GODDARD EARTH SCIENCES

OCI on the PACE mission: prelaunch calibration overview

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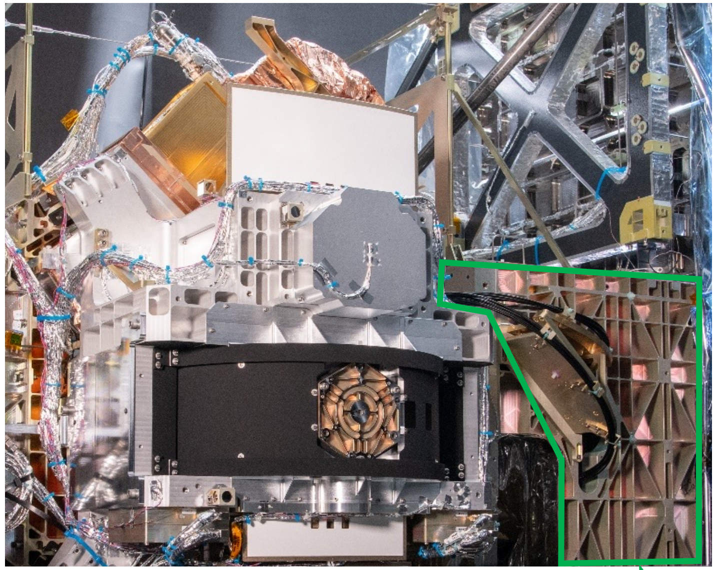
Acknowledgements: Joseph Knuble, **Eric Gorman**, **Brendan McAndrew**, **Jeremy Werdell**, NASA, United States**; Julia Barsi, Leland Chemerys, Kim Jepsen, Samuel Kitchen-McKinley, Jeffrey McIntire**, Science Systems and Applications Inc., United States**; Robert Bousquet, Andrei Sushkov,** Genesis Engineering Solutions, Inc., United States; **Hyeungu Choi**, Global Science & Technology, United States; **Nicholas Collins**, Telophase Corporation, United States; **Robert Eplee, Shihyan Lee, Frederick Pa**tt, Science Applications International Corporation, United States; **Christopher Field**, Aurora Engineering, United States; **Ulrik Gliese**, KBR, United States; **Jacob Hedelius, Kenneth Squire**, Space Dynamics Laboratory, United States; **Bradley Tse**, Microtel, United States; **Eugene Waluschka**, Stellar Solutions, United States

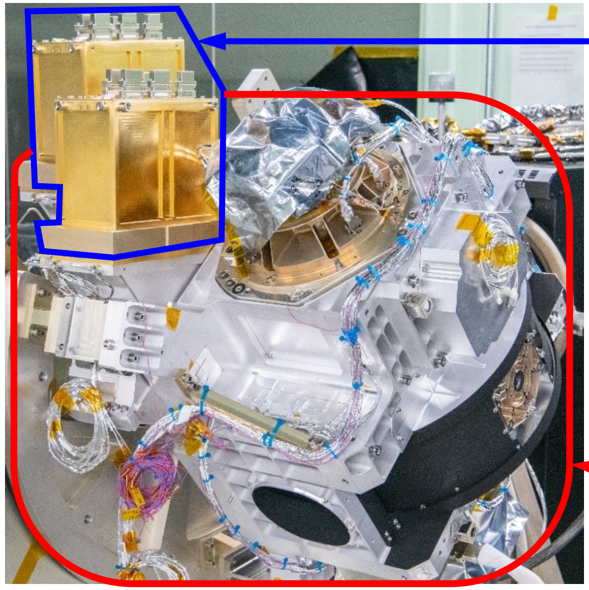
November 15th, 2023; IOCS 2023, St. Petersburg, FL; Sensor Calibration Workshop

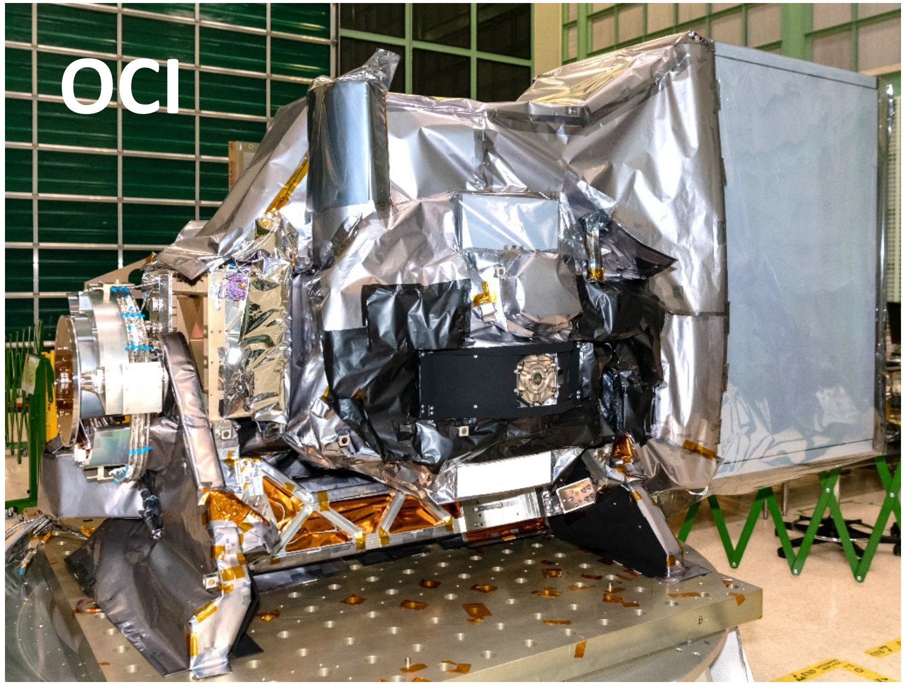
OCI is complete and installed on the Spacecraft

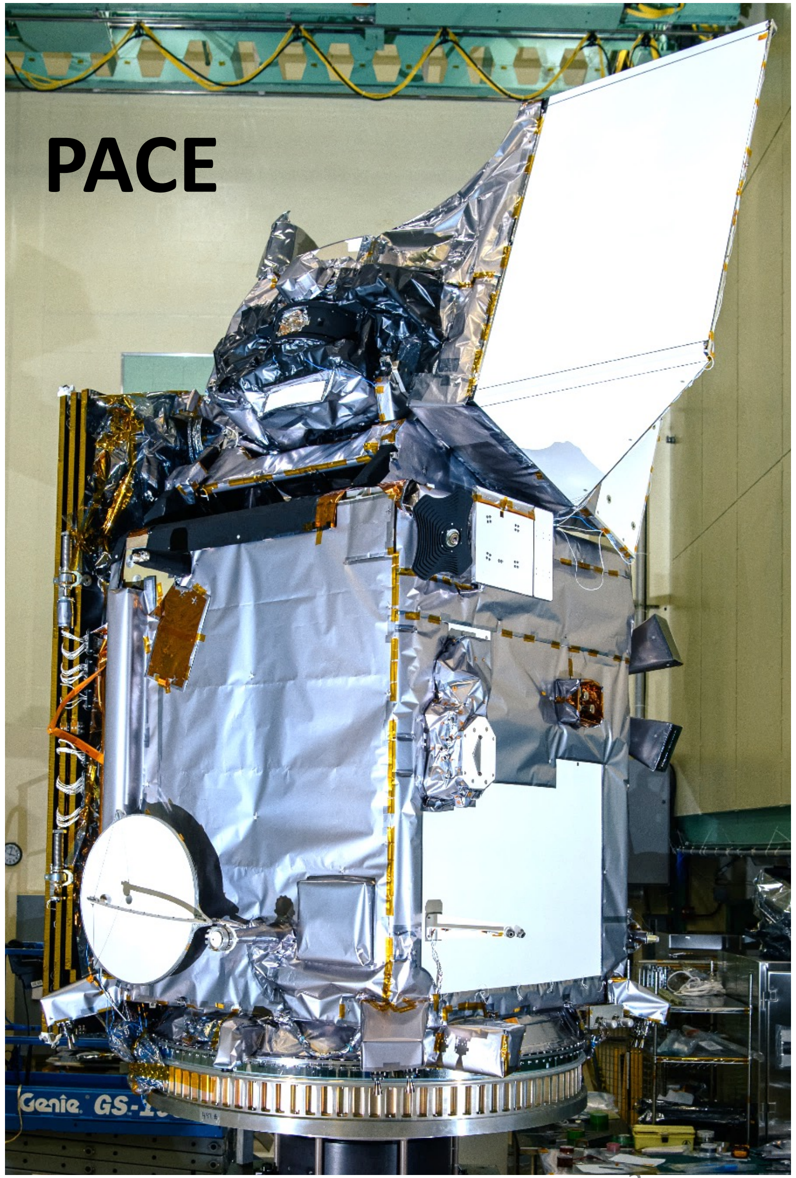
- Arrived Tuesday in Cape Canaveral, FL, for a launch early 2024
- Global hyperspectral imager, 315nm-2260nm
- Tilt once an orbit to avoid sun glint
- On-orbit calibration via:
  - 2 bright solar diffusers
  - 1 dim solar diffuser
  - lunar irradiance
  - spectral mode at 0.625nm sampling
  - solar ‘pulse’ for SWIR hysteresis monitoring

OCI Hardware (from U. Gliese, IGARSS 2023)









Fiber-Coupled 7-Band SWIR Detection System

Hyperspectral UVNIR Detection System

Hyperspectral Optical System

OCI image acquisition

- OCI is a rotating scanner, similar to SeaWiFS and VIIRS (rotating telescope and half angle mirror); rotation rate is 5.7Hz
- Image is acquired via motion of spacecraft in earth view mode (see picture below)
- Image is acquired via rotation of the spacecraft for lunar measurements

