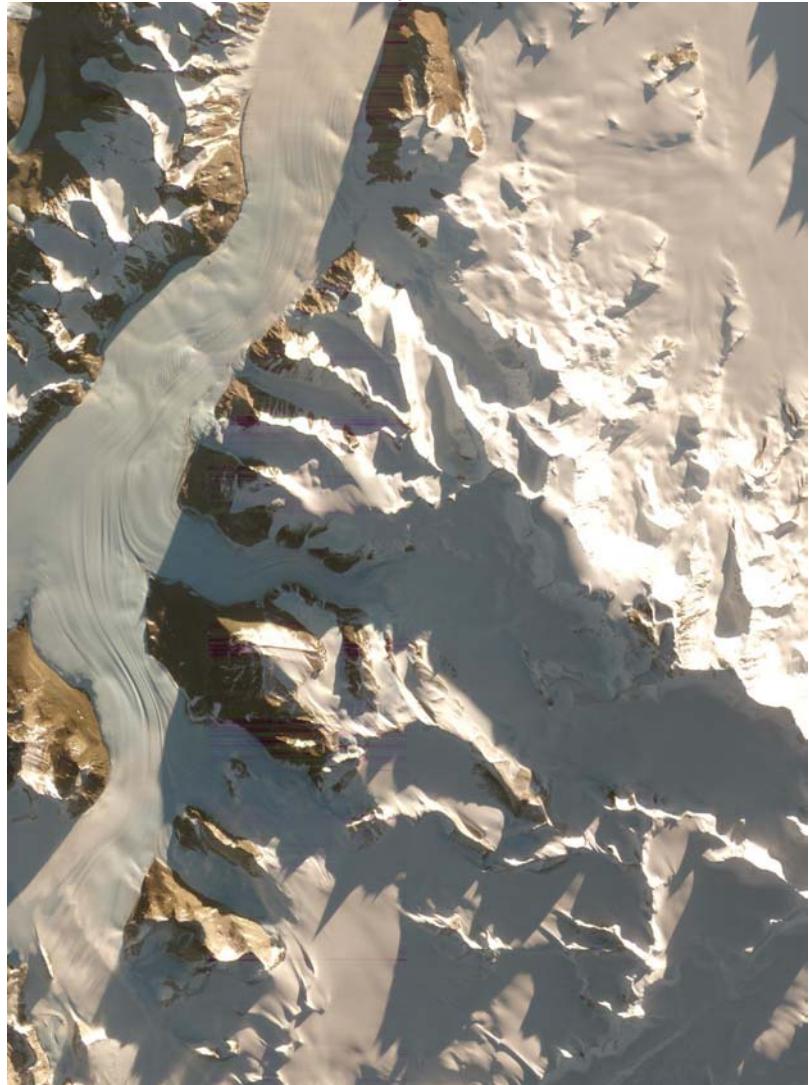
Mission Technology Forum

2001:044, MS 4-3-2

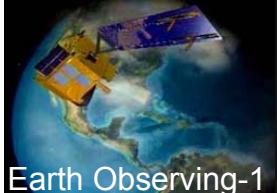


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2001:076, MS 4-3-2



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Earth Observing-1

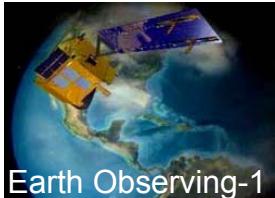


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Flight Performance Assessment

- ◆ *Functional*
- ◆ *Spatial*
- ◆ *Radiometric*





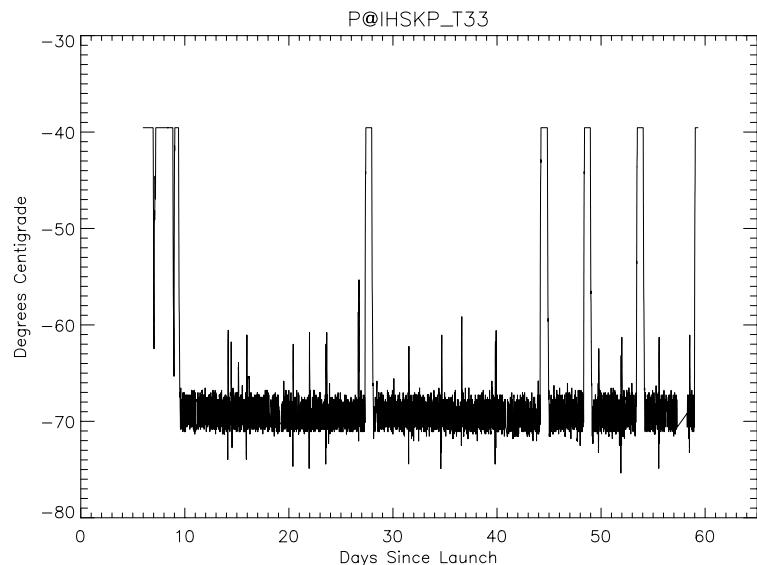
Trending (1 of 4)



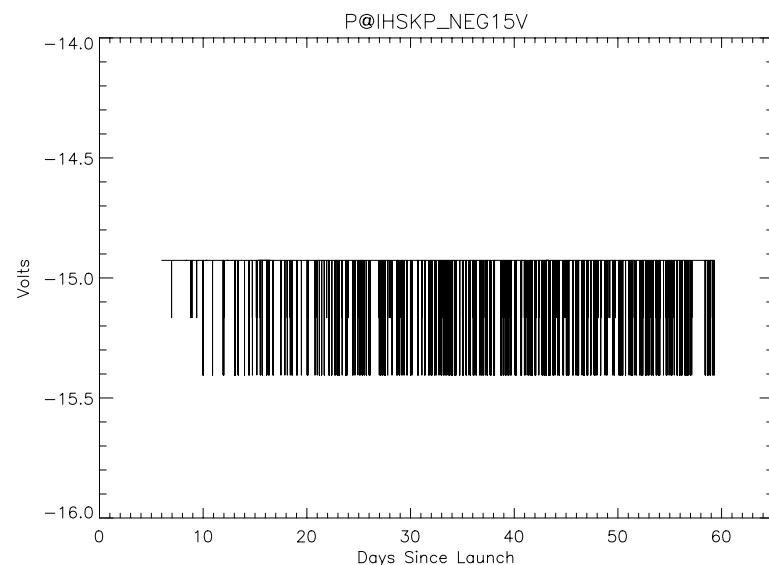
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◆ Telemetry

- All critical voltages, currents, temperatures nominal and well within yellow limits



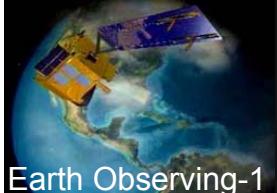
T33 = Top of FPA Radiator



ALICE -15 V



08/15-16/01



Earth Observing-1

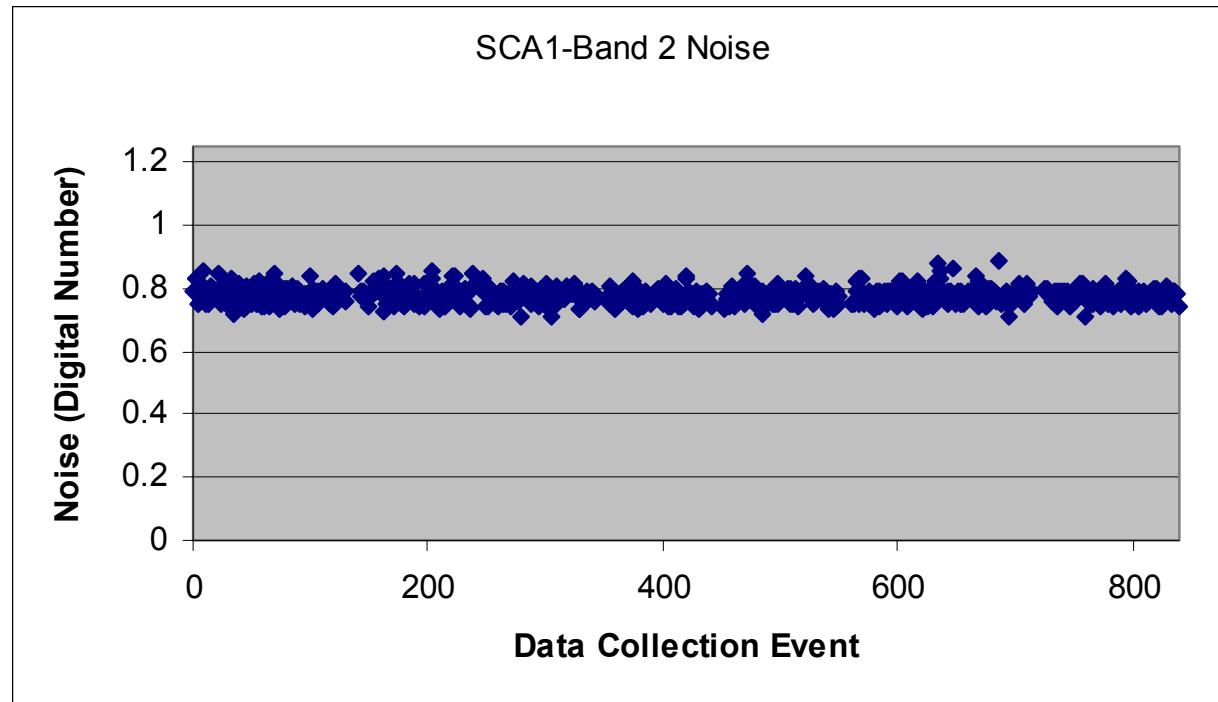
Trending (2 of 4)

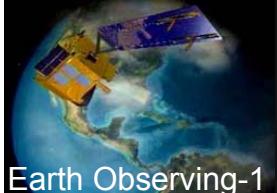


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◆ **Noise**

- *Consistent with pre-flight measurements*
- *All mean SCA and Band noise levels < 1.15 DN*
- *All SCA and Bands noise levels stable to within 0.1 DN*





Earth Observing-1

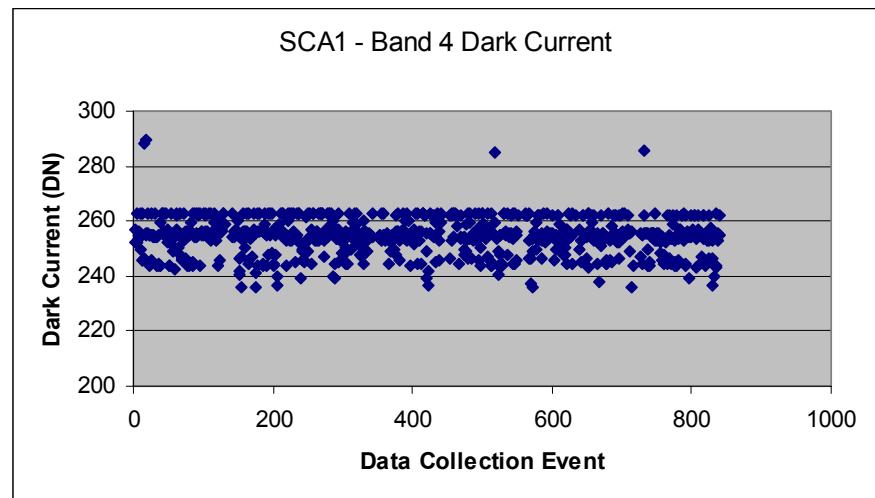
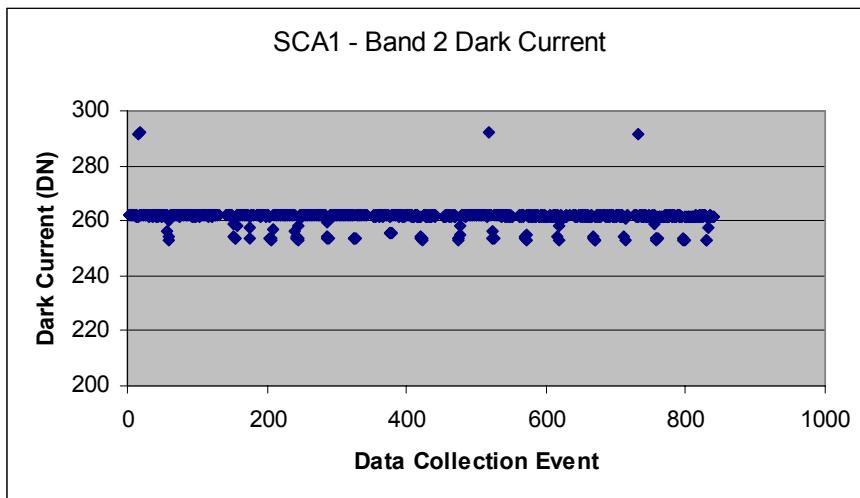
Trending (3 of 4)

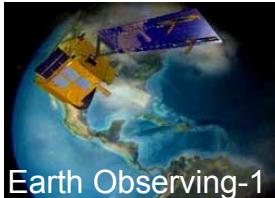


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◆ *Dark Current*

- *Consistent with pre-flight measurements*
- *All bands have excellent stability during single DCE*
- *Bands 1, 2, 3 have excellent stability between DCES*
- *Bands 1p, 4, 4p, 5p, 5, 7, Pan exhibit up to 30 DN variability between DCEs*
 - *Source unknown*



