Improving Calibrations of Lunar Spectral Measurements

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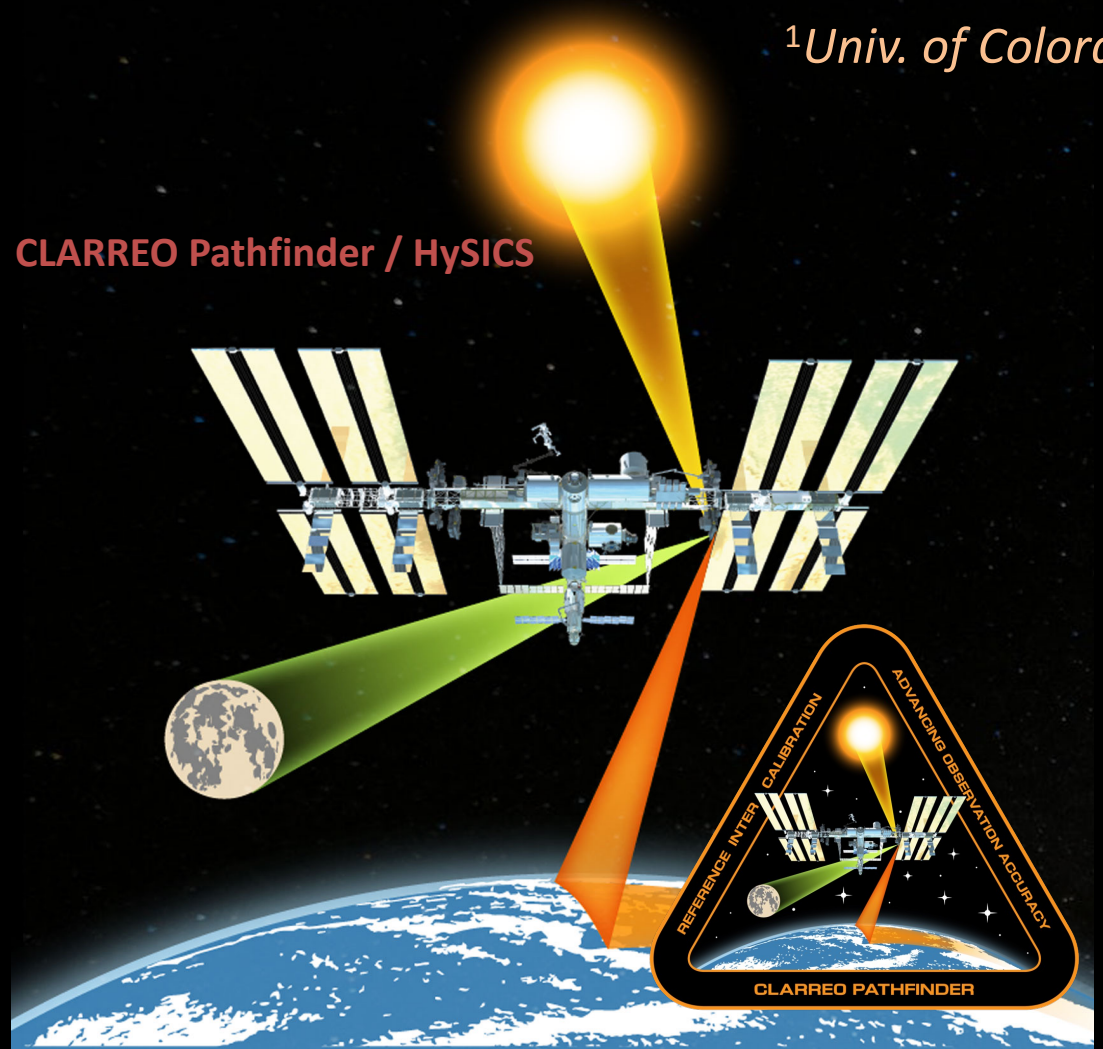
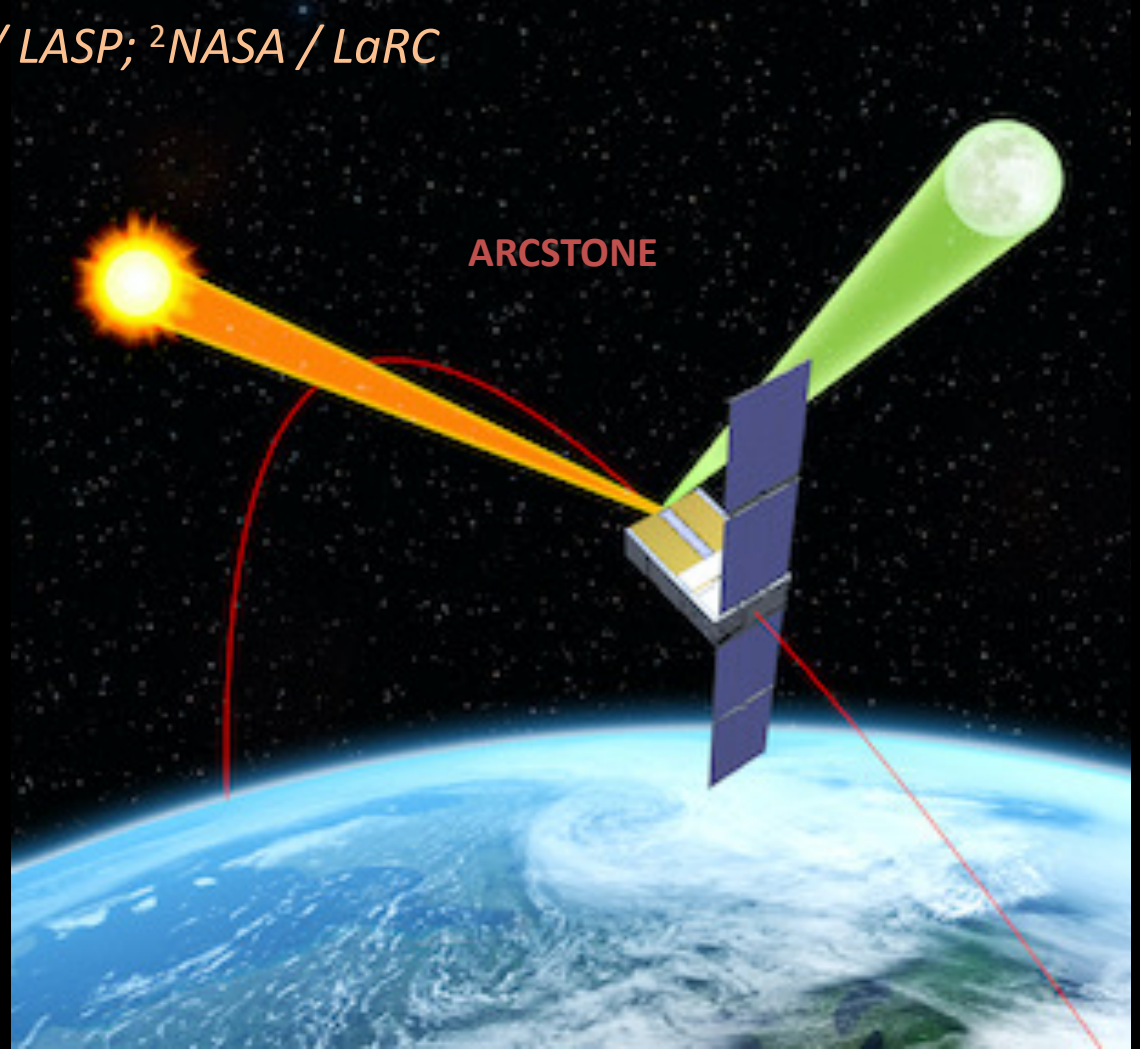
CLARREO Pathfinder / HySICS