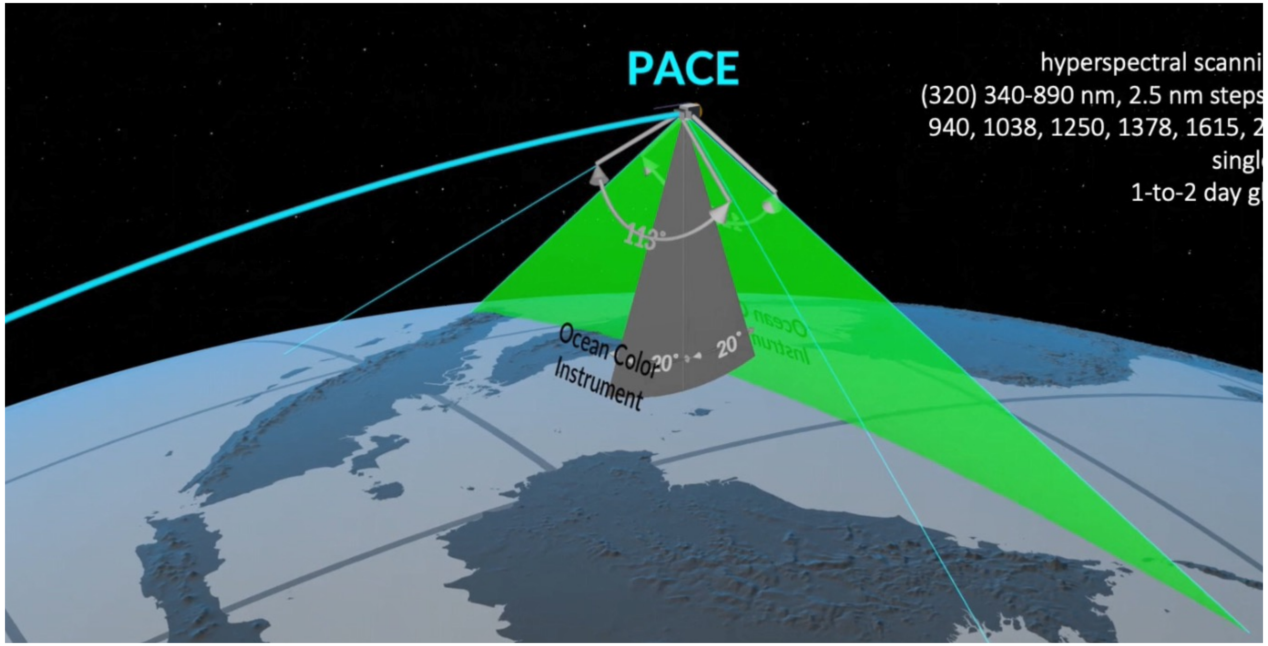
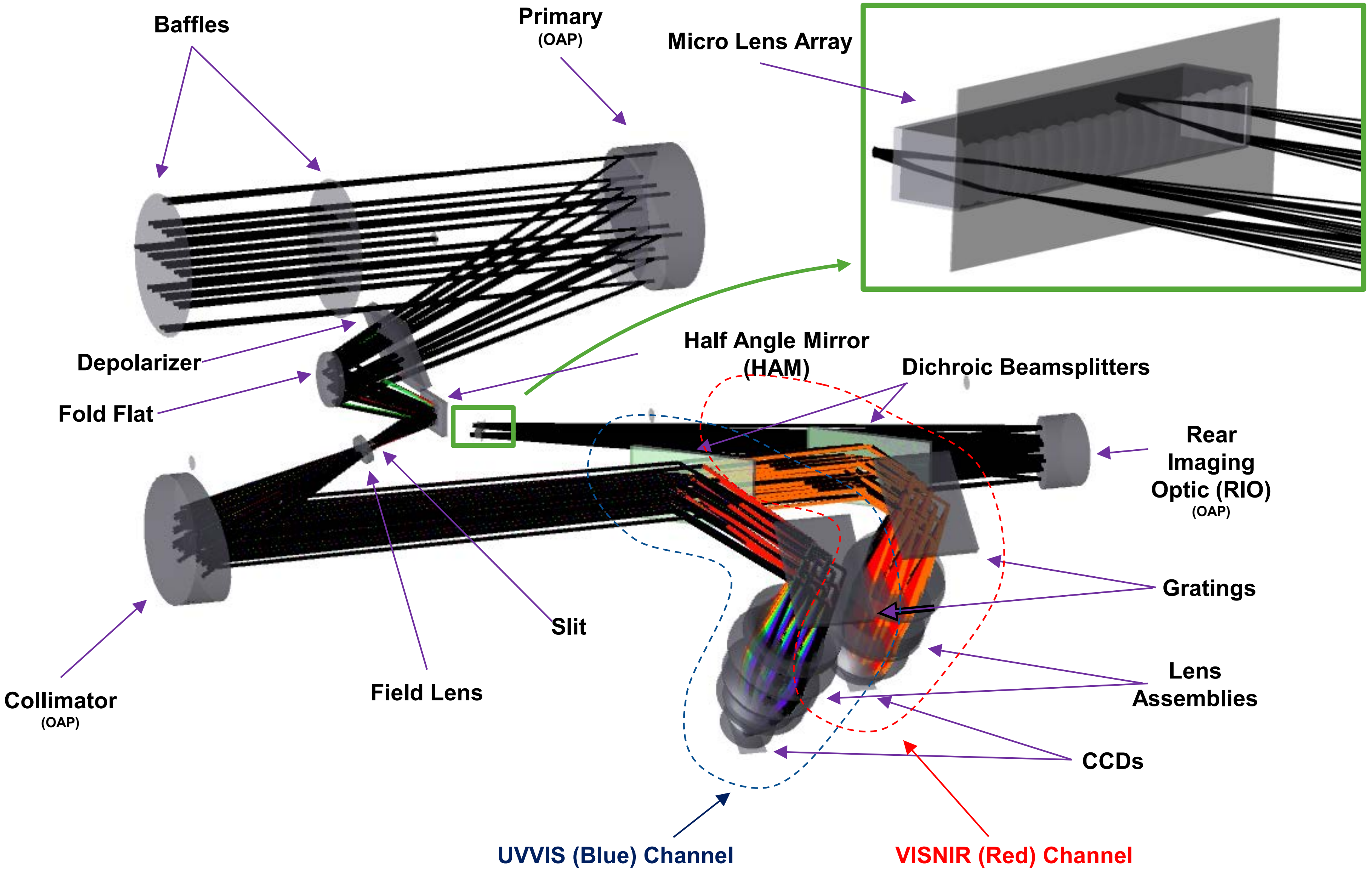


Image from U. Gliese, IGARSS 2023. See backup for full citations.

OCI description: optical path

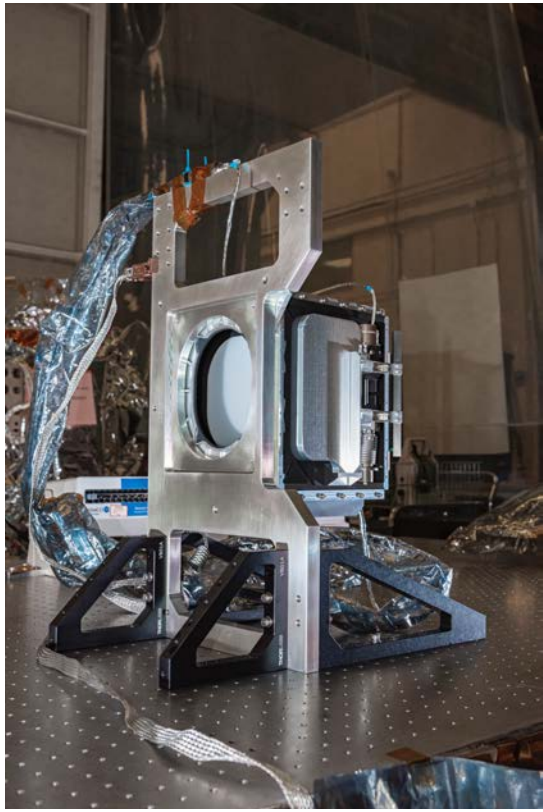


SWIR bands

Picture from:
Gliese et al., Optical and Detector Design of the Ocean Color Instrument for the NASA PACE Mission, IGARSS 2023, Pasadena, CA.

Solar Diffuser

- Daily/monthly for short/medium term (up to 2 years) tracking of radiometric gain changes
- 3 diffusers (2 bright, one dim for linearity) mounted on a 3-sided wheel, see picture
- Long term tracking via lunar irradiance measurements



Lunar measurements

- OCI will measure lunar irradiance twice a month, at +/- 7deg phase angle during the dark side of the orbit via a pitch/slew/roll maneuver
- OCI LOS will be steered a few degree below the moon, slowly sweep across the moon, stop, and slowly sweep back
- Sweep speed will be highly controlled (oversampling factor of 4)

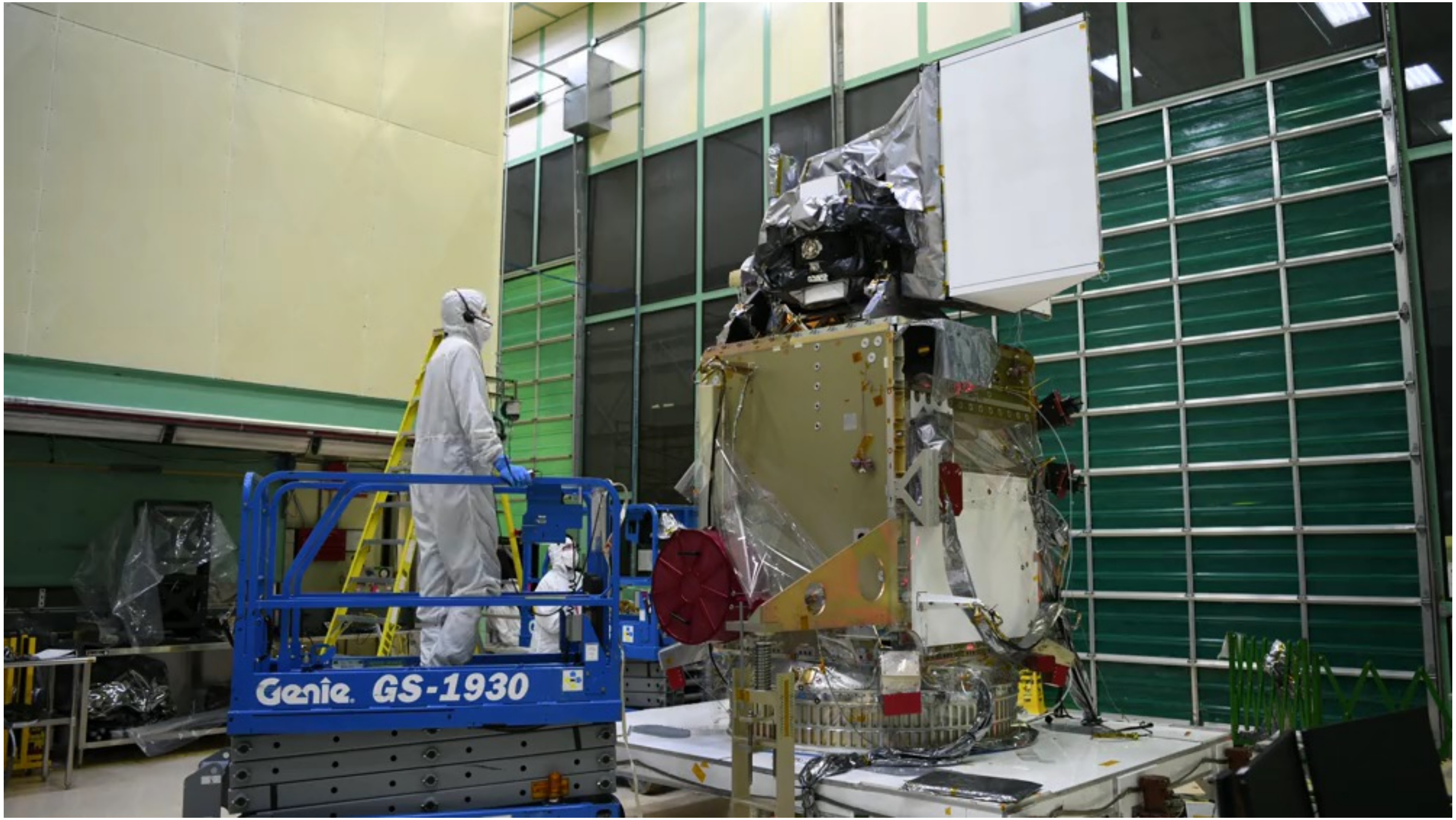
- Additionally, OCI will move its LOS to the center of the moon and stare for ~30 seconds to acquire a scan line with a high contrast signal for SWIR band characterization

OCI Spatial Performance (GSD, IFOV, FoR)

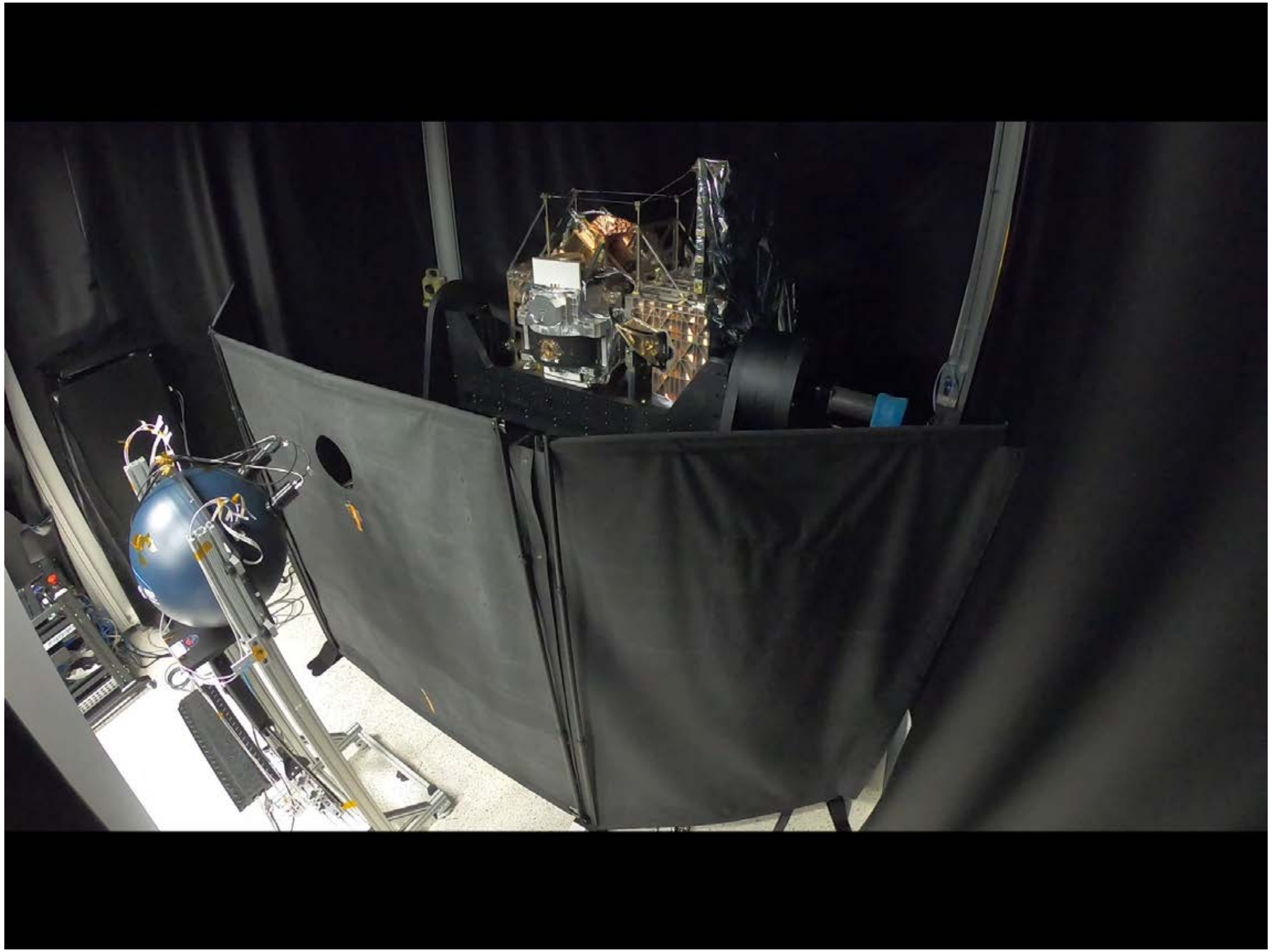
- Ground Sampling Distance (GSD) along scan/track: 0.0888deg/0.0881 deg (distance between pixel centers)
- Instantaneous Field of View (IFoV) along scan/track: 0.0889deg/0.0929deg (area imaged by a pixel)
- Effective spatial resolution for PACE orbit including 20deg tilt at 'nadir': **1.2km** (similar to SeaWiFS, larger than MODIS (1km))
- Field of Regard (FoR) : **- 56.0deg to +56.5deg**
- Swath width on the ground: ~**2700km**
- 2-day global coverage (almost daily global coverage)
- Tilt (-19.9deg and +19.9deg) will be staggered (like SeaWiFS)

Slide from G. Meister,
IGARSS 2023. See backup for full citation.