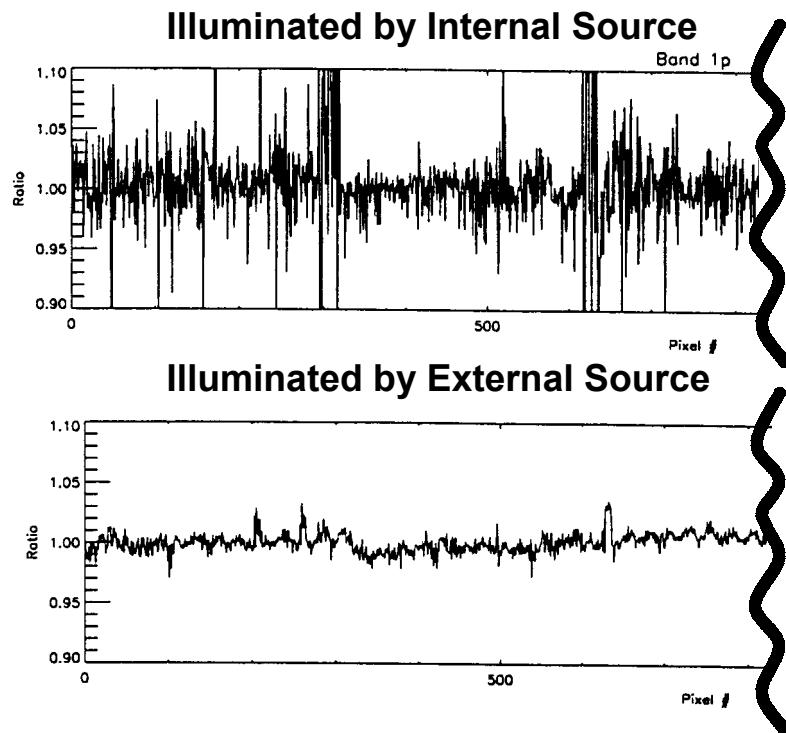
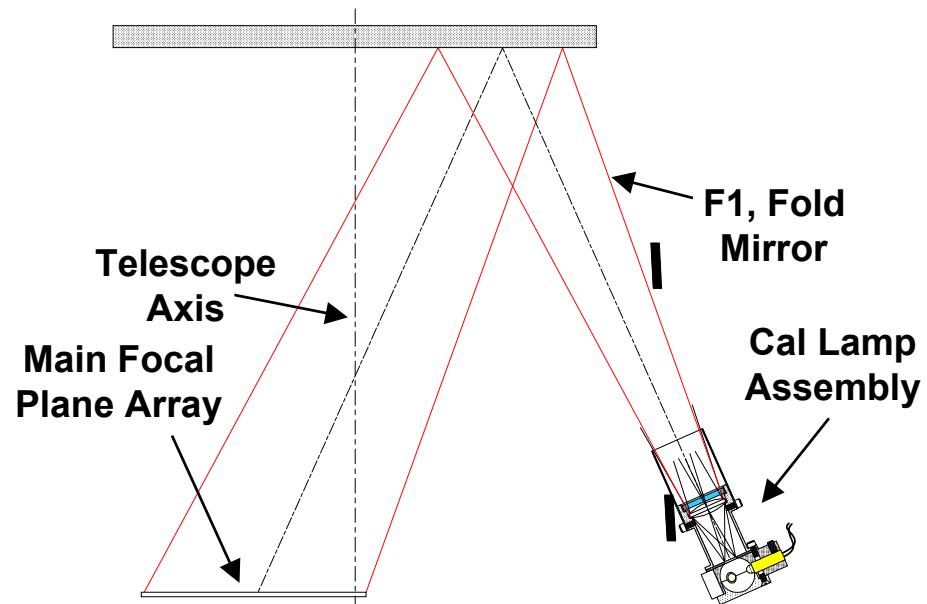


Trending (4 of 4)



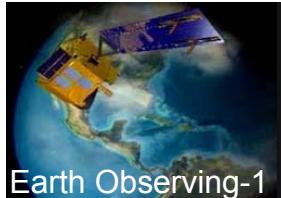
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- ◆ **Contamination**



- ◆ **Comparison of internal reference lamp data with external source simulating a ground scene shows a reduction in the pixel to pixel variability in the latter case by a factor of ~4.**
 - *The difference is due to the different f-number of the telescope (7.5) from the internal reference lamp system (40).*





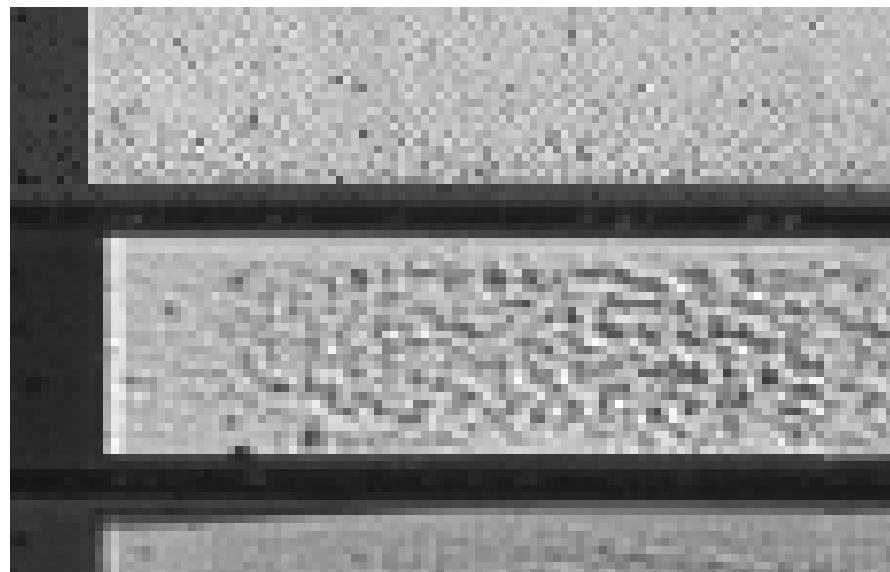
Earth Observing-1

Images of Focal Plane

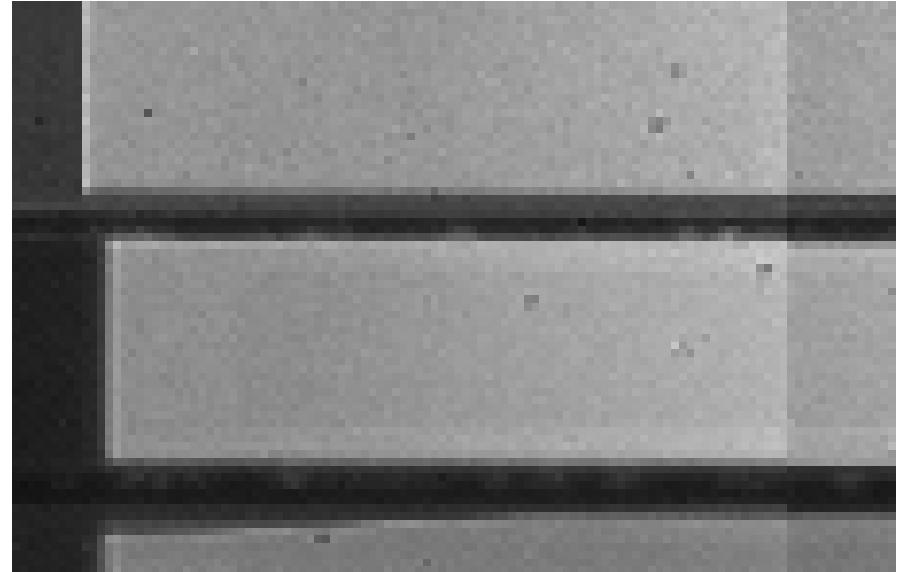


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Before

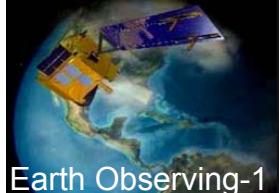


After



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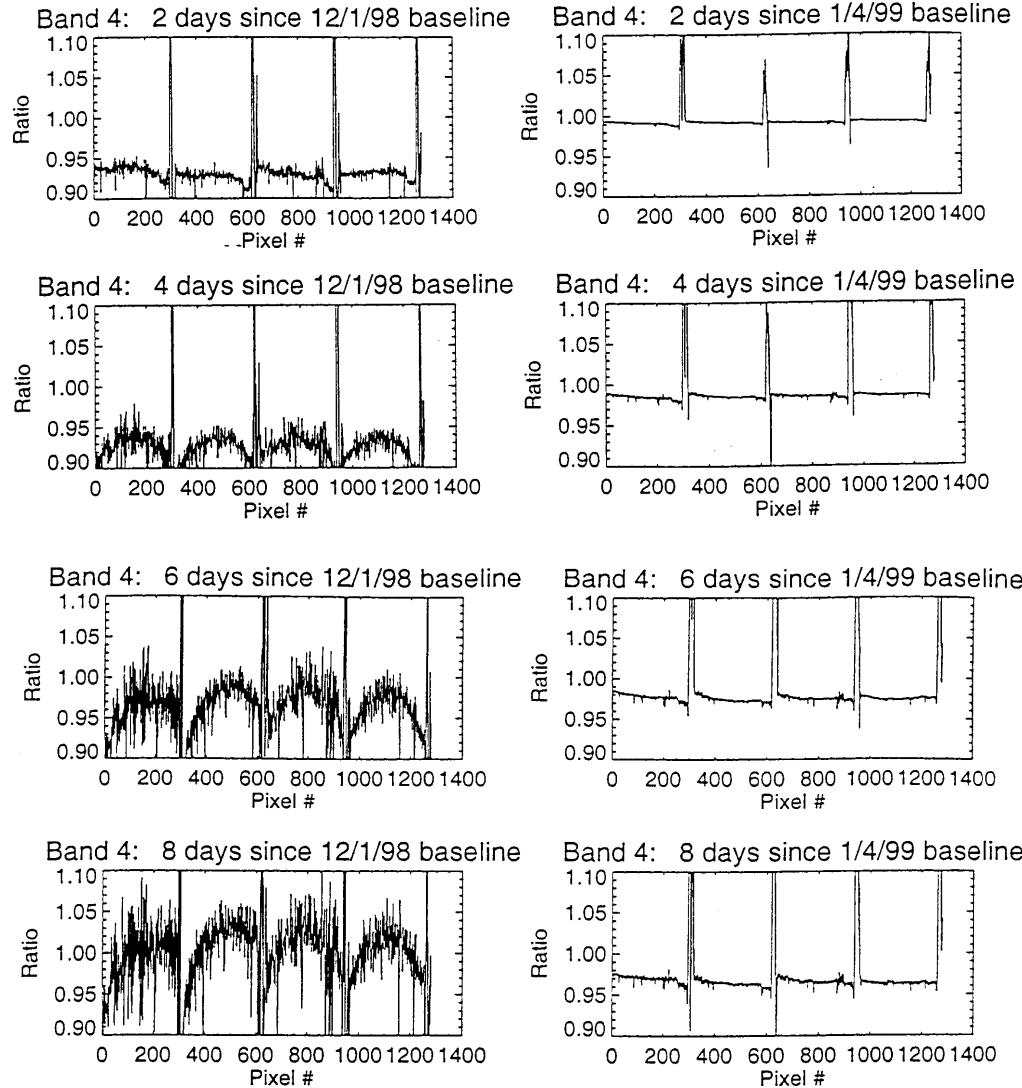


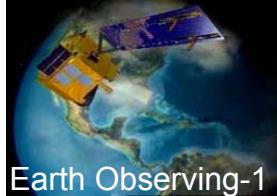
Earth Observing-1

Characteristics of Contamination



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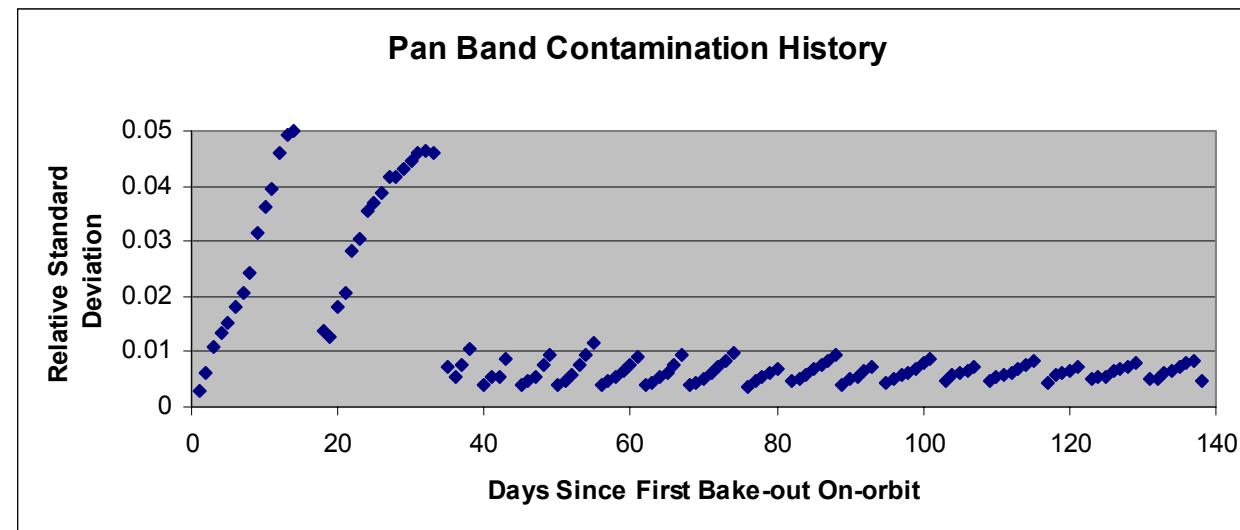
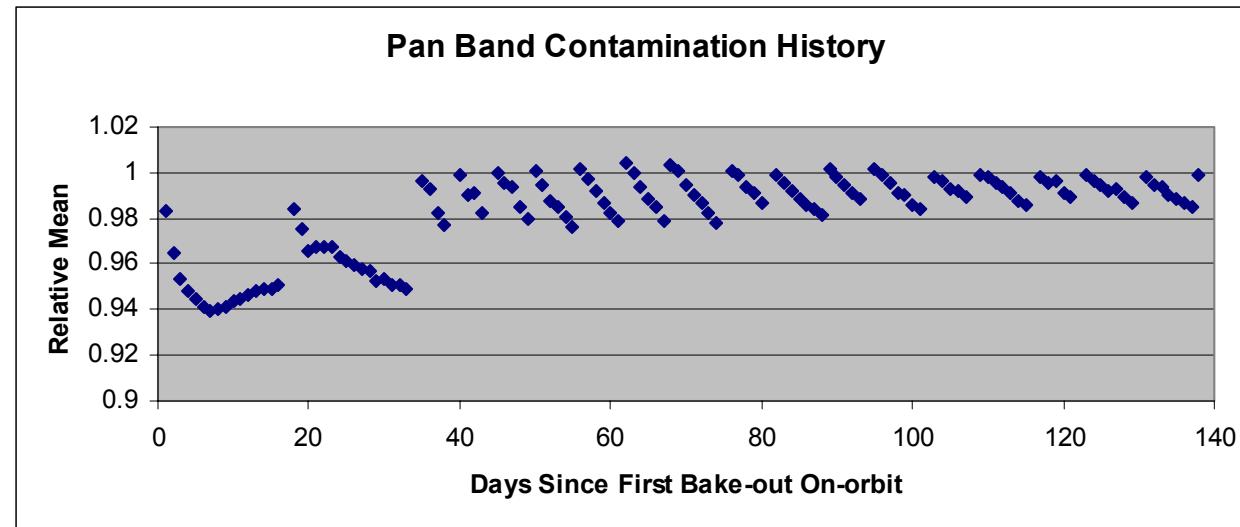


