Calibration considerations for a reduced-timeline optimized approach for VNIR earth orbiting satellites

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SDL/13-xxx

Outline

- Background
- Methodology/Calibration
- Lessons Learned
- Questions

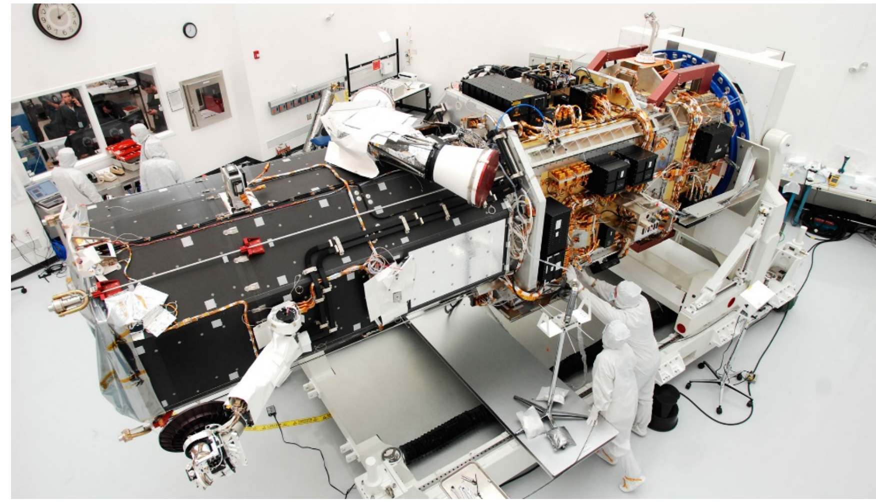
Background

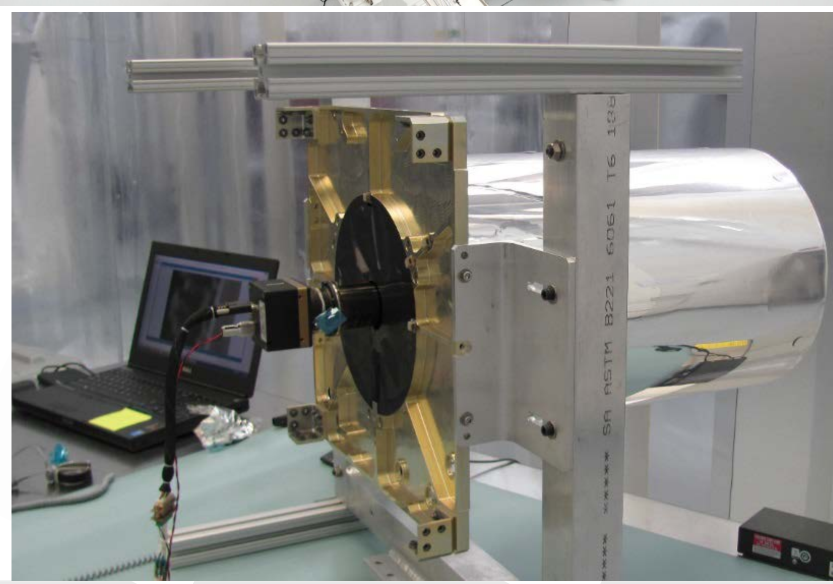
- Calibration suite involved a payload with mostly COTS components designed for ambient earth environment.
- Challenge was to address a matrix of issues for a space environment
- Customer education was a key factor
- Approach involved tight loop with customer and onsite data analysis

Background: Analogy

is to

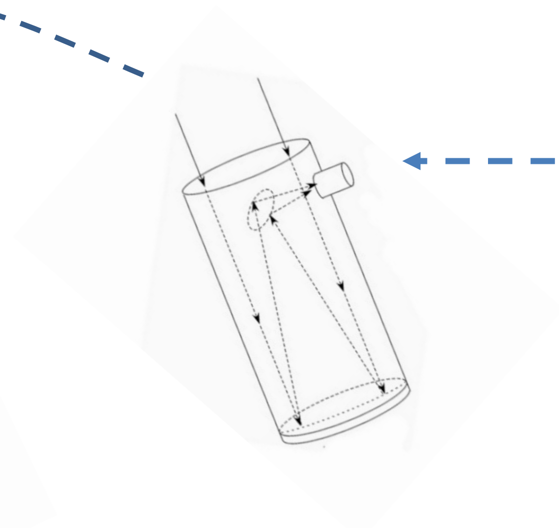
as





Background: COTS Camera

payload



telescope

COTS camera

6600x4400 Bayer or
TRUESENSE pattern
focal plane
(Pixels: 5.50 µm sq.)

Background: Optical Telescope Assembly (OTA) and orbit insertion

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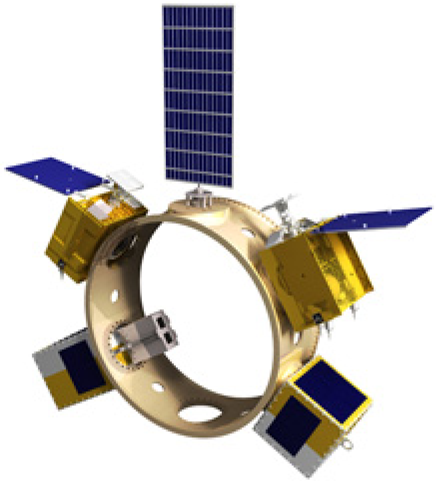
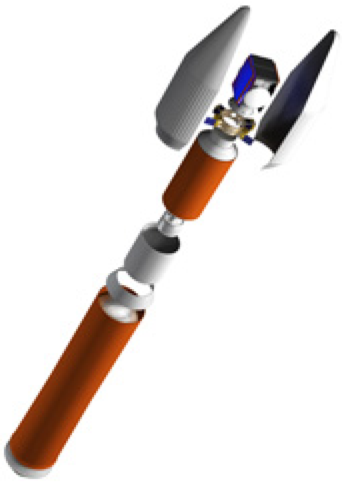
Payload



ESPA Ring

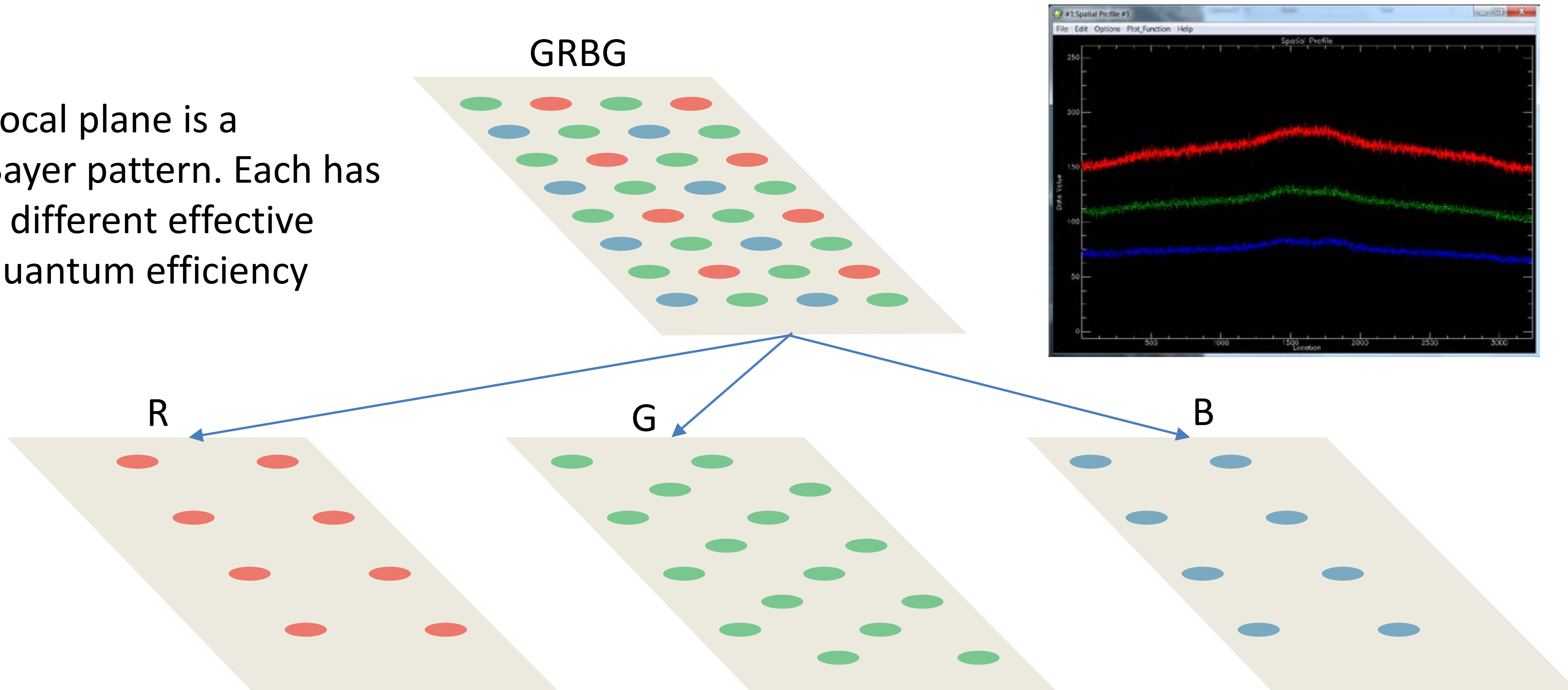


Rocket

The ESPA ring, or the Evolved Expendable Launch Vehicle (EELV) Secondary Payload Adapter was developed to utilize excess launch capacity by mounting additional payloads below the primary spacecraft. This reduces launch costs for the primary mission and enables secondary and even tertiary missions with minimal impact to the original mission.