OCI Tilting on Spacecraft (from J. Knuble, IGARSS 2023)



GLAMR Test Video (from J. Knuble et al., IGARSS 2023)



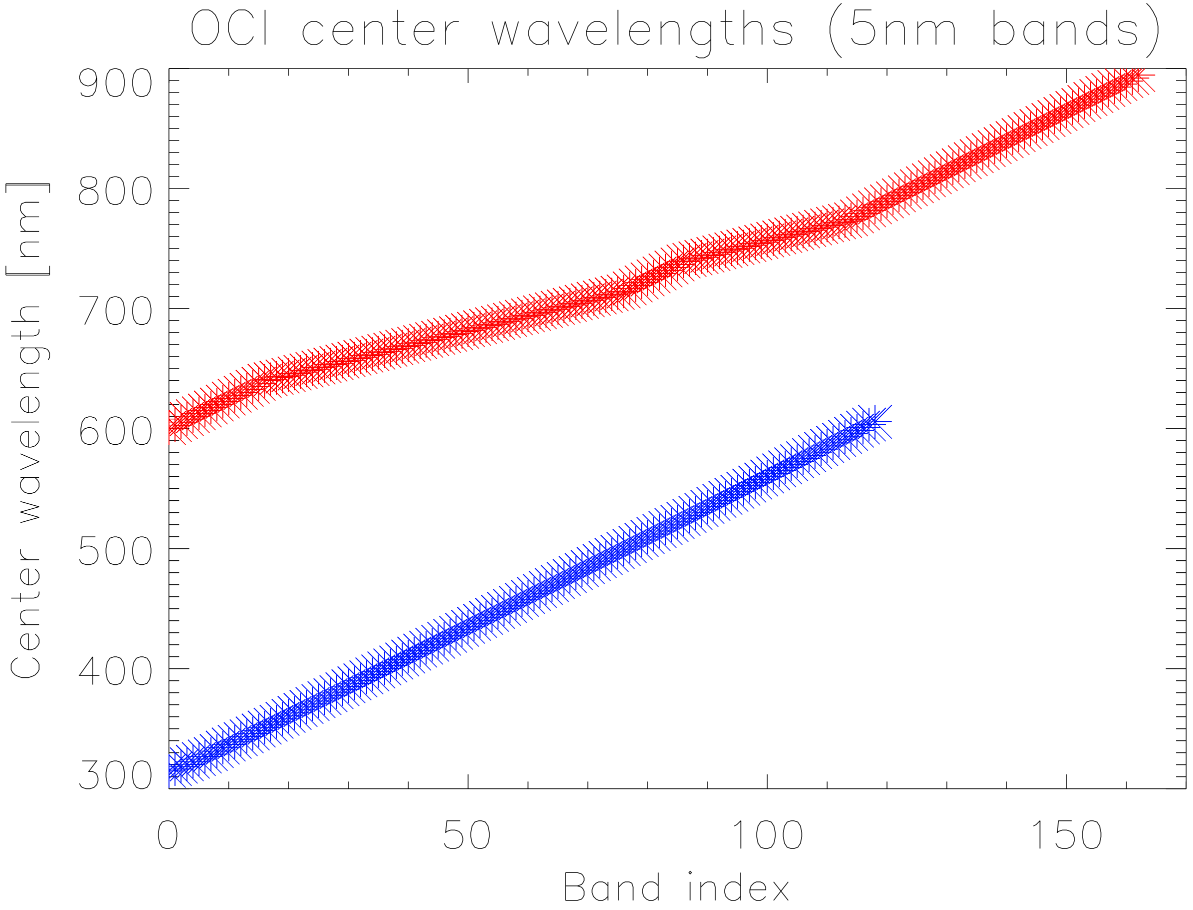
Hyperspectral bands: spectral coverage

- Blue FPA baseline aggregation: 119 L1B bands from **314.9nm to 605.7nm**

  - 116 L2 bands up to 598.3nm

  - Bands below 340nm have reduced radiometric accuracy (TBD on-orbit)

  - Bandwidth: ~5.1nm
- Red FPA baseline aggregation: 163 L1B bands from **600.5nm to 894.6nm**, bandwidth ~5.0nm
- 9 SWIR bands at 7 wavelengths from **940nm to 2260nm**
- See following presentation for details on SWIR bands, bandwidth, out-of-band, etc.



Slide from G. Meister, IGARSS 2023.

Covered in Shihyan's presentation

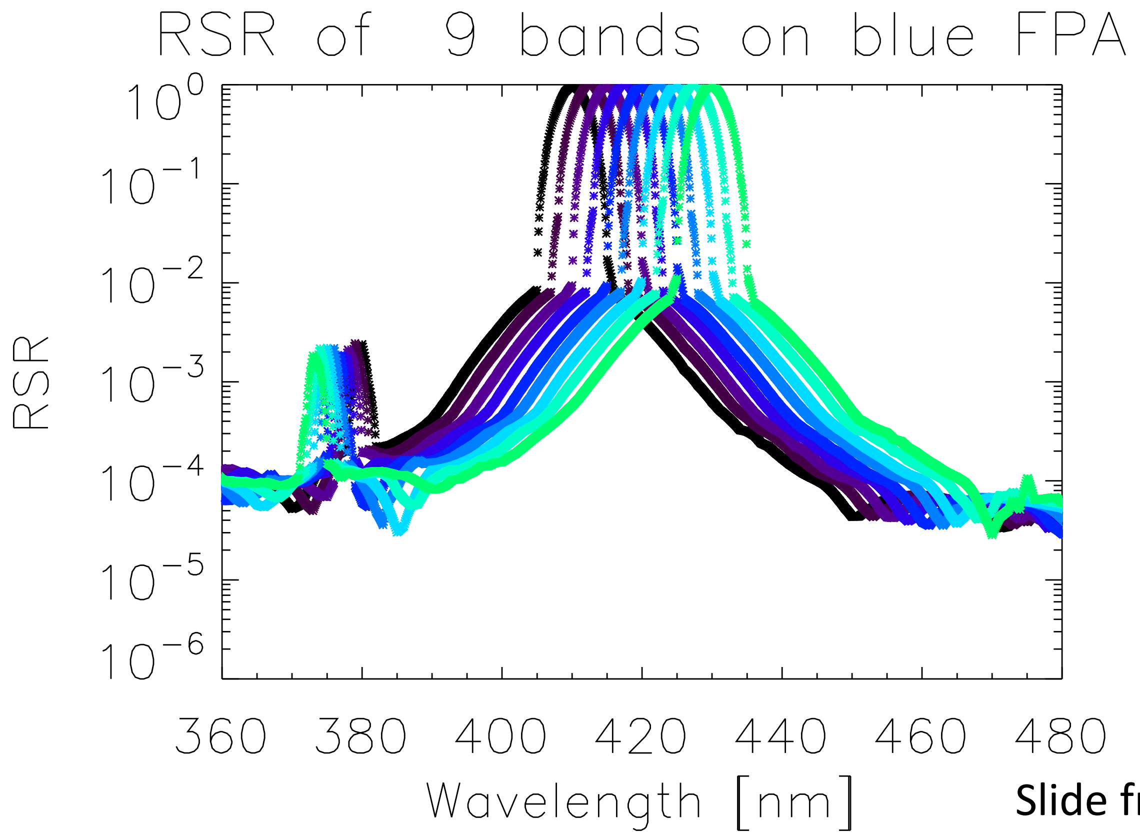
'Ghosts' in blue spectrograph

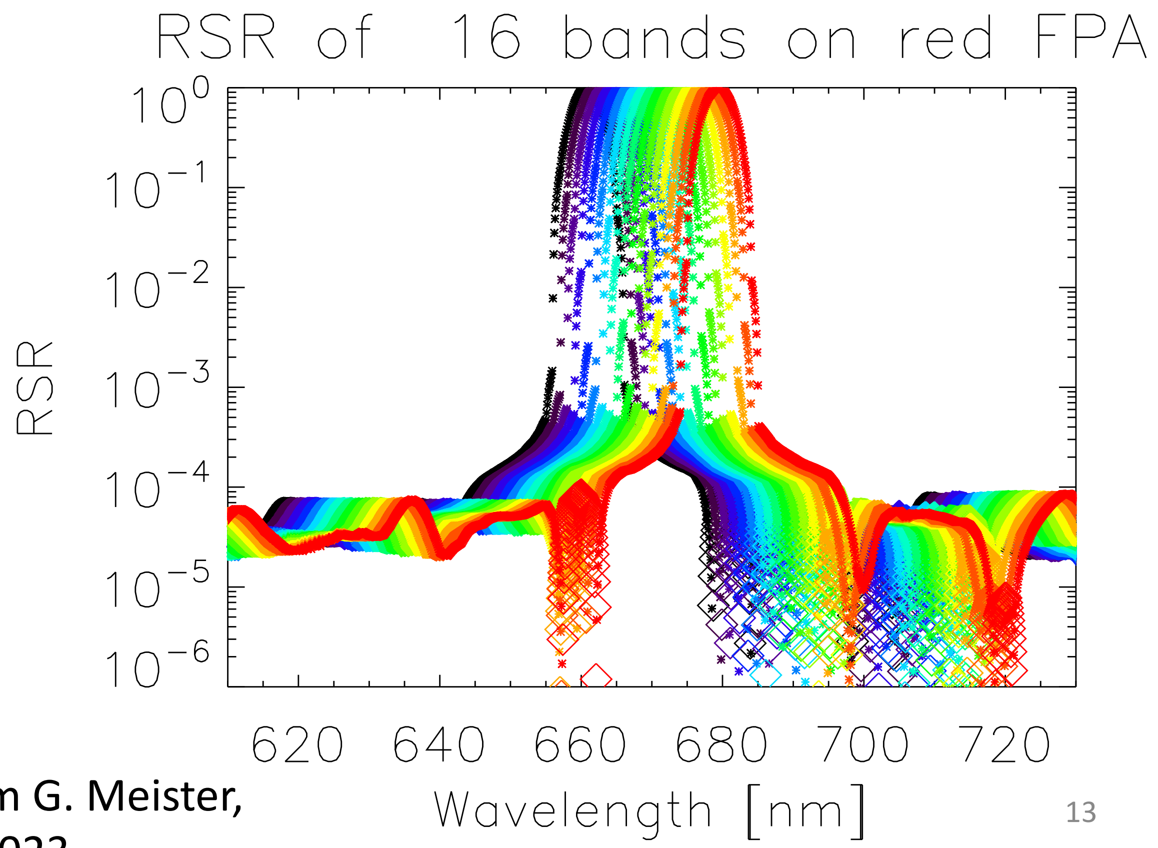
- Identified as reflections of various optical surfaces via raytracing model
- We derived a model based on measurements
- Animation shows modelled crosstalk from +/-15 1km pixels (x-axis) and sender wavelengths (y-axis) into receiving band (function of time)
- We have derived a correction that removes the ghosts (two 'walls' in picture on the right) and along-scan and spectral straylight (remaining features in picture on the right). No correction is applied for adjacent 1km pixels or adjacent 5nm bands.
- Along-track straylight is smaller (limited by telescope aperture) than along-scan and not corrected for.

