

Tropospheric Emissions:
Monitoring of Pollution



TEMPO Solar Calibration

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John Houck*, John E. Davis*, James Carr*,
Raid M. Suleiman*, Kelly Chance*

August 26, 2024

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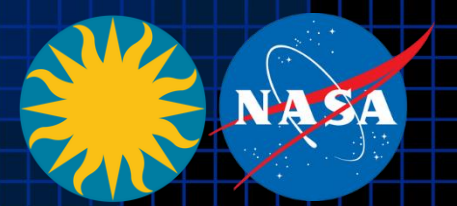
[#] NASA Langley Research Center

* Smithsonian Astrophysical Observatory

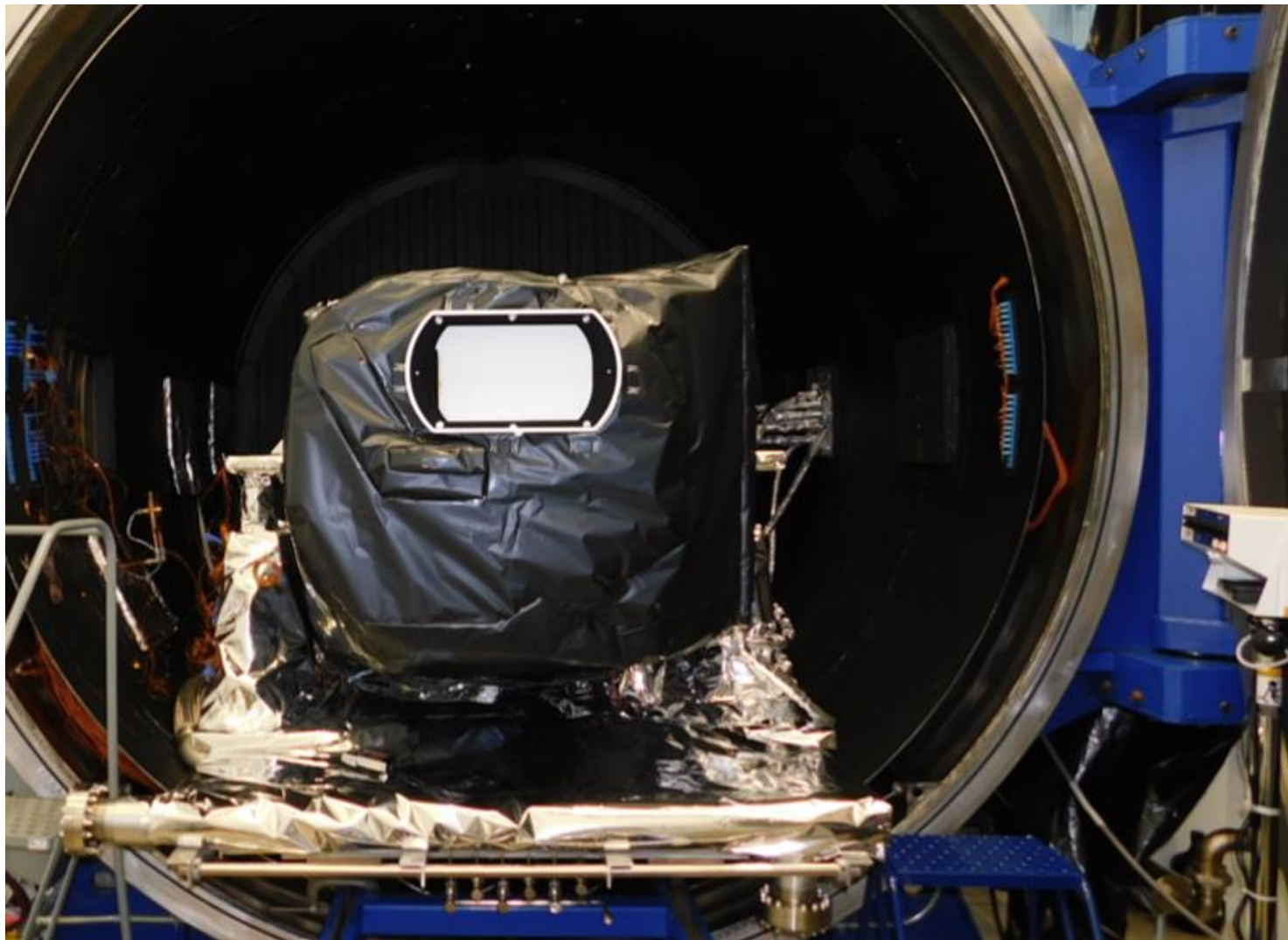




Introduction

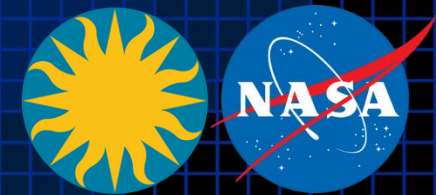


- Level 0-1 Processing Scheme
- Modifications Since Launch
- Irradiance Performance
- Application to GEMS
- Summary and Outlook



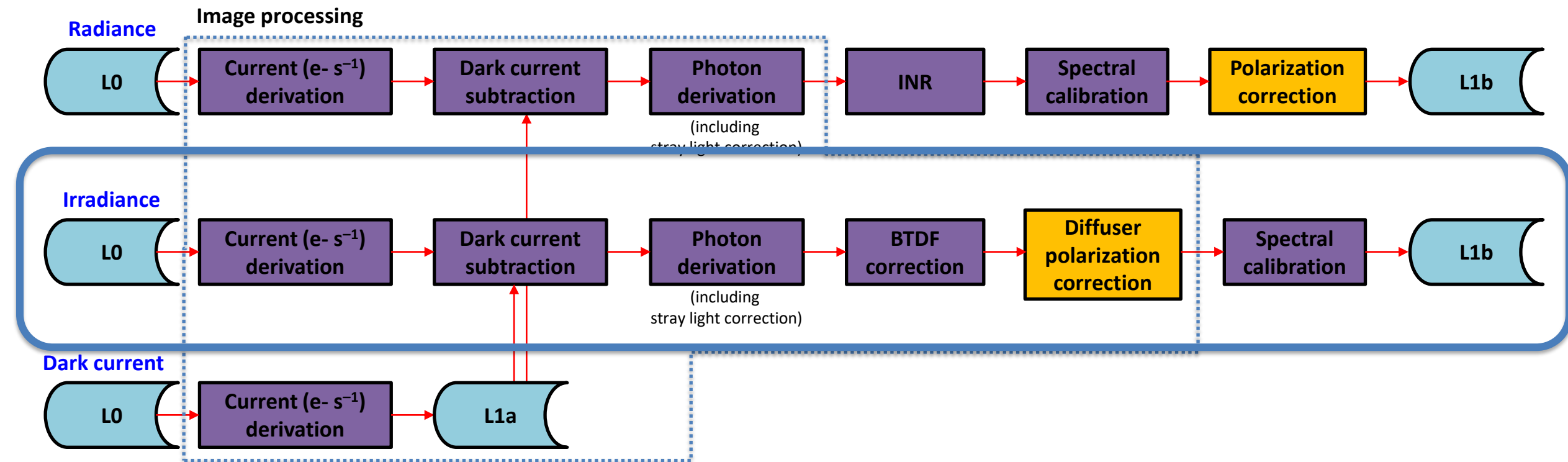


TEMPO L0–1 processor



- Flow chart

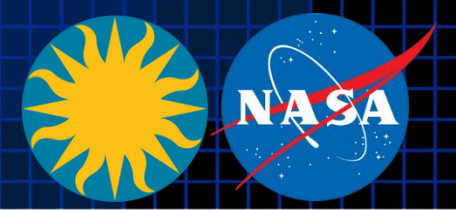
 = Not turned on at launch



Approach for TEMPO adapts elements from GEMS, TropOMI, OMI



Updates since the first light

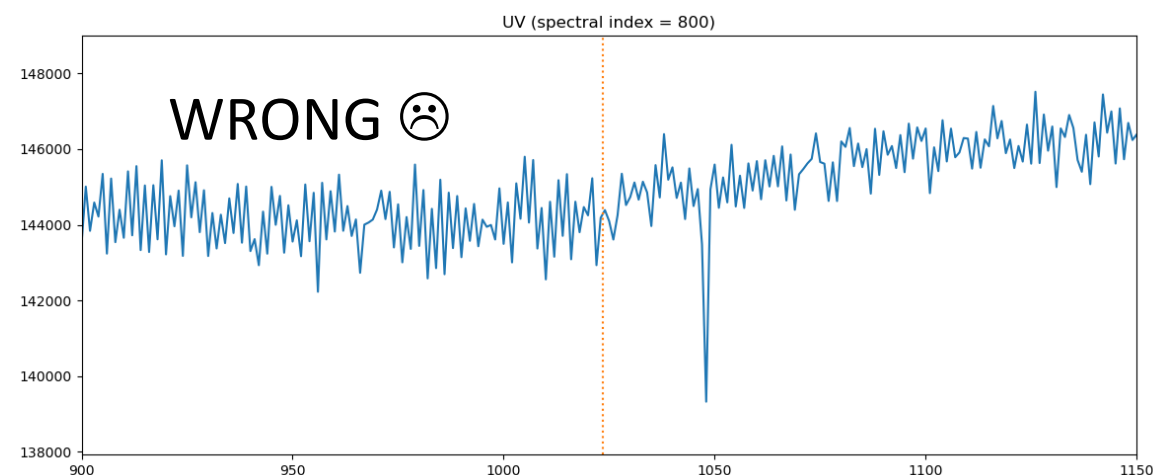
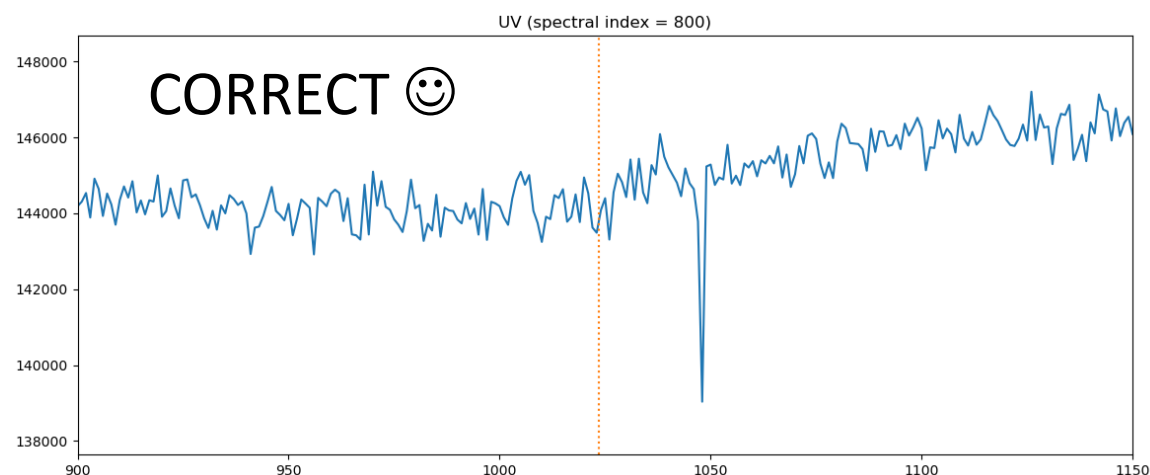


➤ Calibration key data

- *Gain and nonlinearity* (derived from Ball Aerospace, consistent with the radiometric calibration coefficients)
 - It changes the radiance values by 3–5%.
- *Bad pixel mask*
(derived using dark current from July 28 + non-responsive N/S edge pixel flagging + improved saturation flagging)
- *Pixel Response NonUniformity*

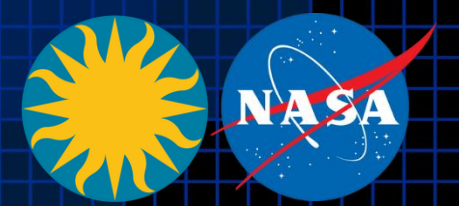
➤ Identification of analog-to-digital configuration

- Refine algorithm for determining correct gain configuration for each image - reduces striping

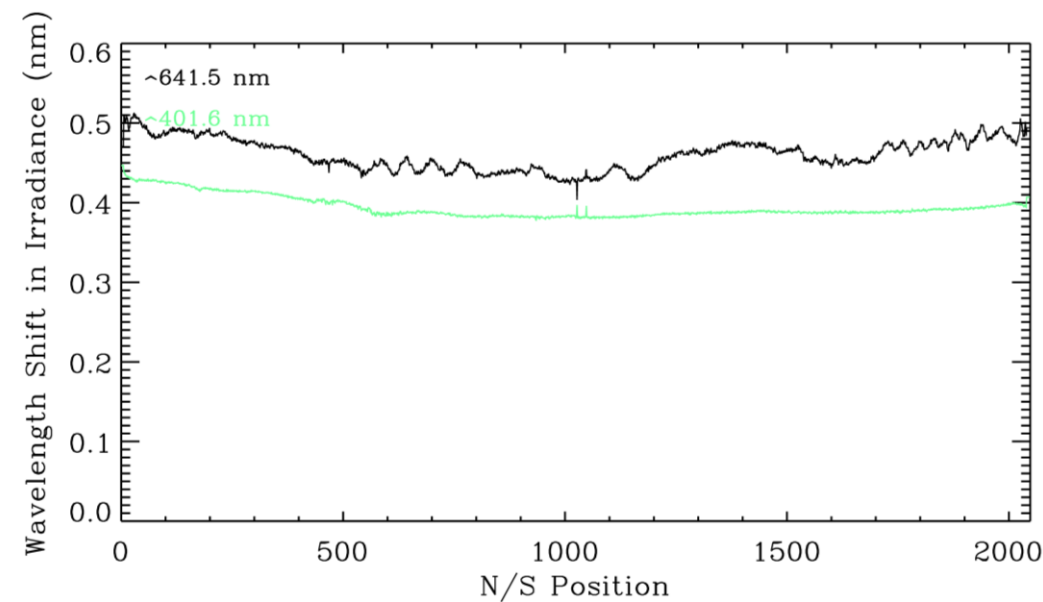
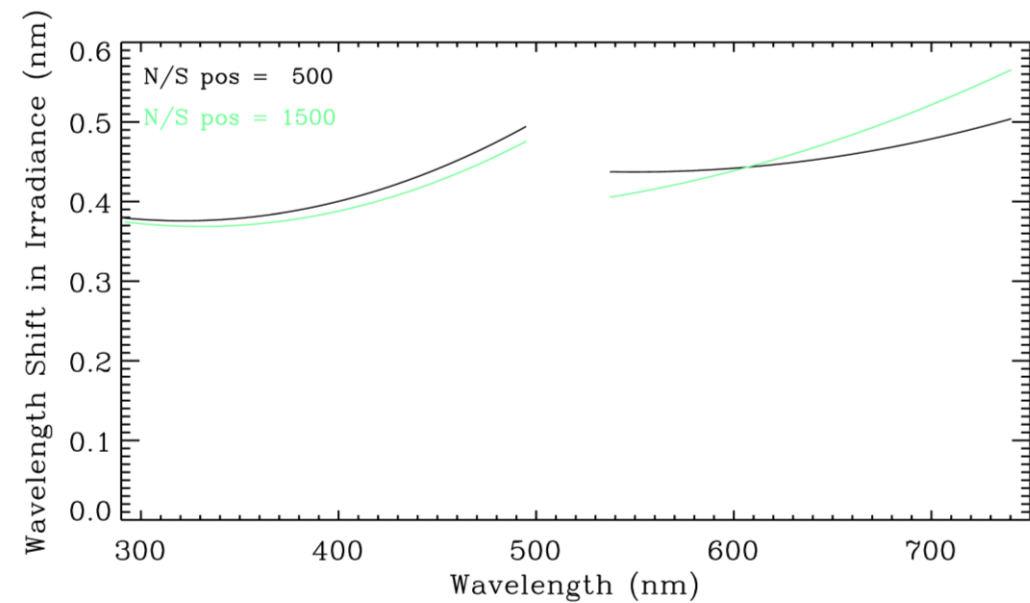




Wavelength Shift from Pre-launch

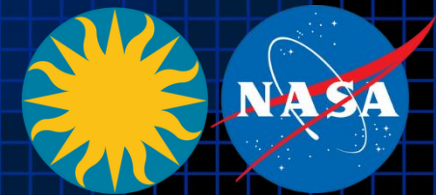


- Large wavelength shifts from pre-launch characterization.
 - Adjustment of nominal wavelength table
 - Possibly indexing error with instrument delivery
- Level 1 and 2 baseline algorithms register wavelength scale of each image.