Background: Bayer/TRUESENSE FPA

Focal plane is a Bayer pattern. Each has a different effective quantum efficiency



The variation on the focal plane given a flat source should be relatively the same with different illumination levels based on the quantum efficiency of the RGB filters.

Background: Operating Environment

From the camera Hardware User’s Manual:

“Always allow sufficient time for temperature equalization, if the camera was kept below 0 C!”

“Avoid operating in an environment without any air circulation, …”

Bonus: The camera is not radiation hardened

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Background: Thermal Analysis

- A thermal cycle analysis was performed on a solid model of the payload over several orbit cycles to characterize the transients and steady-state thermal environment of key components such as the temperature
- The analysis gave us an initial idea of what environment to simulate in THOR

Methodology

Section
As Run Test Schedule
NUC as a Function of Camera Temperature
Camera Parameter Settings
Detailed Focus Analysis for Ambient Temperature and Pressure, Center FOV
Preliminary Conservative Estimate of Delta Focus Uncertainty
CCD Smear Analysis (First Order Assessment)

Take COTS camera in telescope and characterize in space environment.
Also determine what processing is done on orbit.

Methodology: As Run Test Schedule

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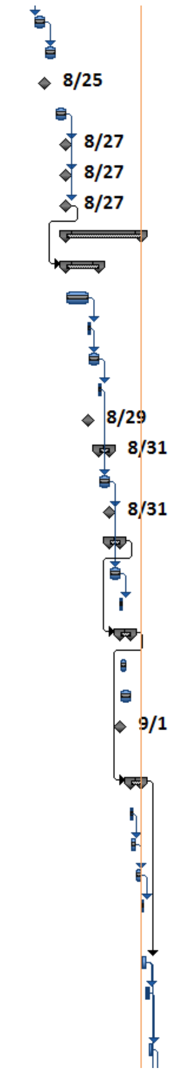
5	Unpack payload, functional, abbreviated bench, install temp sensors	1 day	Mon 8/24/15	Mon 8/24/15	100%
6	Payload Installation into THOR	1 day	Tue 8/25/15	Tue 8/25/15	100%
7	Close the chamger door and start Pumping (evening)	0 days	Tue 8/25/15	Tue 8/25/15	100%
8	THOR Vacuum and 35C testing	1 eday	Wed 8/26/15	Thu 8/27/15	100%
9	Functional Camera Test Under Vacuum	0 days	Thu 8/27/15	Thu 8/27/15	100%
10	35 deg C Test (THOR and Payload at 35 deg C)	0 days	Thu 8/27/15	Thu 8/27/15	100%
11	Cool Chamber/payload to 1st temperature condition	0 days	Thu 8/27/15	Thu 8/27/15	100%
12	**THOR Testing**	**6 days**	**Thu 8/27/15**	**Thu 9/3/15**	100%
13	**1st Payload Temp Condition (East shroud at 270K)**	**3 days**	**Thu 8/27/15**	**Sun 8/30/15**	**100%**
14	Integrating sphere (Full)	1.5 edays	Thu 8/27/15	Fri 8/28/15	100%
15	Configure for Focus/PRF (first indication payload was out of focus)	0.5 edays	Fri 8/28/15	Sat 8/29/15	100%
16	Verify Infinity Focus of visible collimator	0.5 edays	Sat 8/29/15	Sat 8/29/15	100%
17	Focus/PRF (center FOV)	0.5 edays	Sat 8/29/15	Sun 8/30/15	100%
18	Start changing temperatures to 2nd temperature condition (evening)	0 days	Sat 8/29/15	Sat 8/29/15	100%
19	**2nd Payload Temp Condition (East shroud at 333K)**	**0 days**	**Sun 8/30/15**	**Mon 8/31/15**	**100%**
20	Focus/PRF (Full)	1 eday	Sun 8/30/15	Mon 8/31/15	100%
21	Start changing temperatures to 3rd Payload Temp Condition	0 days	Mon 8/31/15	Mon 8/31/15	100%
22	**3rd Payload Temp Condition (East shroud at 348K)**	**1 day**	**Mon 8/31/15**	**Tue 9/1/15**	**100%**
23	Focus/PRF (center FOV)	0.5 edays	Mon 8/31/15	Mon 8/31/15	100%
24	Integrating sphere (Full)	0.5 edays	Mon 8/31/15	Tue 9/1/15	100%
25	**Camera temperature at 35C (internal camera temp)**	**1 day**	**Tue 9/1/15**	**Wed 9/2/15**	**100%**
26	Transition camera temperature to 35C	0.25 edays	Tue 9/1/15	Tue 9/1/15	100%
27	Integrating sphere (Full)	0.75 edays	Tue 9/1/15	Wed 9/2/15	100%
28	Start warming chamber in preparation for focus/PRF ambient vacuum test	0 days	Tue 9/1/15	Tue 9/1/15	100%
29	**Ambient Testing (camera temp ~ 45C)**	**1 day**	**Wed 9/2/15**	**Thu 9/3/15**	**100%**
30	Focus/PRF, ambient Temp, with vacuum, with window (center FOV)	0.2 edays	Wed 9/2/15	Wed 9/2/15	100%
31	Focus/PRF, ambient Temp, without vacuum, with window (center FOV)	0.2 edays	Wed 9/2/15	Wed 9/2/15	100%
32	Focus/PRF, ambient Temp, without vacuum, without window (full FOV)	0.4 edays	Wed 9/2/15	Wed 9/2/15	100%
33	Large area disc, ambient Temp, without vacuum, without window (center)	0.2 edays	Wed 9/2/15	Thu 9/3/15	100%
34	Remove sensor from THOR and prepare for off-axis scatter test	0.3 edays	Thu 9/3/15	Thu 9/3/15	0%
35	Bench ambient sensor/integrating sphere separation distances for off-axis scatter	0.3 edays	Thu 9/3/15	Thu 9/3/15	0%
36	Return payload to shipping container	0.3 edays	Thu 9/3/15	Thu 9/3/15	0%



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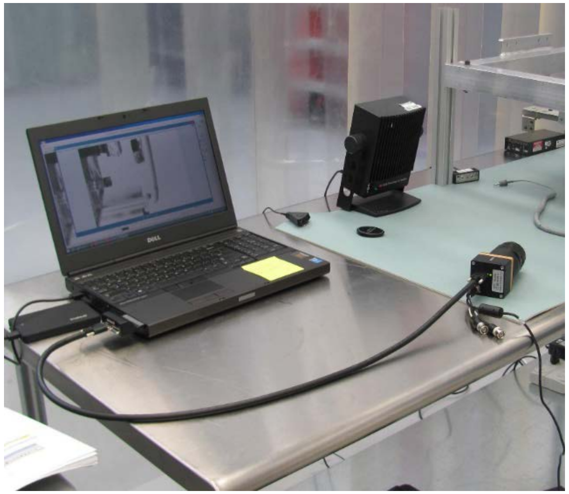
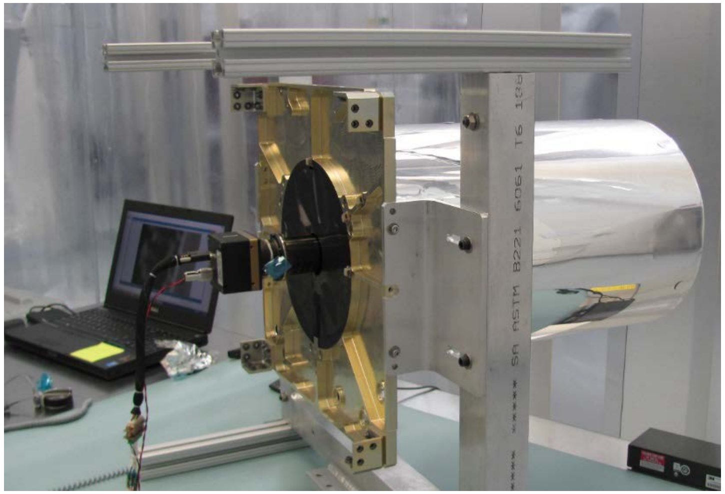
Methodology: Preparation

- Unpacked payload
- Performed payload fit check with mounting frame
- Performed functional camera testing
  - Engineering camera (provided cable, commercial cable, THOR cable)
  - After complete checkout, tested THOR cable with payload camera
- Installed temp sensors and camera heater on payload

Methodology: Camera Cabling





- Vacuum compatible camera cable was built to support operation of the camera while inside the THOR vacuum chamber
  - Cabling was tested in steps
    - Cable built to mirror commercial cable
    - Engineering camera bench testing
    - Flight camera bench testing
    - Functional testing with sensor inside THOR before closing door