Slide from G. Meister, IGARSS 2023.

OCI relative spectral response: blue and red FPA

- More RSR variation (electronic crosstalk) on red FPA, but at very low level (often negative)
- Decline from peak to <1e-3 much faster than in blue FPA
- Ghosts much smaller than in blue FPA





Slide from G. Meister, IGARSS 2023.

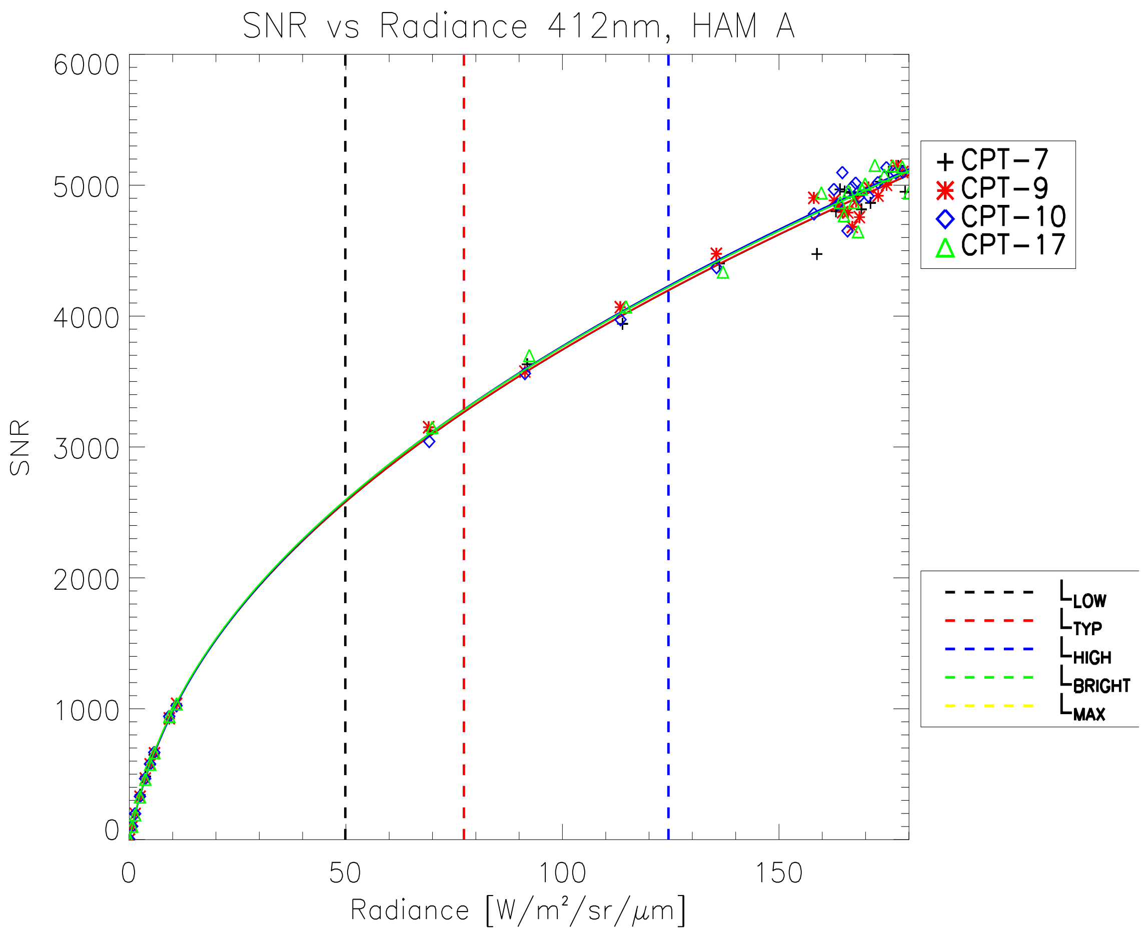
SNR Evaluation

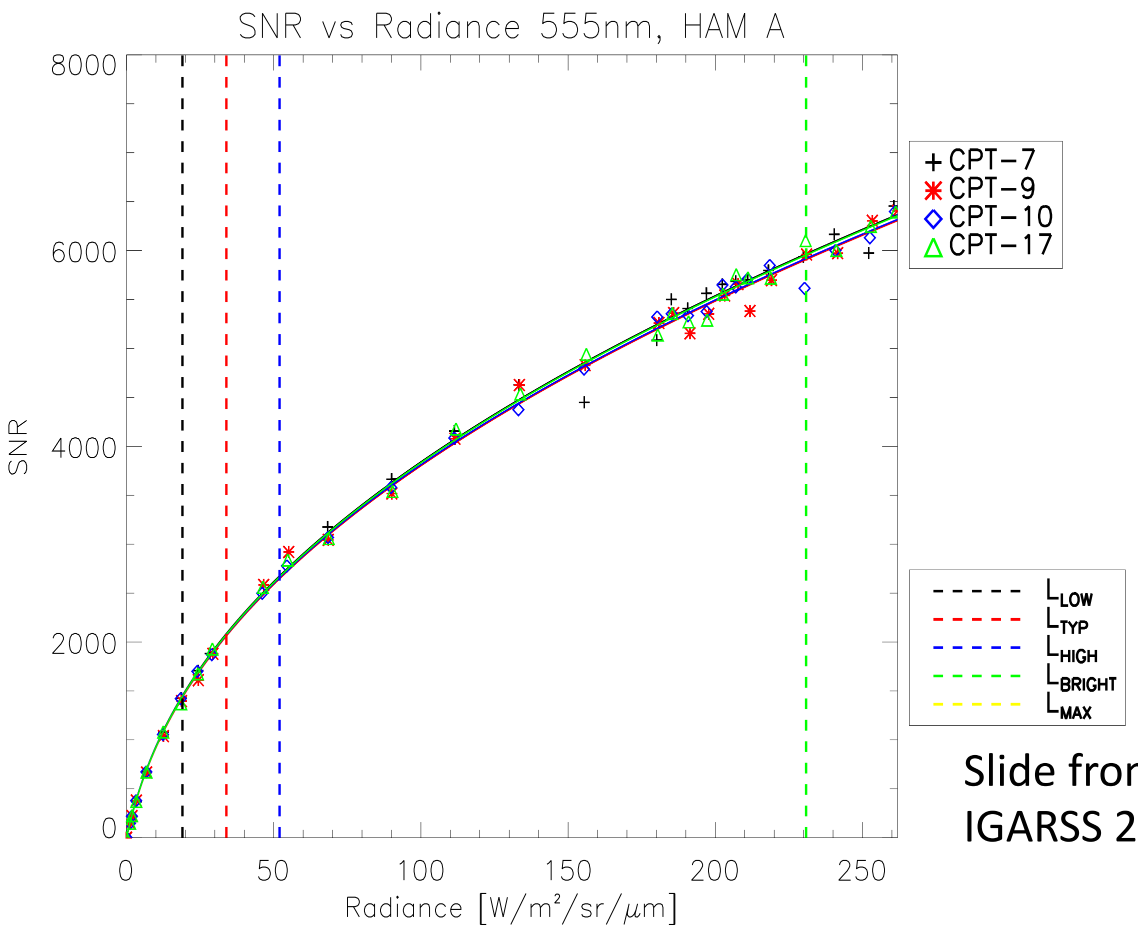
SNR (412 nm and 555 nm)

Measured SNR plotted versus radiance (different lamp levels).

Data – symbols; Colors – TVAC temperatures (nominal, hot op, cold op)

Solid lines – Fit to data; Dashed vertical lines – TOA radiance levels (from requirements)

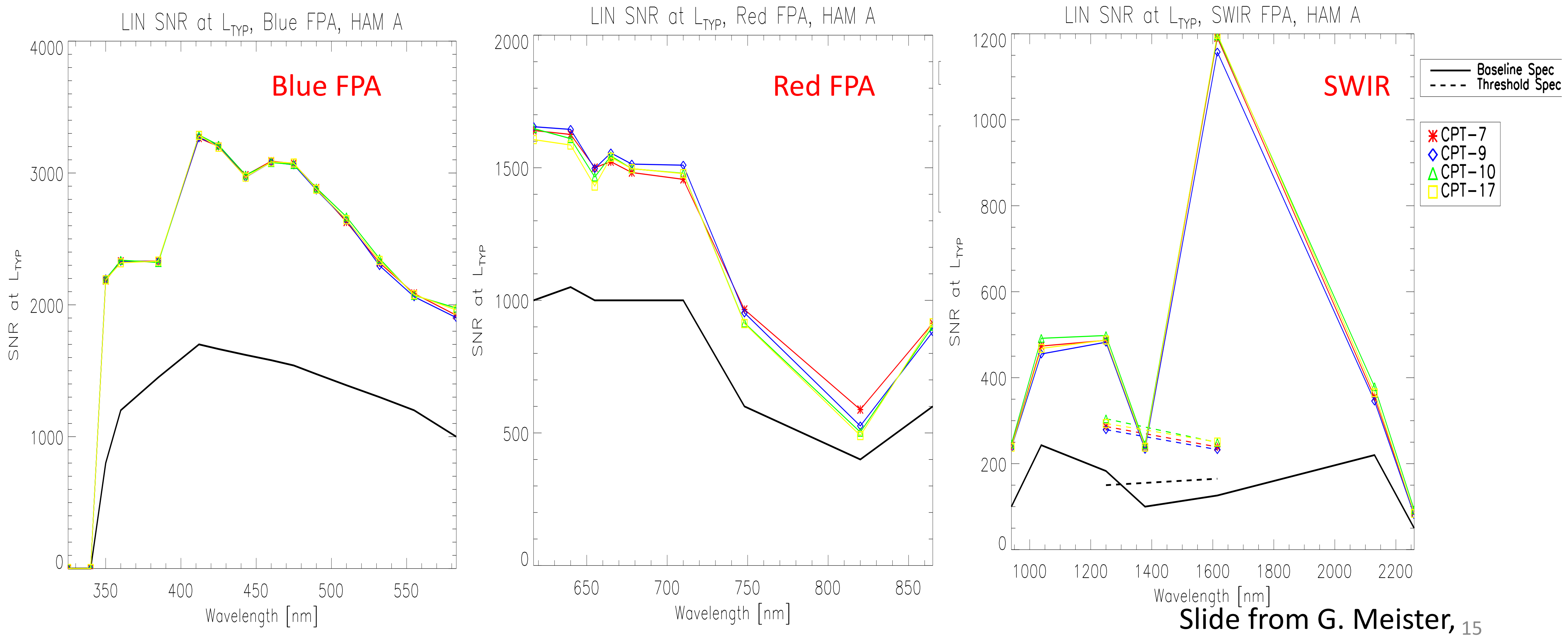




Slide from G. Meister, IGARSS 2023.

SNR at L_{TYP} for multispectral bands

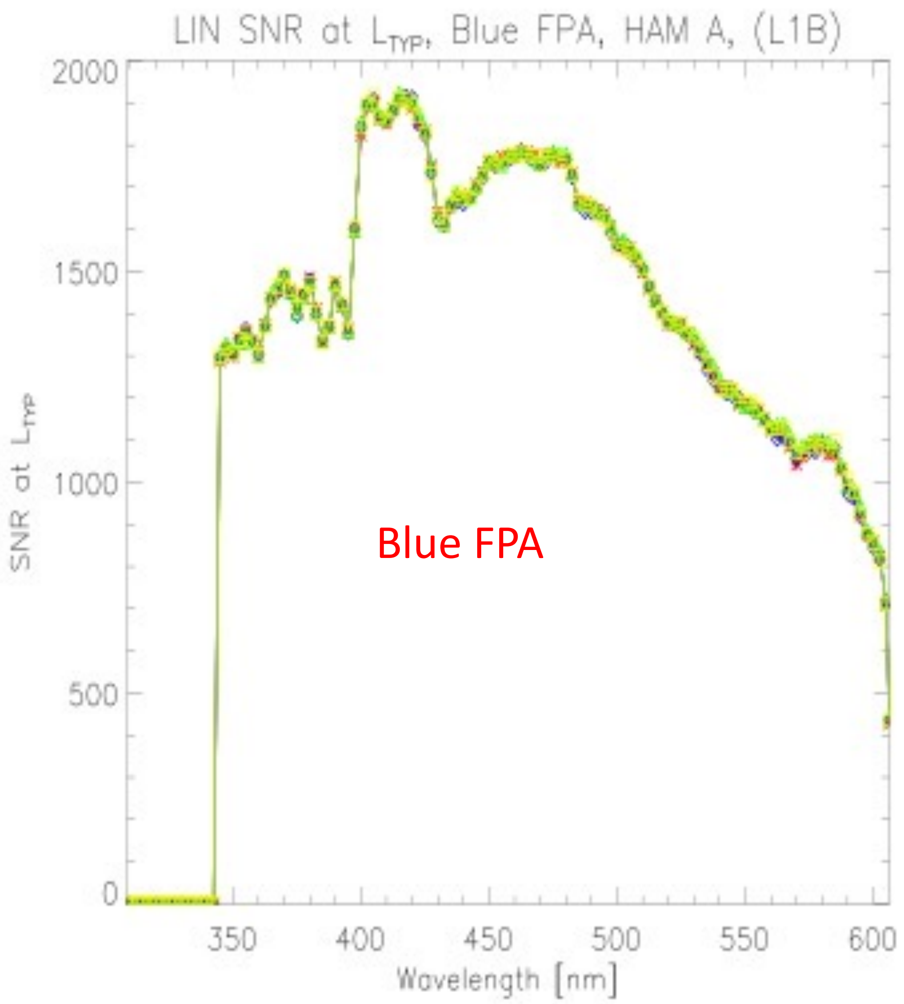
Comparison of different SNR estimates over TVAC tests (HAM A shown; HAM B is consistent).
All multispectral and SWIR bands well above the baseline requirement.