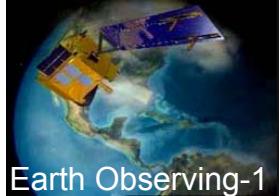
Earth Observing-1

Pan Contamination Trending On-Orbit



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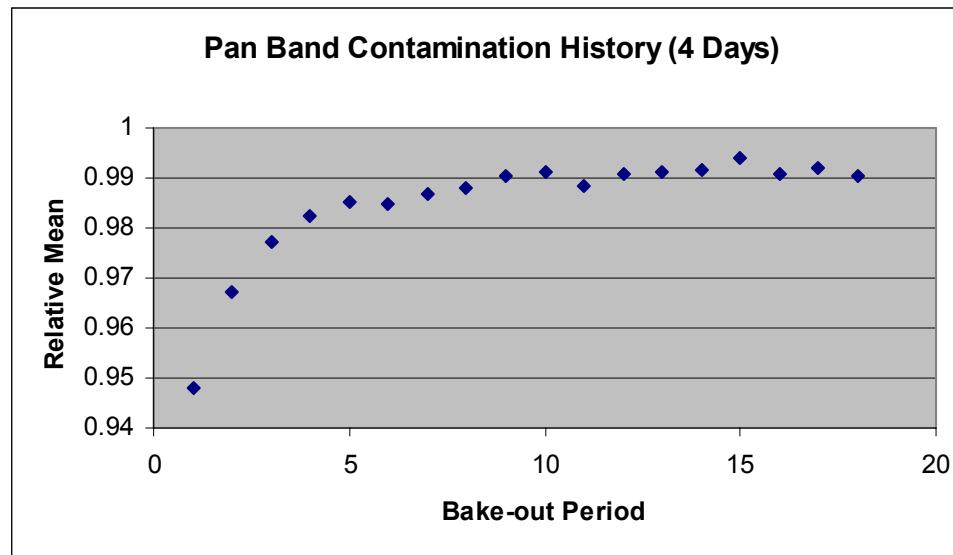
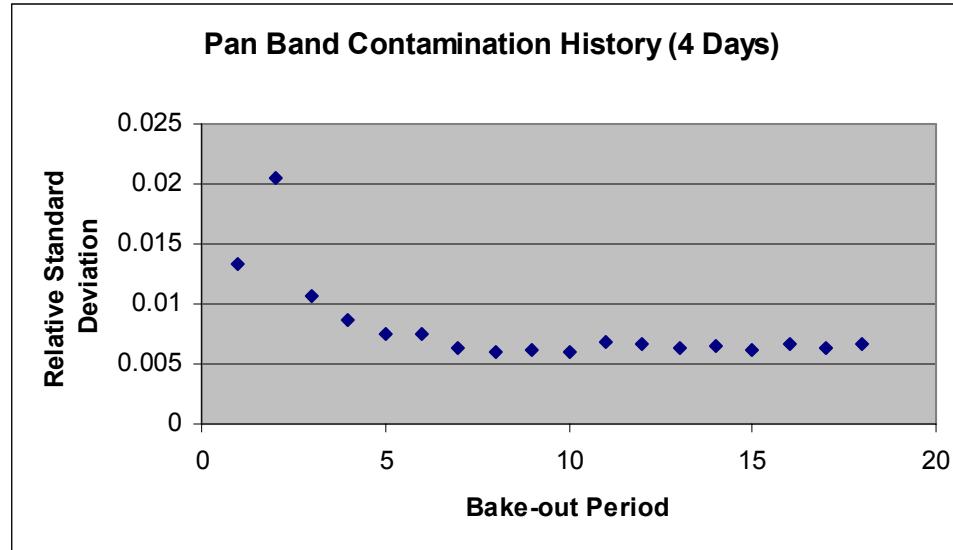


Earth Observing-1

Pan Contamination Trending On-Orbit

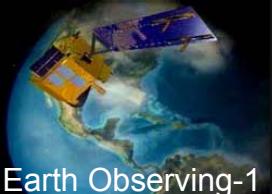


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Earth Observing-1

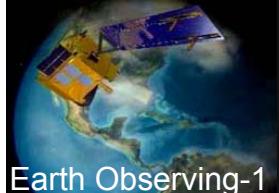
Leaky Detectors



Mission Technology Forum

- ◆ ***Two detectors with high cross-talk (leaky) were identified during ground calibration.***
 - *Band 3 SCA 3 Detector 225*
 - *Band 2 SCA 4 Detector 190*
- ◆ ***Detectors induce spurious signal onto neighboring odd (Band 3) or even (Band 2) detectors of the host SCA only.***





Earth Observing-1

MIT / Lincoln Laboratory



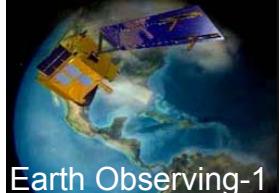
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- ◆ ***Pre-Correction***



08/15-16/01

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Earth Observing-1

MIT / Lincoln Laboratory

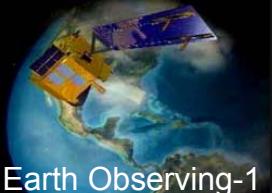


Mission Technology Forum

- ◆ *Pre-Correction*



08/15-16/01



Earth Observing-1

Correction Methodology (1 of 7)



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- ◆ ***Geometrically shift odd and even pixels***
- ◆ ***Subtract dark current from each pixel***
- ◆ ***Transform leaky and standard pixels to radiance space by radiometrically calibrating pixels***
- ◆ ***Generate difference array for the average of standard pixels to the left and right of corrupted pixels***
- ◆ ***Fit cubic polynomial function f to standard pixel values v. difference array values***
- ◆ ***Compute correction factor array for corrupted pixels***

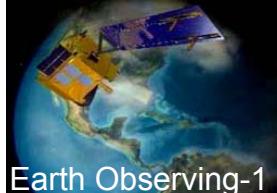
$$C(n) = f(0) + f(1)*L_s(n) + f(2)*L_s(n)^2 + f(3)*L_s(n)^3 \text{ for } n=0, 160$$

- ◆ ***Correct corrupted pixels***

$$L_L(n) = L_L(n) - C(n) \text{ for } n = 0, 160$$

- ◆ ***Save corrected image***





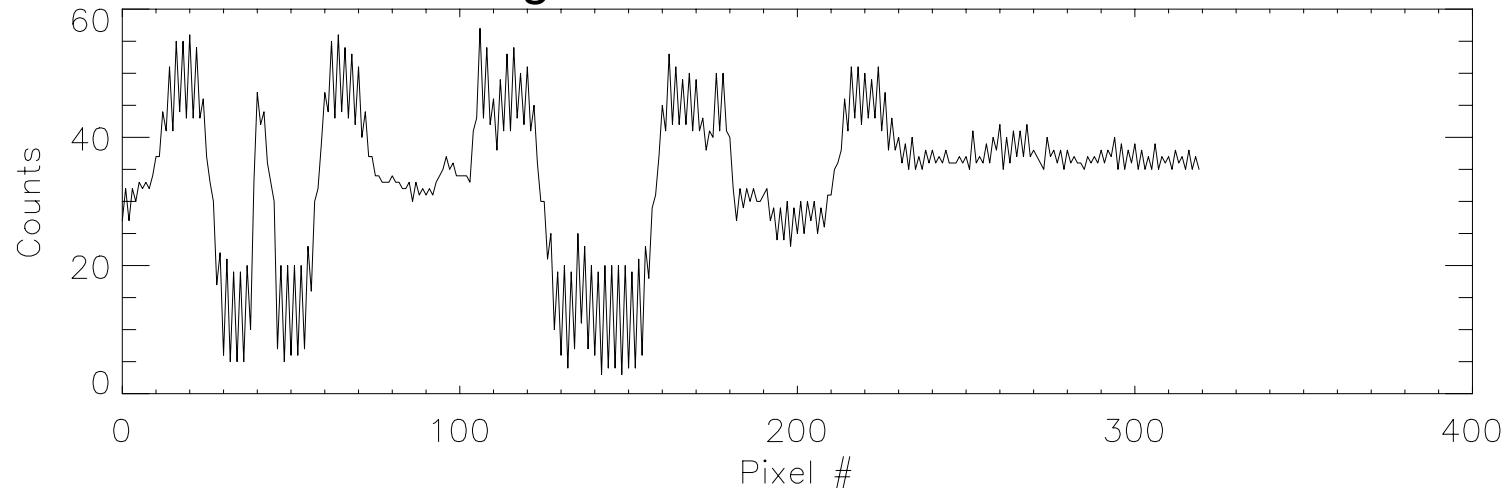
Earth Observing-1

Correction Methodology (2 of 7)

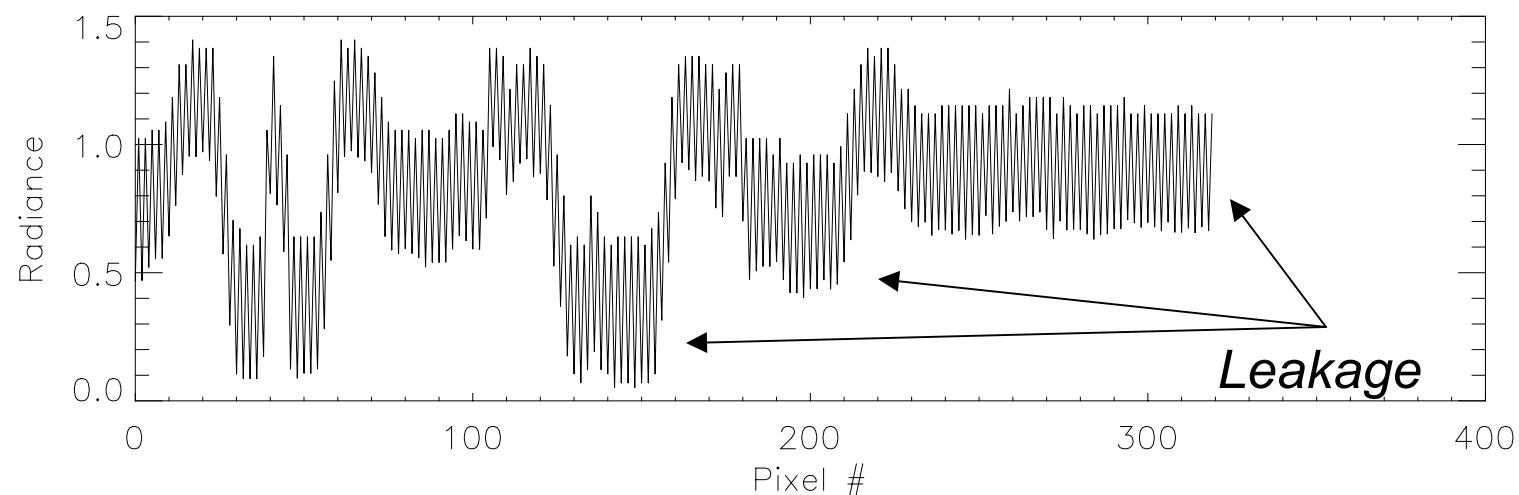


Mission Technology Forum

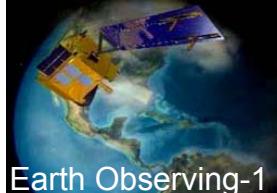
Original dark subtracted data



Radiometrically corrected data



08/15-16/01



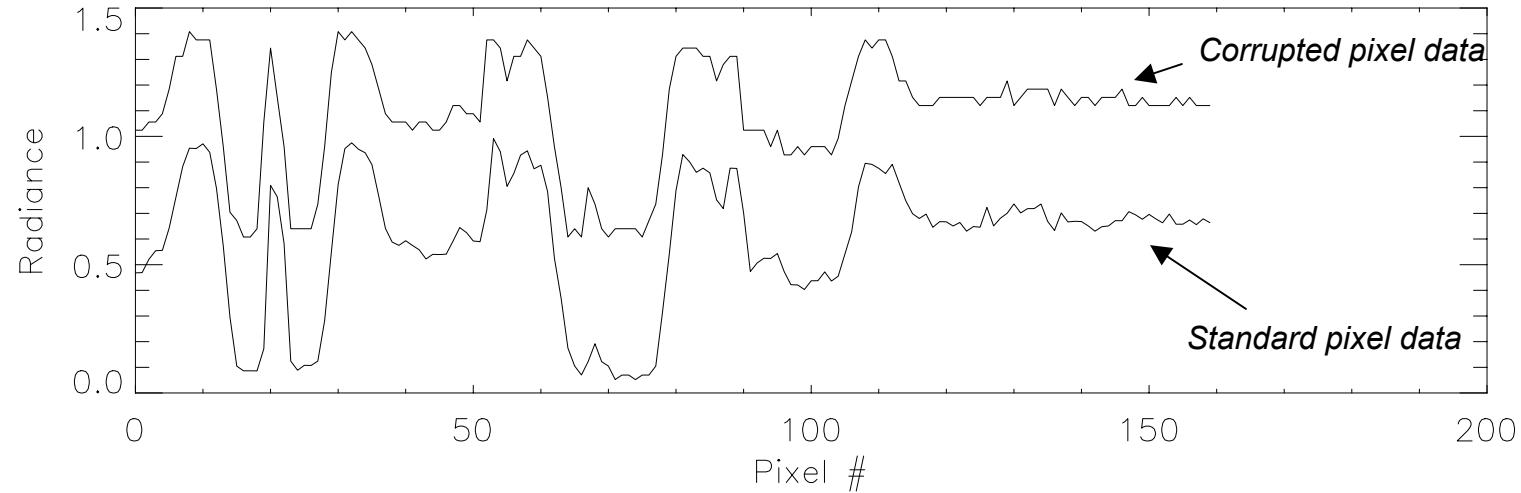
Earth Observing-1

Correction Methodology (3 of 7)