Methodology: Payload Temperature Sensor Locations

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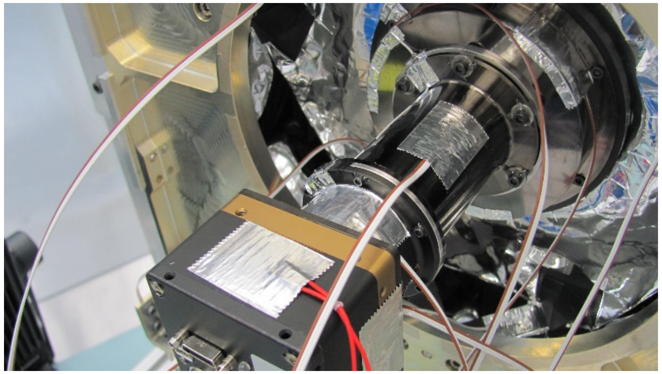
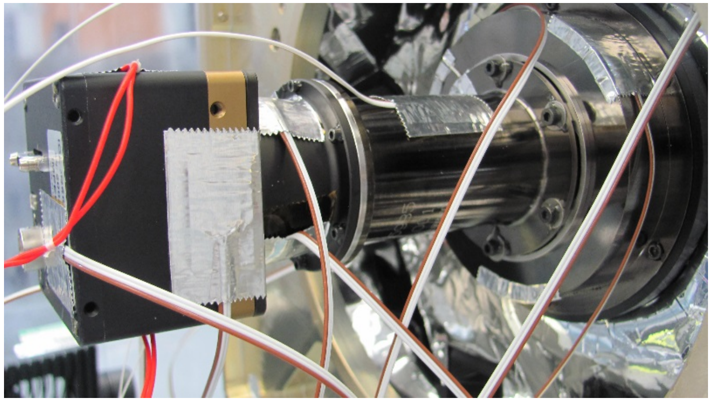
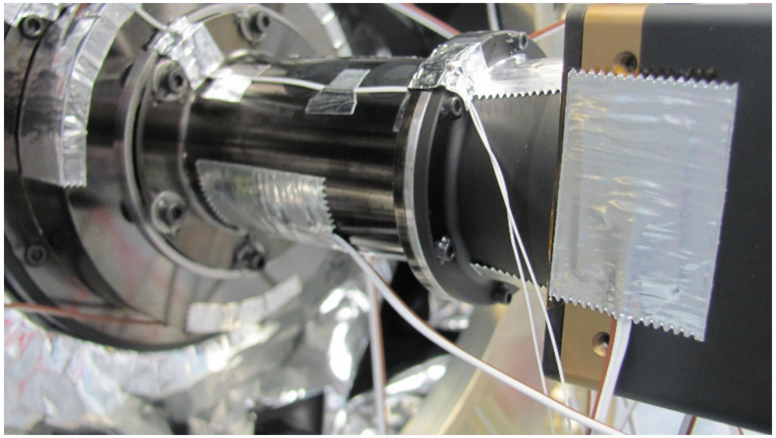


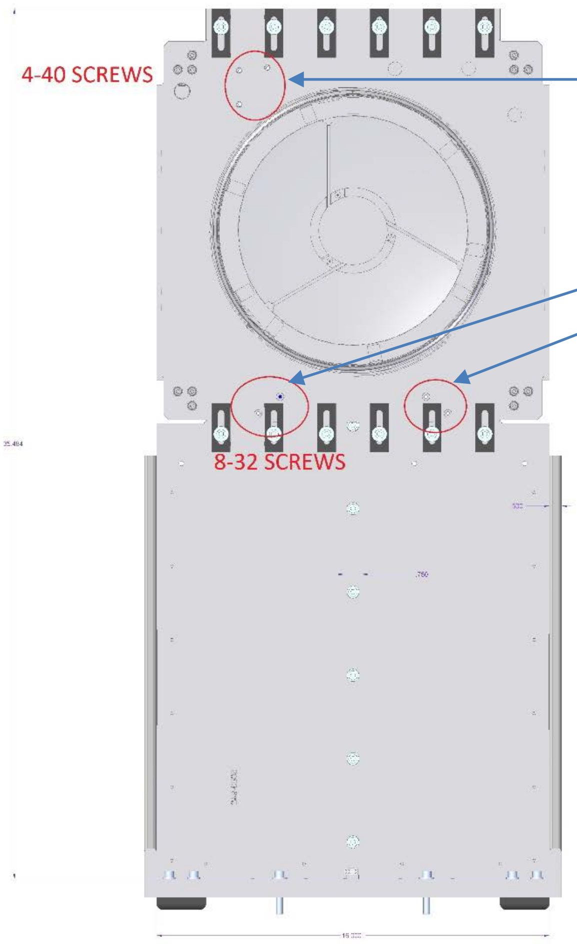




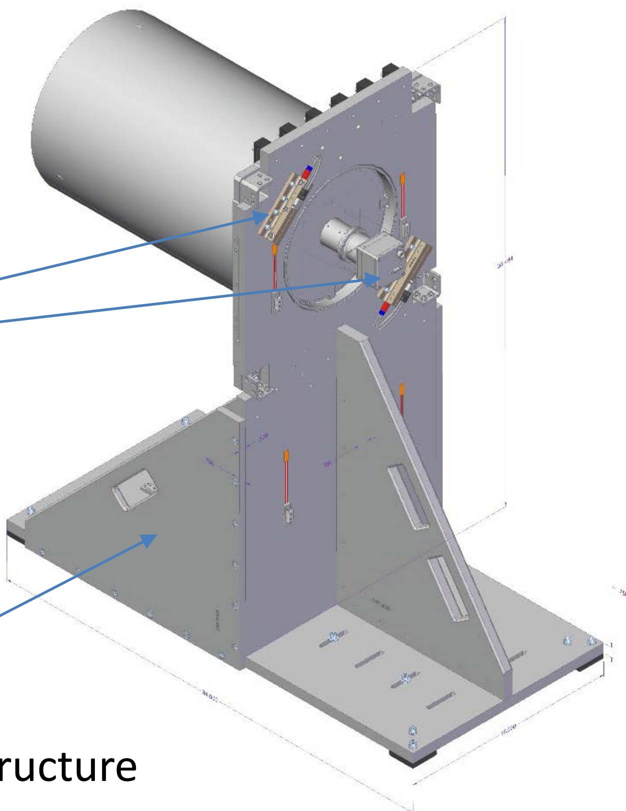
Photos of other temperature sensor locations provided with ancillary test data

Methodology: Mounting of the Payload to the Vertical Mounting Structure

Utilized 7 baseplate mounting holes with screws and bolts for good thermal contact between payload and mount



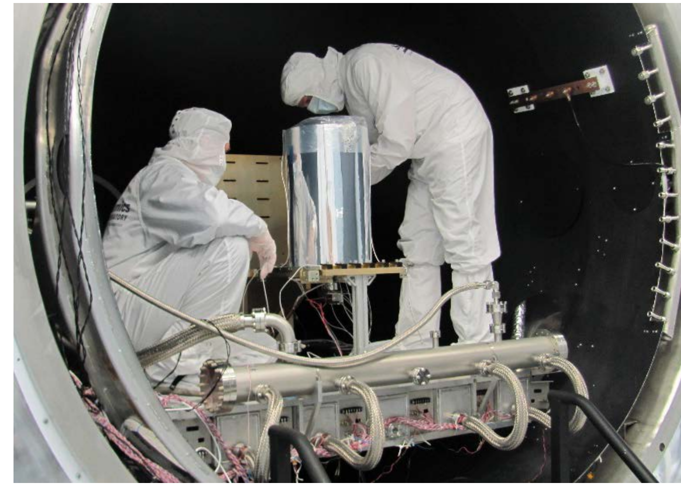
Two trim heaters used to maintain temperature of vertical mount at 30°C



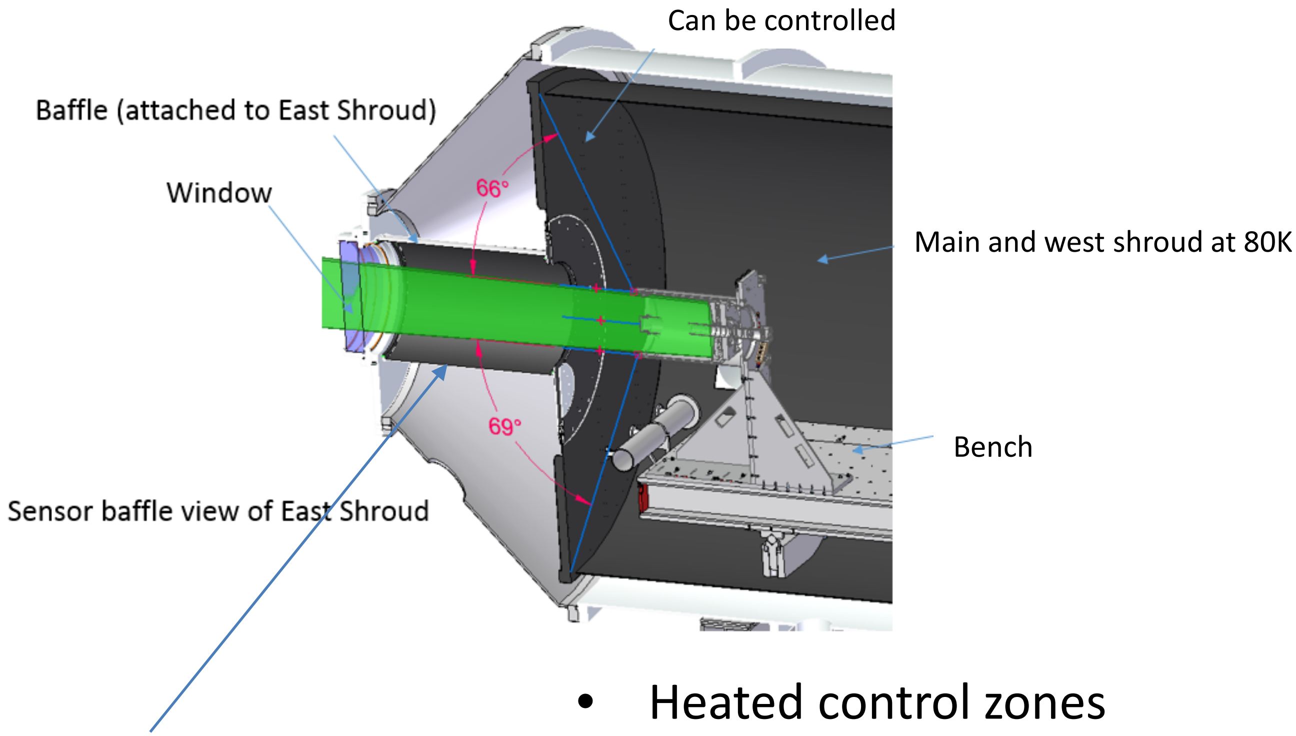
SDL built vertical mounting structure

Methodology: Payload Installation into THOR

- Initial vertical mounting plate alignment inside THOR performed prior to sensor installation
- Joint effort to install payload onto mounting fixture and position inside the THOR chamber
- Routed payload temperature sensor cables
- Routed all cables
- Before closing chamber door
  - Checked camera operation with payload inside THOR
    - Camera functional
    - First light observations while viewing calibration sources