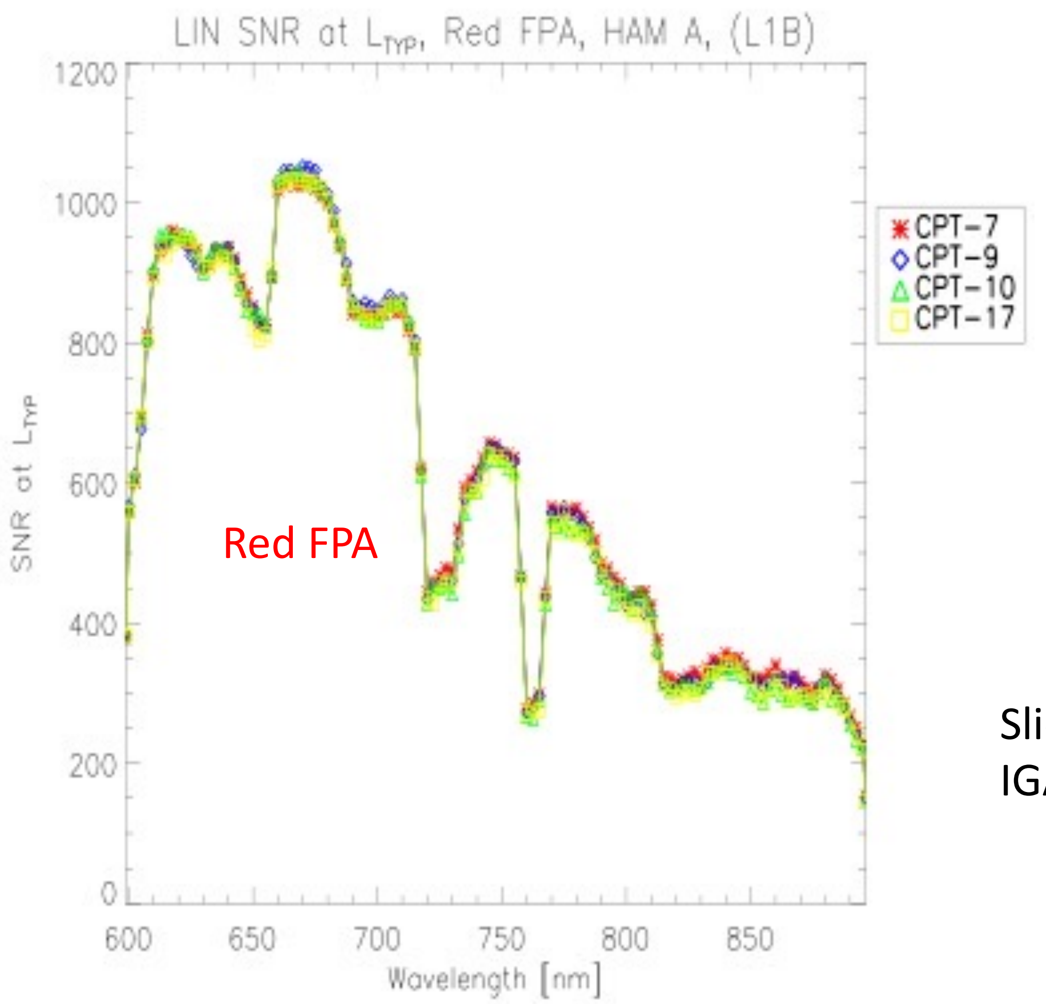


Slide from G. Meister, IGARSS 2023.

SNR at L_{TYP} for hyperspectral bands

Comparison of different SNR estimates over TVAC tests (HAM A shown; HAM B is consistent).
Very high SNR even for hyperspectral bands (spectral aggregation needed above 800nm).





Slide from G. Meister, IGARSS 2023.

Radiance Calibration Equation

$$Lt = K1*K2(t)*(1-K3(T-Tref))*K4(\theta) *K5(dn)*Kp*dn$$

- Lt = Radiance, unit: W /(m^2 µm sr)
- K1 = absolute gain factor; unit: (W /(m^2 µm sr))/dn
- K2(t) = relative gain factor as a function of time t; unitless
- K3 = temperature correction [(deg C)$^{-1}$] (vector)
- T = Temperatures measured at relevant locations [deg C] (vector)
- Tref = Reference Temperature [deg C]
- θ =scan angle [deg]
- K4 = (θ) response versus scan ; unitless
- K5 = nonlinearity factor ; unitless
- dn = dark-corrected instrument counts

Kp: polarization correction applied in Level-2 code (correction needs TOA radiance polarization information)

K1, Kp and K3-K5 have been derived for all bands

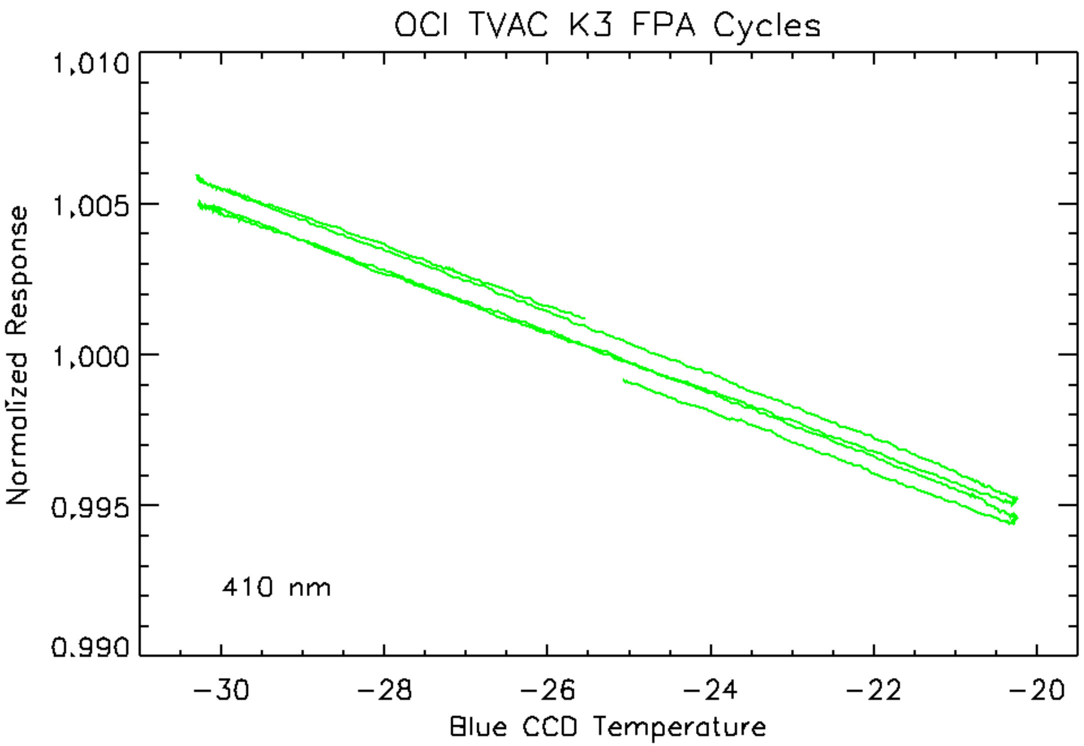
- K2 will be derived on-orbit from solar diffuser and lunar measurements

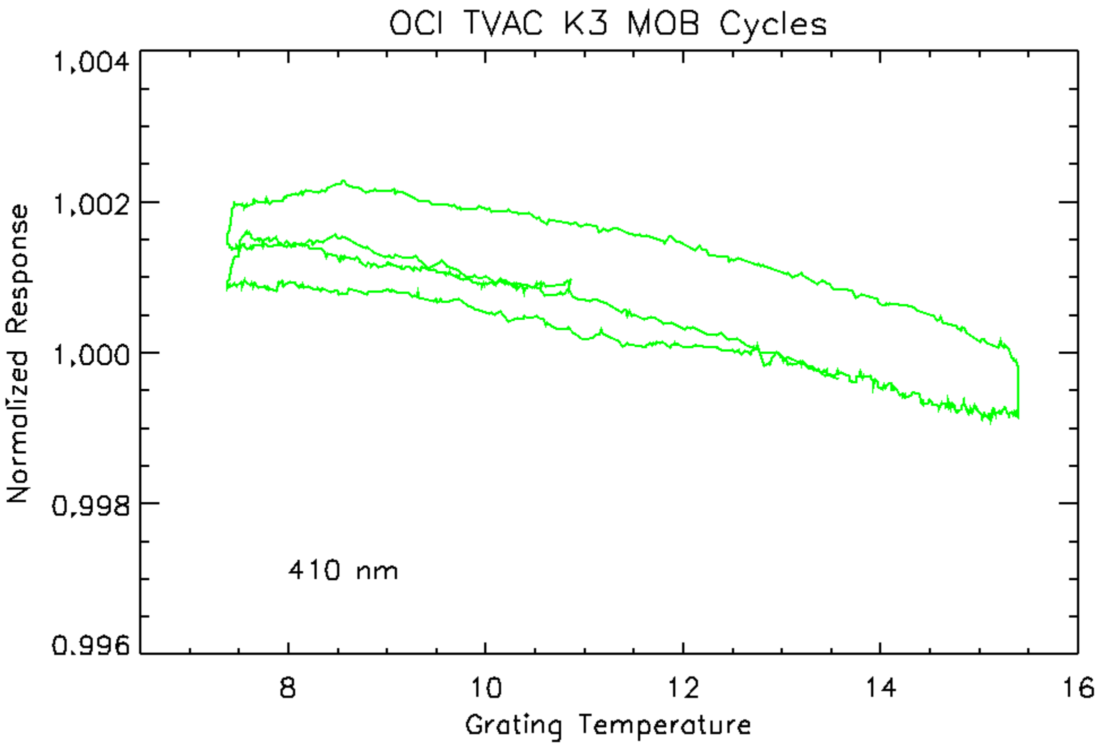
Slide from G. Meister, IGARSS 2023.