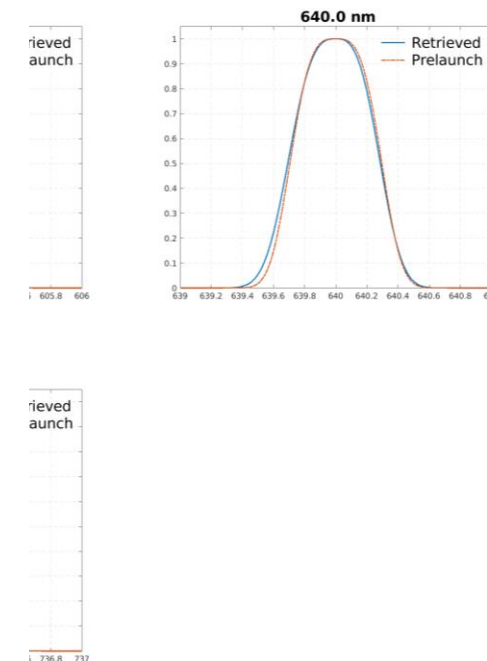
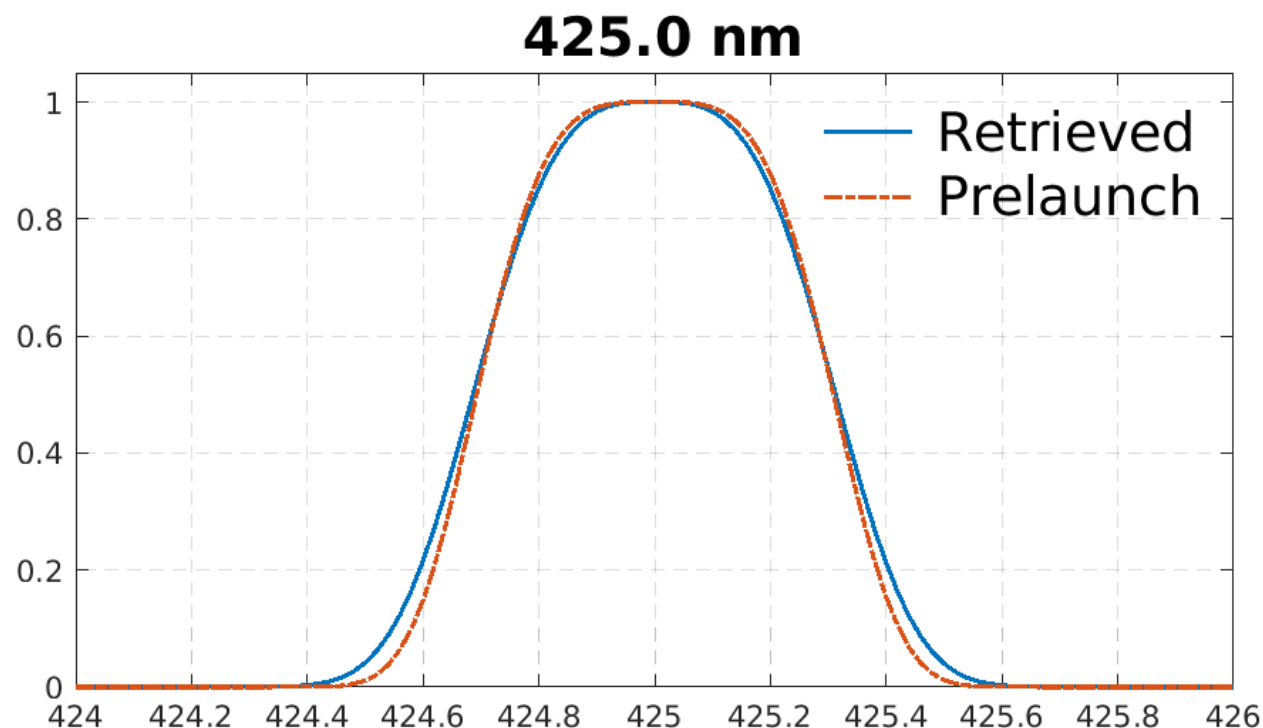
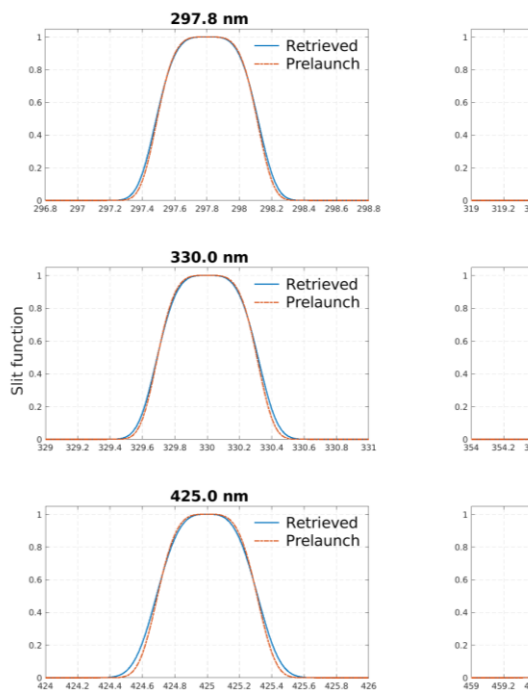




Spectral bandpass calibration

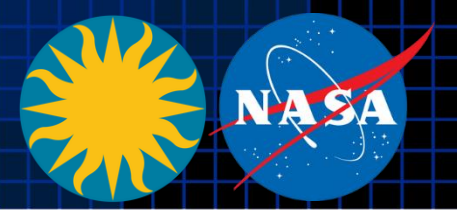


- Deriving in-flight spectral response function assuming asymmetric super Gaussian – wings slightly wider than prelaunch

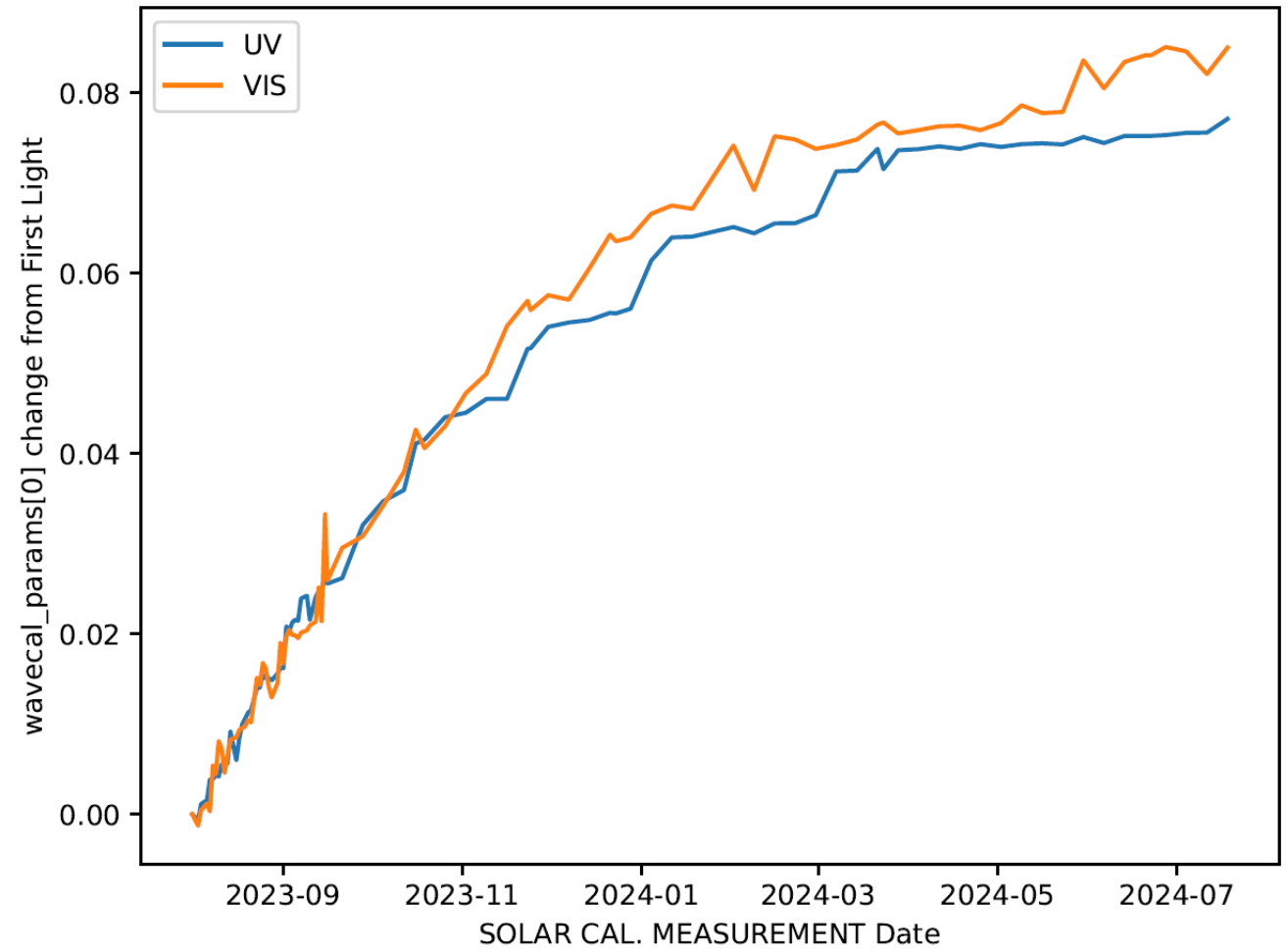




Wavelength Stability

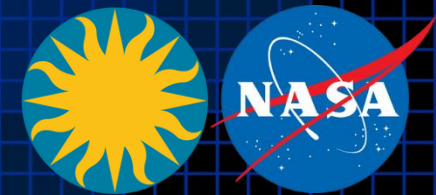


- Wavelength scale has changed (shifted) ever so slightly since First Light
- Much more stable since ~ Spring 2024