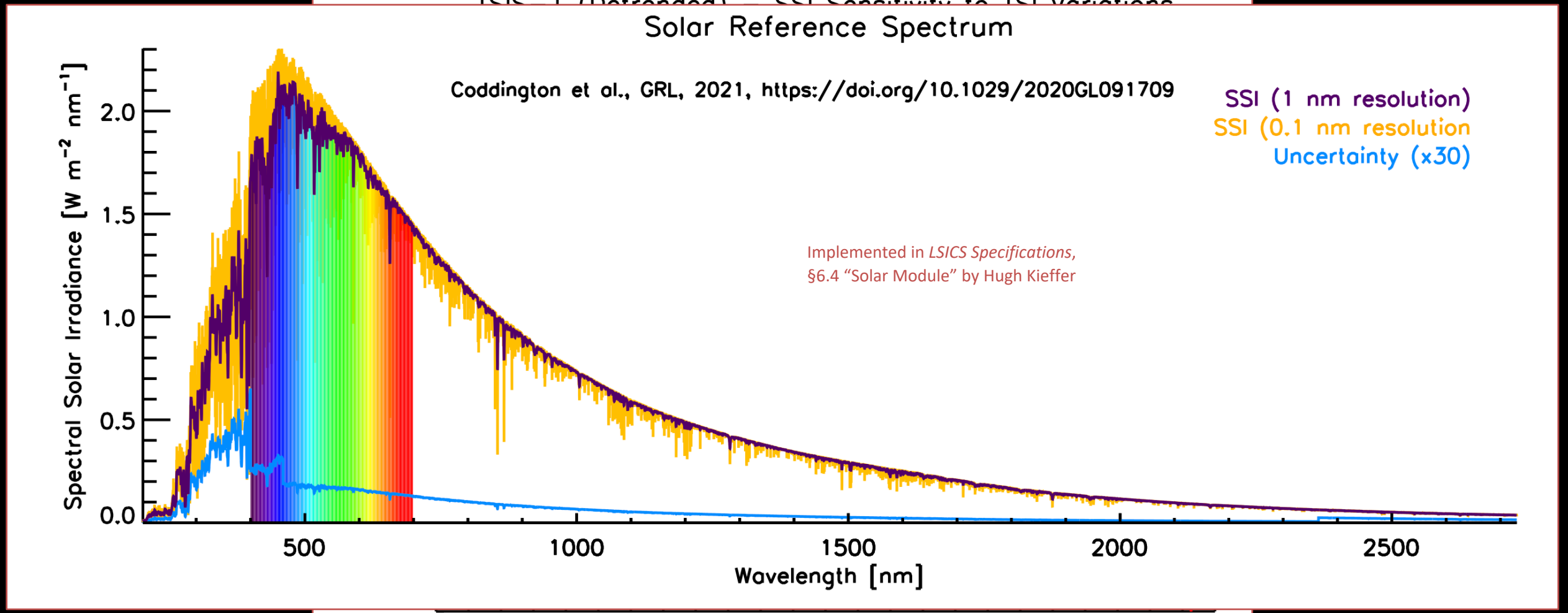


ARCSTONE



On-Orbit Spectral Reference

- The Sun is the best-known long-term on-orbit spectral reference

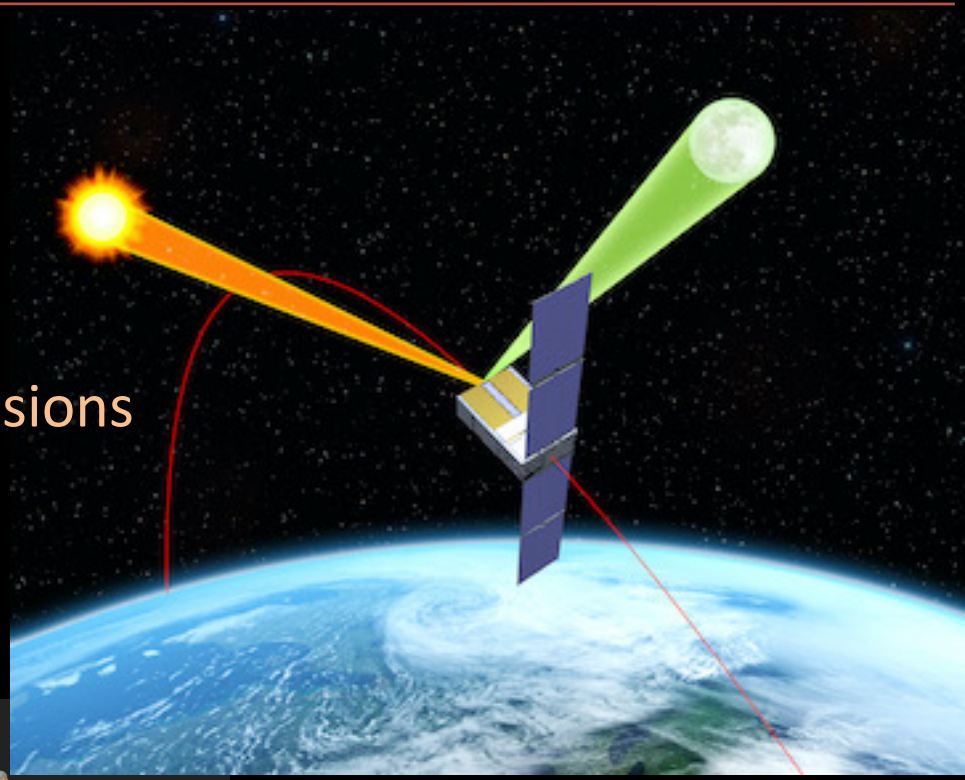


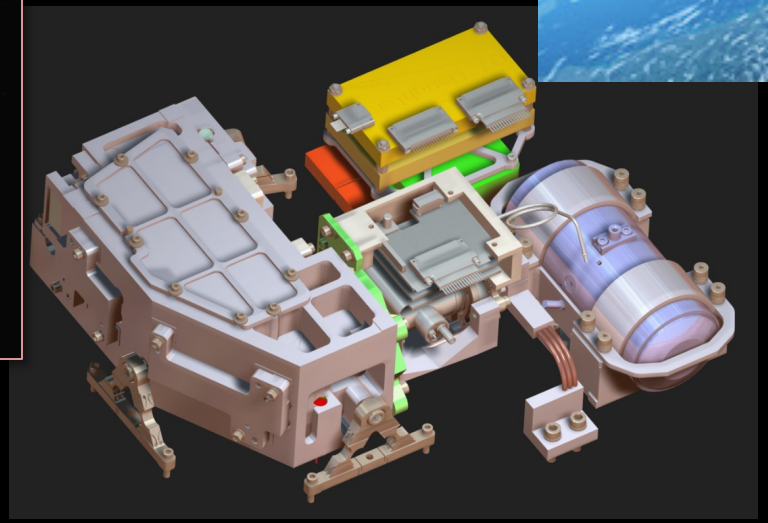
Implemented in *LSICS Specifications*, §6.4 "Solar Module" by Hugh Kieffer

Kopp, Nemec, Shapiro, *Ap.J.*, in review

ARCSTONE

- Empirical model of Lunar Spectral Irradiances
- Current Lunar Model: ROLO 2005
  - Accuracy 5 – 10%
- No onboard calibration references
- Calibrations of past, current, and future instruments/missions
  - Can bridge data gaps
- InVEST 12-U CubeSat