K3: Temperature dependence

Temperature dependence measured during TVAC testing with white light source:
- variation dominated by detector (FPA) temperature (see e.g. 410nm example below)
- impact of main optical bench (MOB) is minor, no impact from Data Acquisition Unit (DAU)
- very small (unexpected) variation detected with mirror side for red FPA (<0.02%/deg)

Temperature dependence measured during TVAC testing with monochromatic light source:
- 0.02nm/deg wavelength shift (negligible, not corrected) for red FPA



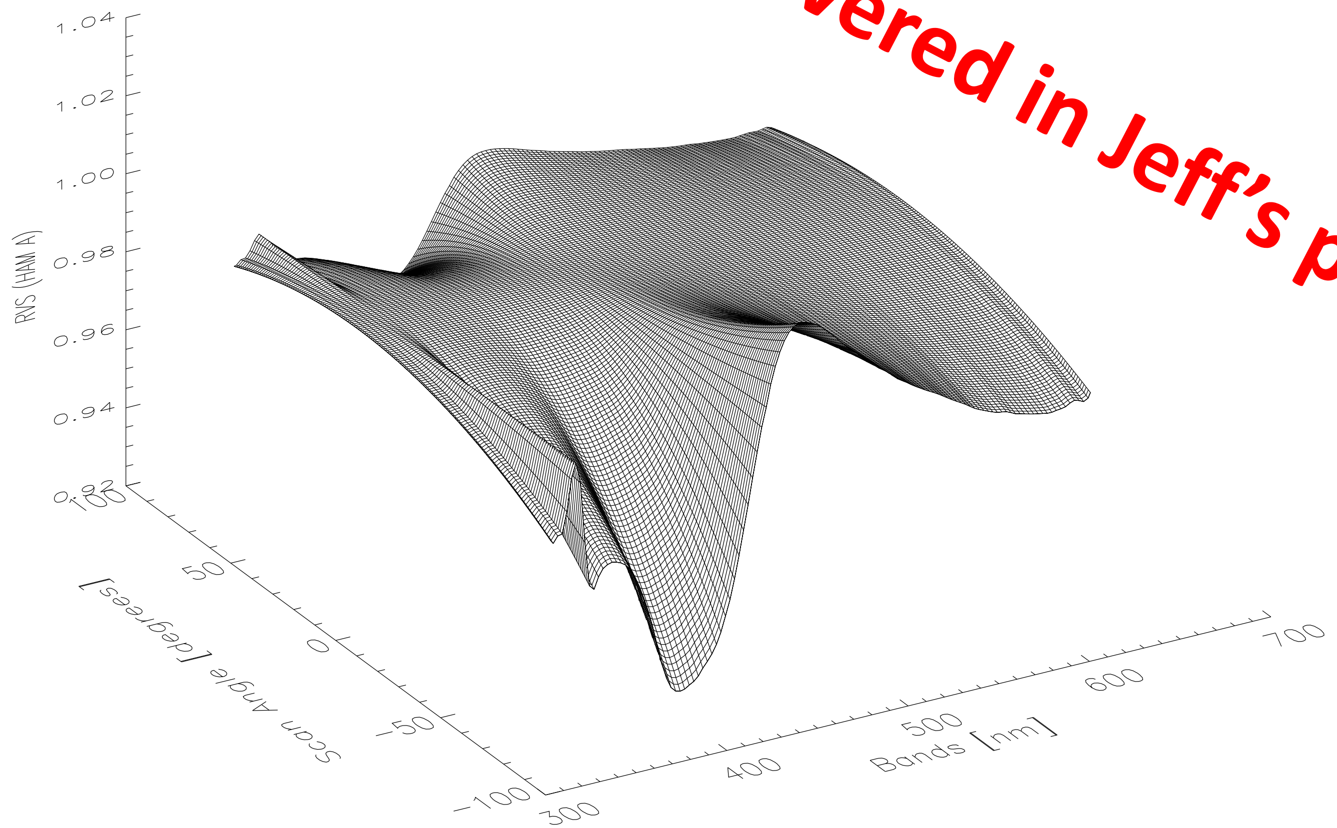


K4: Response Versus Scan Angle (RVS)

Instrument response to constant radiance measured at different scan angles

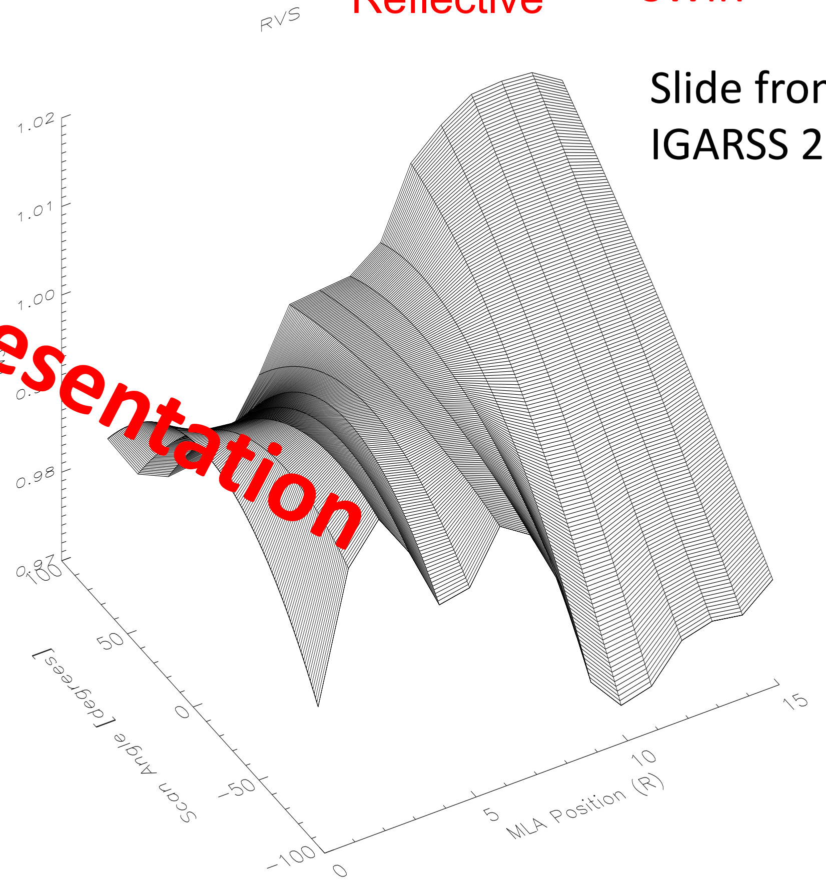
- variation below 900nm agrees well with model predictions, symmetric around nadir
- RVS in the SWIR bands increases linearly with scan angle (this was unexpected)
- Ray trace model suggests fiber alignment as a possible reason

Blue FPA



Covered in Jeff's presentation

Reflective SWIR

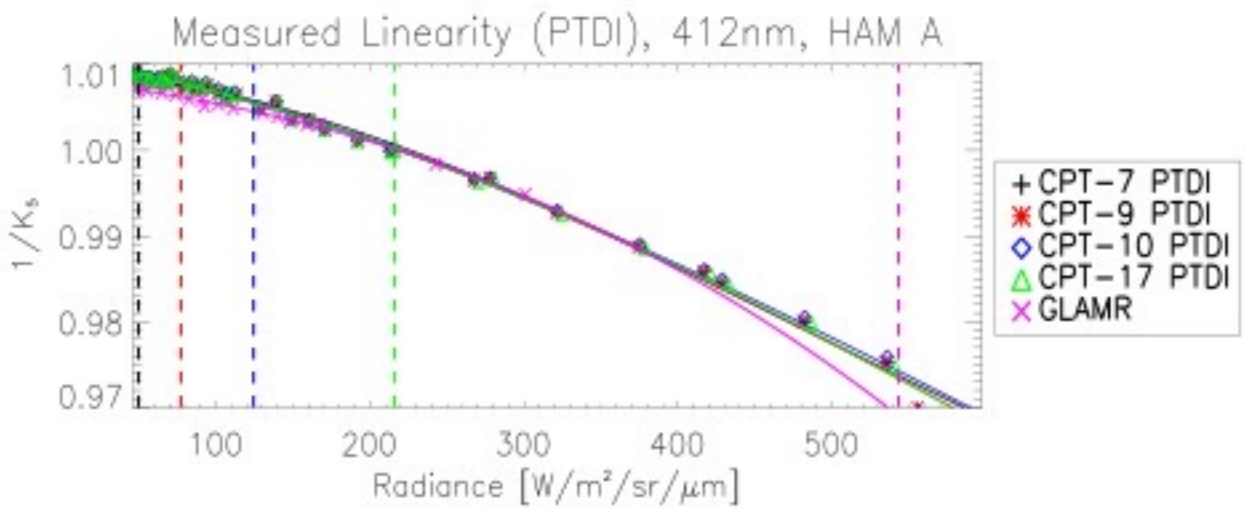


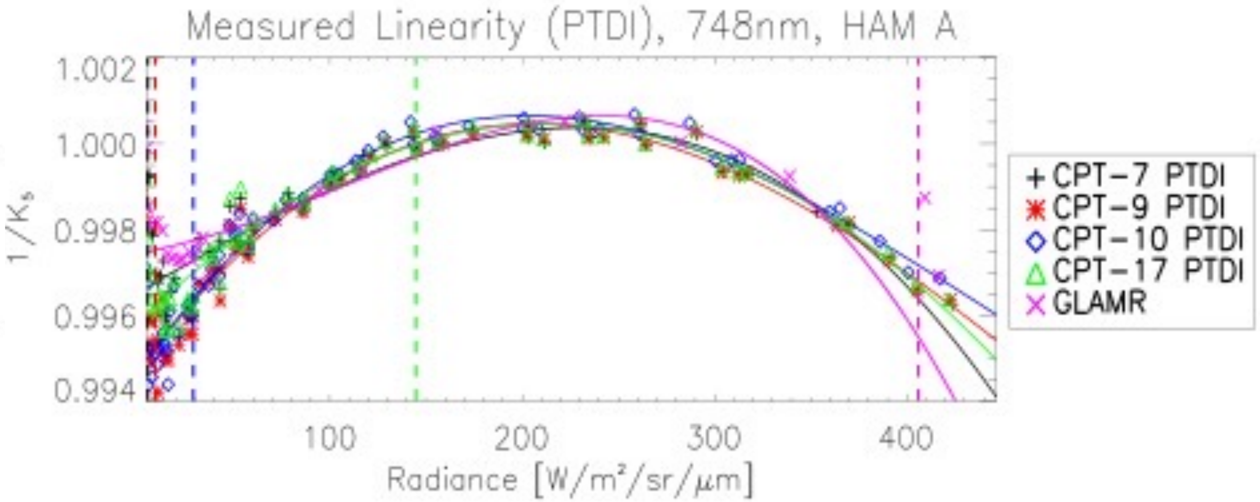
Slide from G. Meister, IGARSS 2023.

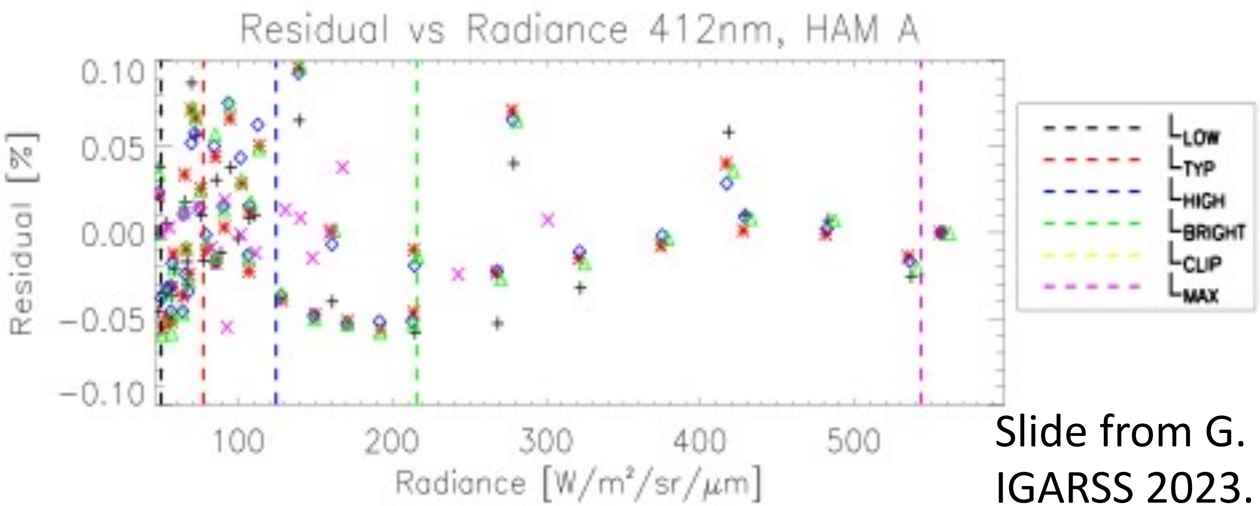
K5: Linearity

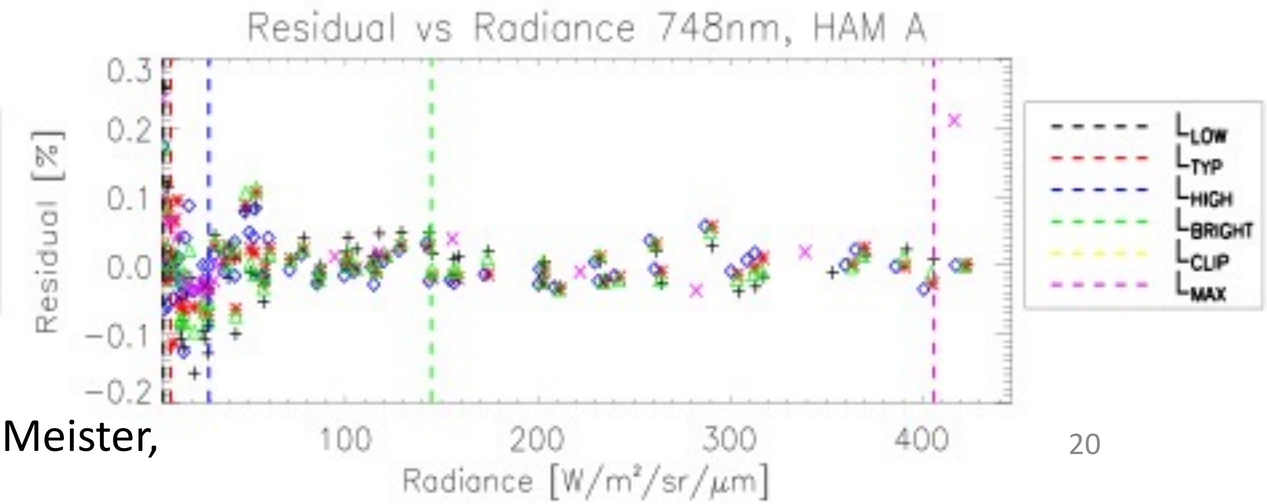
Comparison of white light progressive time-delay integration (PTDI) and GLAMR power stepping