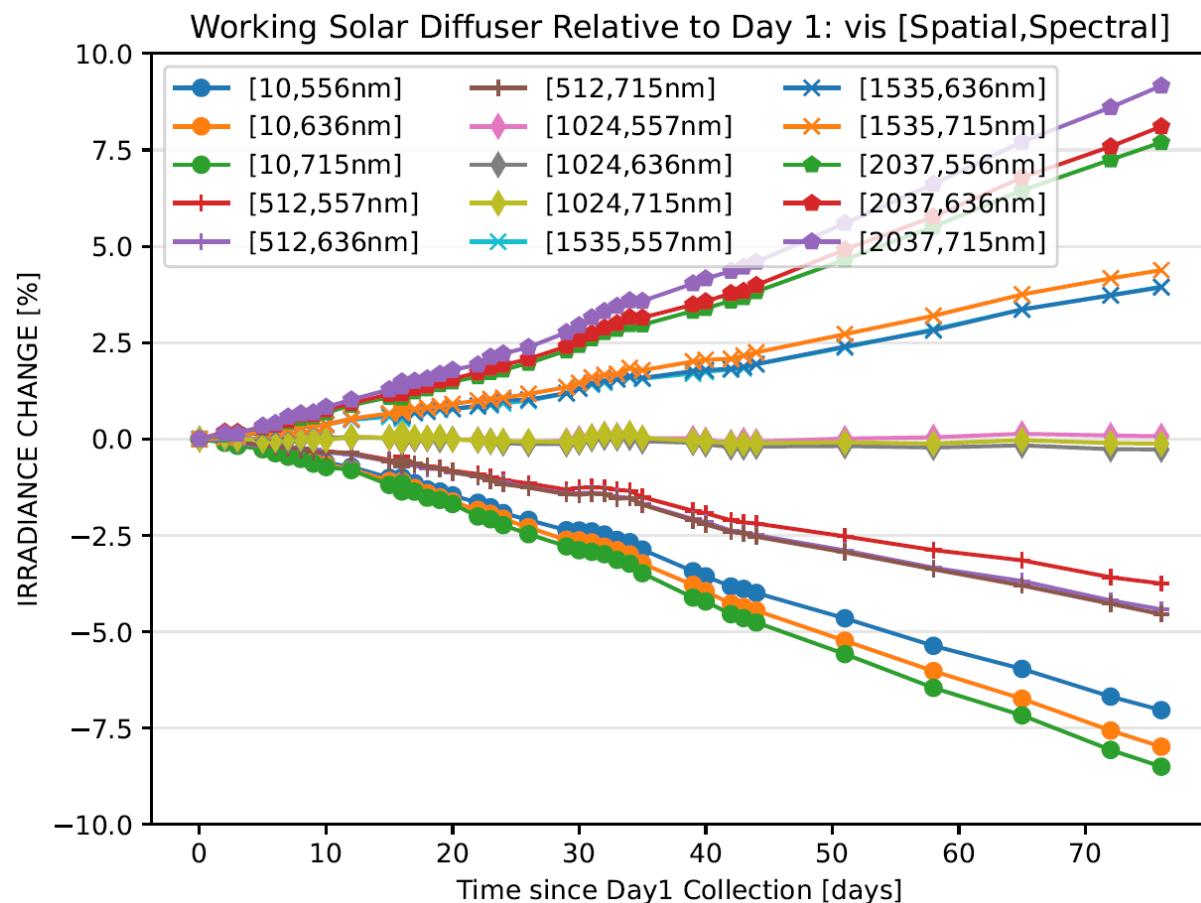
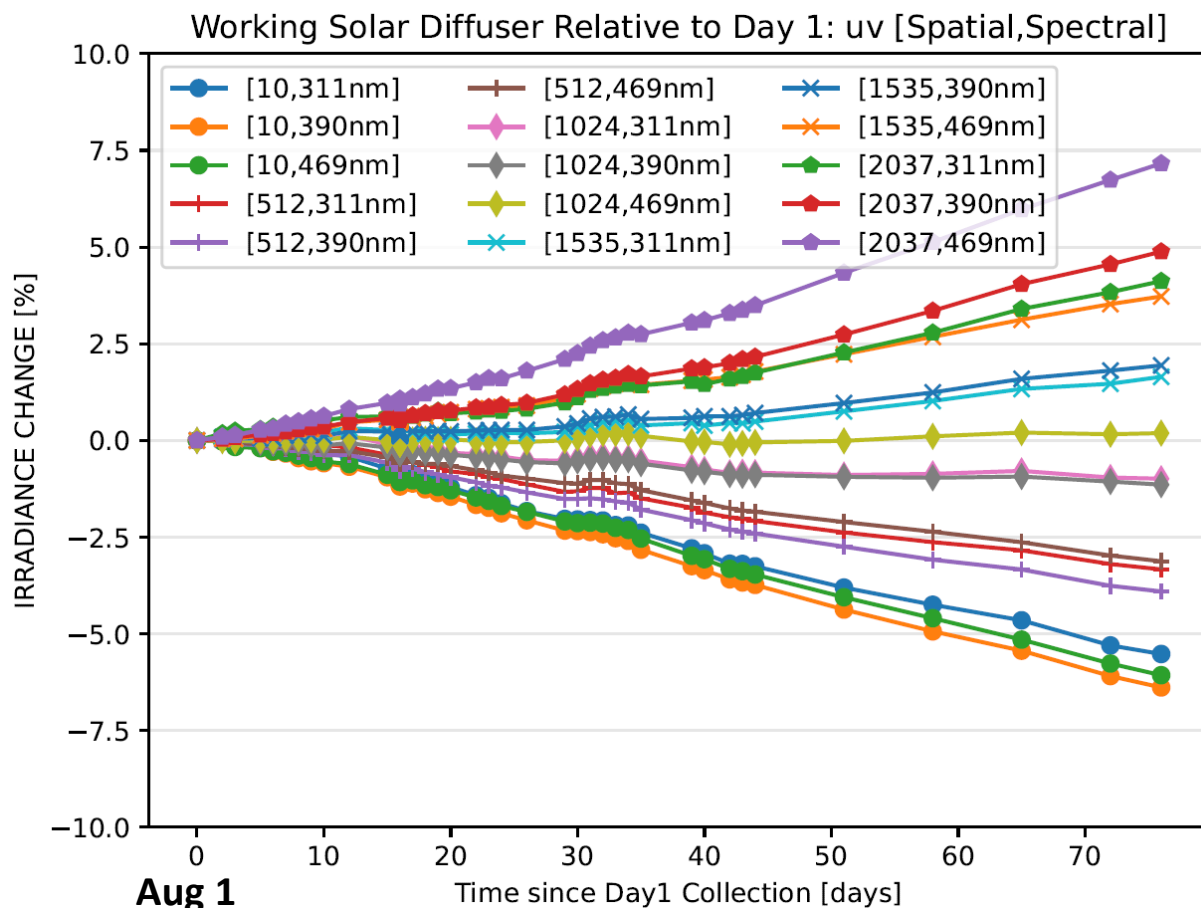




Angular dependence of BTDF - 1



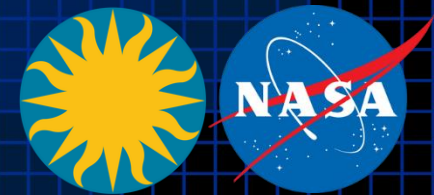
Temporal irradiance changes (as expected from GEMS measurements)



BTDF = Bidirectional Transmission
Distribution Function

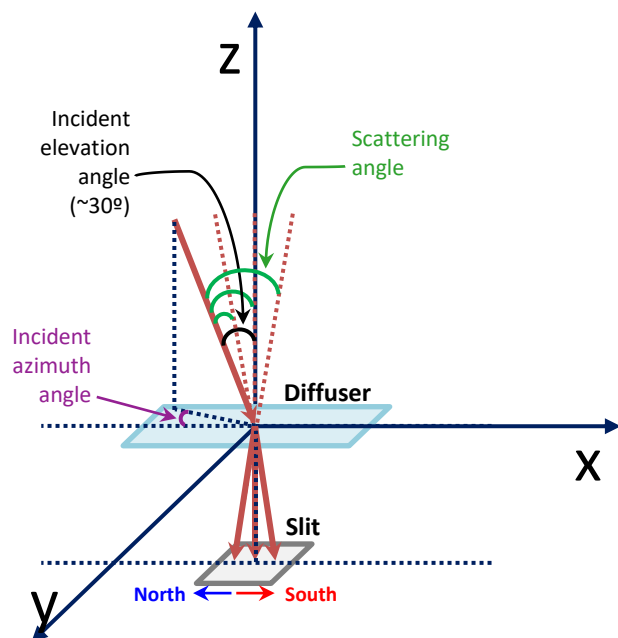


Correcting angle-dependence of BTDF -2



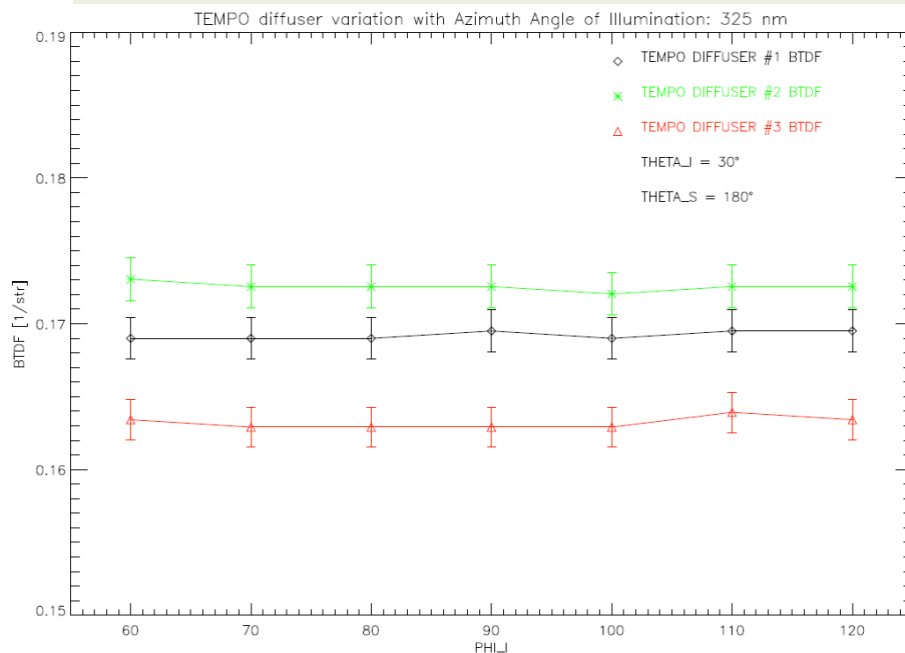
- First-principle correction using ‘scattering angles’ will be implemented.

Geometry of solar cal.



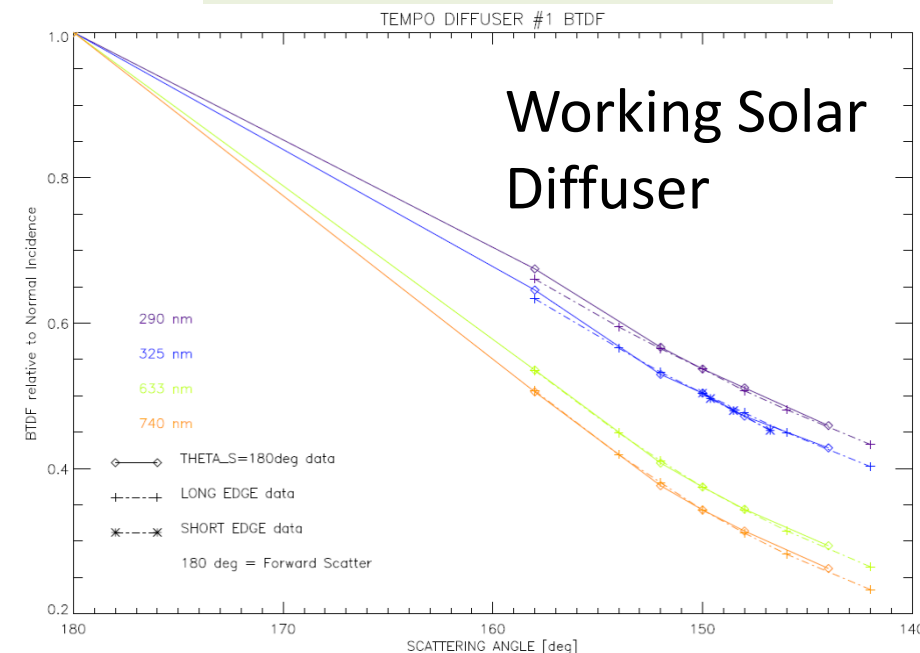
[Credit: Heesung Chong]

BTDF at center of diffuser (aka middle of N-S slit)
independent of azimuth angle



Incident Azimuth Angle

BTDF has robust dependence on scattering angle



Working Solar Diffuser

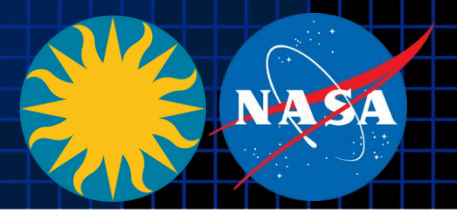
(Forward)

Scattering Angle

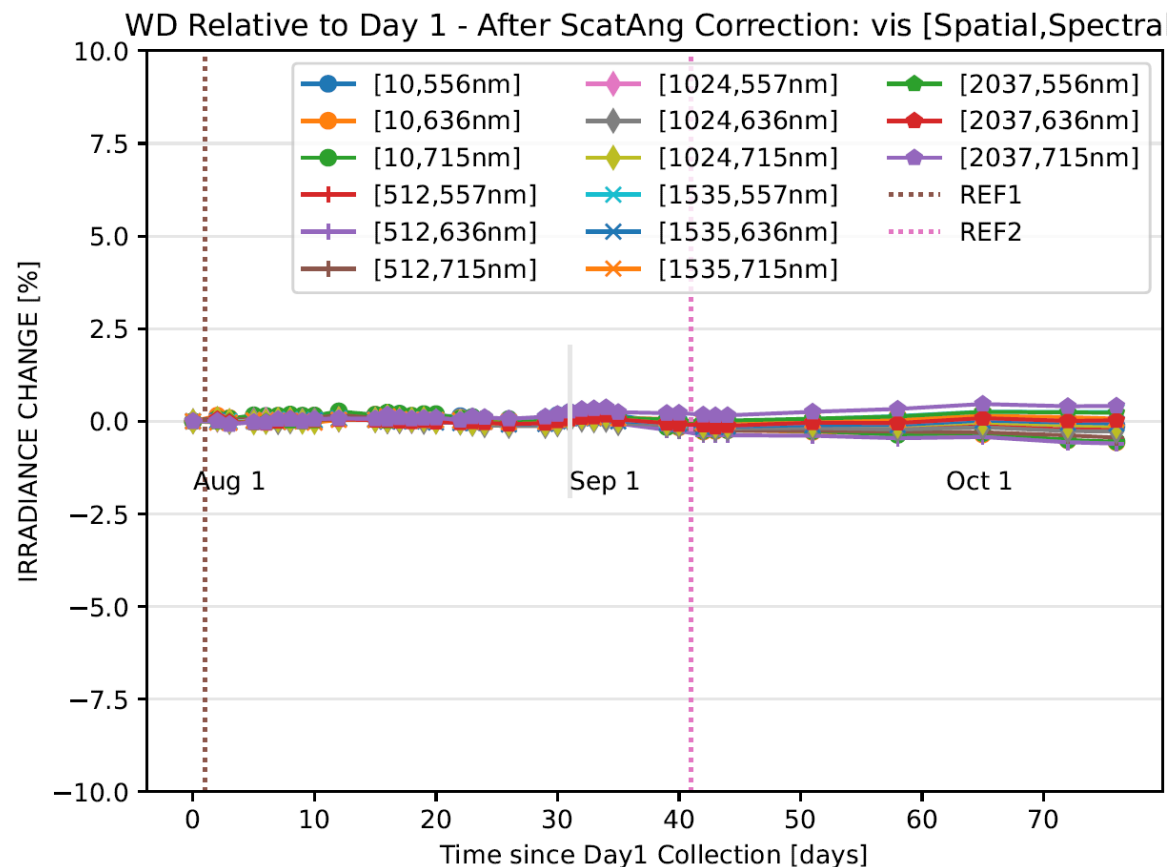
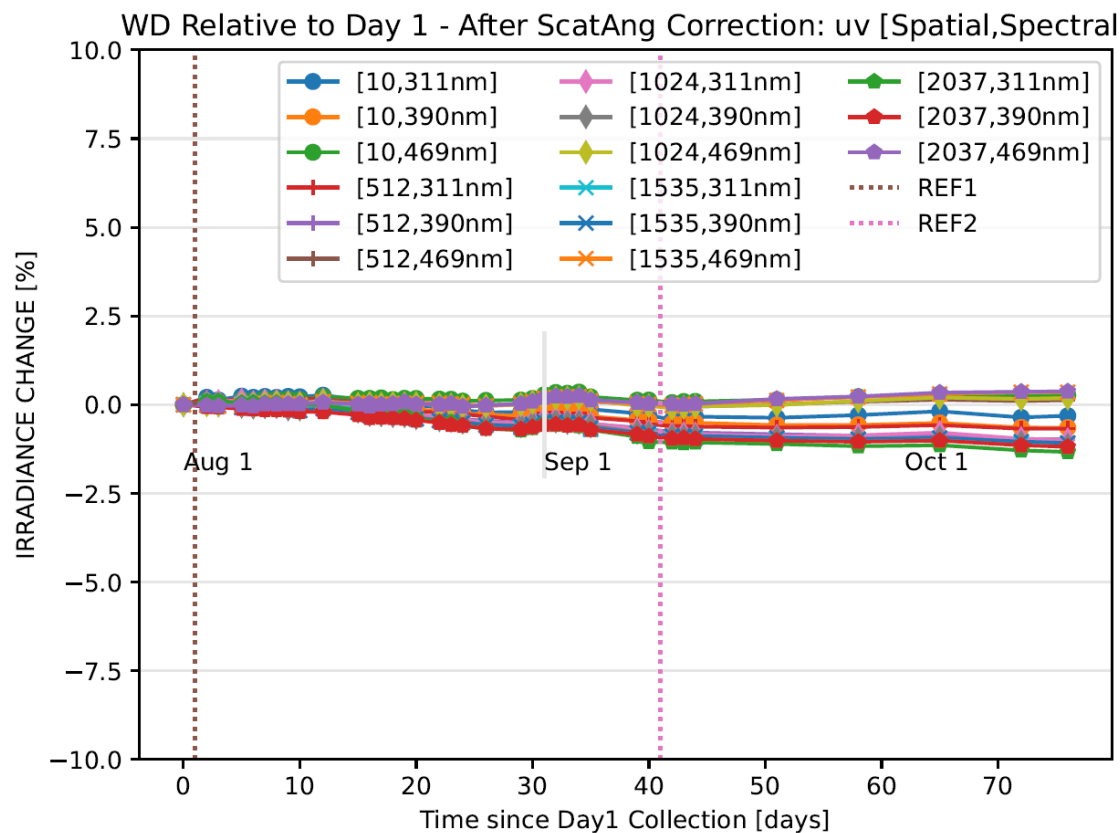
BTDF = Bidirectional Transmission
Distribution Function