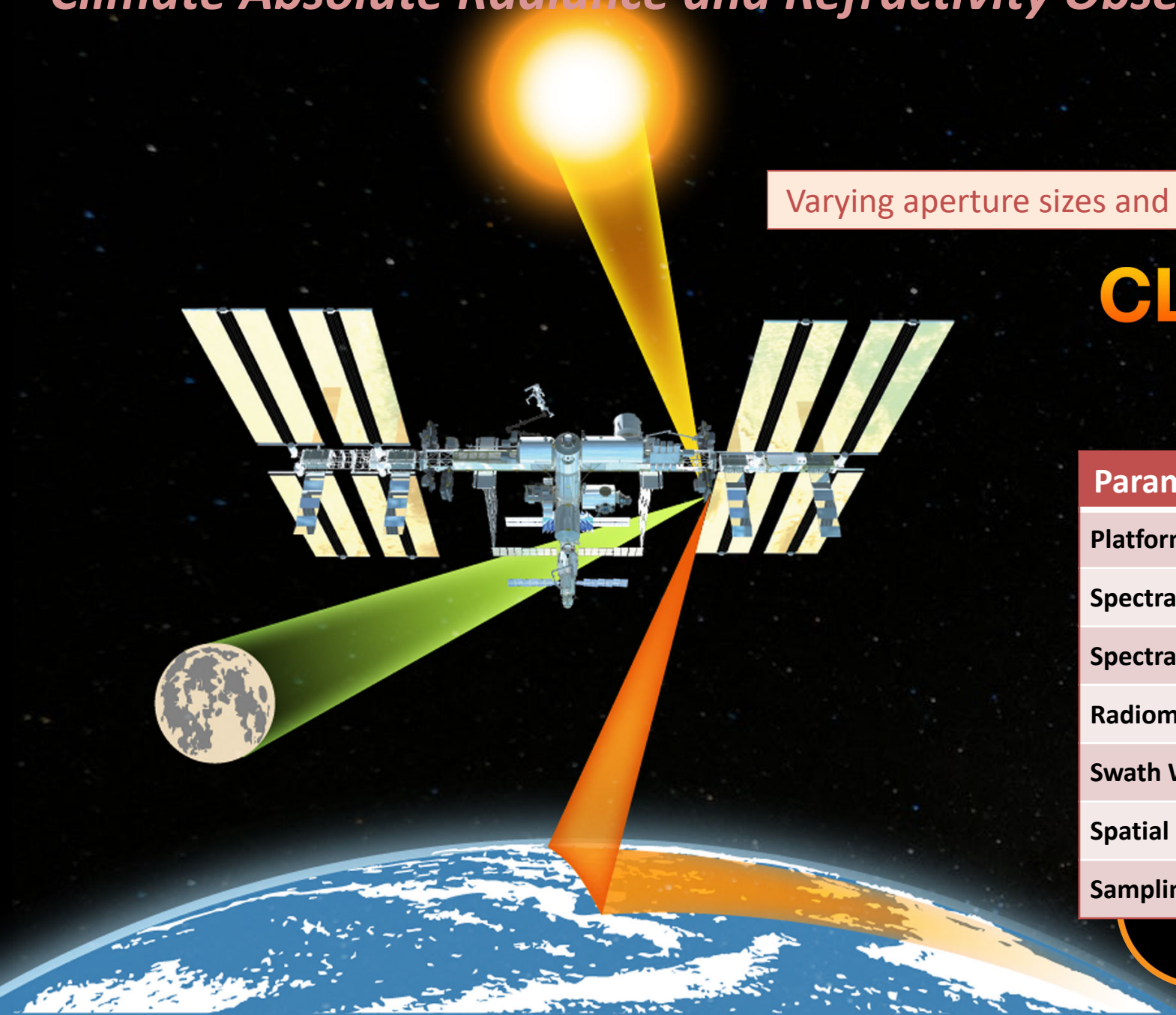


Reflectance of lunar surface stable to < 10^{-8} / year

Climate Absolute Radiance and Refractivity Observatory (CLARREO) Pathfinder

National Aeronautics and Space Administration

NASA



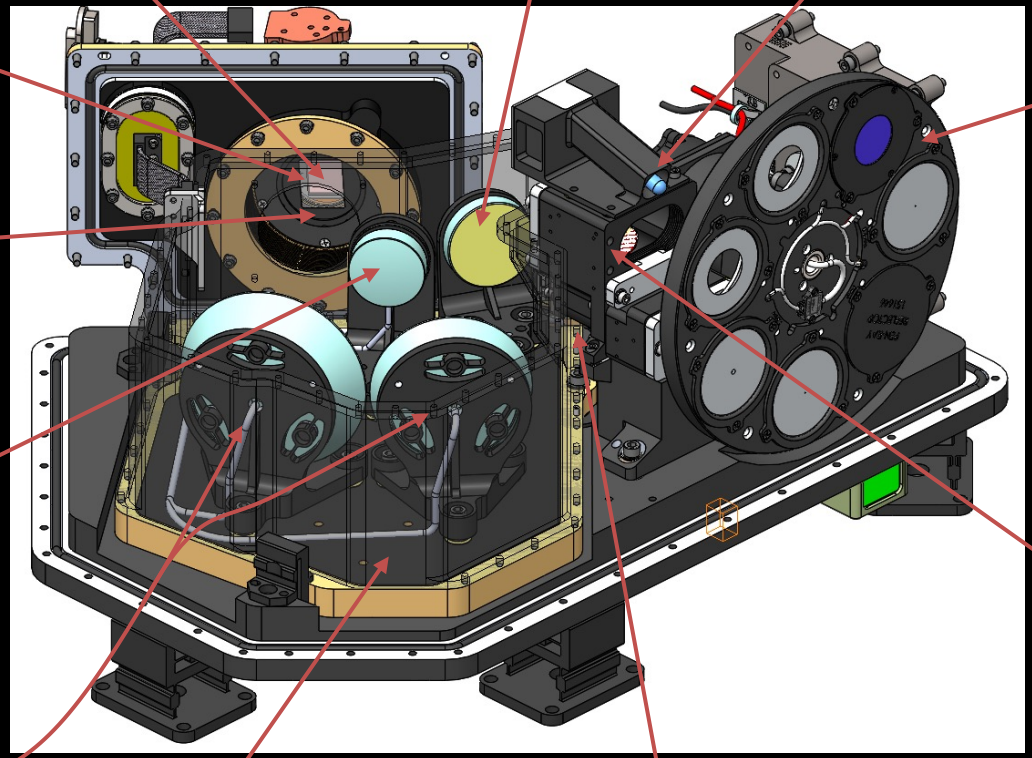
Varying aperture sizes and integration times enable solar cross-calibrations