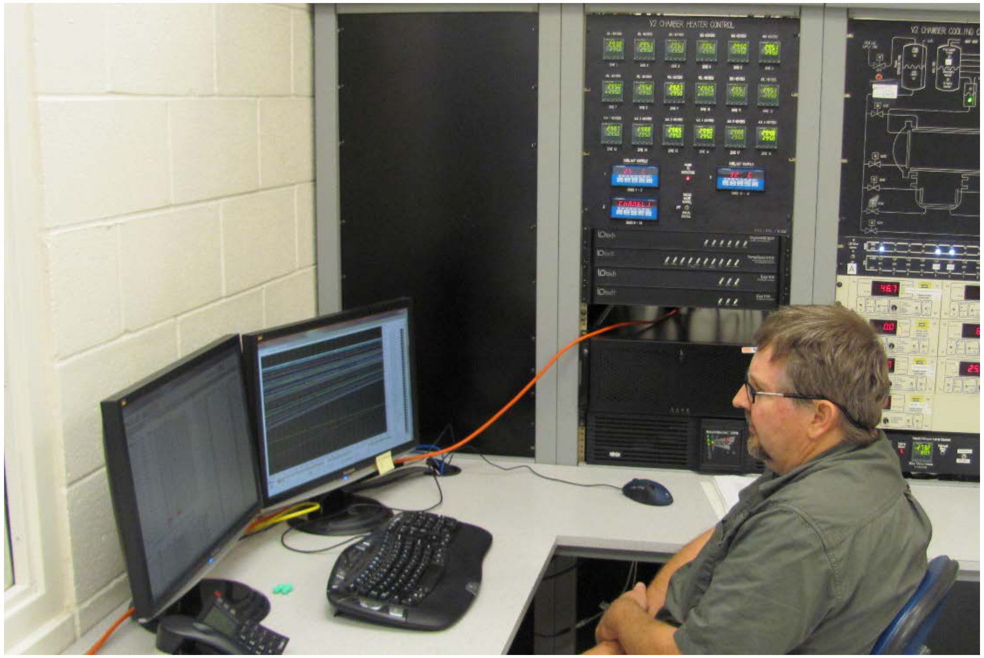
Methodology: Payload TVAC Test Inside THOR Chamber

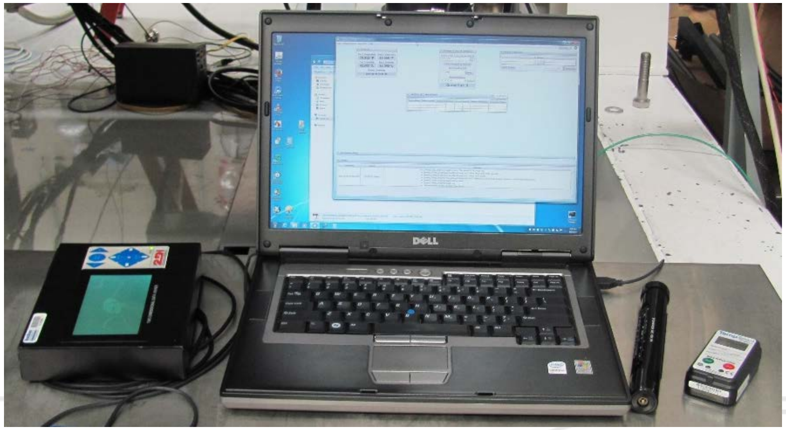


Baffle between east shroud and window is bolted to east shroud but does not have dedicated heater control

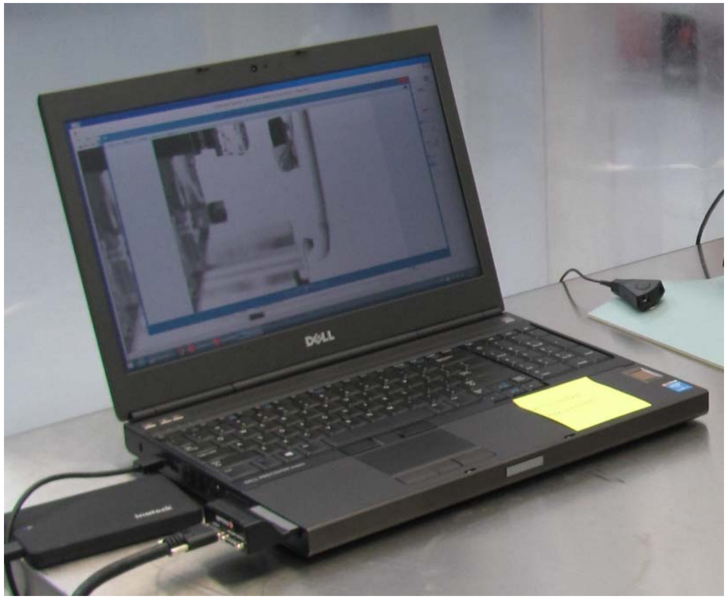
- Heated control zones
  - Vertical baseplate (303K, 30°C)
  - East shroud (270K, 333K, 348K set points)
  - Bench (302K, ~29.5°C)
  - Camera (internal temperature sensor)

Methodology: Payload and THOR Temperature/Vacuum Monitoring Instrumentation





Methodology: Payload Data Collection Station and Camera Parameter Settings

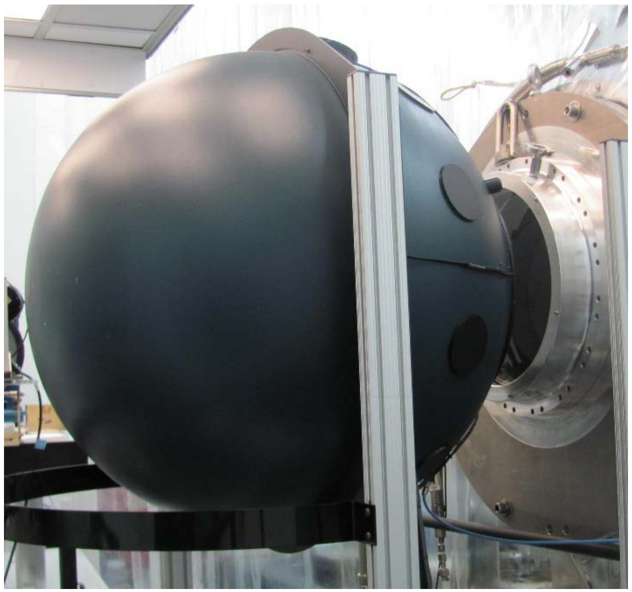


- Camera software was used for data capture
- Camera parameters were set using configuration utility for camera non-volatile memory

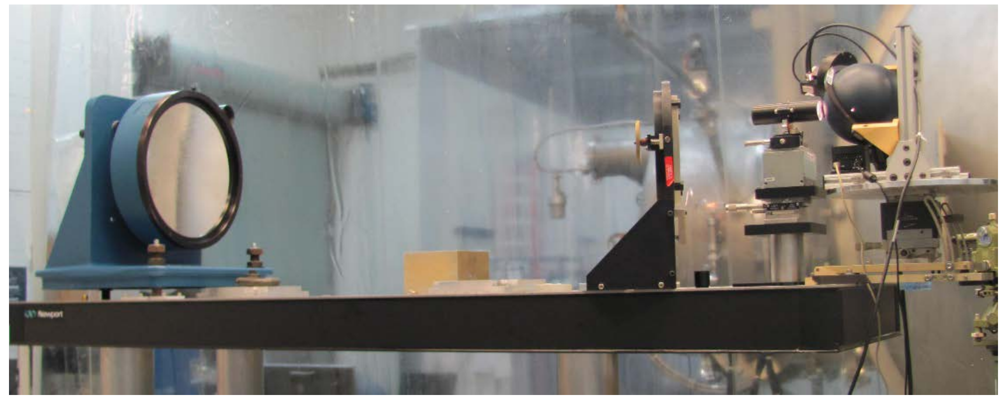
TEMPERATURE (°C)
AGC (ON/OFF)
AEC (ON/OFF)
LUMINANCE LEVEL THRESHOLD (COUNTS)
ANALOG GAIN SETTING
EXPOSURE TIME SETTING
PRE-AMPLIFIER GAIN (-3DB,0, +3DB)
BIT DEPTH (8 OR 12)
MONOCHROME OR BAYER – FRAMELINK EXPRESS OPTION
WHITE BALANCE (ON/OFF)
BLACK COMPENSATION (ON/OFF)
TAP BALANCE (ON/AUTO)
DPC (Off, Static, Dynamic, Combined)
HPC (Off, Static, Dynamic, Combined)
OFFSET