Correcting angle-dependence of BTDF - 3



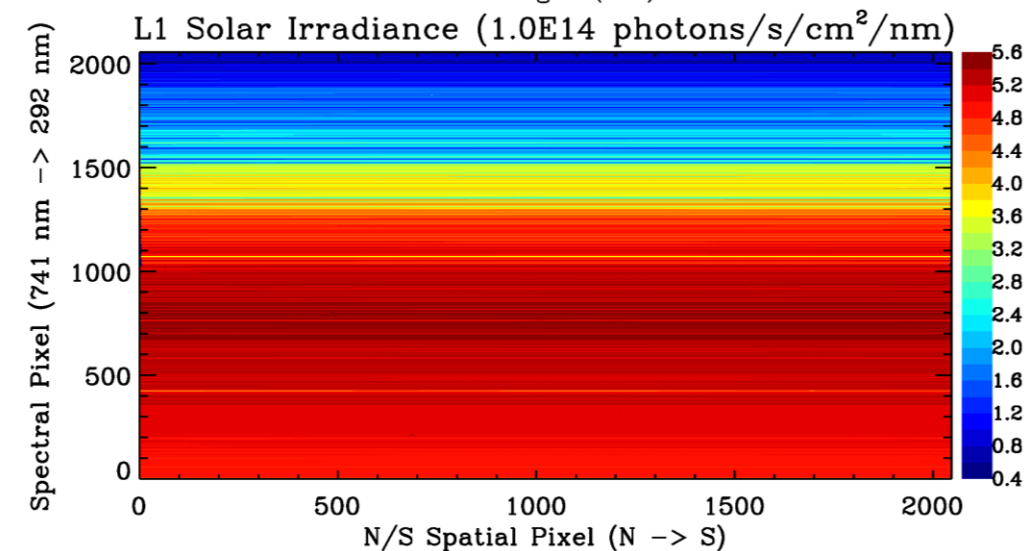
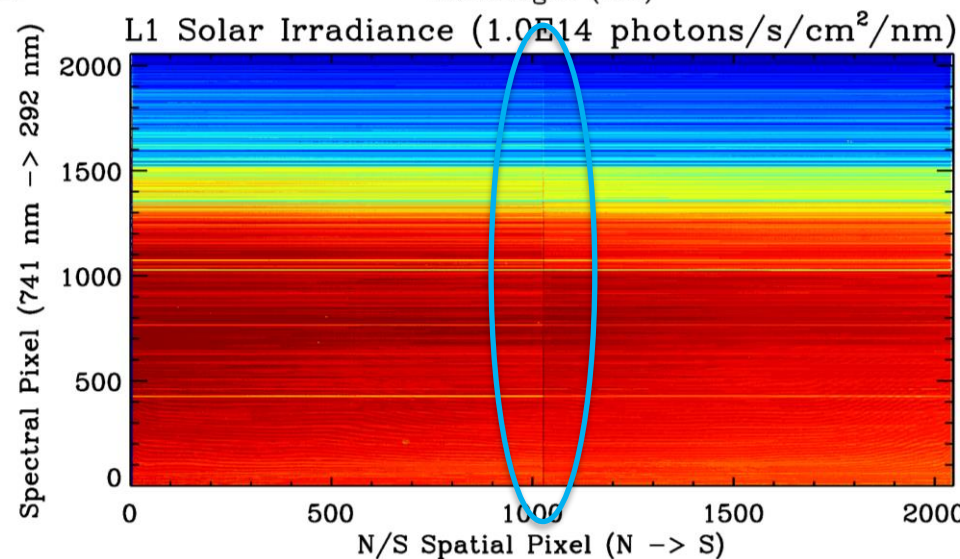
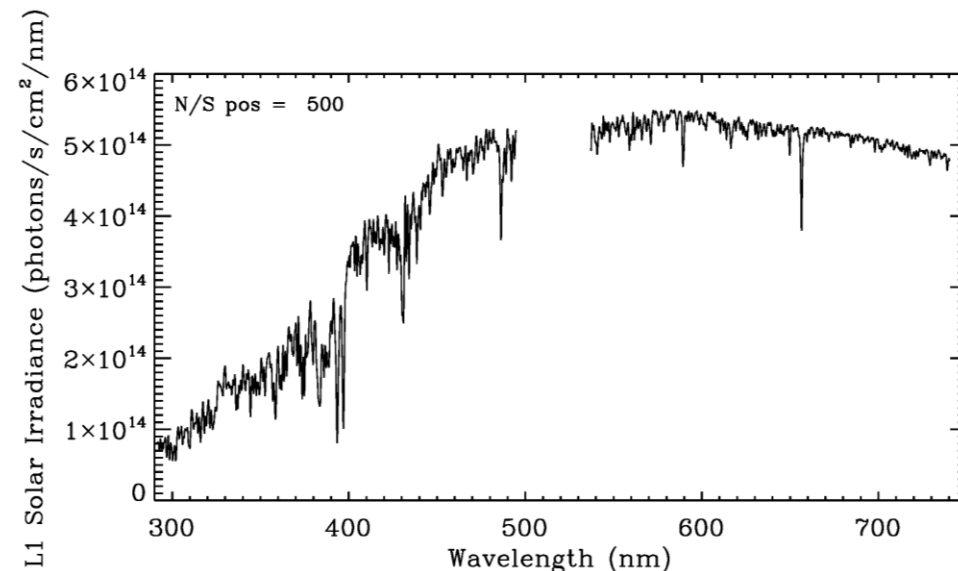
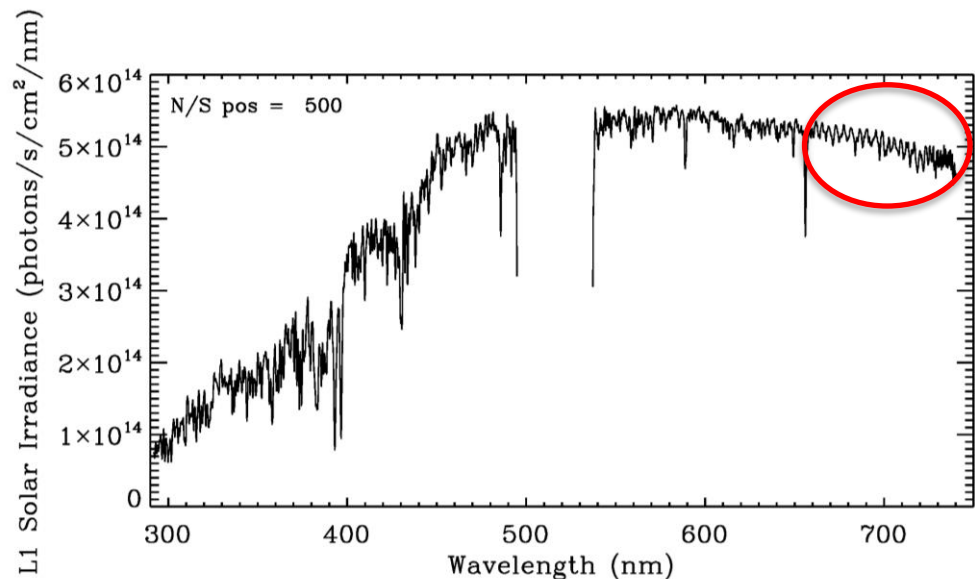
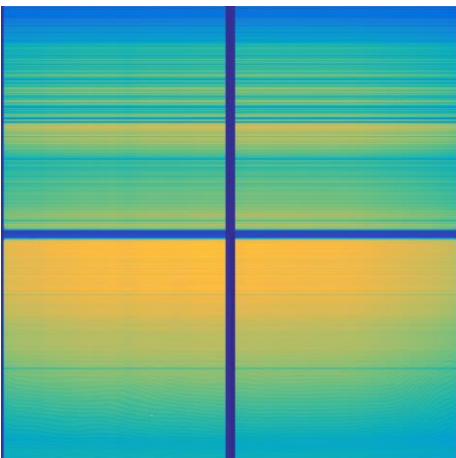
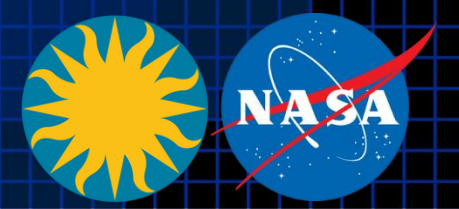
- After applying scattering angle correction, trend is significantly reduced





First Light: Working Diffuser Solar

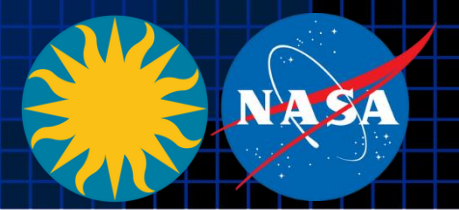
@12:18 am ET, August 1, 2023



Synthetic Data

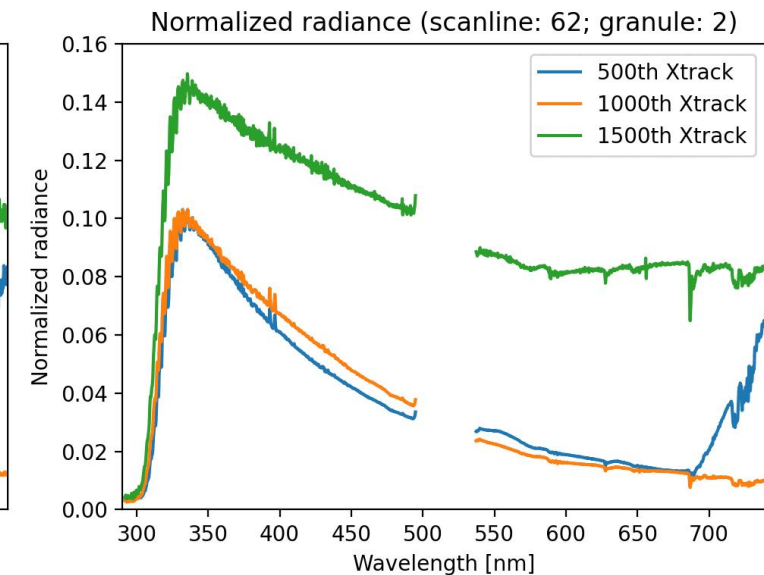
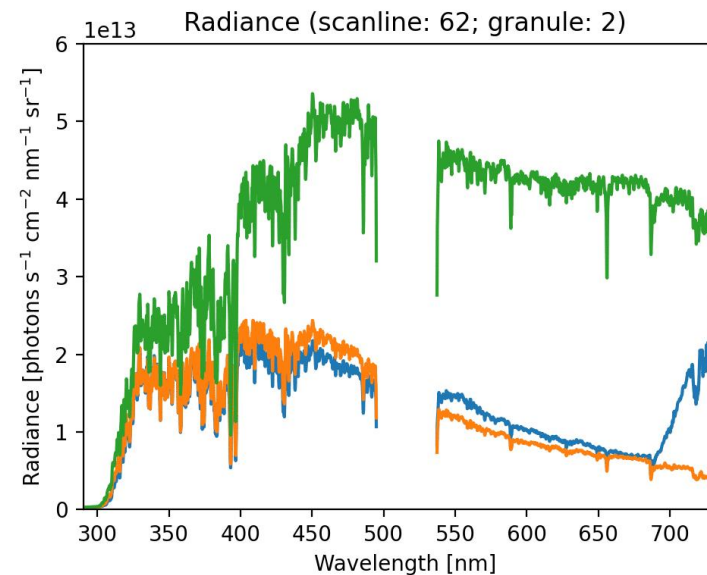
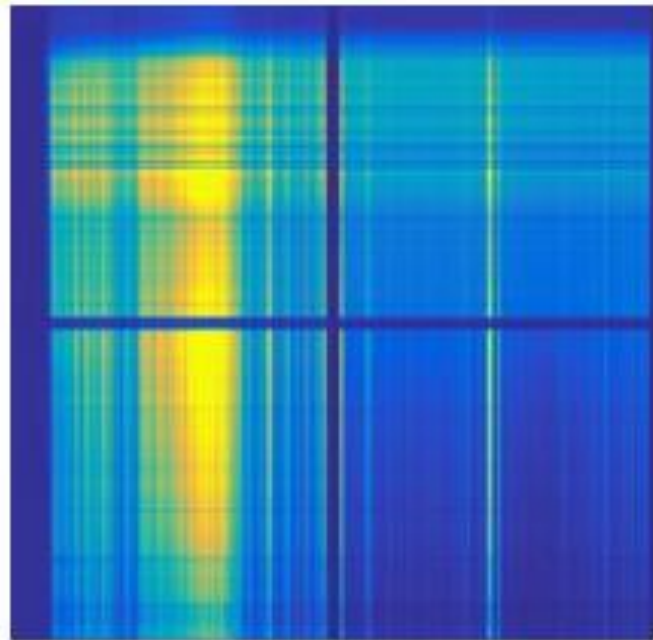
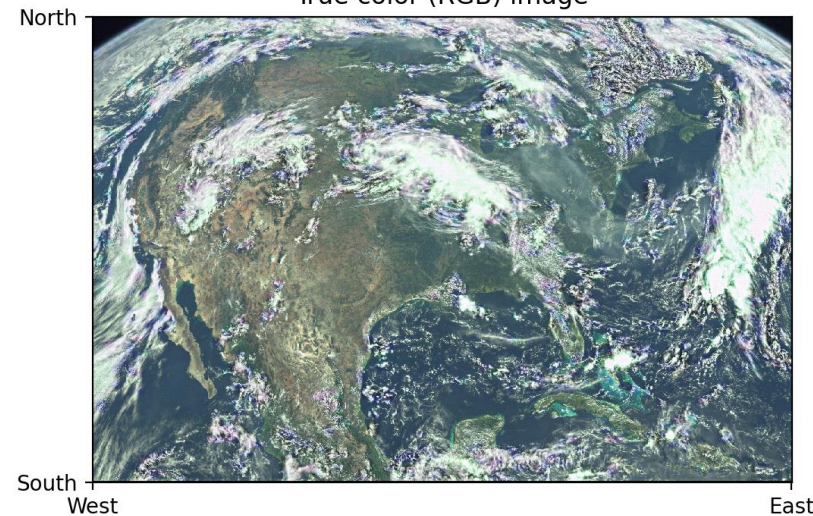