CLARREO Pathfinder

Parameter	Goal
Platform	International Space Station
Spectral Range	350 nm – 2260 nm
Spectral Resolution	6 nm (3-nm sampling)
Radiometric Uncertainty	0.3% (spatial/spectral average)
Swath Width	10 degrees (~70 km at nadir)
Spatial Sampling	0.5 km (nadir)
Sampling Rate	15 Hz

CLARREO PATHFINDER

Hyper Spectral Imager for Climate Science (HySICS)



Focal Plane Array (FPA)
- HgCdTe 640x480 pixel array
- Held at 152.5 K to limit dark current

Fold Mirror
- Directs light into Offner spectrometer

Pen-ray
- For on-orbit spectral dispersion calibration

Order Sorting Filter
- Linearly variable filter to eliminate higher order stray light on detector

Aperture Wheel and Apertures
- Select from 6 apertures, pen-ray mirror, or blank
- Apertures: 20 mm (x2), 0.5 mm (x2), intermediate, and transmissive diffuser

Zero-order Trap
- Vantablack coating (carbon-based) to absorb zeroth (and other) orders from grating

4MA (4-Mirror Anasitgmat)
- Instrument telescope
- 78-mm focal length
- 4 diamond-turned aluminum mirrors located in vertical plane

Offner Grating
- Zeiss 2-zone grating
- 350-2300 nm
- Low polarization sensitivity

Offner Mirrors
- Aluminum coated

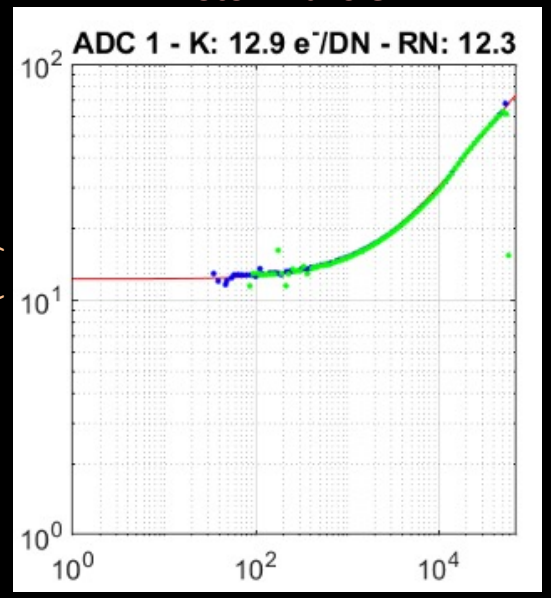
Offner Cold Bench
- Completely enclosed to limit stray light
- Held at -15 °C to limit blackbody radiation

Slit (hidden at this angle)
- 28 um wide x 14.4 mm long
- Carbon nanotube shields on front and back surfaces reduce scatter