Calibration: Source Configurations

40” integrating sphere



Visible collimator with collimating mirror

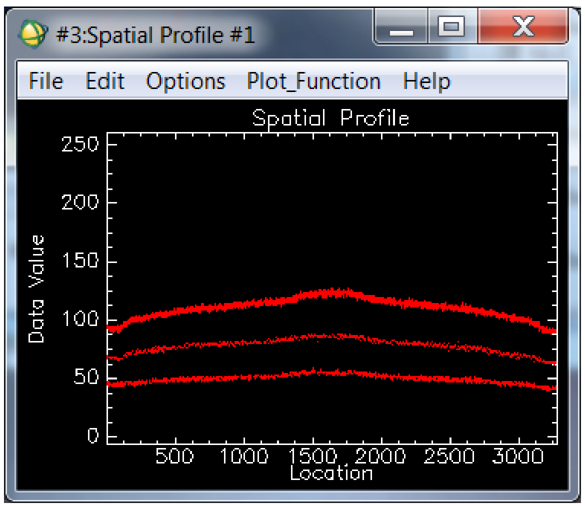


Switching between two configurations

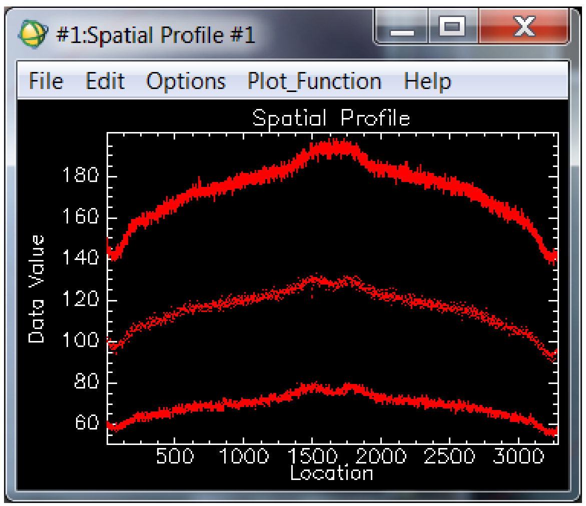
Calibration: NUC Summary

- We looked at different NUC images to assess variability
- We chose three dates representing various camera temperatures and other system differences
- Finding: NUC sensitivity to temperature is minimal

08/28/2015 (43% bit depth)



08/31/2015 (68% bit depth)



09/01/2015 (80% bit depth)

Wide variety in use of dynamic range among integrating sphere radiance in order to determine if NUC is affected

Calibration: Typical Integrating Sphere Image

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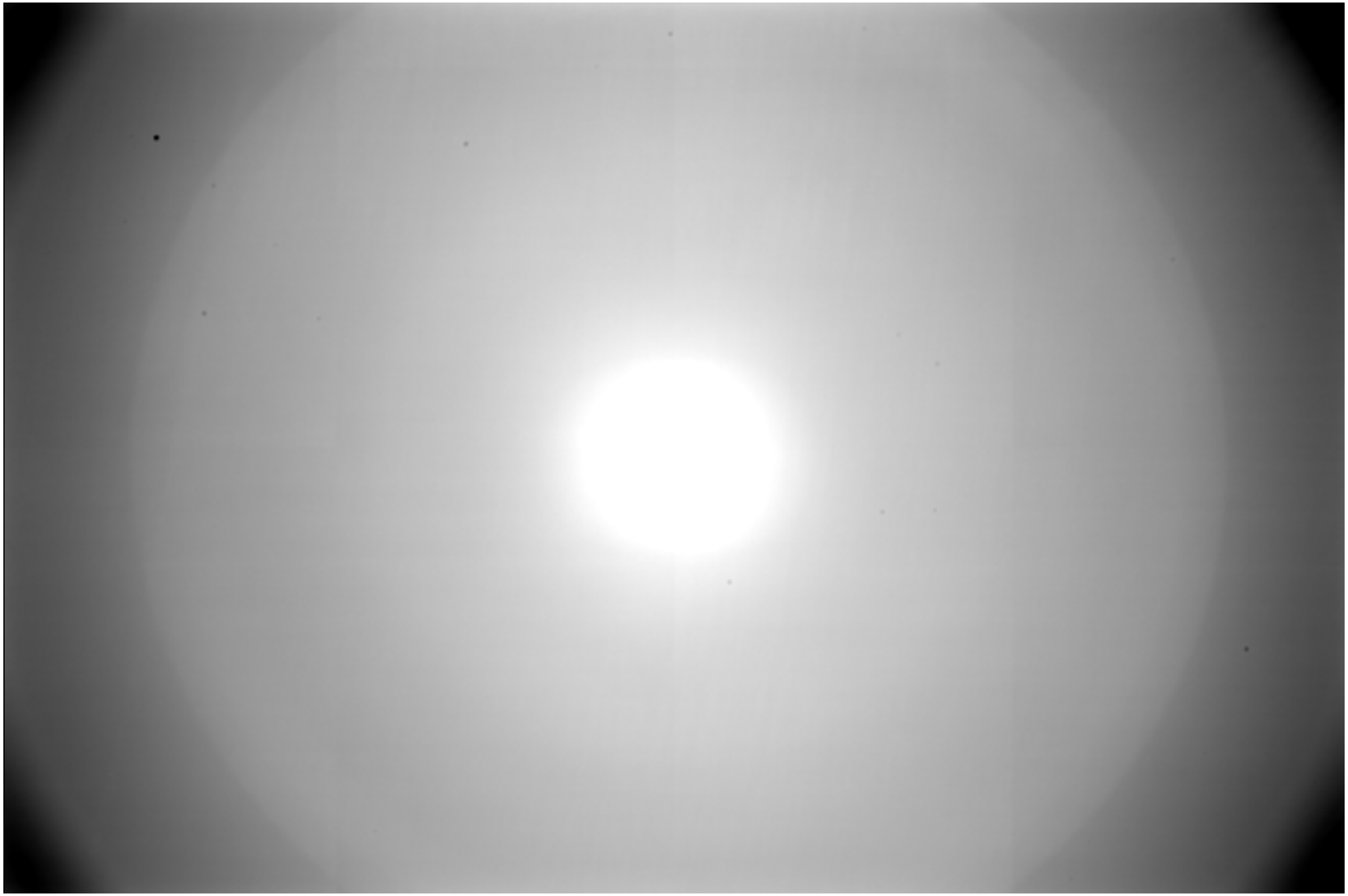


Calibration: NUC Variability vs Temperature

Standard Deviation correlates well with temperature increase

Dark Field Noise Levels

Temp (C)	T1 = 17.25	T2 = 21.75	T3 = 34.75
Mean (counts)	6.003	6.004	6.008
Std Dev (counts)	.08	.09	.12

NUC Difference Statistics

Temp (C)	T3/T1	T3/T2	T2/T1
Std Dev (counts)	.008	.001	.008

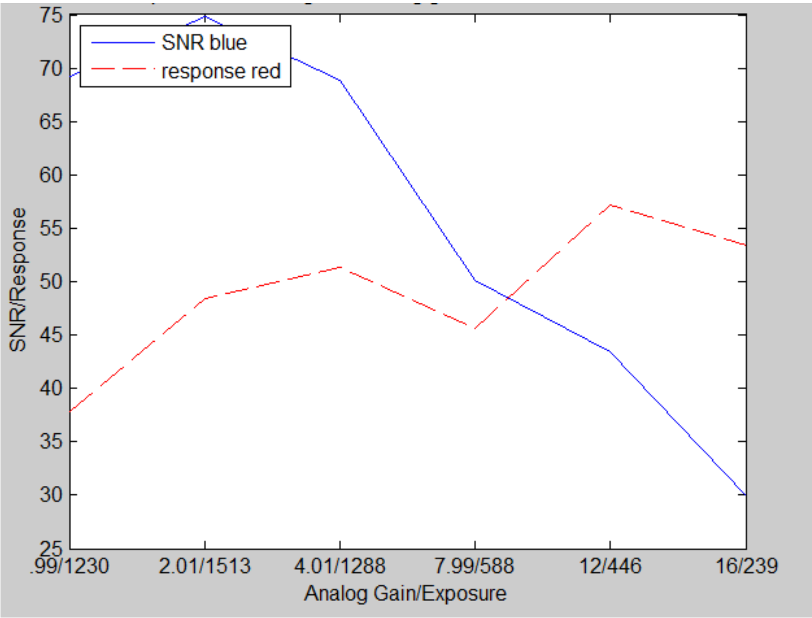
- Mean difference is zero in each
- Worse case scenario is .008 for standard deviation (2 counts/8 bit)
- Expect nominal to be closer to .001 std dev (.25 counts/8bit)

Calibration: Camera Settings

- Exposure Time
- Gain and Offset
- White Balance
- Black Level Correction
- Tap Balancing
- Flat Field Correction
- Defective Pixel Correction