First Light: Earth Imaging Started @11:13 ET, August 2, 2023



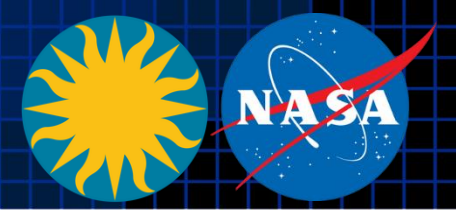
D15914/S001

True color (RGB) image





Instrument SNR Requirements



- Instrument performance requirements were derived from L1 precision requirements
- Signal to Noise Ratio (SNR) is the dominant factor for instrument performance

Earth-View TEMPO Signal to Noise Ratio (SNR) Verification Summary

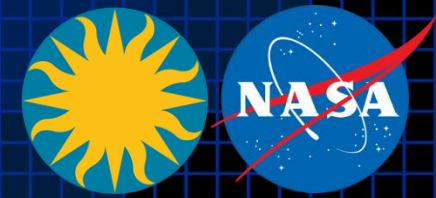
Req Number	Requirement		BOL SNR			EOL SNR	
	Atmospheric Constituent	Wavelength (nm)	SNR Requirement e- / e-	As-Measured SNR	Margin	Predicted EOL SNR	Margin
IRD-320 TSS-59	O3	290	19.6	N/A	N/A	N/A	N/A
	O3	300	46.1	49	5.4%	45	-2.4%
	O3	305	161.9	191	17.8%	178	10.1%
	O3	310	377	471	24.9%	447	18.5%
	O3	320	1220	1664	36.4%	1621	32.8%
	O3, H2CO	330	2003	2829	41.2%	2779	38.7%
	O3, H2CO, Cloud	340	2013	2867	42.4%	2827	40.4%
	H2CO, Cloud	350	1414	2717	92.1%	2685	89.9%
	NO2	420	836	2138	155.8%	2127	154.4%
	NO2	430	675	1681	149.0%	1670	147.4%
	NO2	450	733	1875	155.8%	1865	154.4%
	Cloud	490	1176	1886	60.4%	1879	59.8%
	O3	540	1109	1813	63.5%	1806	62.9%
	O3	600	987	1577	59.8%	1571	59.1%
	O3	650	898	1383	54.0%	1376	53.2%
	Cloud	690	820	1195	45.8%	1188	44.9%

Table of radiance SNR requirement and with Beginning of Life (BOL) as-built performance (4 Pixels coadded)

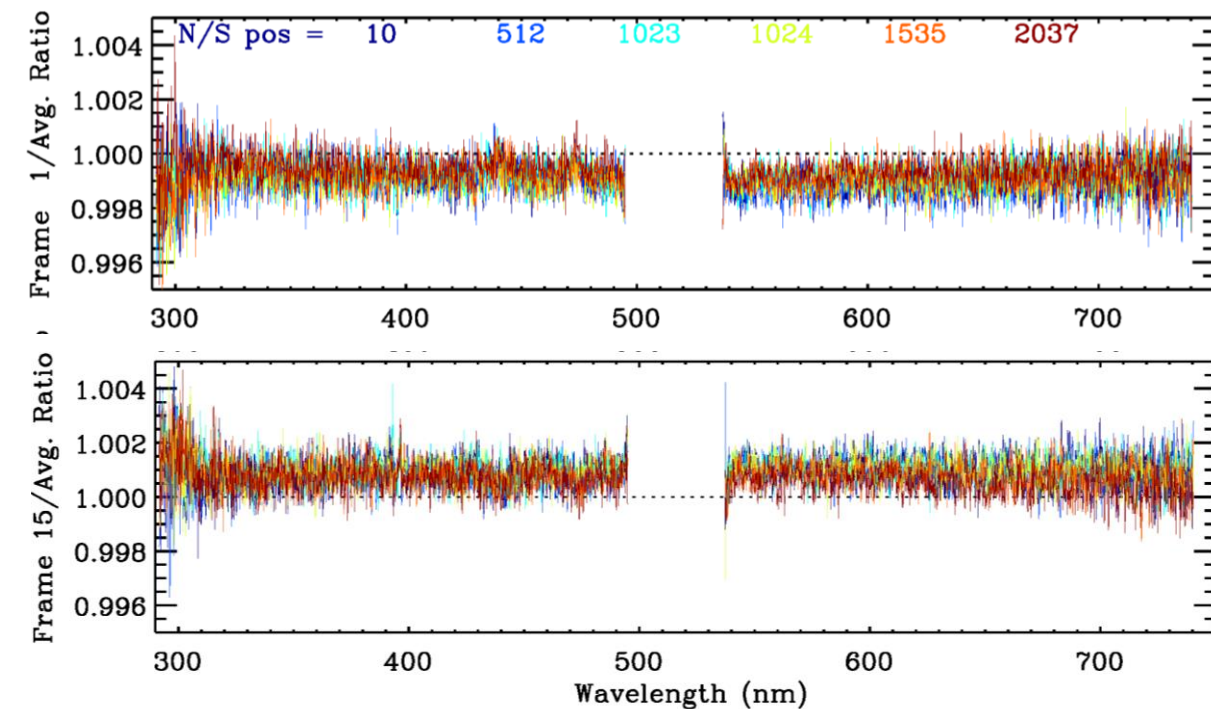
- The Instrument shall meet the SNR requirements in Table for the provided nominal spectral radiances when measuring every point in the entire FOR in a revisit time of 1 hour or less, by binning no more than 4 spatial pixels.
- The Instrument shall perform solar calibration measurements with SNRs greater than or equal to 2 times those for the nominal radiances.



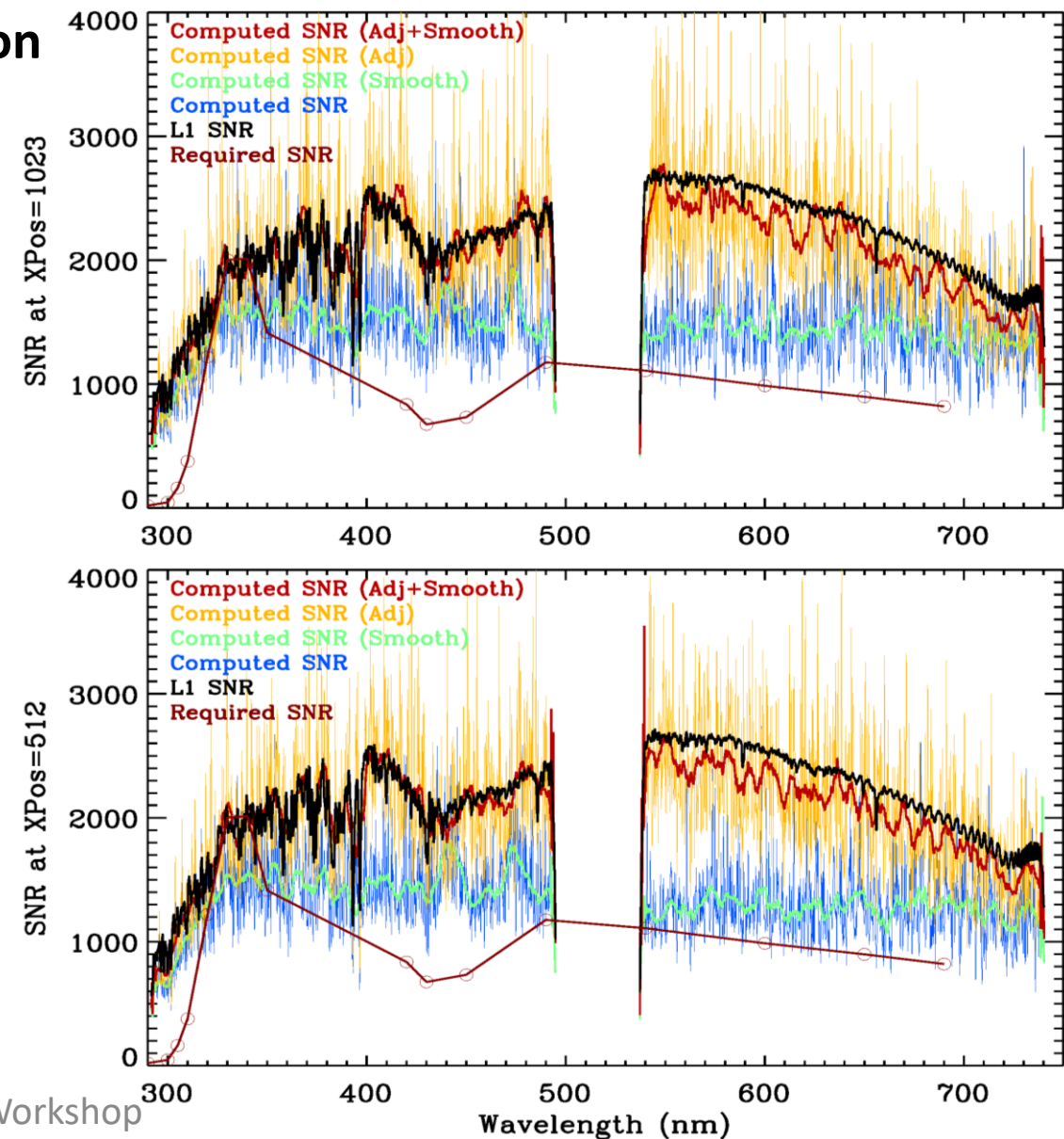
Solar Irradiance SNR



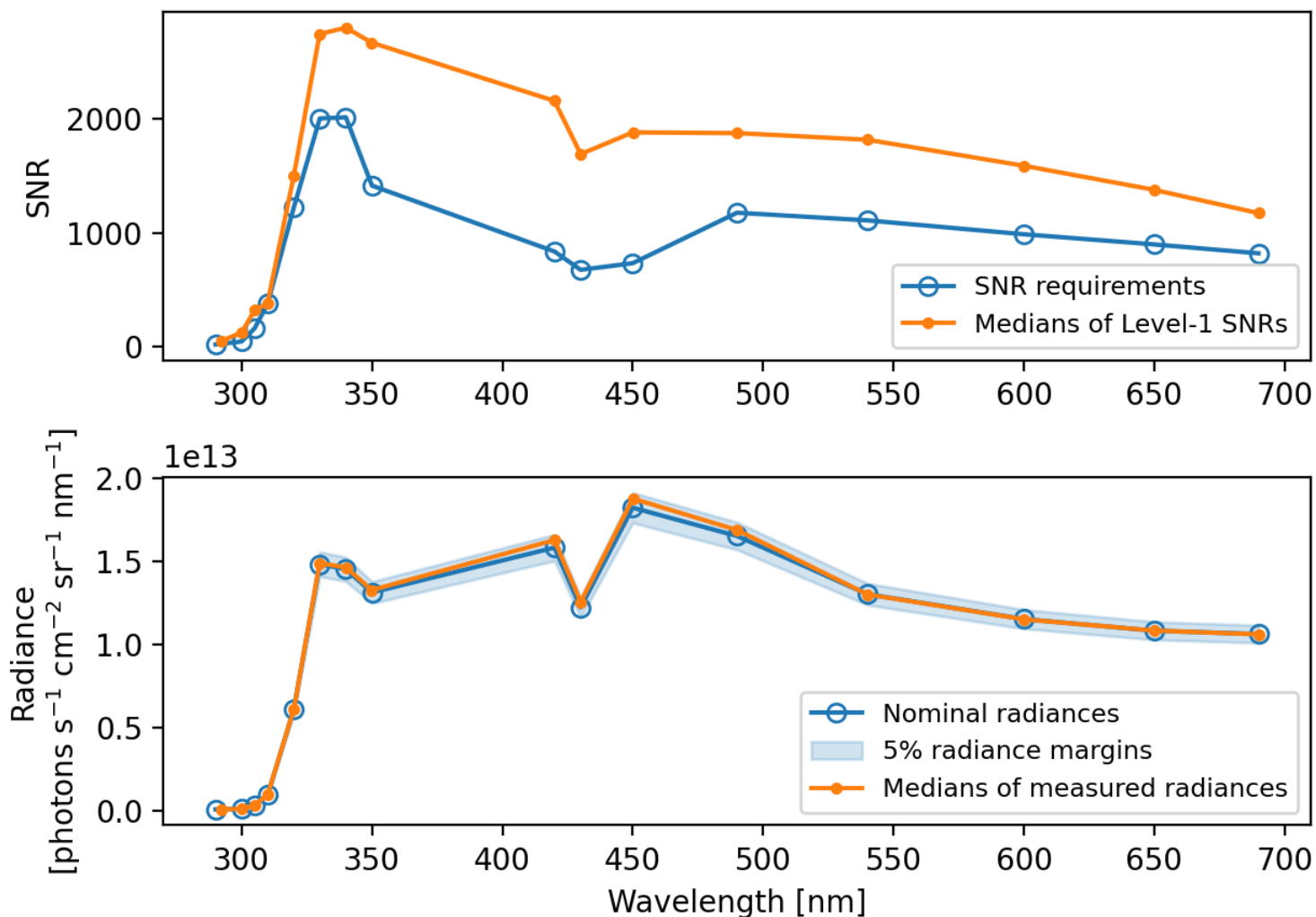
- 15 frames of working solar diffuser measurements on 8/17/2023 for SNR verification.



- After accounting for variation, we verify :
 - ✓ L1 Signal to Noise Ratio (SNR) calculation is correct
 - ✓ We can meet the solar SNR requirement.