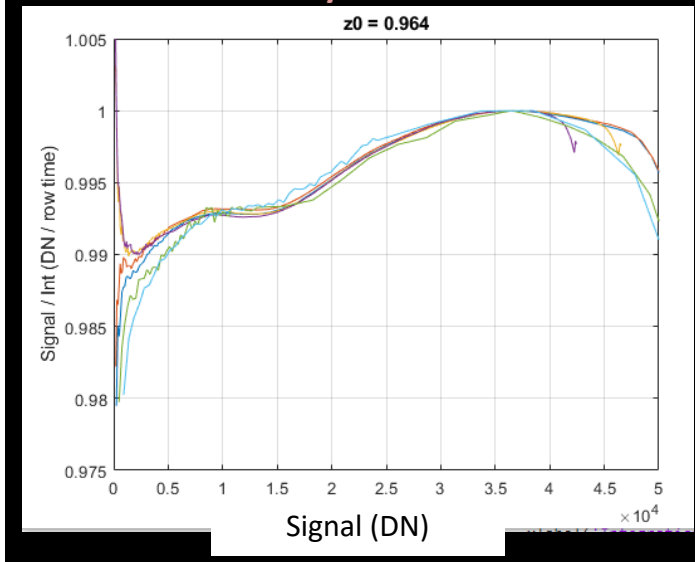
HySICS Calibrations – FPA

- Thermal Stability
  - All tests measured performance over full operational temperature range: 147.5 K – 155 K
- Photon Transfer Measurement
  - Transfer gain (13 e-/DN)
  - Read Noise (12 DN)
- Linearity
  - Linear to better than 0.5% over 75% of the dynamic range
  - Correctable to better than 500 ppm
- Fixed Pattern Noise (offset ~ 8000 DN)
- Full-Sensor Offset Noise
  - Two-row correction
- After-Image Measurements