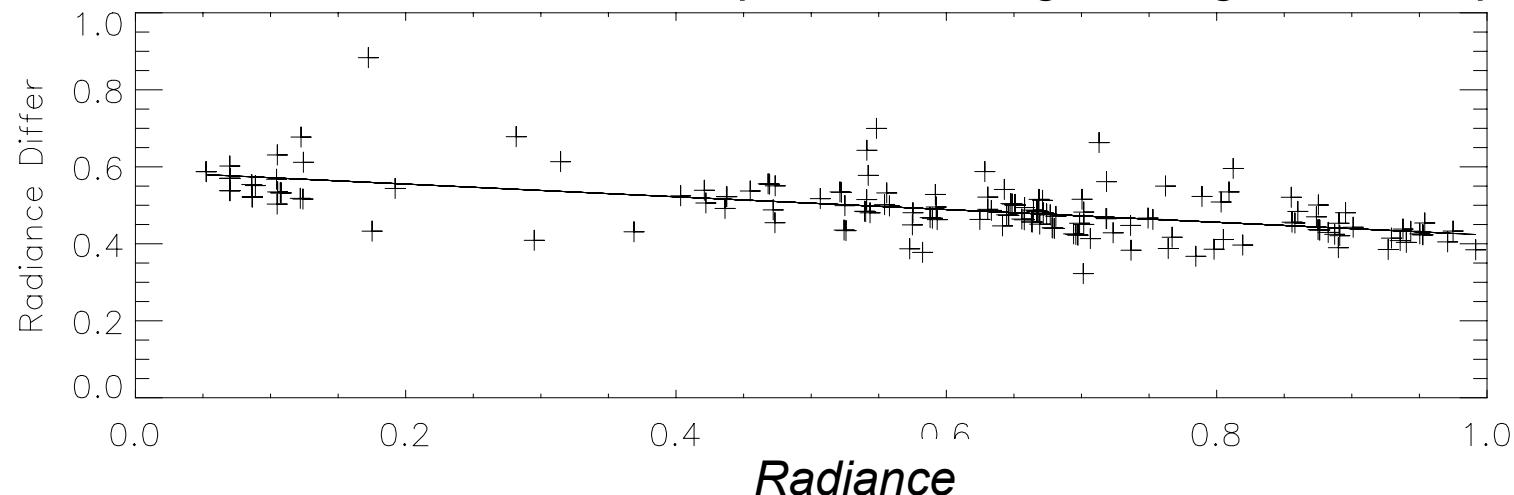


Mission Technology Forum

Radiometrically corrected data

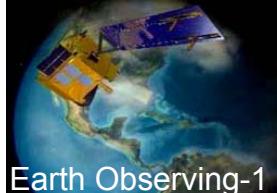


Difference between corrupted and neighboring standard pixels



08/15-16/01

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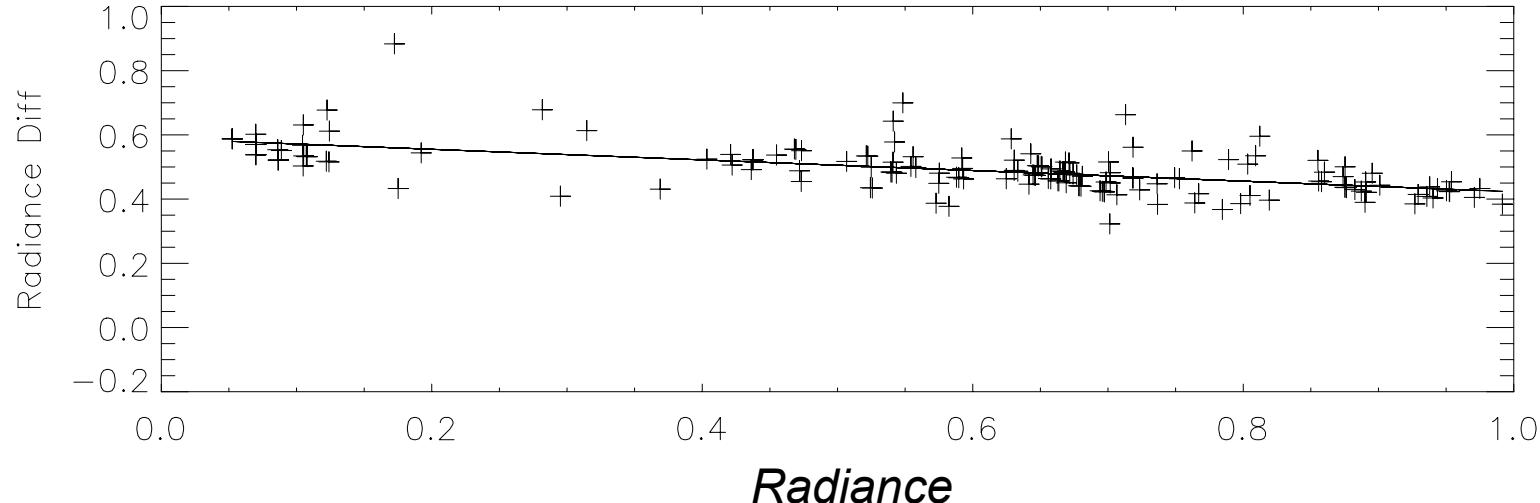
Earth Observing-1

Correction Methodology (4 of 7)

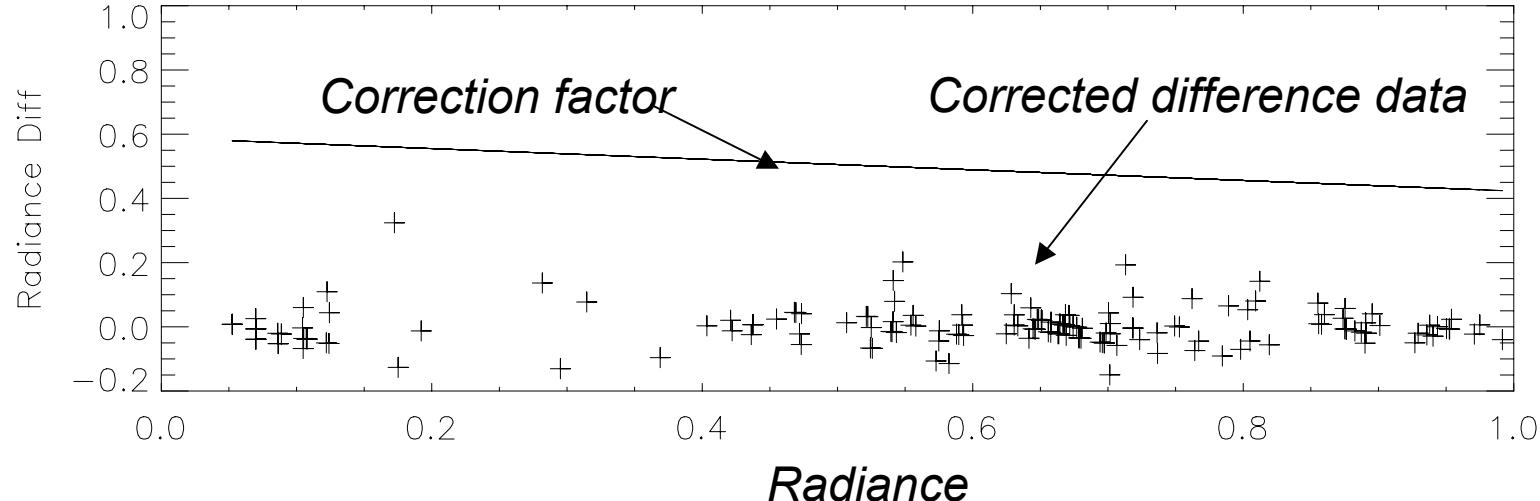


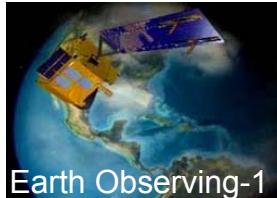
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Difference between corrupted and neighboring standard pixels



Demonstration of correction algorithm to difference data. Note: Pixel to pixel variations are preserved.





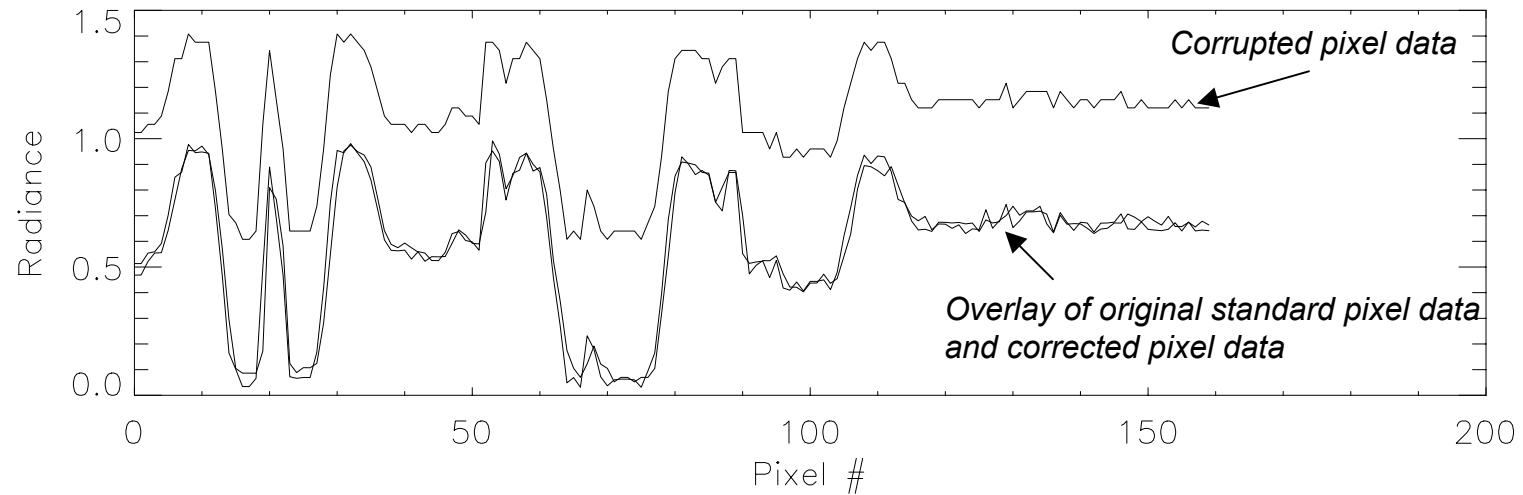
Earth Observing-1

Correction Methodology (5 of 7)

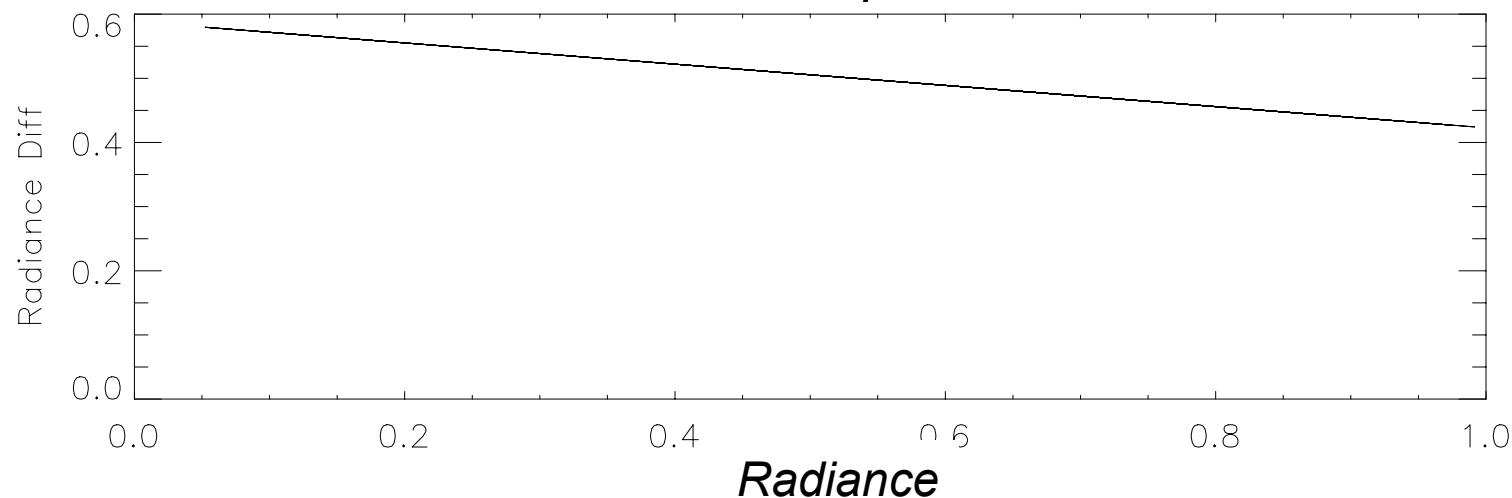


Mission Technology Forum

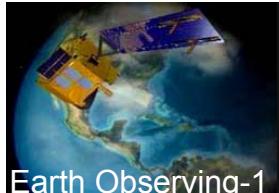
Overlay of corrupted and corrected data.



Difference between corrupted and corrected data.