Radiance SNR: September 01, 2023

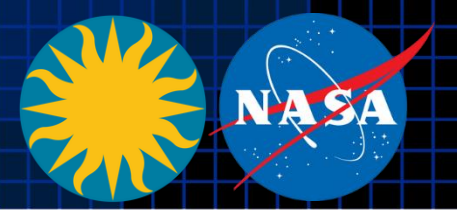


➤ **Used radiance data from all thirteen scans on September 1.**

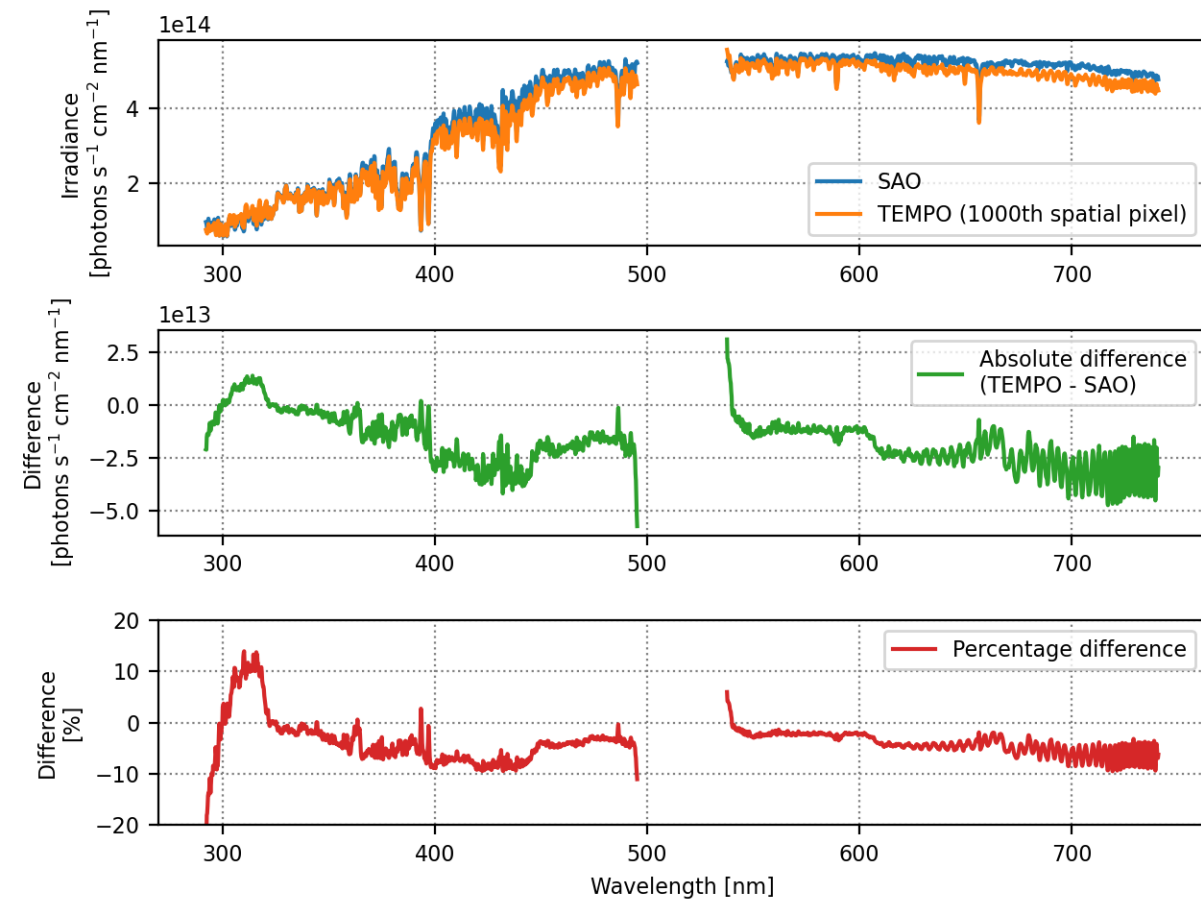
- ✓ For each nominal wavelength, select pixels within +/-5% of the nominal radiance.
- ✓ Calculate median of SNRs for the searched pixels for each wavelength (upper panel).
- ✓ Calculate the median of radiances for the searched pixels for each wavelength (lower panel).



Irradiance Comparison

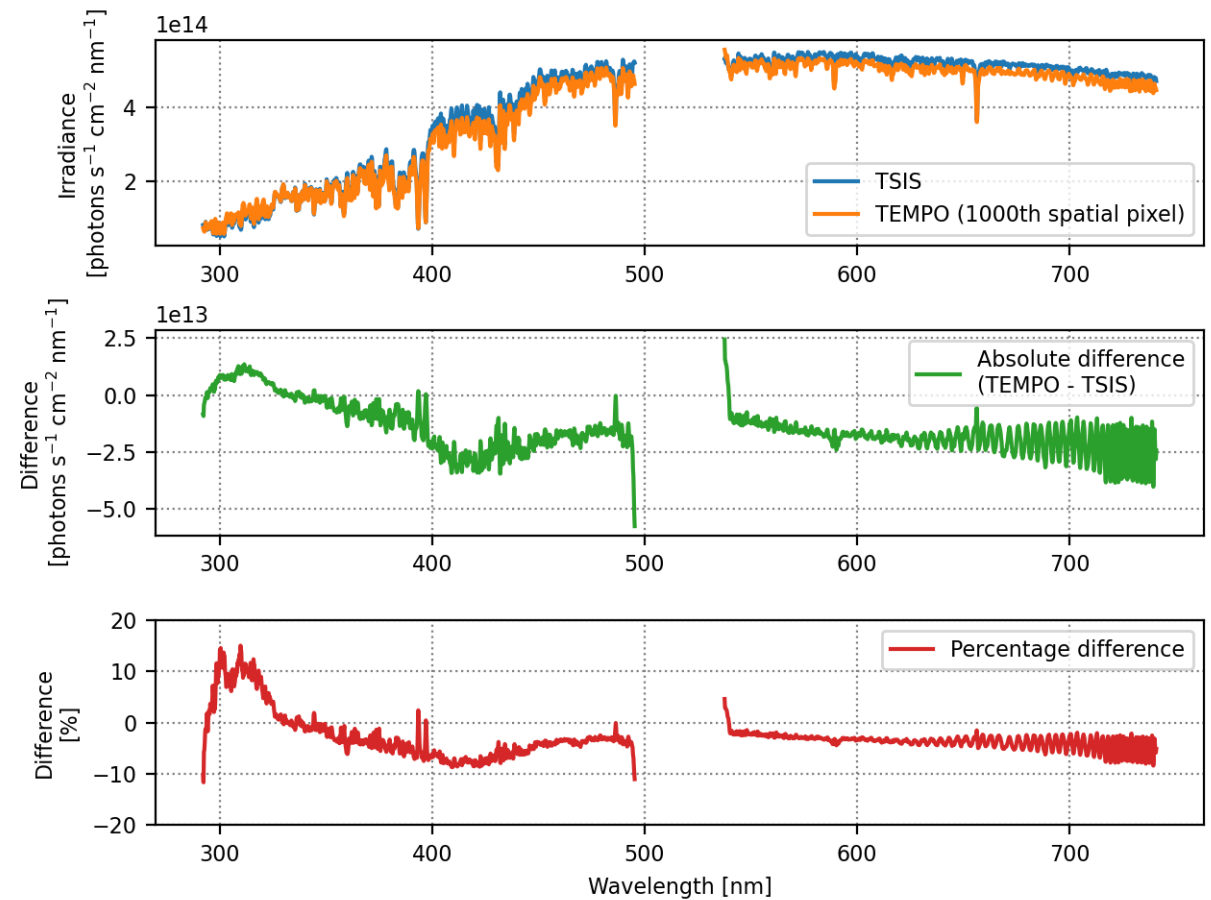


TEMPO vs. SAO (Chance & Kurucz 2010)



[Credit: Heesung Chong]

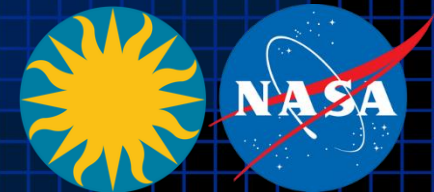
TEMPO vs. TSIS (Coddington et al. 2021)



- TEMPO first light irradiance biased low (0-10%) above 320 nm
- Below 320 nm biased high (0-10%)



Irradiance Comparison Similar w/TropOMI

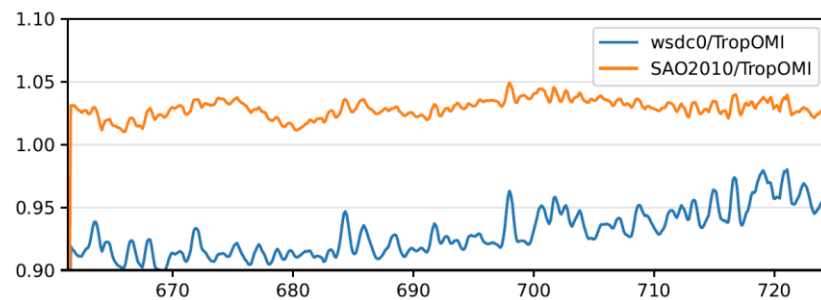
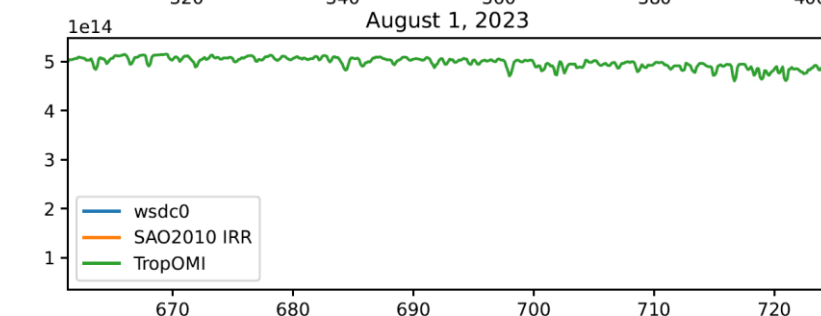
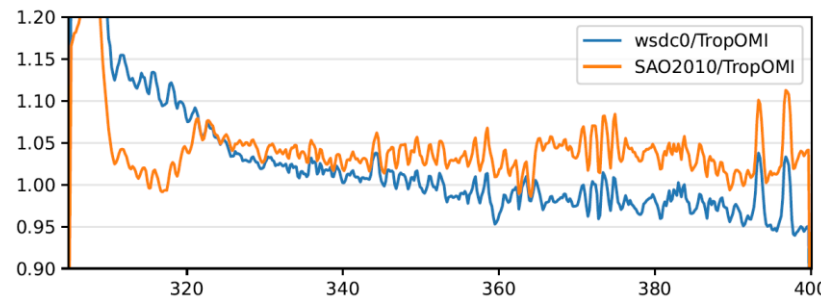
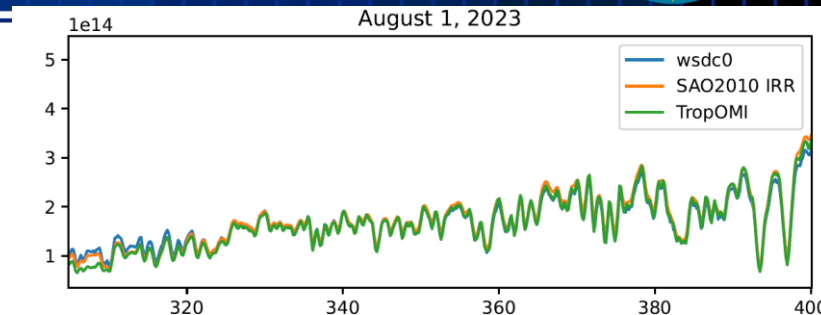
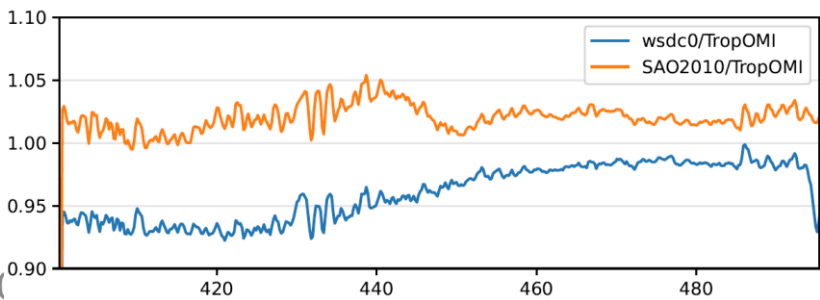
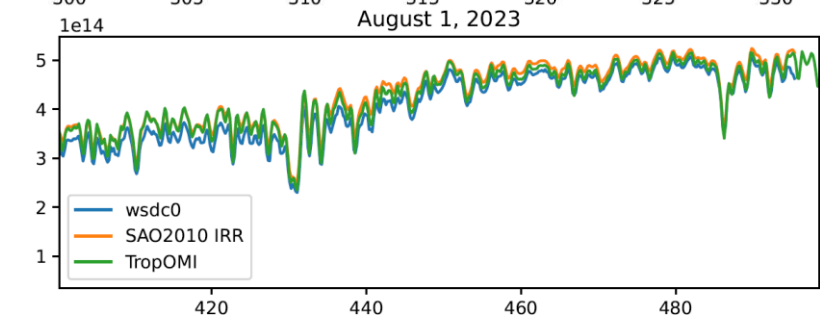
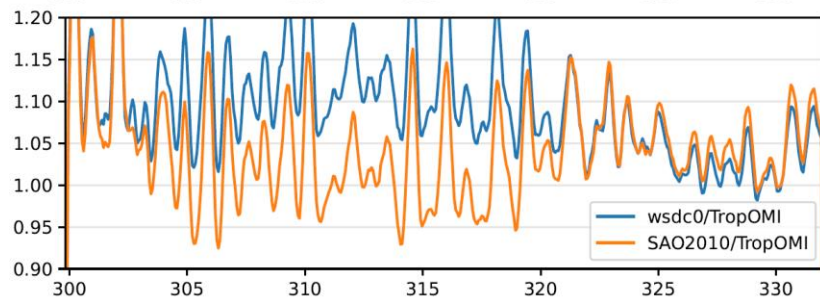
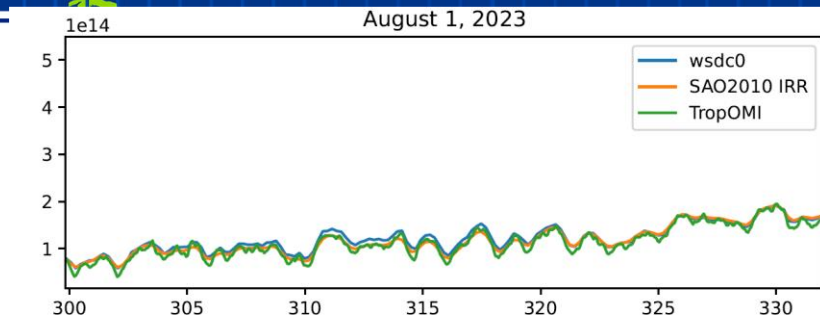