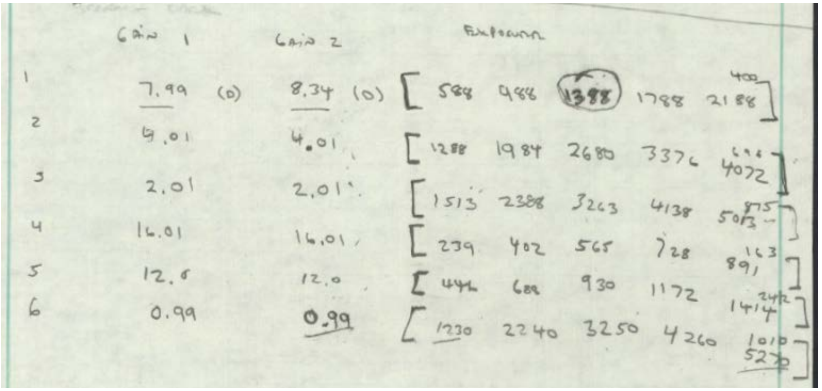
TEMPERATURE (°C)
AGC (ON/OFF)
AEC (ON/OFF)
LUMINANCE LEVEL THRESHOLD (COUNTS)
ANALOG GAIN SETTING
EXPOSURE TIME SETTING
PRE-AMPLIFIER GAIN (-3DB,0, +3DB)
BIT DEPTH (8 OR 12)
MONOCHROME OR BAYER – FRAMELINK EXPRESS OPTION
WHITE BALANCE (ON/OFF)
BLACK COMPENSATION (ON/OFF)
TAP BALANCE (ON/AUTO)
DPC (ON/OFF)
HPC (ON/OFF)
OFFSET

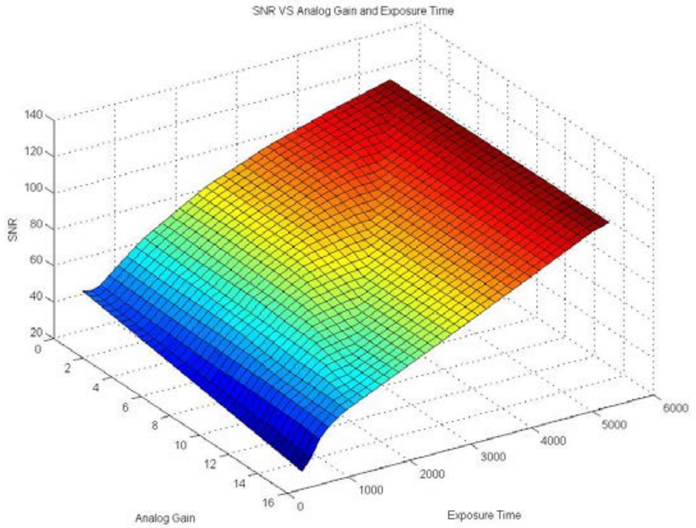
Calibration: Response/SNR: Gain/Exposure



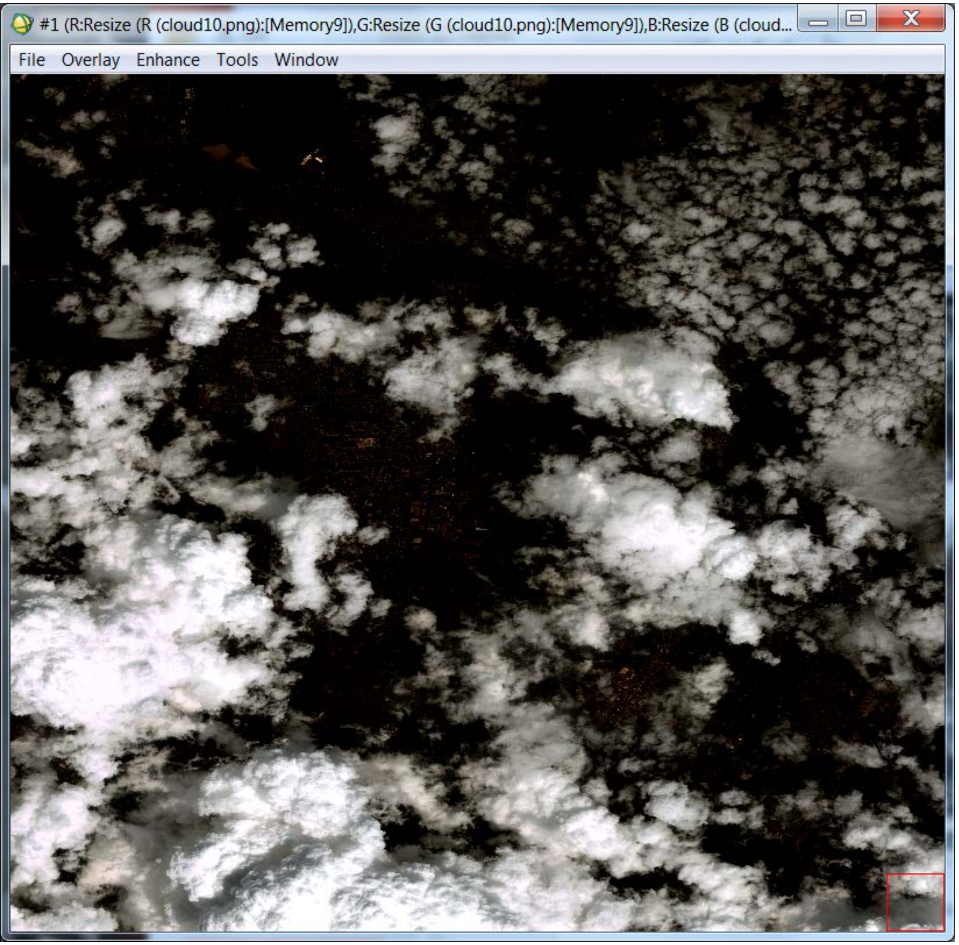
- Chart shows that SNR degrades for gains above 2.1
- Gains between 2.01 and 7.99 appear to be a good balance between response and SNR