08/15-16/01



Earth Observing-1

Correction Methodology (6 of 7)



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Uncalibrated Image



Calibrated Image



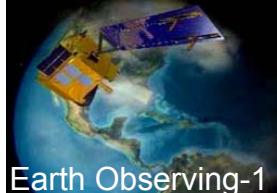
Leaky Pixel

Leaf Image



08/15-16/01

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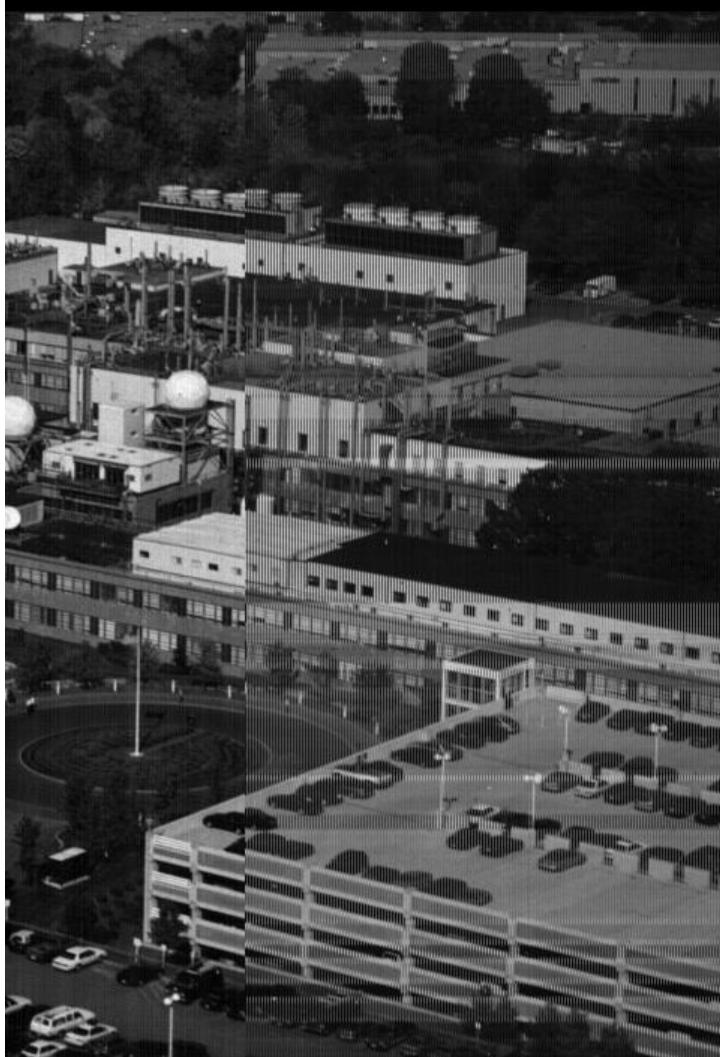
Earth Observing-1

Correction Methodology (7 of 7)



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Uncalibrated Image



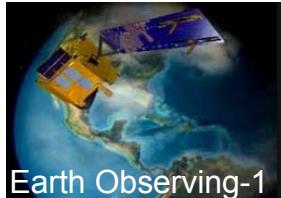
Calibrated Image



MIT/LL Image



08/15-16/01

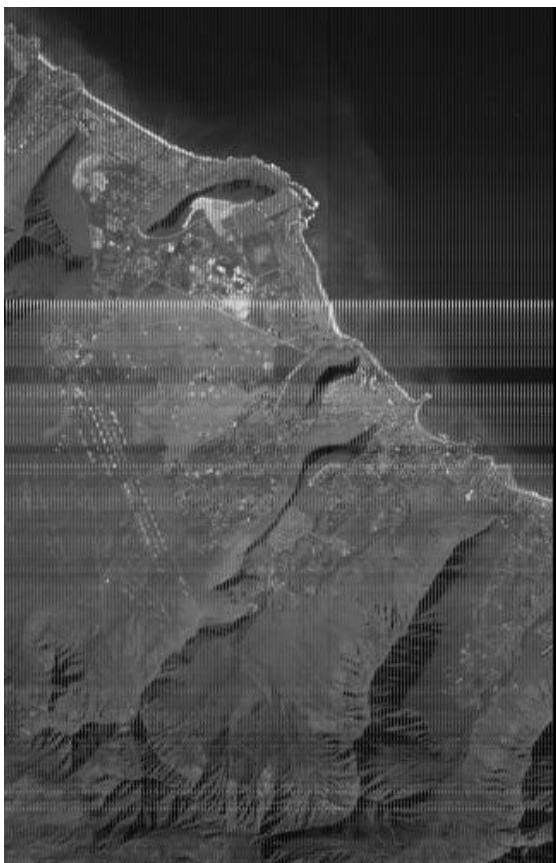


Oahu, 2000:354, Detail



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Original



Corrected

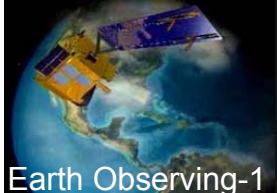


Corrected, High Contrast



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Earth Observing-1

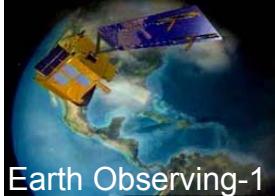


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Flight Performance Assessment

- ◆ *Functional*
- ◆ *Spatial*
- ◆ *Radiometric*





Earth Observing-1

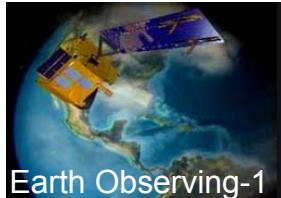
On-Orbit Spatial Performance Assessment



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- ◆ **Objective:** Verify instrument spatial performance across entire field of view
 - Modulation Transfer Function
 - Pixel Lines of Sight
 - Band-to-Band registration
 - Image Reconstruction Algorithm
- ◆ **In-flight Targets**
 - Lunar edge ~ every 30 days (7° phase angle)
 - Bridges NYC, Seoul Korea, Florida
 - Canals Suez
 - Cities Boston, NYC, Chicago
 - Stars Vega, Rasalhague (Alpha Ophiucus), Pleiades



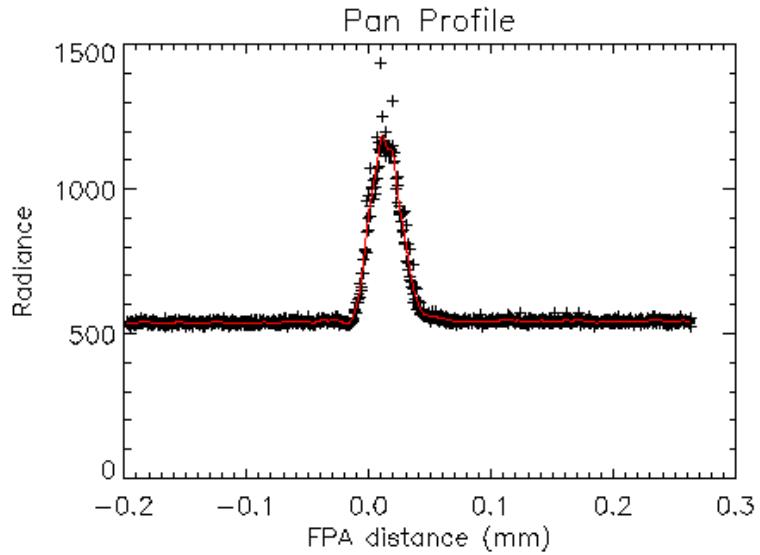
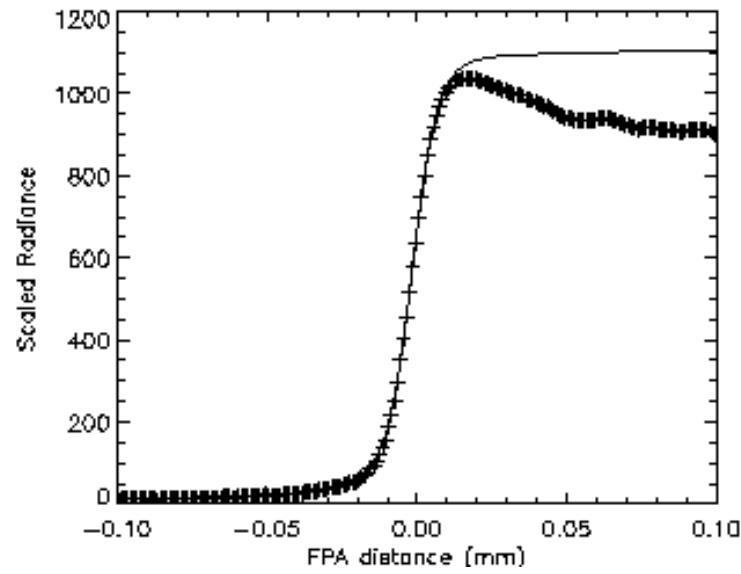


Earth Observing-1

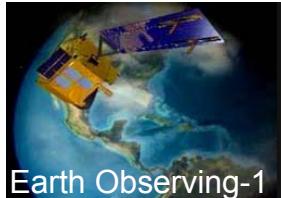
Focus : Lunar Edge



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08/15-16/01



Earth Observing-1

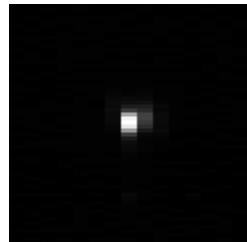
Vega Image, SCA 4 PSF Fit



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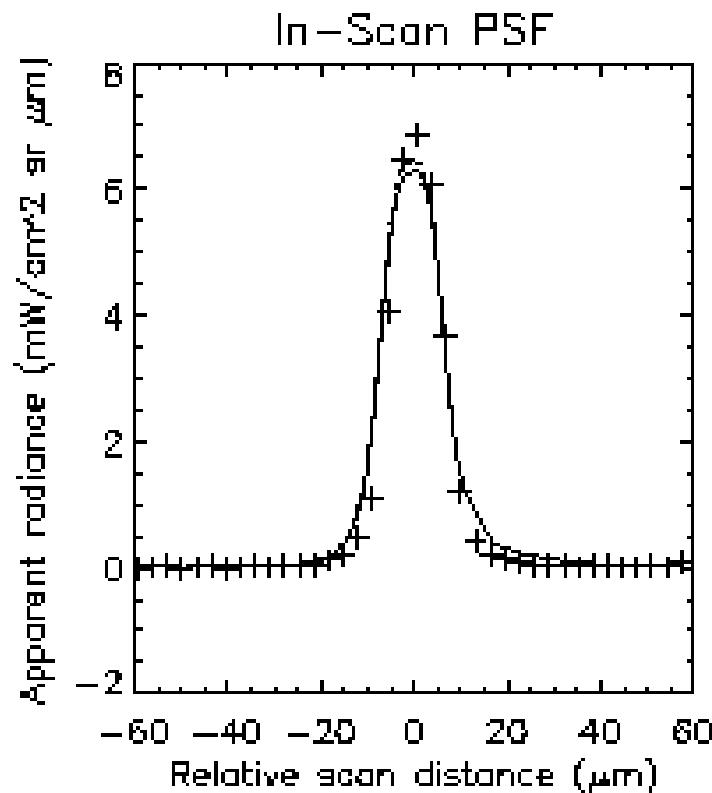
True Values:

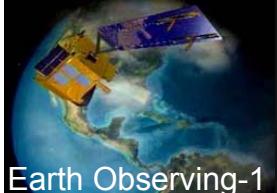
R.A. = 279.234735 deg
Dec. = 38.783692 deg
V magnitude = 0.03 (A0Va)



Fitted Values & Formal Errors:

R.A. = 279.089265 ± 0.0000003 deg
Dec. = 38.460552 ± 0.0000001 deg
Peak Rad. = 6.4937 ± 0.0013 mW/(cm² sr μm)





Earth Observing-1

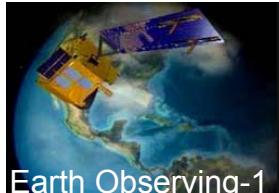


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Flight Performance Assessment