Irradiance

Ratio

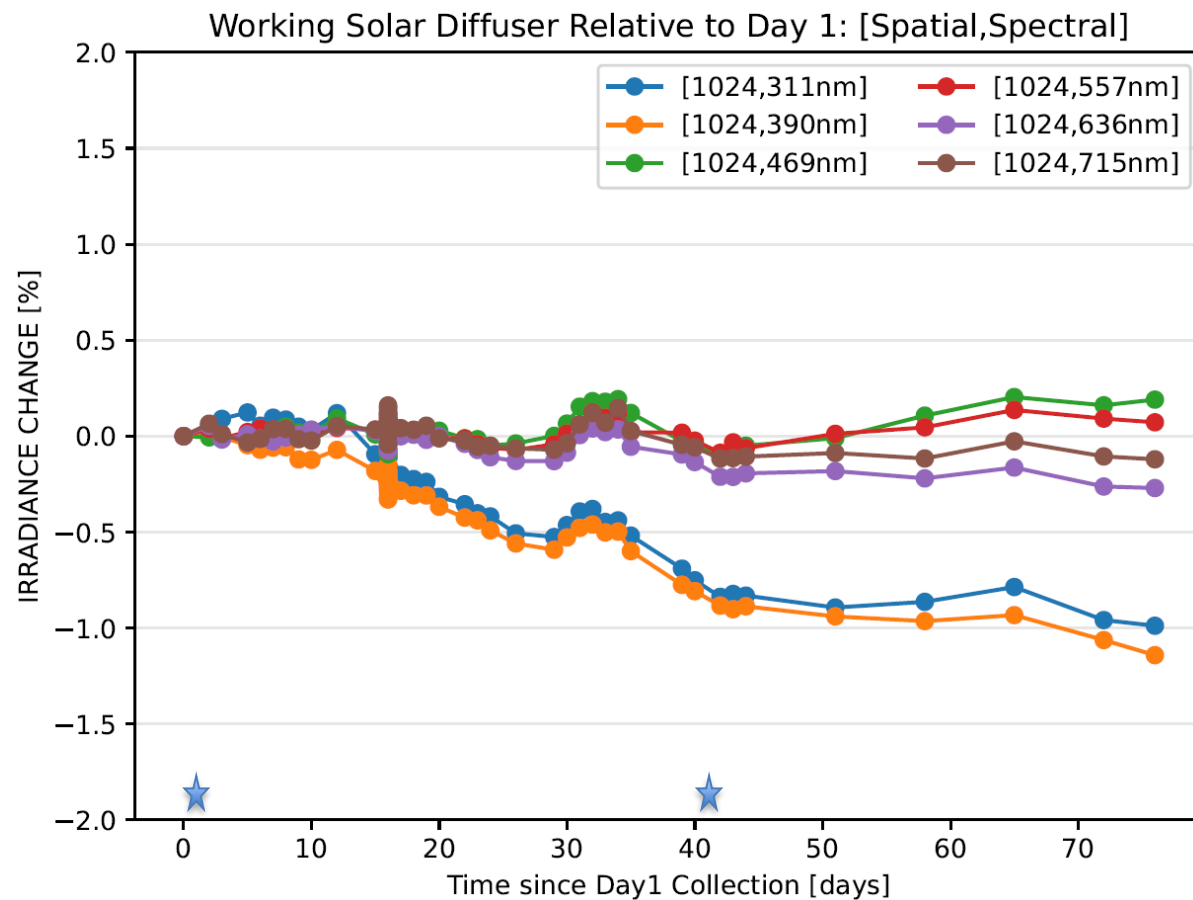
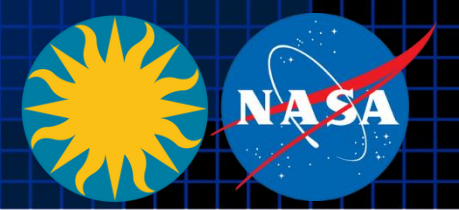
Irradiance

Ratio

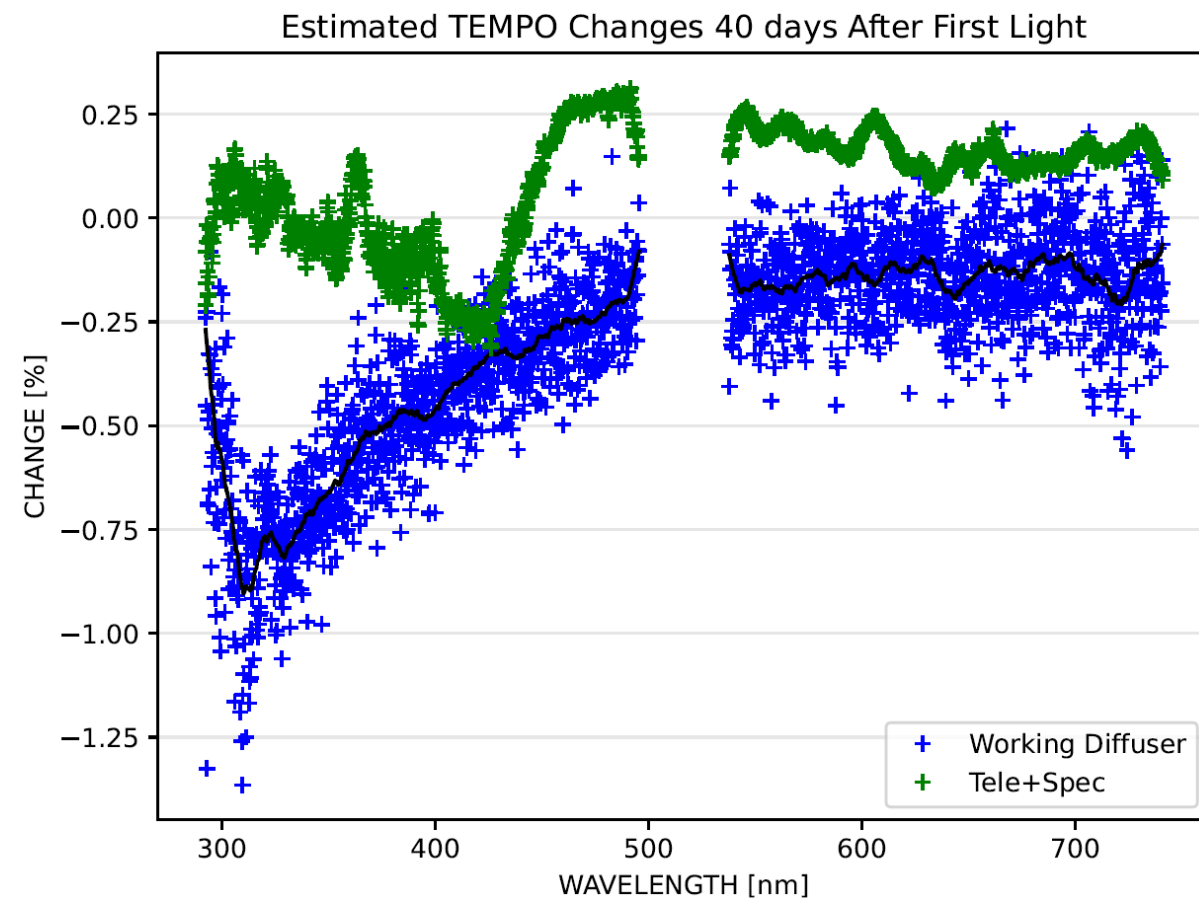




Sensor Response Evolution

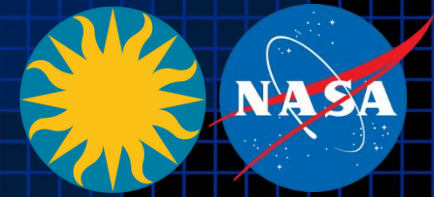


Reference Solar Measurements = ★
(Aug 2, 2023; Sep 11, 2023)





Saturation



50 ms

Number of saturated

100 ms

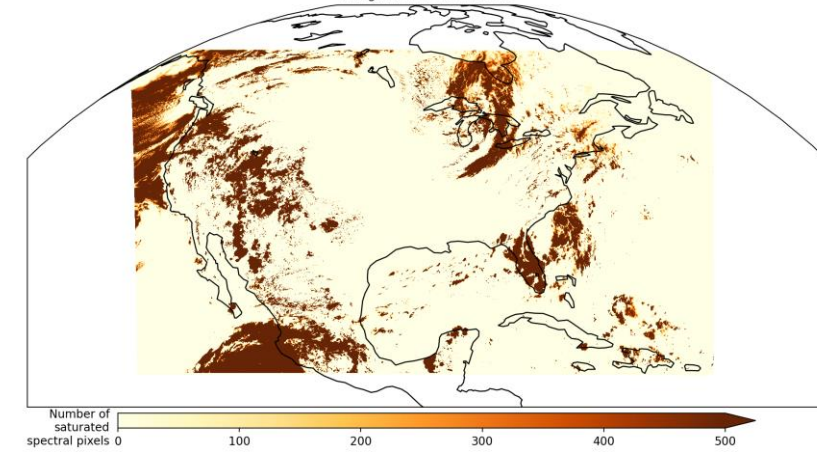
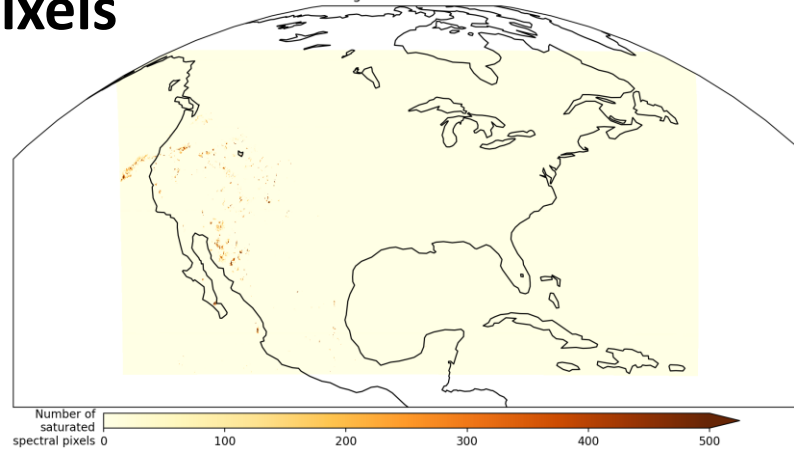
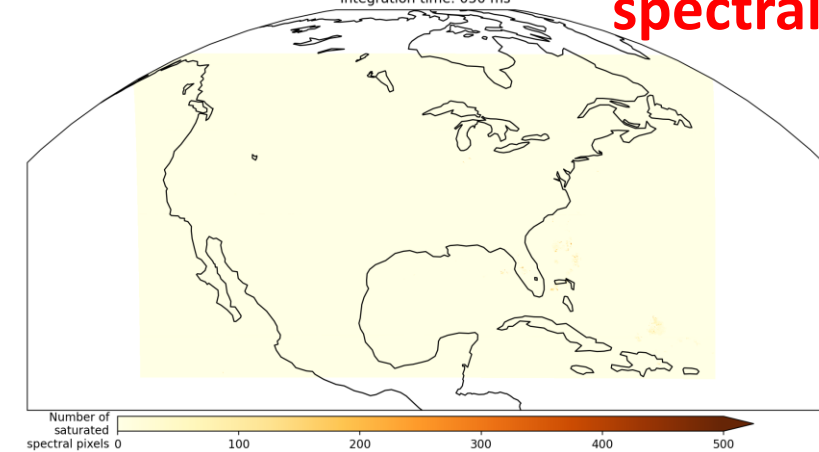
178 ms

spectral pixels

August 17, 2023 17:36:05 UTC (Scan 001)
Integration time: 050 ms

August 17, 2023 23:34:03 UTC (Scan 005)
Integration time: 100 ms

August 17, 2023 22:02:19 UTC (Scan 004)
Integration time: 178 ms



[Credit: Heesung Chong]

Percentage of saturated **spatial** pixels, as a function of wavelength (excluding bad pixels)