Gain and Exposure Sweep Settings

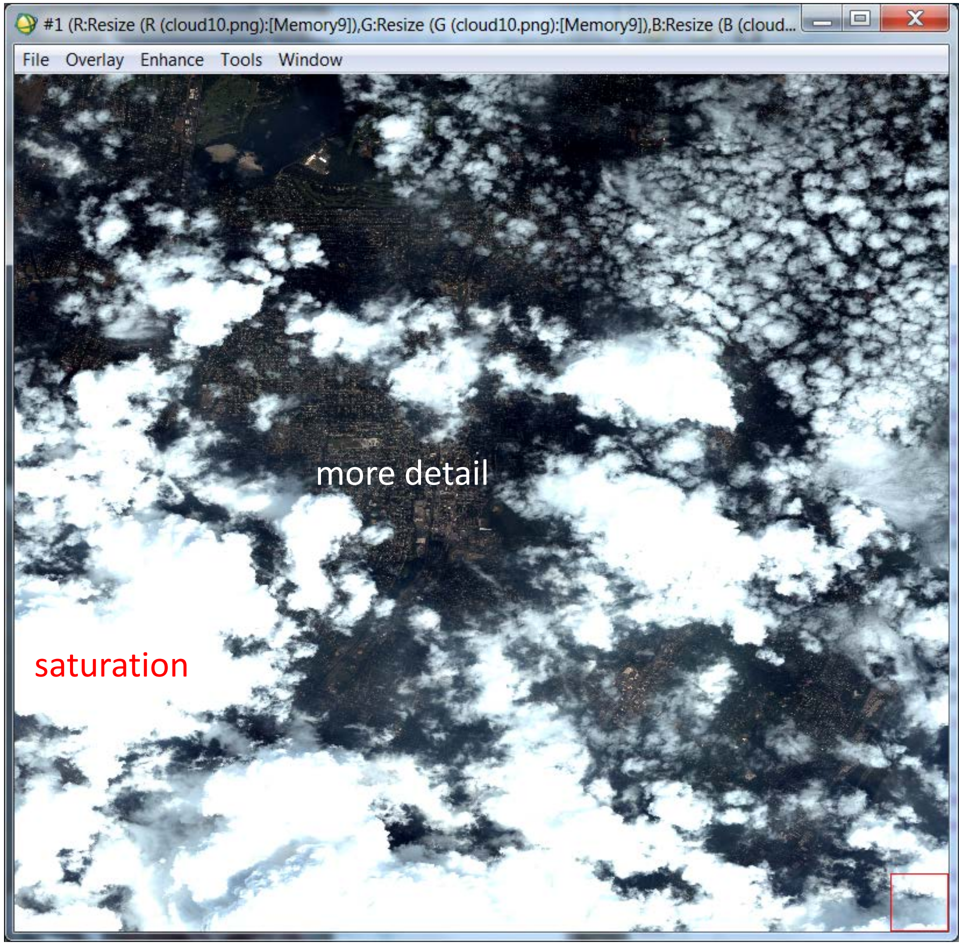




Calibration: Response/SNR: AGC and Dynamic Range



Cloudy scene with AGC

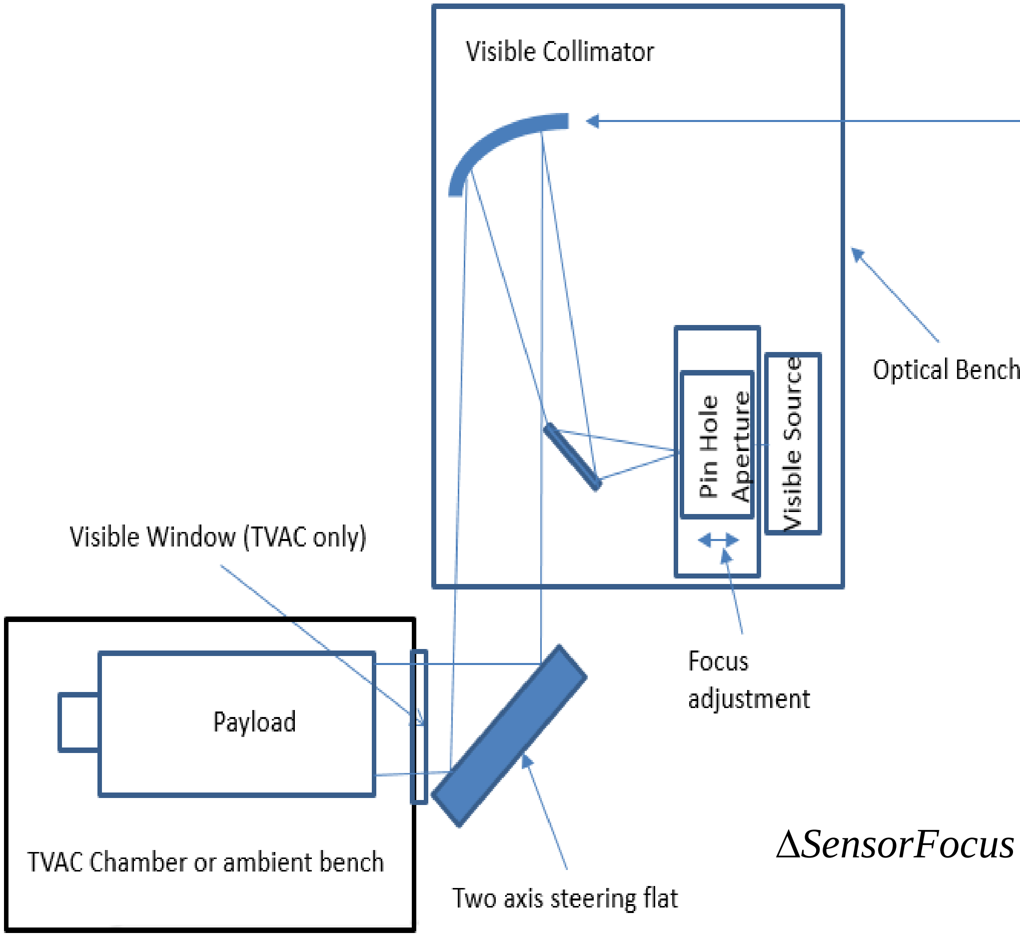


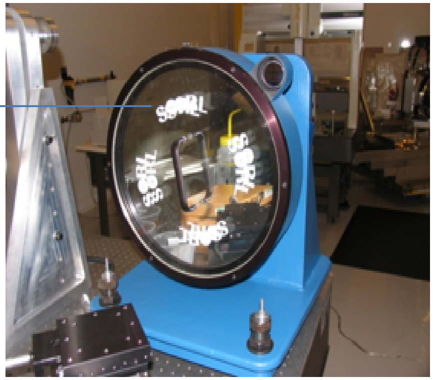
Cloudy scene with exposure to image land detail

Calibration: Steps for Focus Data Analysis

1. Quantify RGB NUC that can be used to normalize RGB pixels (i.e., place RGB pixels on the same scale) to allow for subsequent pinhole response analysis
2. For each pinhole image
   – Perform dark correction (i.e., pinhole image – dark image)
   – Apply RGB NUC
   – Calculate encircled energy figure of merit
   – Store results
3. SORL focus analysis for payload best focus
   – Plot encircled energy as function of SORL focus setting
   – Perform curve fit to determine the SORL focus that maximizes encircled energy
4. Relate SORL focus to payload delta focus

Calibration: Focus Measurement Configuration





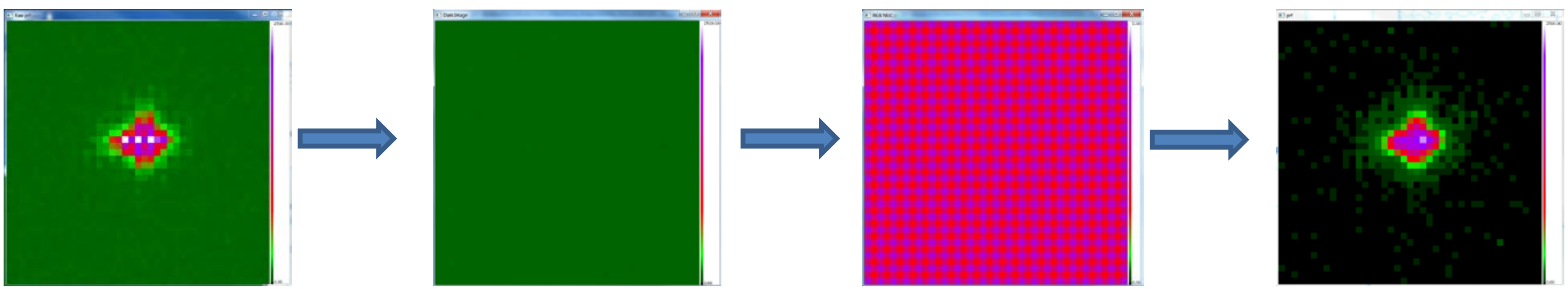
Material	Zerodur
Focal length	60.189 inches
Off-axis distance	3.9 inches
Mirror diameter	13.998 inches
Scratch/Dig	60/40
Clear aperture	13.5 inches
Coating	AlSiO
Surface accuracy figure	1/15.6 wave P-V @ 632 nm
Reflectance	> 89% at 632 nm

$$\Delta SensorFocus = \left(\frac{f_{Sensor}}{f_{Collimator}}\right)^2 \times \Delta CollimatorFocus$$

Calibration: Corrected Image (for each pinhole image)

- Applied dark offset measurement and RGB NUC derived from large area disc measurement
  - Each pinhole image processed separately (i.e., no averaging) to avoid smearing due to image-to-image variation of pinhole response
  - Dark image is the average of 10 dark images

Raw Image | Dark Image | RGB NUC Image | Corrected Image



Calibration: Encircled Energy Figure of Merit

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- Quantifies the fraction of energy within a circle of pixels to the total energy of all pixels within the pinhole response subwindow
  - For this analysis, radius set to 4 pixels (set to this value to show magnitude differences as function of focus setting)
  - Subwindow size set to 41X41 pixels (to ensure defocused pinhole response remains in window)
- Based on measurement and optical modeling of a previous program, Ensquared energy was an unbiased estimator of best focus compared to FWHM
  - Focus Optimization of the SPIRIT III Radiometer, Optical Engineering, 1997

$$EncircledEnergy = \frac{\sum_{\sqrt{(i-i_c)^2+(j-j_c)^2} \le Rad} response_{i,j}}{\sum_{i,j} response_{i,j}}$$

Where
i and *j* are the indices over sub window
i_c and j_c are the intensity weighted centroid position