- ◆ *Functional*
- ◆ *Spatial*
- ◆ *Radiometric*





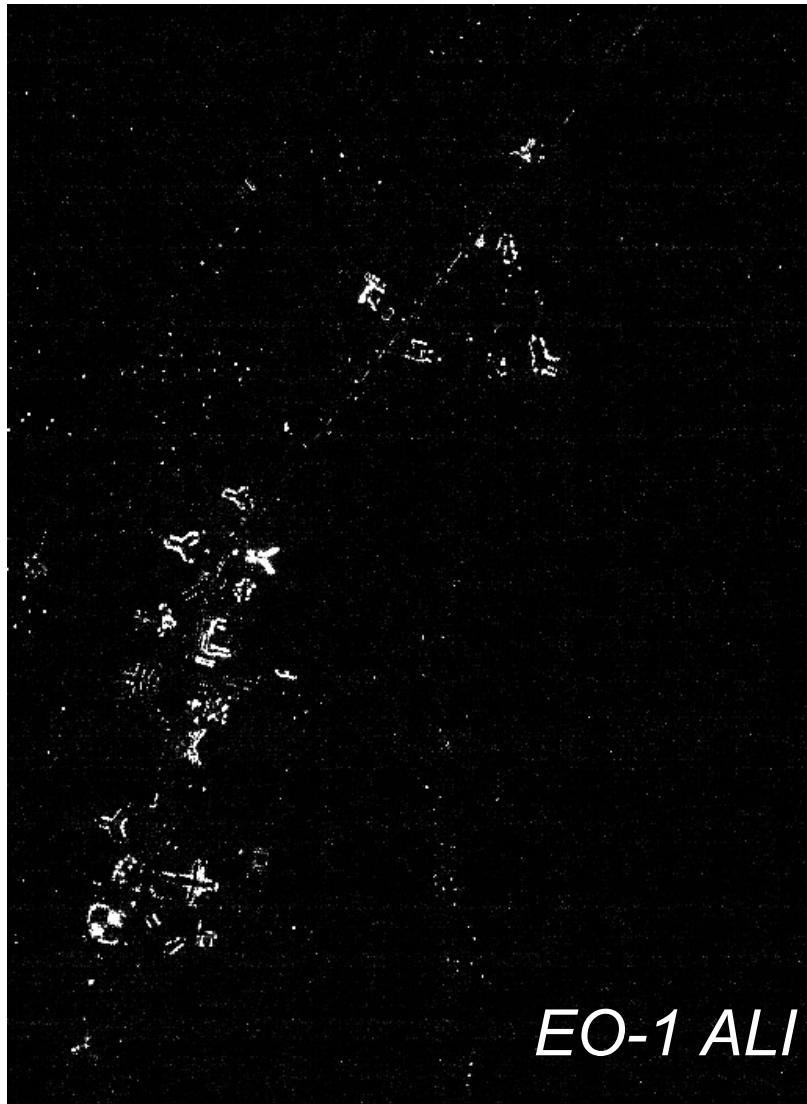
Earth Observing-1

Sensitivity

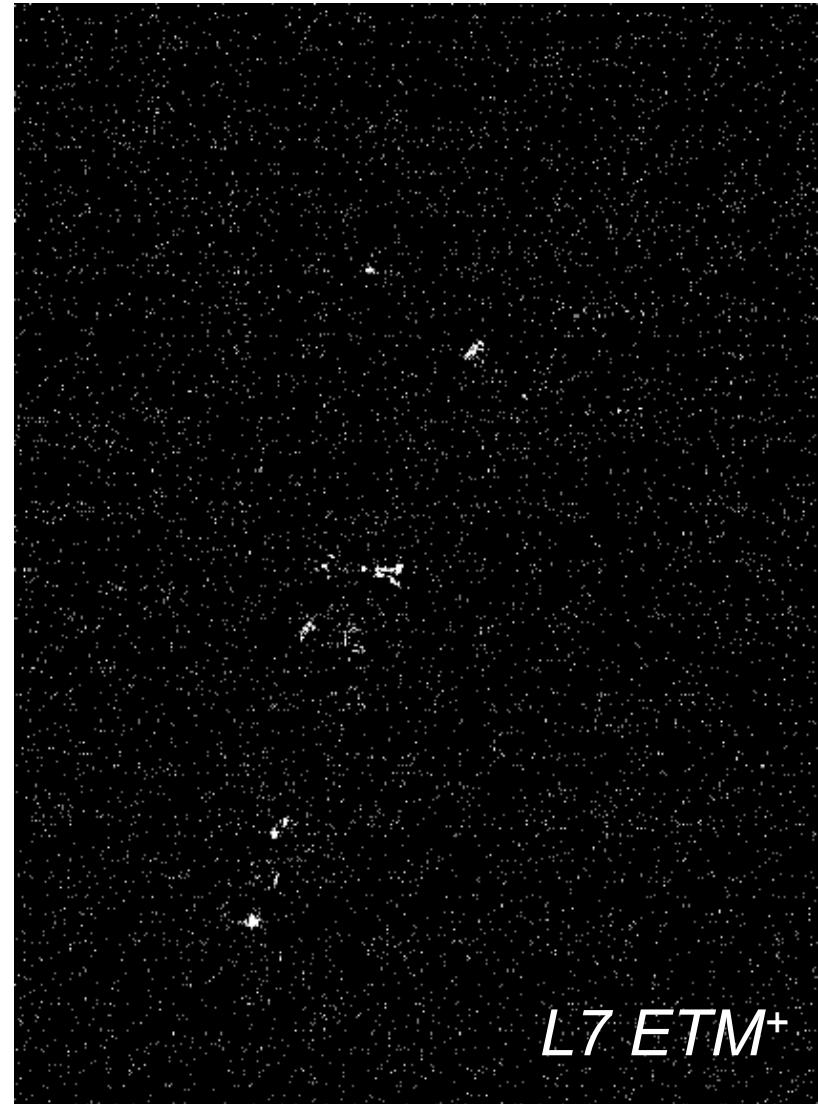


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Las Vegas at night 2001:093, Pan



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Earth Observing-1

Sensitivity

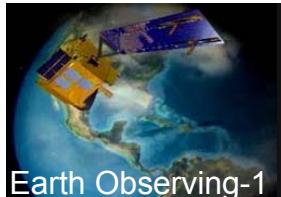


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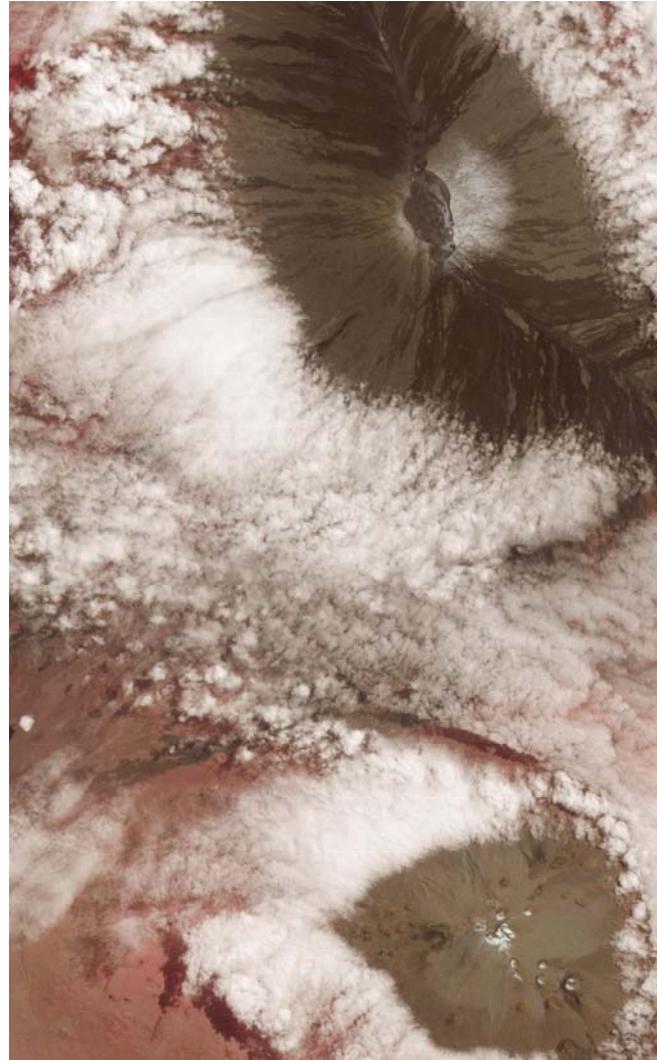


Earth Observing-1

Saturation Radiance

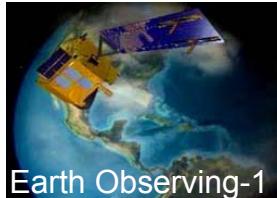


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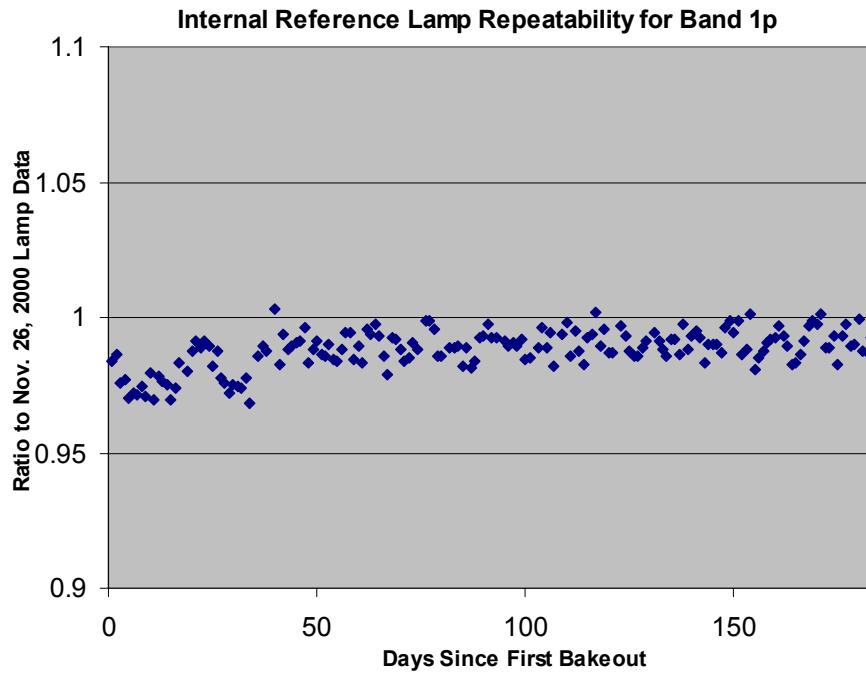
Earth Observing-1

Instrument Stability

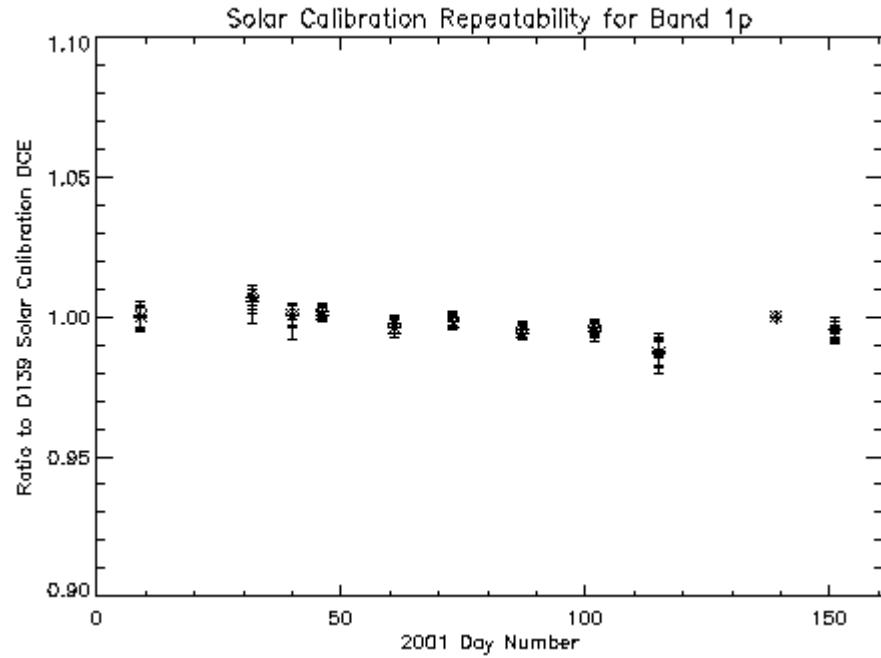


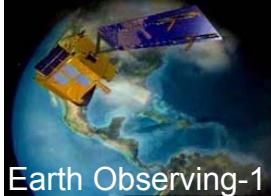
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Internal Reference Lamps



Solar Calibration



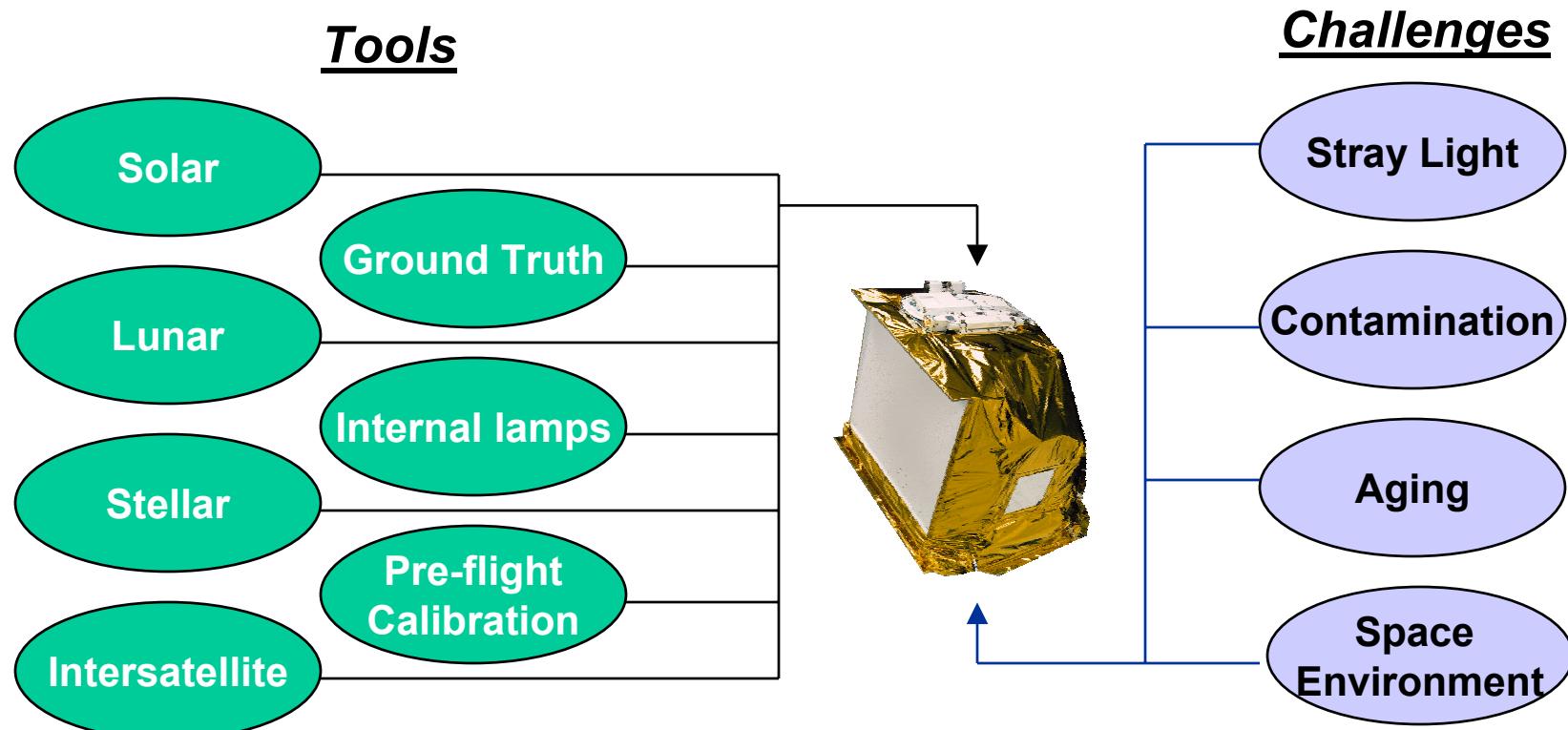


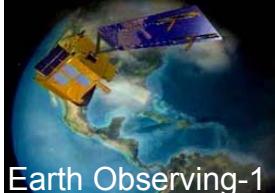
On-Orbit Radiometric Performance Assessment



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- ◆ ***Objective: Absolute measurement of scene flux at every detector***
 - *All bands*
 - *Varying scene intensities*
 - *Long term stability*