50 ms

100 ms

178 ms

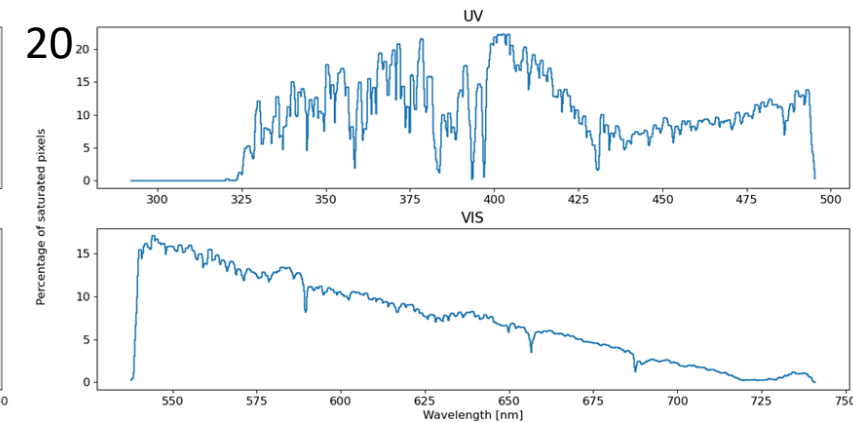
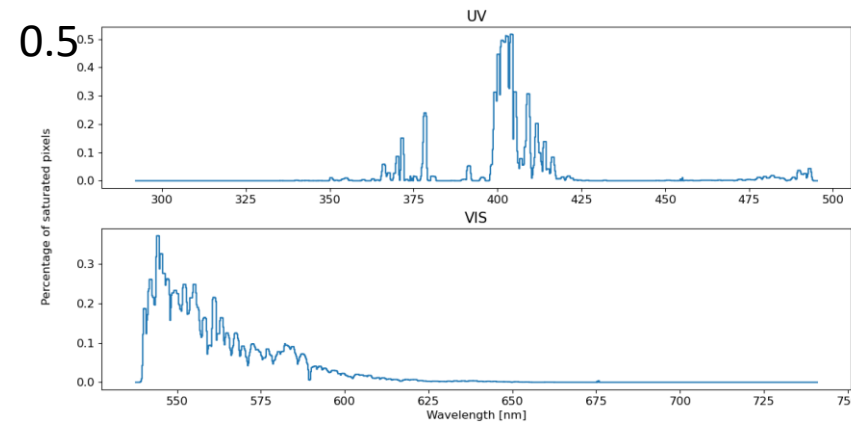
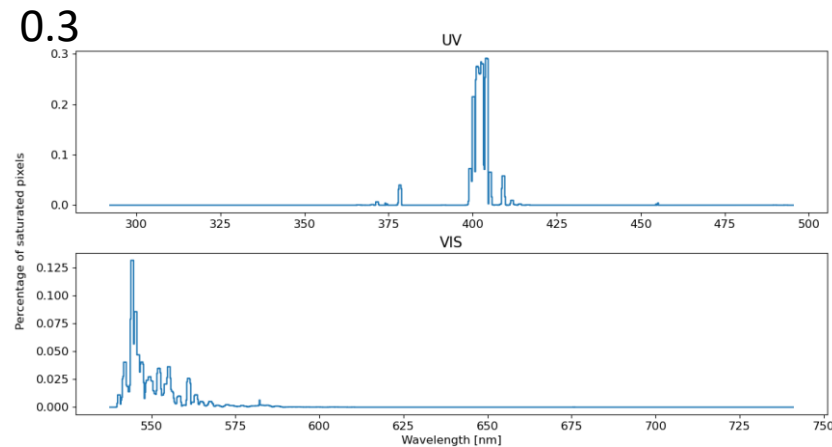
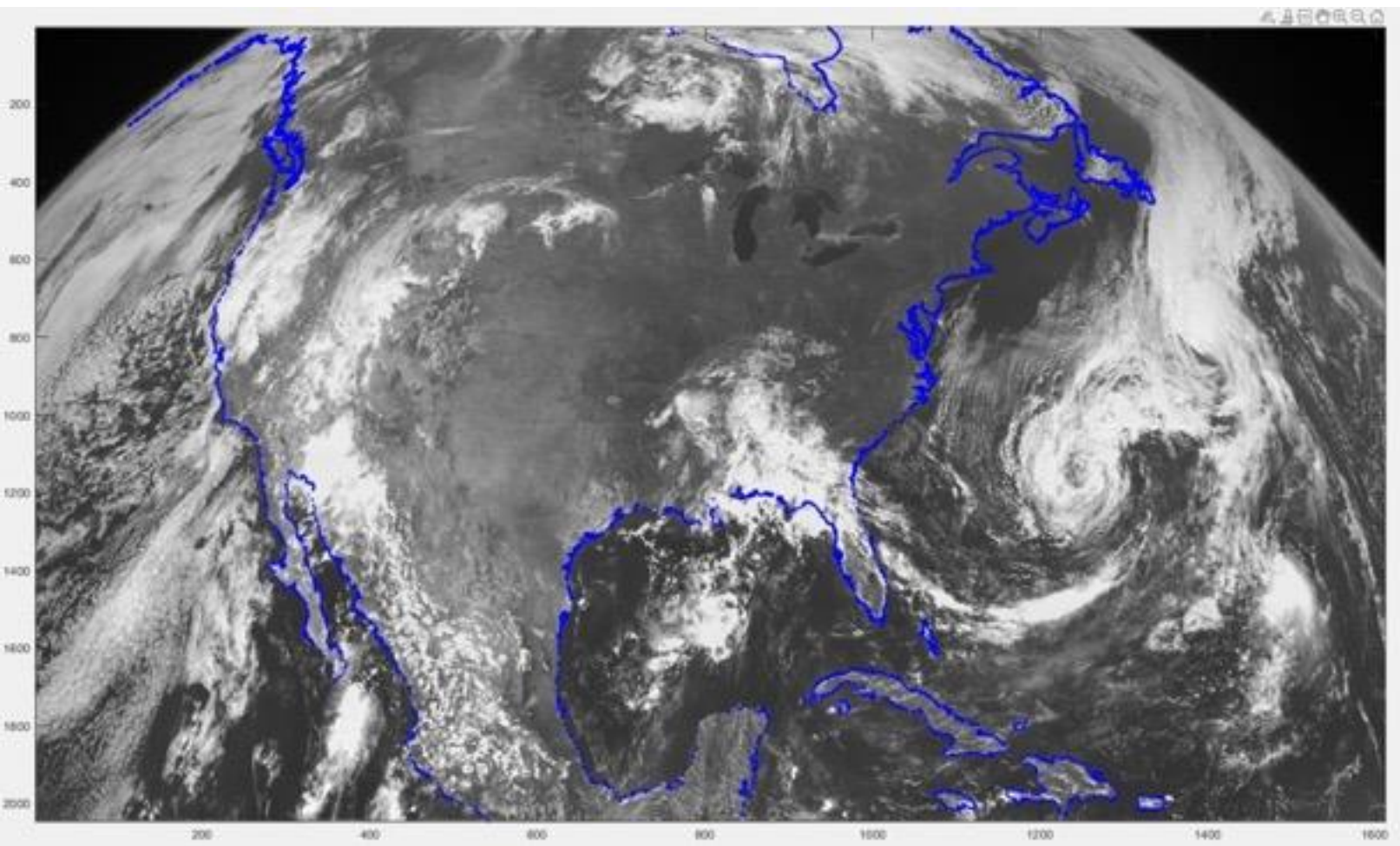
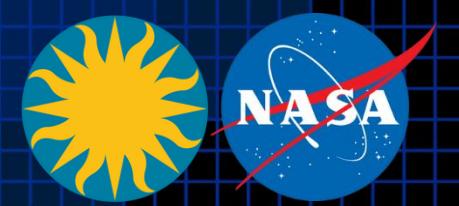
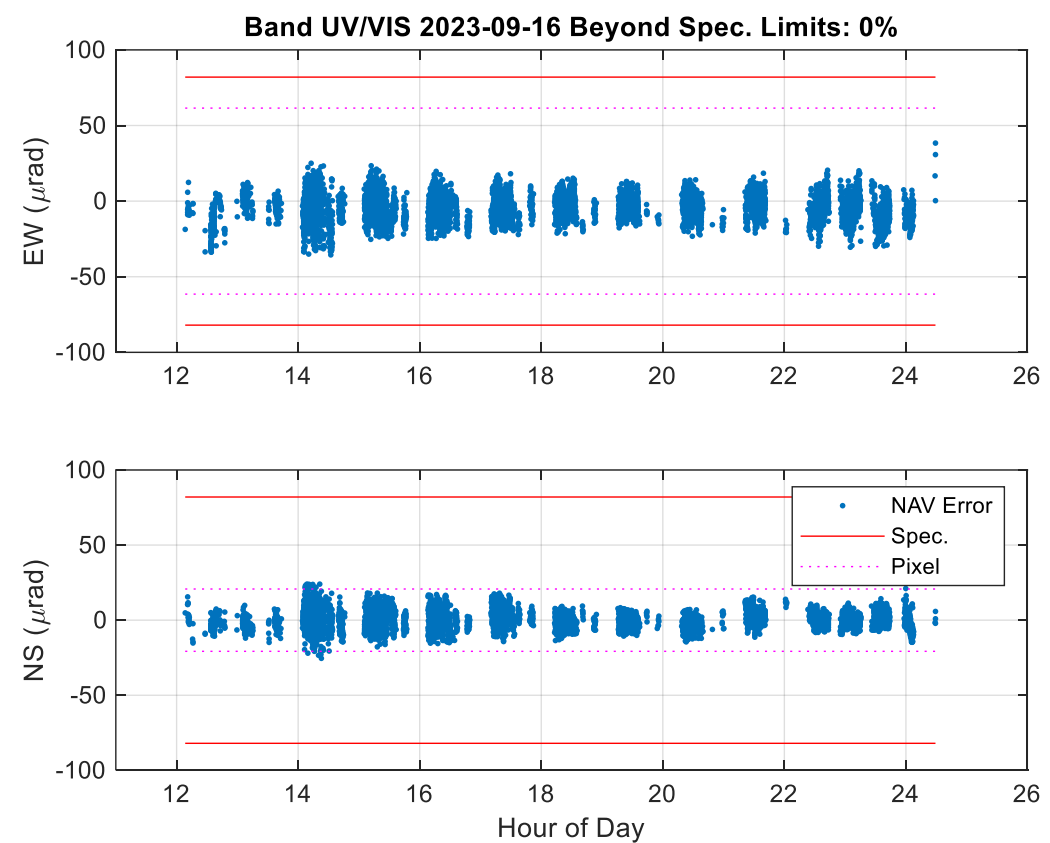
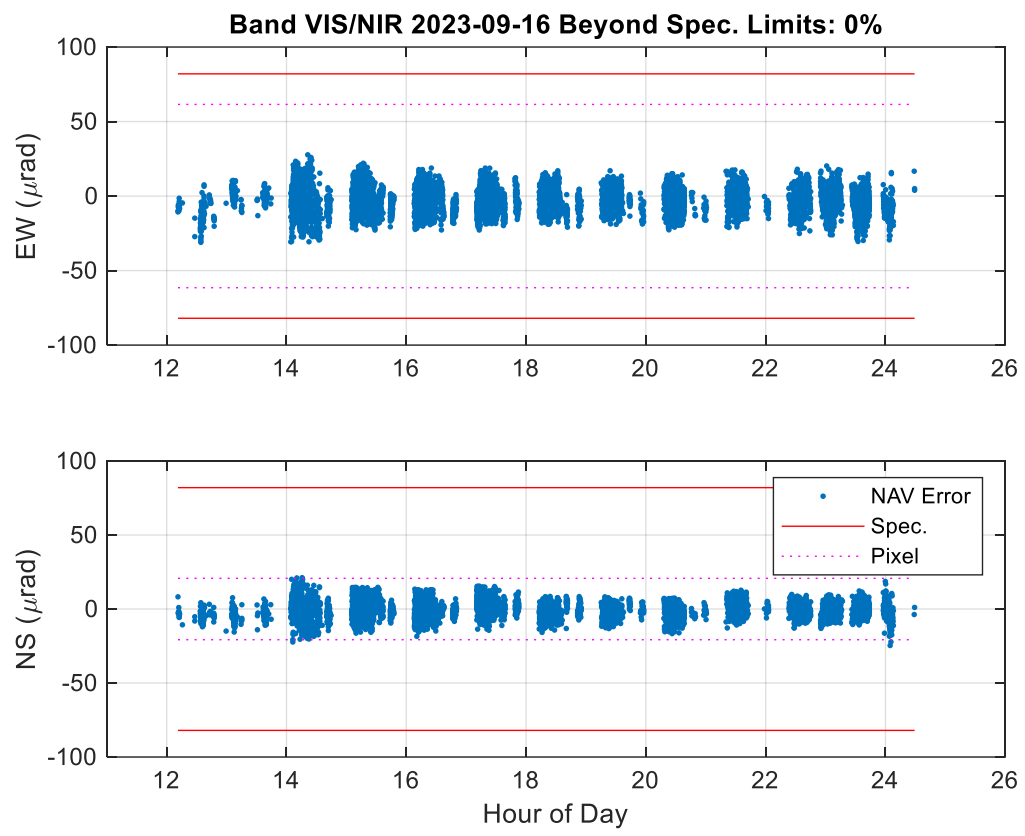




Image Navigation and Registration Status



- **INR Requirements are Met**
 - ✓ Navigation error limits exceeded = 0% (3s) of evaluations (Pass)
 - ✓ Optimized scanning performs worse at start of day
- **Tuning efforts aim to improve start-of-day performance**
 - ✓ Illumination is very low for earliest scans
 - ✓ May have separate tunings for Optimized and CONOPS scanning
- **Consistent NS biases observed in UV/VIS**
 - ✓ Not a specification compliance issue
 - ✓ Should investigate and correct in any case



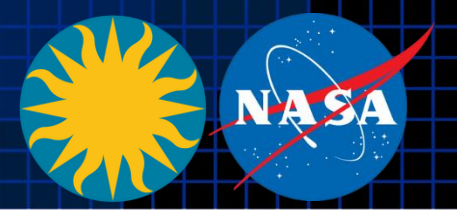
➤ Registration meets < 4km requirement; Effective jitter much smaller than requirement

[urad]

	EW Mean	EW Std	NS Mean	NS Std	Out of Limit
VIS/NIR	-2.0981	6.0594	-1.4832	4.1732	0
UV/VIS	-3.3226	6.1935	-0.128	4.3225	0



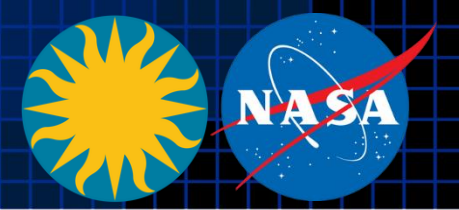
Calibration and L1b Validation



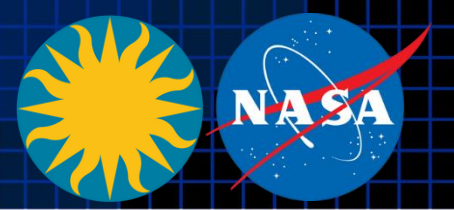
- Verify and update image correction steps in the L0-1 processing during Commissioning Phase and Nominal Operation
 - System linearity, zero-input, relative gains, saturation blooming, dark current variation and temperature-dependent correction, check quality flags, evolution of solar diffuser, noise calculation, straylight
- Assess wavelength calibration and its performance
 - Will assess performance of routine processing (wavelength calibration in both L0-1b & L1-2 via high-resolution solar reference and atmospheric absorption)
 - Pre-launch measured instrument line shape will be compared with that derived from solar irradiance
- Assess radiometric calibration using a multi-pronged approach
 - Internal assessment of images, assess performance of routine processing
 - Comparison solar irradiance with solar reference and correlative contemporaneous sensors (e.g., OMPS, TROPOMI, GOME-2, EPIC, MODIS, VIIRS)
 - Comparison with radiative transfer simulation
- Assess and improve INR accuracy
 - Alignment issue, ephemeris reliability, IRU time synchronization, scan tailoring verification
 - Different configuration for special observation

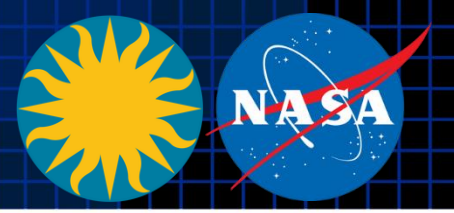


Summary and outlook



- Initial look has been done for each core element of Level 1b cal/val plan
- Level 1b irradiance updated (v3) when L1b radiance was released in May 2024
- Image processing
 - Calibration key data and octant phase identification have been updated since the first light.
 - Refining image processing steps (e.g., electronic offset removal, smear correction, and dark current correction to account for temperature dependence), dynamic bad-pixel flagging, and updating other quality flags are underway.
- BTDF
 - A scattering-angle-based correction is implemented to reduce/eliminate seasonal dependence
- Spectral calibration
 - Wavelength grids have been updated and optimized
 - First Light Irradiance used for nominal wavelengths
 - > 0.4nm shift from pre-launch
 - Relative to FL, adjustments are estimated using Chebyshev polynomials
 - Spectra has gradual temporal blue shift (uv & vis) – nearly stable since March 2024
- Stray light correction is applied
 - Spectrally bland SL residual is possible – developing correction for UV
- INR detected static boresight angular offset
 - Initial solar incidence angles differ by $\sim 0.3^\circ$ from nominal 30°





Backup



Solar Calibration Geometry