Calibration: SORL Focus Analysis for Payload Best Focus

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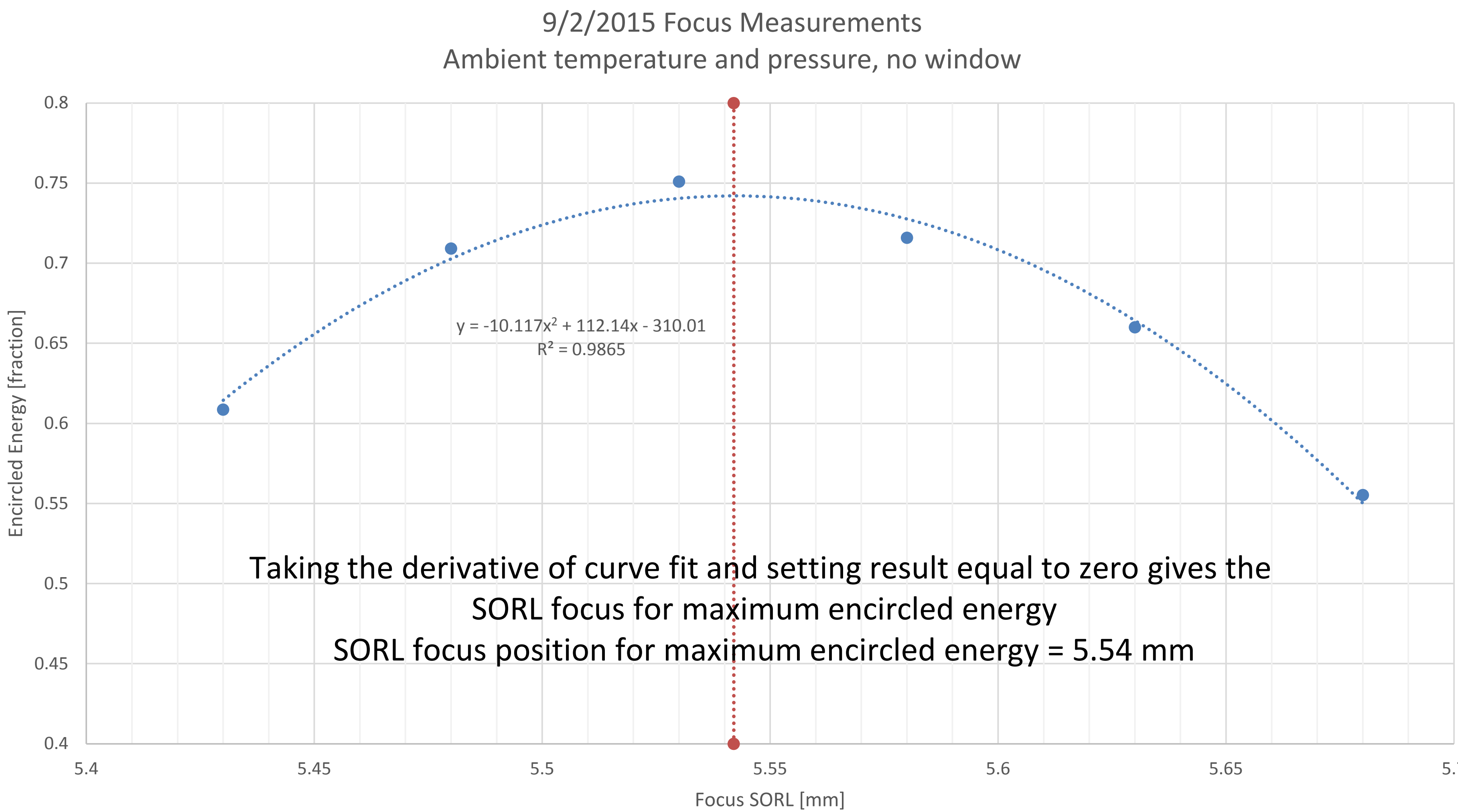
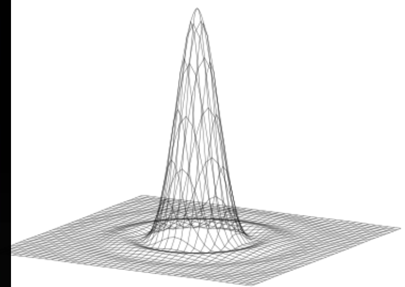
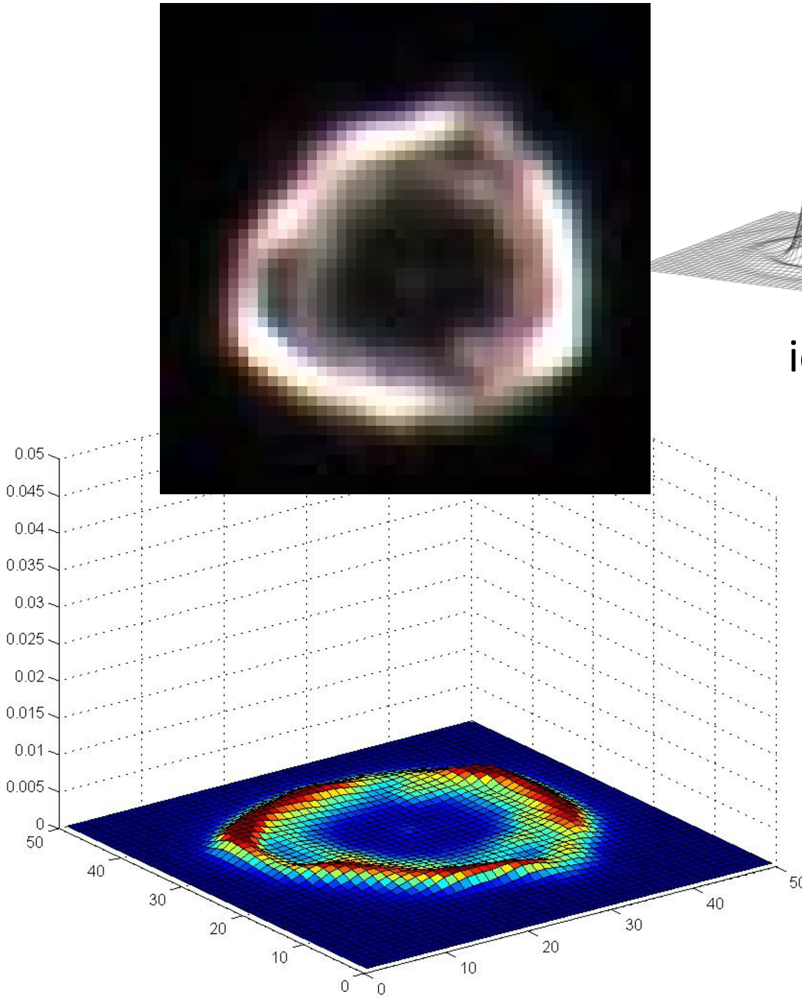


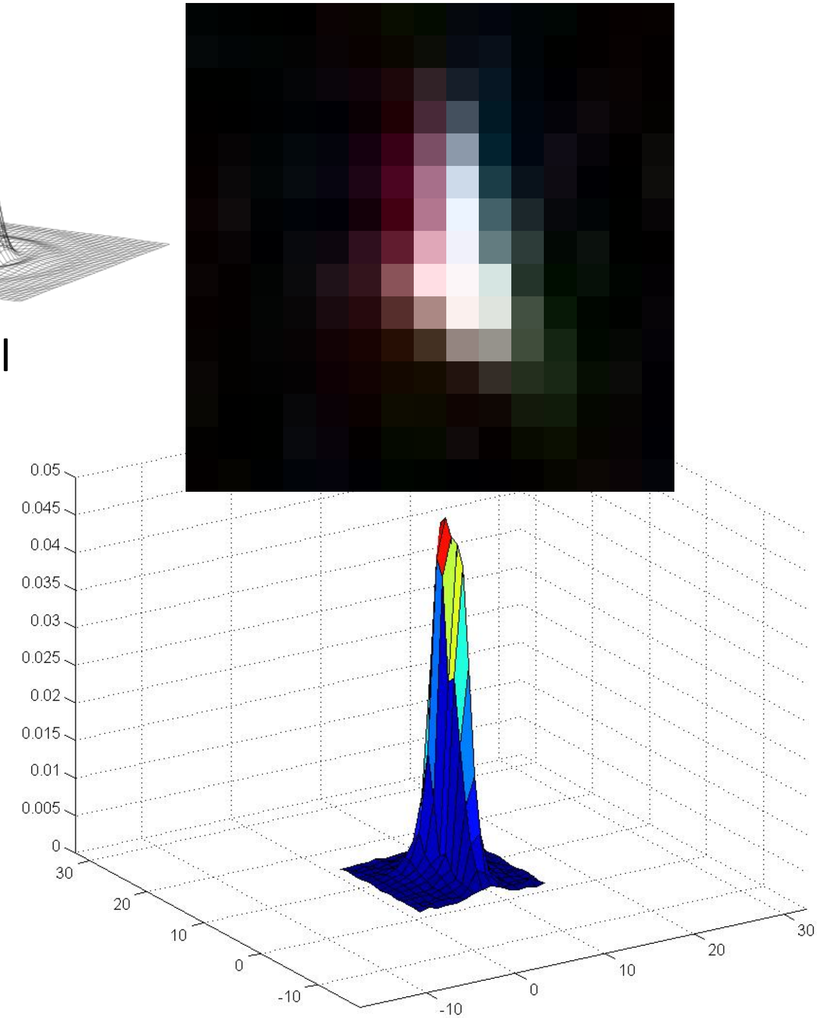
Calibration: Focus Study



ideal



ring



uneven

Calibration: Focus Study Customer Education

Calibration: Payload Delta Focus Uncertainty (sources of uncertainty)

Uncertainty	Note
Collimator infinity focus	How well do we know the infinity focus of the collimator mirror
Focus uncertainty due to THOR visible window	How well do we know the focus error due to window mounted on the front of THOR
Focus uncertainty due to the difference between quick look and detailed data analysis	Estimate of the potential improvement of the payload focus (as determined during quick look) compared to performing data analysis
Focus uncertainty due to off-axis distance of collimator mirror	Uncertainty due to off-axis distance of collimator mirror
Focus uncertainty due to conversion of collimator delta focus to payload delta focus	Uncertainty in the ratio of the focal length squared used to convert collimator delta focus to payload delta focus
Depth of payload focus	Theoretical depth of focus (sometimes referred to as circle of confusion) due to the diffraction limit

Calibration: Payload Focus Uncertainty Summary

Uncertainty Component	Payload Focus Uncertainty of Measurement (mm)
Collimator infinity focus	0.05
Focus uncertainty due to THOR visible window	0.30
Focus uncertainty due to the difference between quick look and detailed data analysis	0.167
Focus uncertainty due to off-axis distance of collimator mirror	0.083
Focus uncertainty due to conversion of collimator delta focus to payload delta focus	0.06
Depth of payload focus	0.103
RSS total	0.38

Focus uncertainty due to THOR visible window is worst case without taking any steps to minimize thermal gradients

Calibration: CCD Smear

- Smear is a known artifact of CCD arrays (known to produce smeared images under the right conditions) (example shown below)

- It is reasonable to expect that some earth view images will contain CCD smear
  - Particularly those with specular reflection of sunlight
    - Clouds, water, etc.
- Haven't seen any literature that indicates damage to the array due to CCD smear

Calibration: Smear Amplitude Summary

- The smear amplitude appears to be dependent on source level rather than pixel RGB response
  - (Smear amplitude ND1 Attenuation) / (Smear amplitude Open) = 4/38 = 0.11
  - Theoretical attenuation ND1 / Open = 0.1 / 1.0 = 0.1
  - Reasonable correlation

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Lessons Learned

- Calibration is essential (not facetious!)
- Customer had initially just considered an integrating sphere for NUC
- Need enough equipment/space to quickly redirect, can't just use integrating sphere in dark room, etc.
- Education/socialization necessary
- Work closely with customer (on site)
- Risk/benefit must be considered
- A launch was persevered as a result of calibration ($)

Questions