- Generally results are comparable for Red and Blue FPAs
- No PTDI for SWIR bands – GLAMR data used







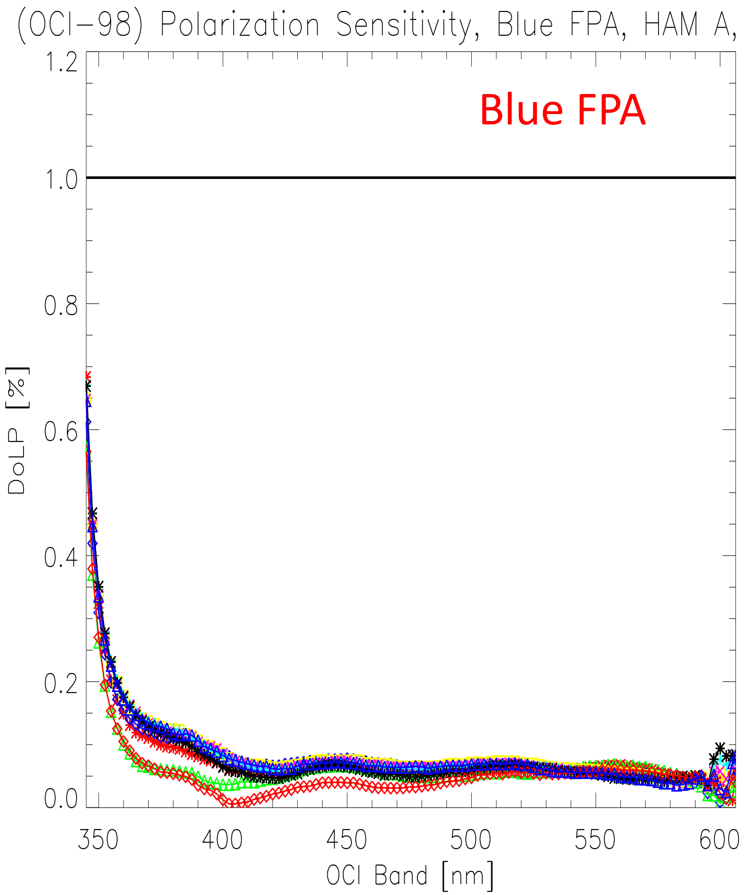


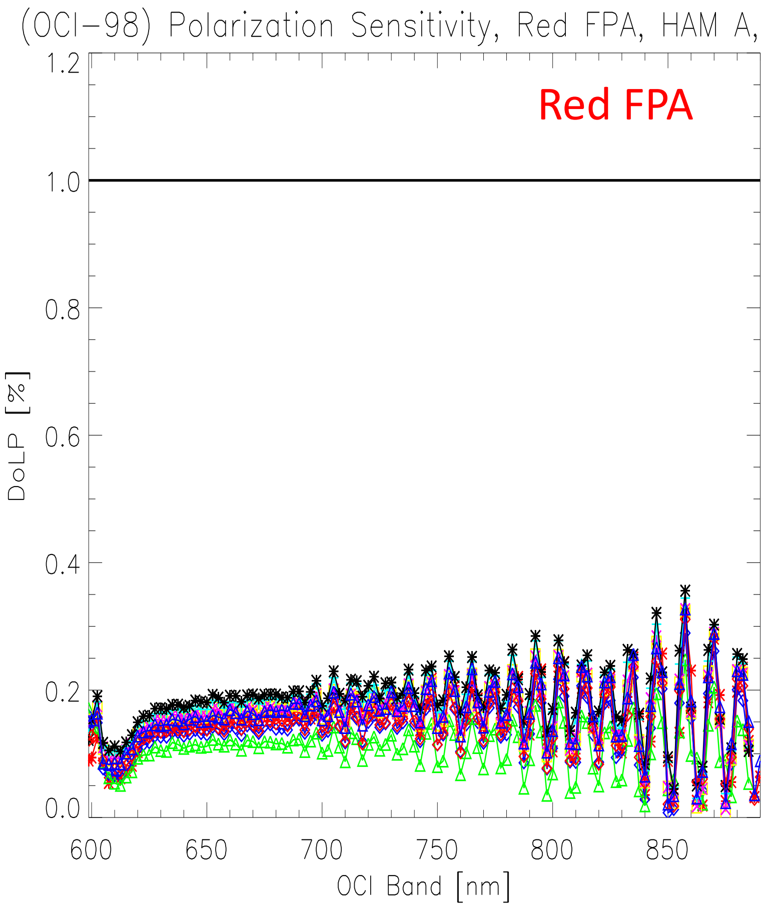
Slide from G. Meister, IGARSS 2023.

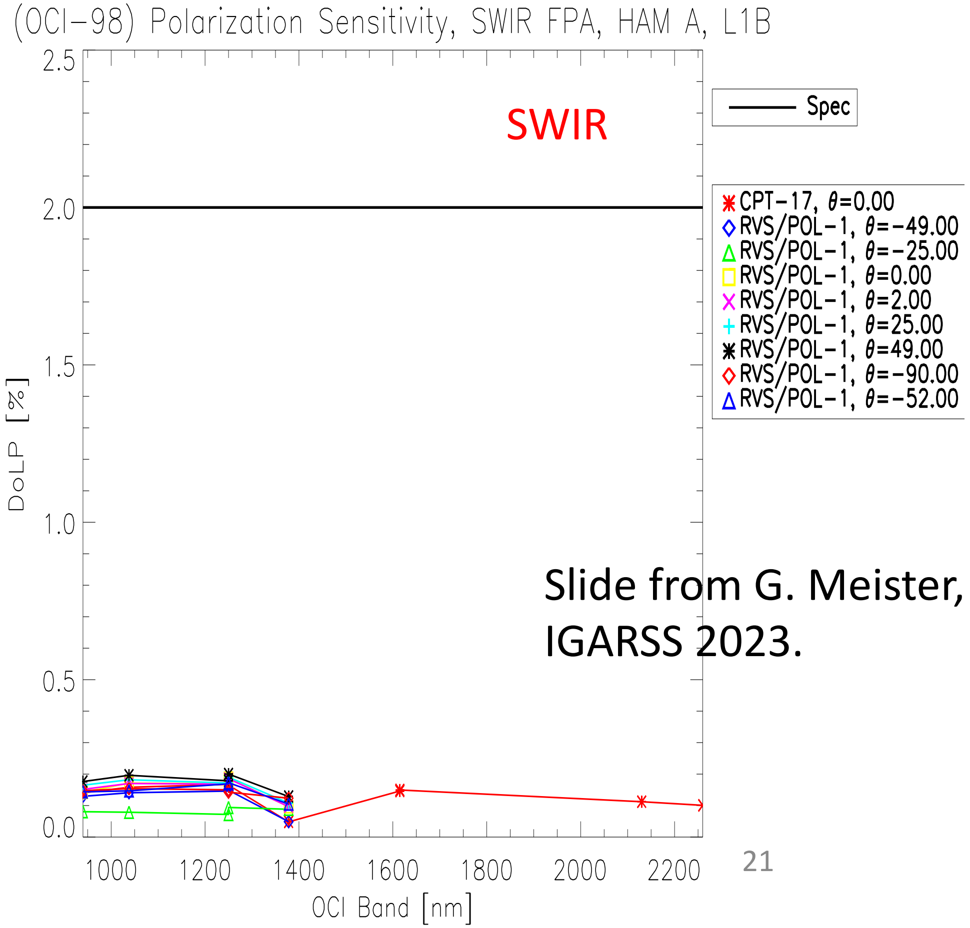
Kp: Polarization Sensitivity

Polarization amplitude measured at different scan angles

- Amplitude generally less than 0.4 % except in UV (below about 350 nm)
- Oscillations in red FPA a feature of the depolarizer
- Phase angle also determined – Mueller matrix components derived from amplitude and phase



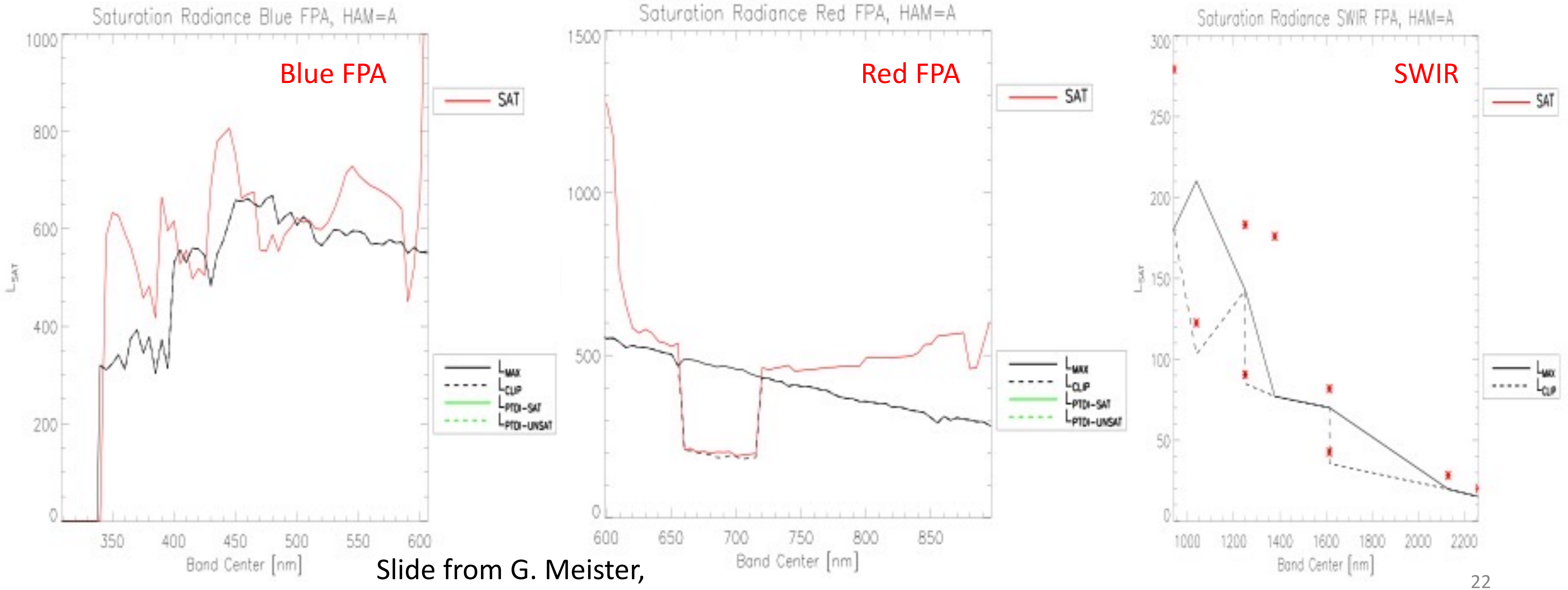




Slide from G. Meister, IGARSS 2023.