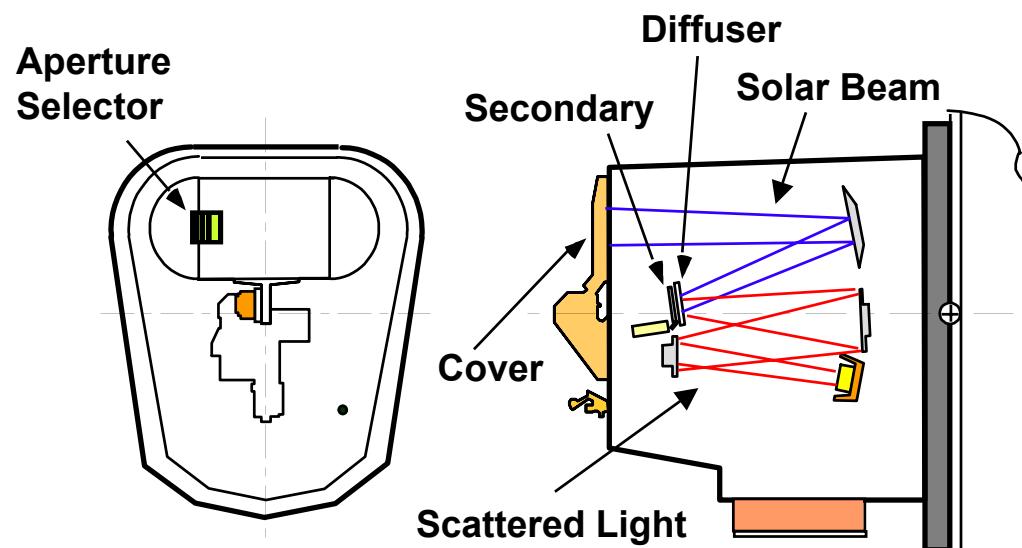
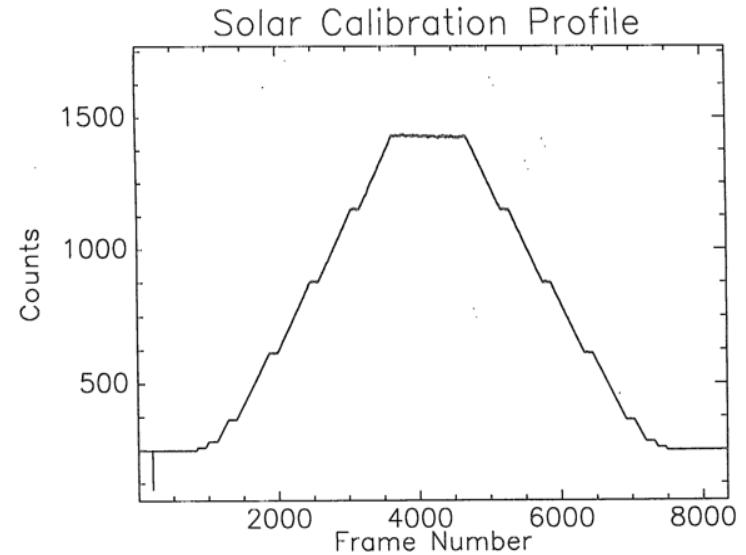
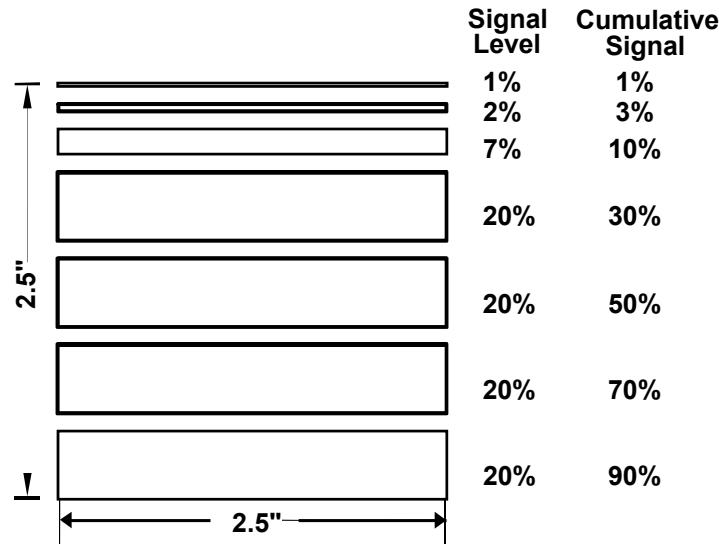


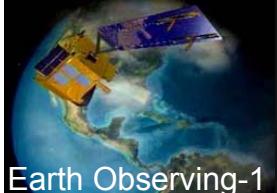
Earth Observing-1

Solar Calibration



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Earth Observing-1

Radiometric Calibration



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◆ *Lunar Calibration*

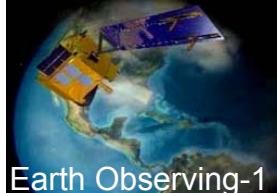
- Calculate Lunar spectral irradiance ($E_M(\lambda)$)
 - Account for geometric effects and phase dependencies
- Compare to SeaWifs Lunar spectral irradiance measurement



◆ *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





Earth Observing-1

Radiometric Calibration

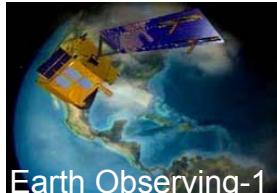


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◆ **Ground Truth Referencing**

- *Lake Frome, Australia 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*



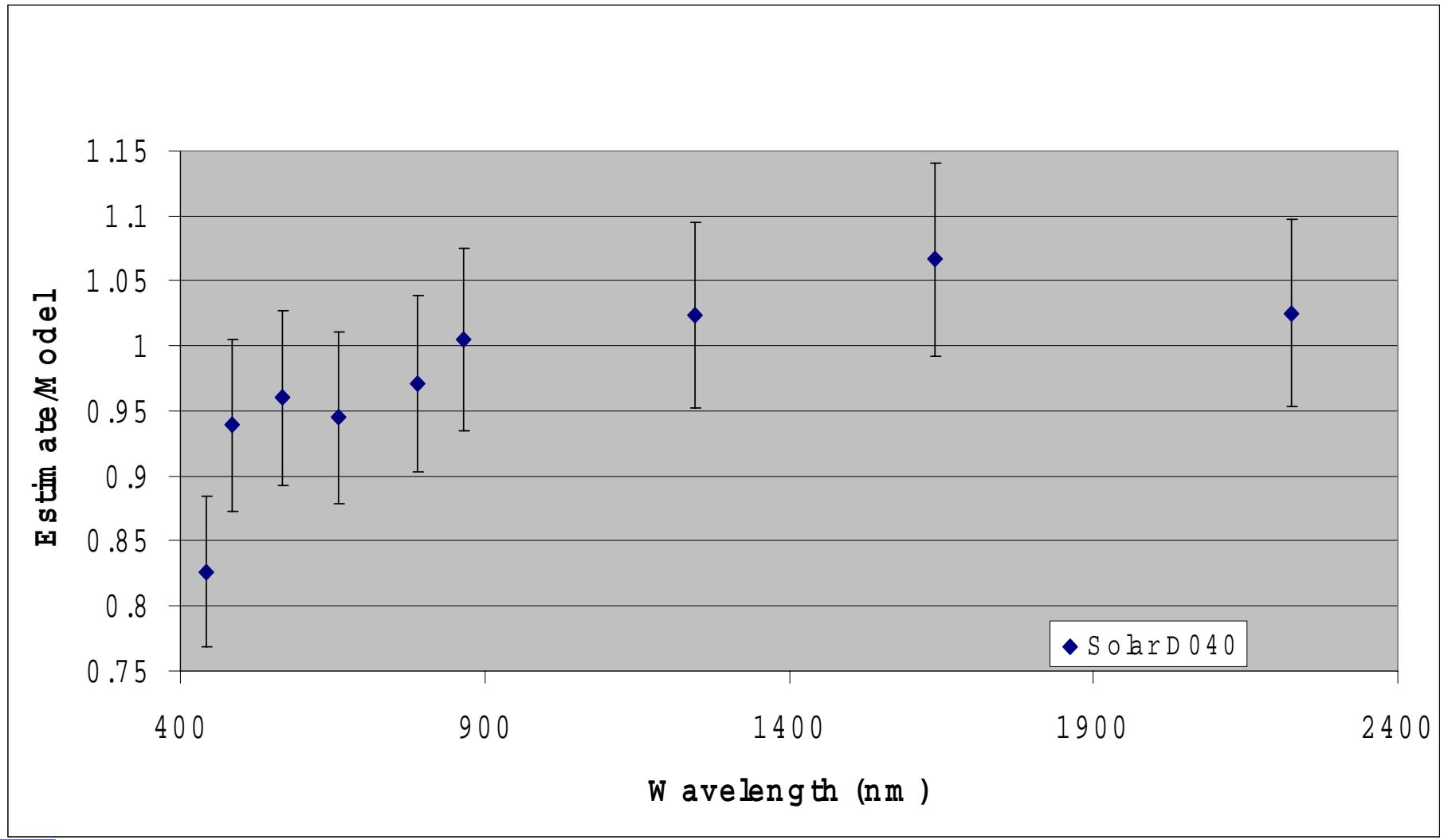


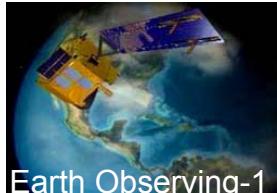
Earth Observing-1

Radiometric Calibration



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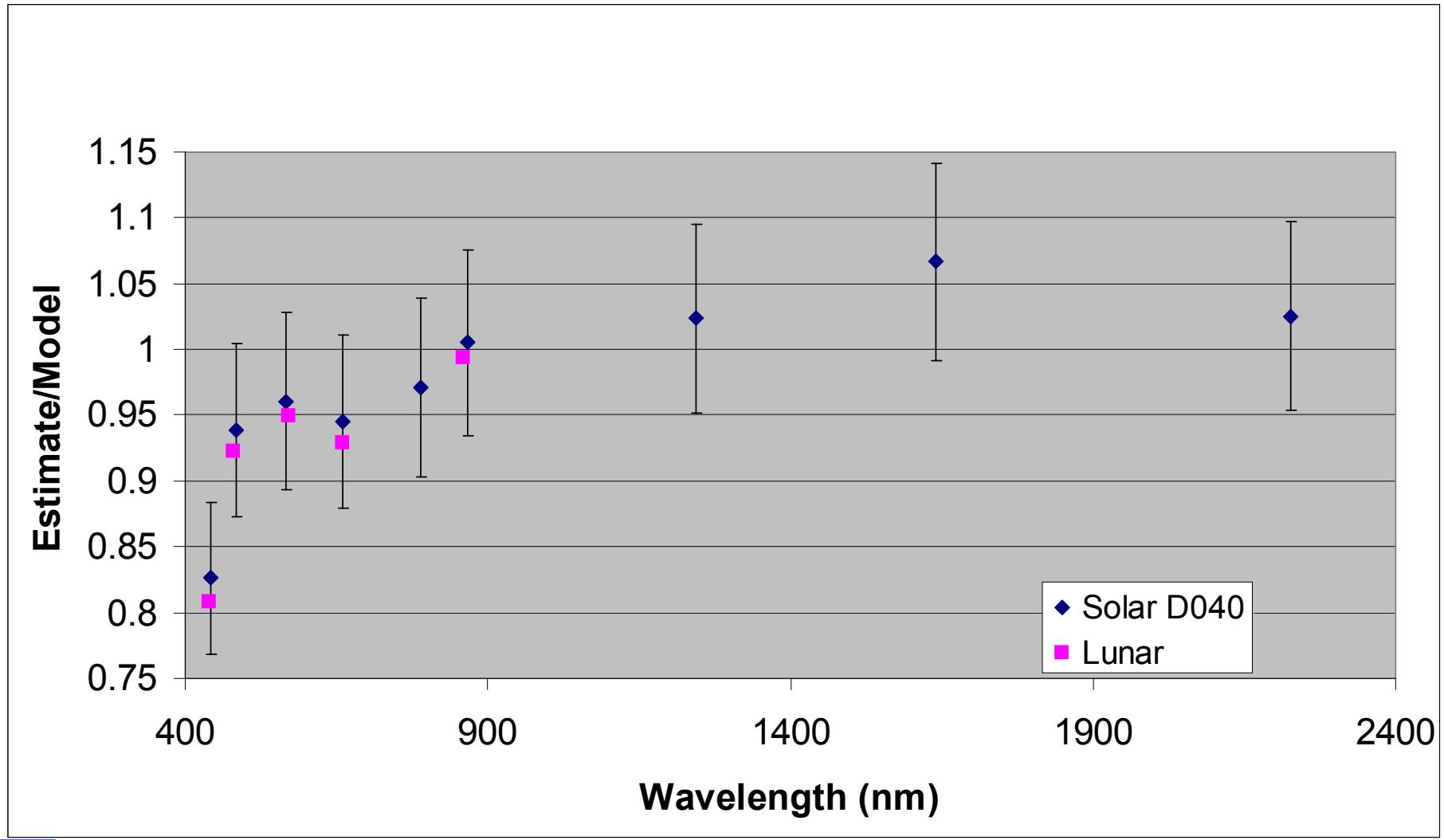