Saturation

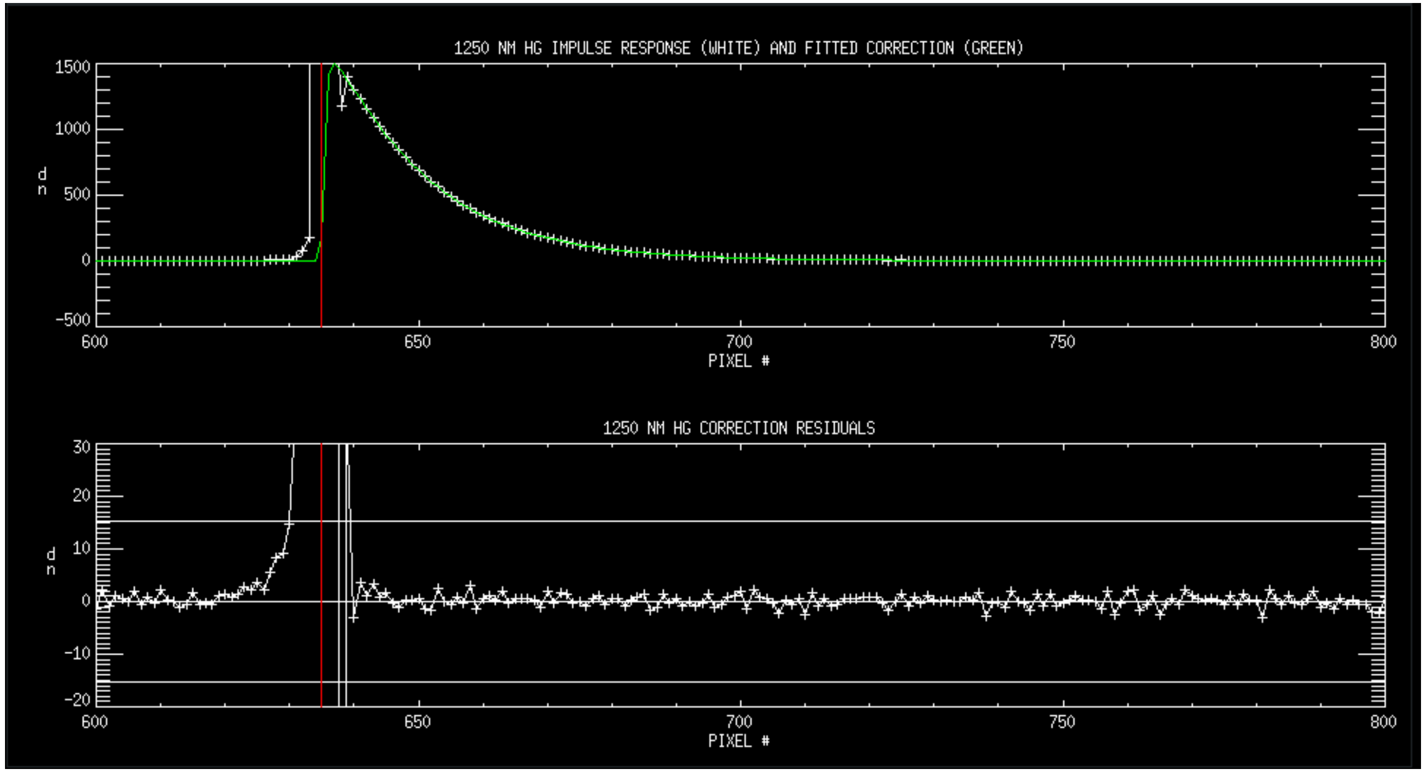
- Saturation above L_{MAX} (or L_{CLIP}) for most bands, indicating expected science data range to be met.
- Some bands saturate a little early in blue FPA; this was expected.
- Reduced dynamic range from 660nm-715nm to increase SNR for FLH product (and at 1038nm for atm. cor.).



Slide from G. Meister, IGARSS 2023.

SWIR band hysteresis

- Due to SWIR band detector and electronics characteristics, significant hysteresis is observed after a strong radiance gradient (e.g. cloud/ocean boundary)
- We developed a correction for ETU that reduces the impact to within the noise 3 pixels after the radiance transition (see below for example; red line is 1km x1km stimulus)
- Effect is expected to be linear and to follow the superposition principle, so we expect good performance of the flight unit correction with real on-orbit data



Hysteresis will be monitored on-orbit via lunar measurements (stare mode) and a dedicated on-board device (SPCA: Solar Pulse calibration Assembly)

Slide from G. Meister, IGARSS 2023.

Summary/Outlook

- Prelaunch calibration of OCI completed successfully in Sep. 2022 – thanks to OCI Systems Engineering, OCI I&T Team, and GLAMR team!
- Testing of OCI after integration to Spacecraft completed in October 2023; one more round of (limited) testing planned for December 2023 at the launch site
- Performance of OCI passed all requirements, exceeded expectations in many aspects; all calibration LUTs have been created for operational processing of dn to radiances
- We are on track for launch early 2024 (January 30^{th}?)

Slide from G. Meister, IGARSS 2023.

Backup

K1 (gain), dispersion, bandwidth, out-of-band

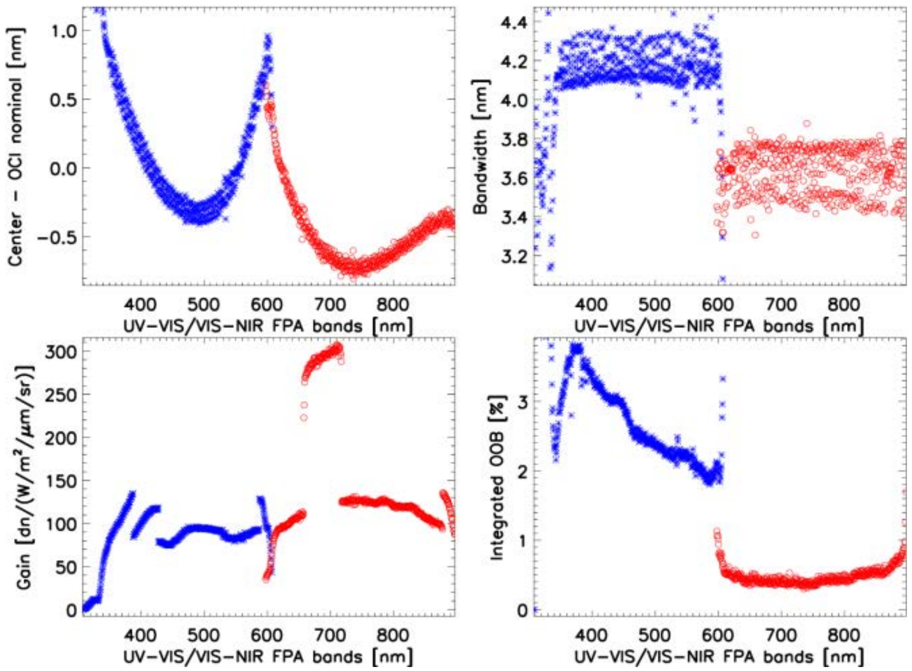


Figure 4. Results for all UV-VIS (blue stars) and VIS-NIR (red circles) FPA bands. Top left plot shows the spectral dispersion as the difference from the measured center wavelengths to the nominal center wavelengths of each band. Top right shows the bandwidth for each band. Bottom left shows the measured absolute system gain. Bottom right shows the integrated out-of-band response ratio.

Table 1. SWIR measured center wavelength, bandwidth, integrated OOB response ratio, and absolute system gain (SG: standard gain; HG: high gain).

Band Name	Center [nm]	FWHM [nm]	IOOB [%]	Gain [dn/(W/m2/sr/um)]
940 SG	939.7	44.3	0.20	448
1038 HG	1038.3	74.4	0.13	2028
1250 SG	1250.4	28.5	0.16	684
1250 HG	1248.5	28.6	0.13	5494
1378 SG	1378.2	14.4	0.19	763
1615 SG	1619.6	73.7	0.11	1571
1615 HG	1618.0	73.6	0.11	12186
2130 SG	2130.6	49.3	0.12	4652
2260 SG	2258.4	72.8	0.18	6440

Figure and table taken from Kitchen-McKinley et al., PACE OCI Flight Unit Prelaunch Spectral Characterization, IGARSS 2023, Pasadena, CA.

Selected OCI publications:

- - Jeff McIntire, Samuel Kitchen-McKinley, Hyeungu Choi, Gerhard Meister, "Progressive TDI measurements with the PACE OCI ETU," Proc. SPIE 11829, Earth Observing Systems XXVI, 118290S (1 August 2021); https://doi.org/10.1117/12.2594239
- Eugene Waluschka, Nicholas R. Collins, William B. Cook, Eric T. Gorman, George M. Hilton, Joseph J. Knuble, Gerhard Meister, Jeffrey W. McIntire, "PACE Ocean Color Instrument polarization testing and results," Proc. SPIE 11829, Earth Observing Systems XXVI, 118290R (1 August 2021); https://doi.org/10.1117/12.2594029
- Samuel Kitchen-McKinley, Jeff McIntire, Hyeungu Choi, Gerhard Meister, "PACE OCI pre-launch ETU spectral characterization and performance," Proc. SPIE 11829, Earth Observing Systems XXVI, 118290Q (1 August 2021); https://doi.org/10.1117/12.2594306
- Gerhard Meister, Joseph J. Knuble, William B. Cook, Eric T. Gorman, P. Jeremy Werdell, "Calibration plan for the Ocean Color Instrument (OCI) engineering test unit," Proc. SPIE 11151, Sensors, Systems, and Next-Generation Satellites XXIII, 111511W (10 October 2019); https://doi.org/10.1117/12.2550820
- Jeff McIntire, Sam Kitchen-McKinley, Dan Todaro, Gerhard Meister, "Simulating response versus scan angle characterization on OCI for the upcoming PACE mission," Proc. SPIE 11151, Sensors, Systems, and Next-Generation Satellites XXIII, 111511D (10 October 2019); https://doi.org/10.1117/12.2532782
- Gorman, E., D. A. Kubalak, P. Deepak, et al. 2019. "The NASA Plankton, Aerosol, Cloud, ocean Ecosystem (PACE) mission: an emerging era of global, hyperspectral Earth system remote sensing." Sensors, Systems, and Next-Generation Satellites XXIII 11151 111510G [10.1117/12.2537146]
- Gerhard Meister, Joseph J. Knuble, Leland H. Chemerys, Hyeungu Choi, Nicholas R. Collins, Robert E. Eplee, Ulrik Gliese, Eric T. Gorman, Kim Jepsen, Samuel Kitchen-McKinley, Shihyan Lee, Jeffrey W. Mcintire, Frederick S. Patt, Bradley C. Tse, Eugene Waluschka, P. Jeremy Werdell, “Test Results from the Prelaunch Characterization Campaign of the Engineering Test Unit of the Ocean Color Instrument of NASA’s Plankton, Aerosol, Cloud and Ocean Ecosystem Mission” Front. Remote Sens., 23 June 2022 Sec. Multi- and Hyper-Spectral Imaging https://doi.org/10.3389/frsen.2022.875863.
- J.Werdell; M. Behrenfeld; P. Bontempi; E. Boss; B. Cairns; G. Davis; B. Franz; U. Gliese; E. Gorman; O. Hasekamp; K. Knobelspiesse; A. Mannino; V. Martins; C. McClain; G. Meister; L. Remer, "The Plankton, Aerosol, Cloud, ocean Ecosystem (PACE) mission: Status, science, advances." Bulletin of the American Meteorological Society 100 (9): 1775–1794, 2019, doi: 10.1175/bams-d-18-0056.1.

Selected OCI publications (continued):

- Shihyan Lee, Gerhard Meister, Samuel Kitchen-McKinley, Joseph Knuble, Ulrik Gliese, Robert Bousquet, "PACE OCI crosstalk characterization based on pre-launch testing," Proc. SPIE 12729, Sensors, Systems, and Next-Generation Satellites XXVII, 1272919 (19 October 2023); https://doi.org/10.1117/12.2677567

- Joseph J. Knuble, Gerhard Meister, Hyeungu Choi, Nicholas R. Collins, Kim Jepsen, Shihyan Lee, Jim McCarthy, Robert Bousquet, William B. Cook, Colby Jurgenson, Ulrik Gliese, Eric T. Gorman, "Measurement techniques for the high-contrast and in-field stray light performance of OCI," Proc. SPIE 12729, Sensors, Systems, and Next-Generation Satellites XXVII, 127290P (19 October 2023); https://doi.org/10.1117/12.2682126

- U. Gliese, Z. Rhodes, K. Squire, K. S. Jepsen, B. Cairns, B. L. Clemons, J. Cook, R. Esplin, R. H. Estep Jr., E. T. Gorman, E. Kan, G. Meister, W. Lu, D. B. Mott, F. S. Patt, J. Peterson, R. G. Schnurr, "Pulse response of the shortwave infrared detection system of the ocean color instrument for the NASA PACE Mission," Proc. SPIE 12729, Sensors, Systems, and Next-Generation Satellites XXVII, 127290O (19 October 2023); https://doi.org/10.1117/12.2684367

- Robert E. Eplee Jr., Gerhard Meister, Shihyan Lee, Kenneth J. Squire, Ulrik Gliese, Joseph J. Knuble, Deepak Patel, "Prelaunch radiometric calibration of the thermal response of the PACE Ocean Color Instrument," Proc. SPIE 12685, Earth Observing Systems XXVIII, 1268509 (4 October 2023); https://doi.org/10.1117/12.2677463

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