Earth Observing-1

Radiometric Calibration

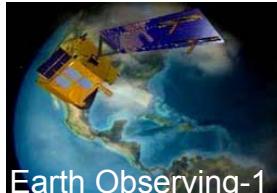


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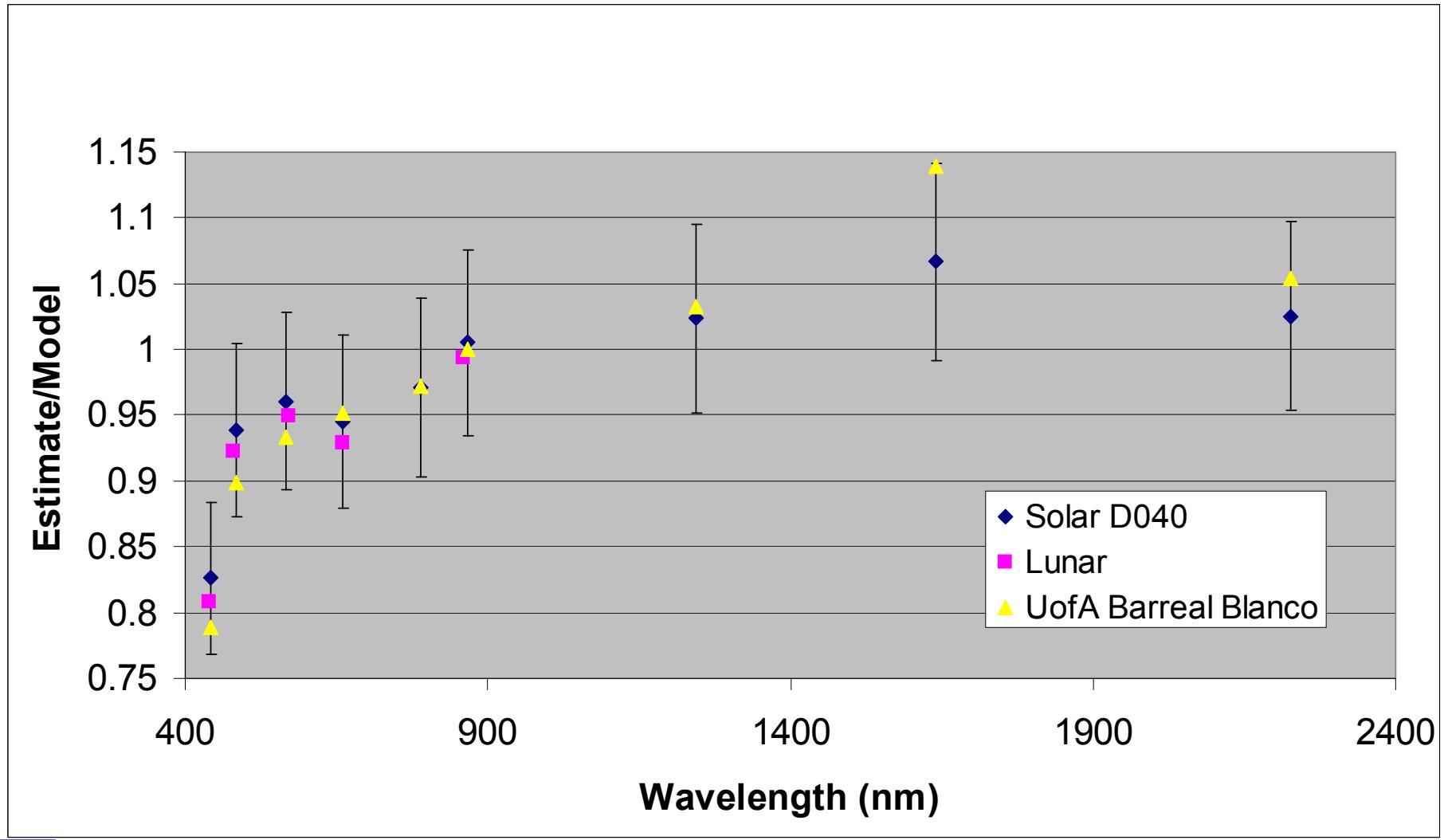


Radiometric Calibration



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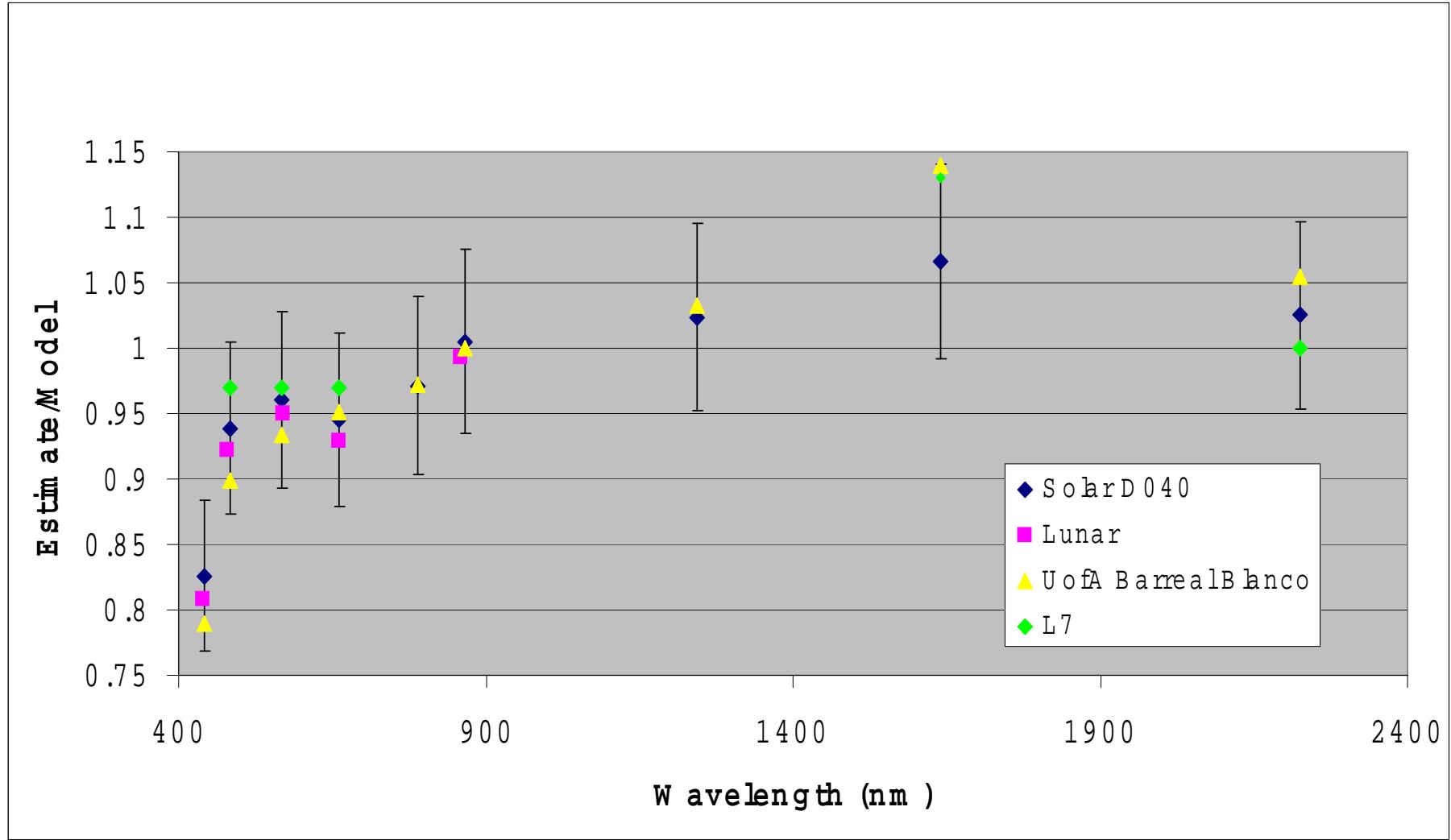


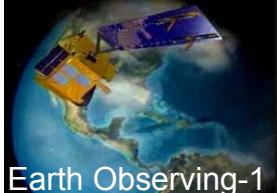
Radiometric Calibration



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Earth Observing-1

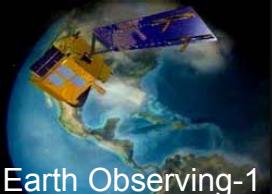
Sources of Radiometric Error



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- ◆ ***Pre-flight calibration inaccuracies***
 - *Unlikely due to good agreement between MIT/LL and GSFC measurements of integrating sphere output*
- ◆ ***Change in instrument response since ground calibration***
 - *Contamination*
 - *Difficult to determine*
- ◆ ***Stray Light***
 - *Expected stray light effects during manufacturing of mirrors*





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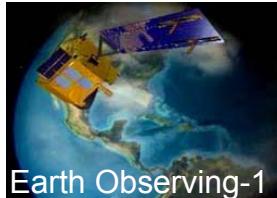
Stray Light



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- ◆ *Telescope delivered did not meet specification on primary and tertiary mirror finish*
- ◆ *Expected significant stray light effects on orbit for bands 1p, 1*
- ◆ *Three Earth limb scans have been taken to characterize effects on orbit*
- ◆ *Preliminary analysis confirm two sources of stray light*
 - *Mirror scatter*
 - *Reflected light from black structure and baffles*



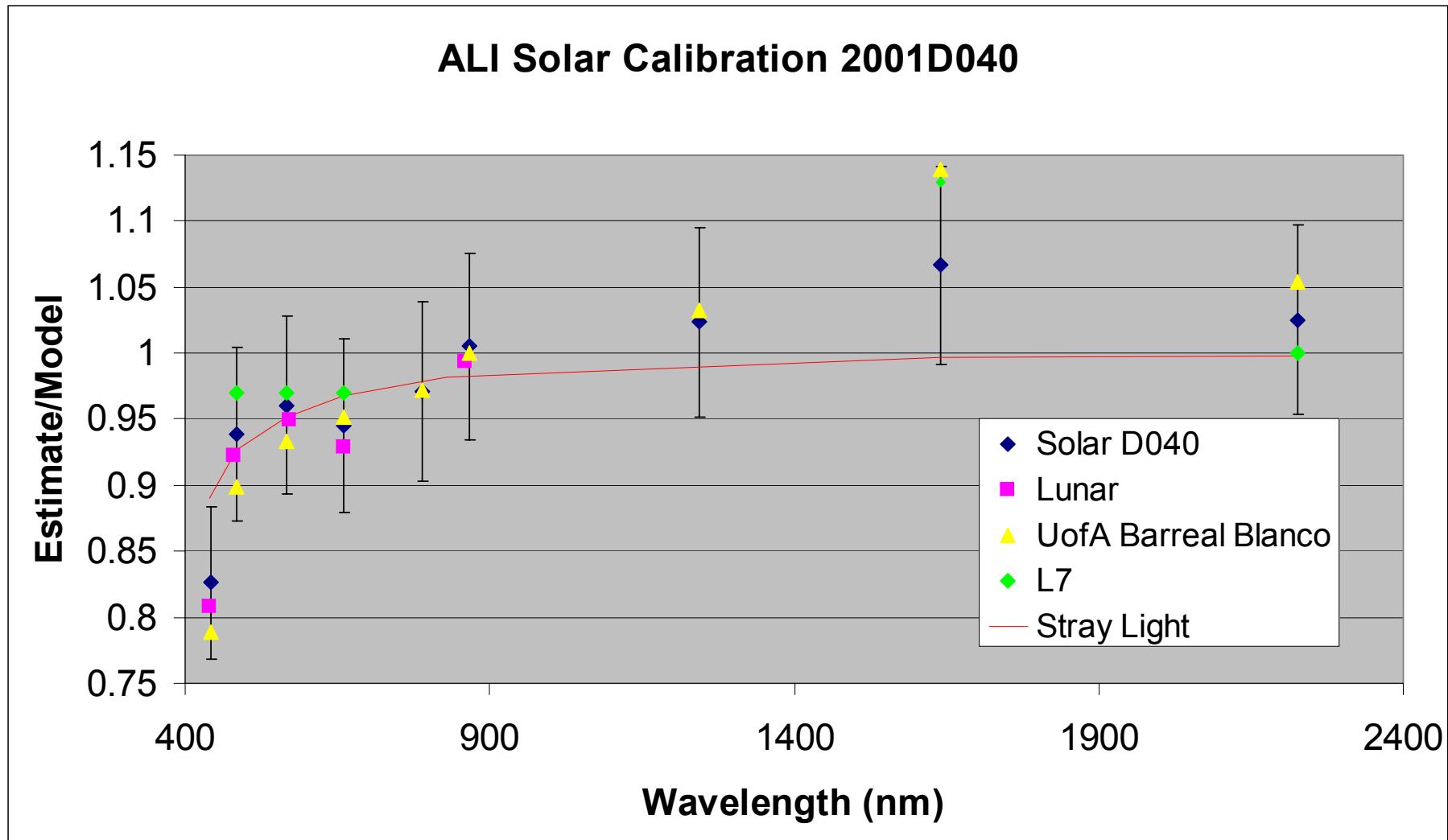


Earth Observing-1

Radiometric Calibration

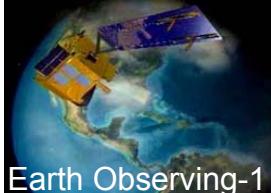


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ALI Calibration Matrix

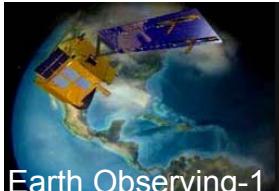


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	Spectral Response Function	Response Coefficient	Zero Signal Offset	Pixel Angular Position	Modulation Transfer Function
Component Tests and Analysis	●✓	○✓	○✓	—	○✓
Subsystem Tests: Telescope and MS/Pan	○✓	○✓	○✓	○✓	○✓
Instrument-Level Laboratory Tests	●✓	●✓	○✓	●✓	●✓
On-Orbit Measurements:					
Solar Diffuser	—	●✓	—	—	—
Closed Aperture Cover	—	—	●✓	—	—
Internal Sources	—	○✓	—	—	—
Lunar Scans	—	○✓	○✓	—	○✓
Earth Scenes	—	○✓	—	○✓	○✓

● Primary Measurement ○ Secondary Measurement ✓ Completed





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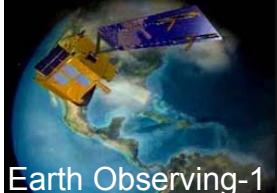
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Summary



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Summary



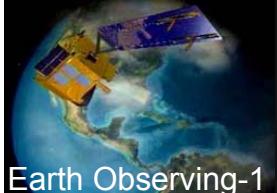
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- ◆ *ALI technology provides path for low cost, high performance, remote sensing instruments*
- ◆ *On-orbit results indicate excellent performance*
- ◆ *All major aspects of ALI technology validation have been met*
- ◆ *MIT Lincoln Laboratory team supporting the LDCM technology transfer phase of this program*



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Earth Observing-1

MIT / Lincoln Laboratory Reports



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- ◆ *EO-1-1: Instrument and Flight Operations Overview* Released
- ◆ *EO-1-2: Spectral Calibration* Released
- ◆ *EO-1-3: Radiometric Calibration* Released
- ◆ *EO-1-4: Detector Lines of Sight Calibration* Released
- ◆ *EO-1-5: Dark Current and Noise Characterization and Anomalous Detectors* Released
- ◆ *EO-1-6: Dark Current Stability Over One-half Orbit Period During First 60 Days* Released
- ◆ *EO-1-7: Dark Current and Noise Trending for the First 60 Days* Released
- ◆ *EO-1-9: Leaky Detector Characteristics and Correction* In Progress
- ◆ *EO-1-10: Flight Spatial Performance Assessment* In Progress
- ◆ *EO-1-11: Flight Radiometric Performance Assessment* In Progress
- ◆ *MIT/LL Technical Report 1061: Modulation Transfer Function* Released