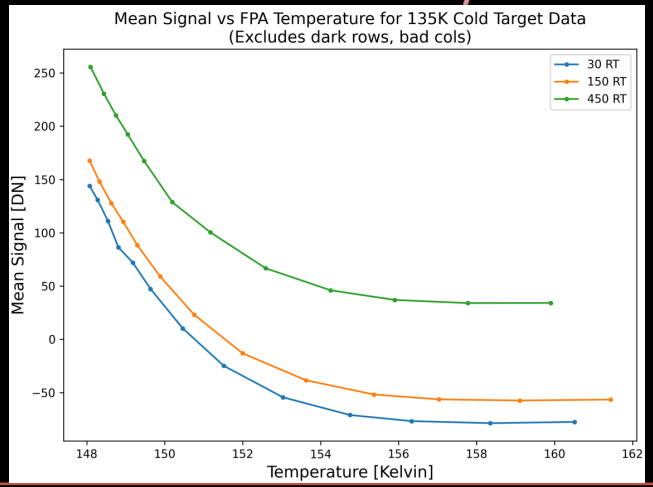
Photon Transfer



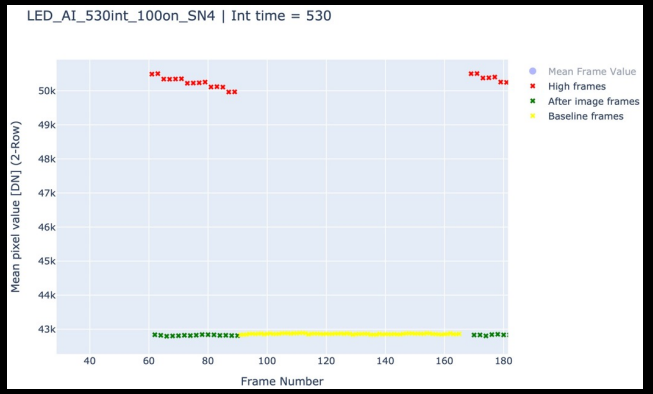
Linearity Correction



Thermal Sensitivity

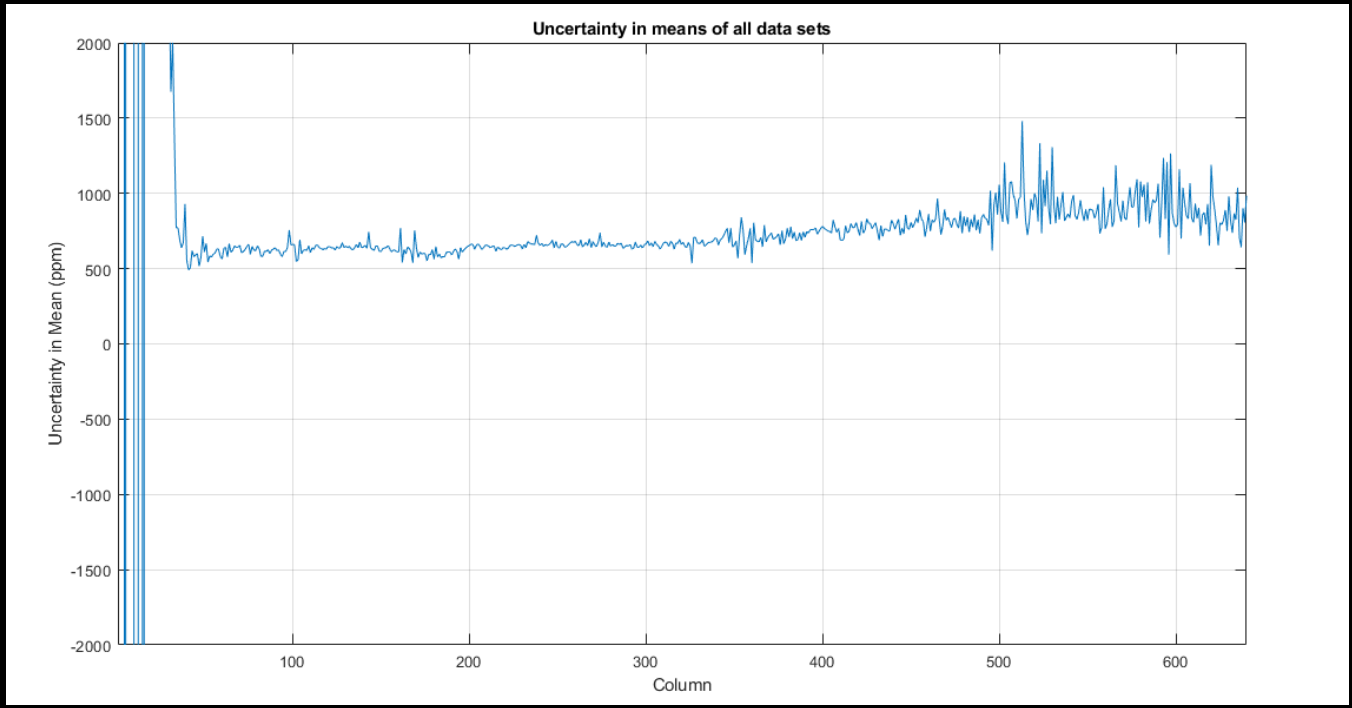


After-Image Measurement

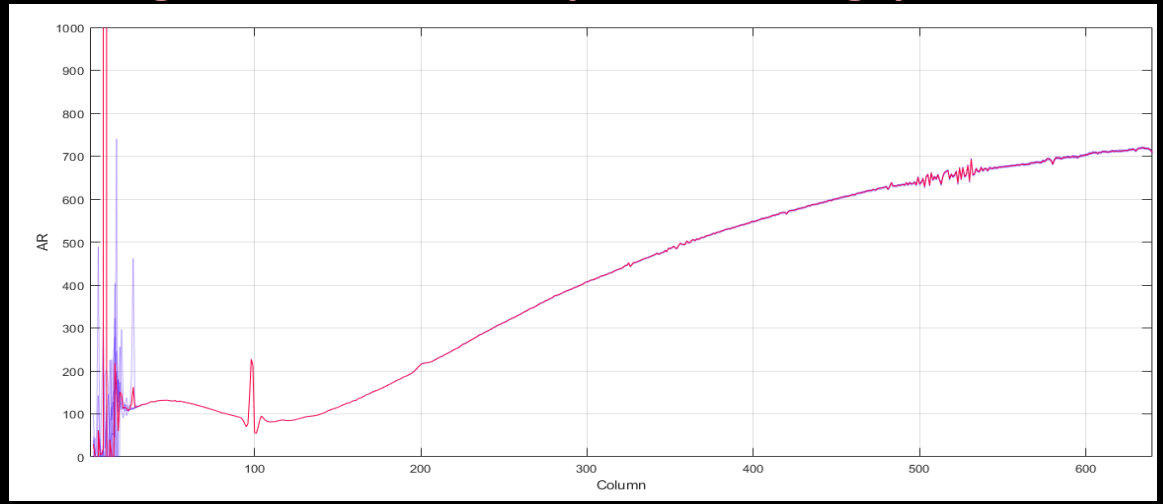


HySICS Calibrations – Aperture Throughput Ratio Measurements

- Throughput ratio measured for each pair of apertures (large/small, large/intermediate, small/intermediate)
  - Accounts for aperture sizes, optical-train efficiencies, and diffraction and scatter
  - Will use large/intermediate or a combination of that and intermediate/small for final ratio
- Uncertainties < 0.1%



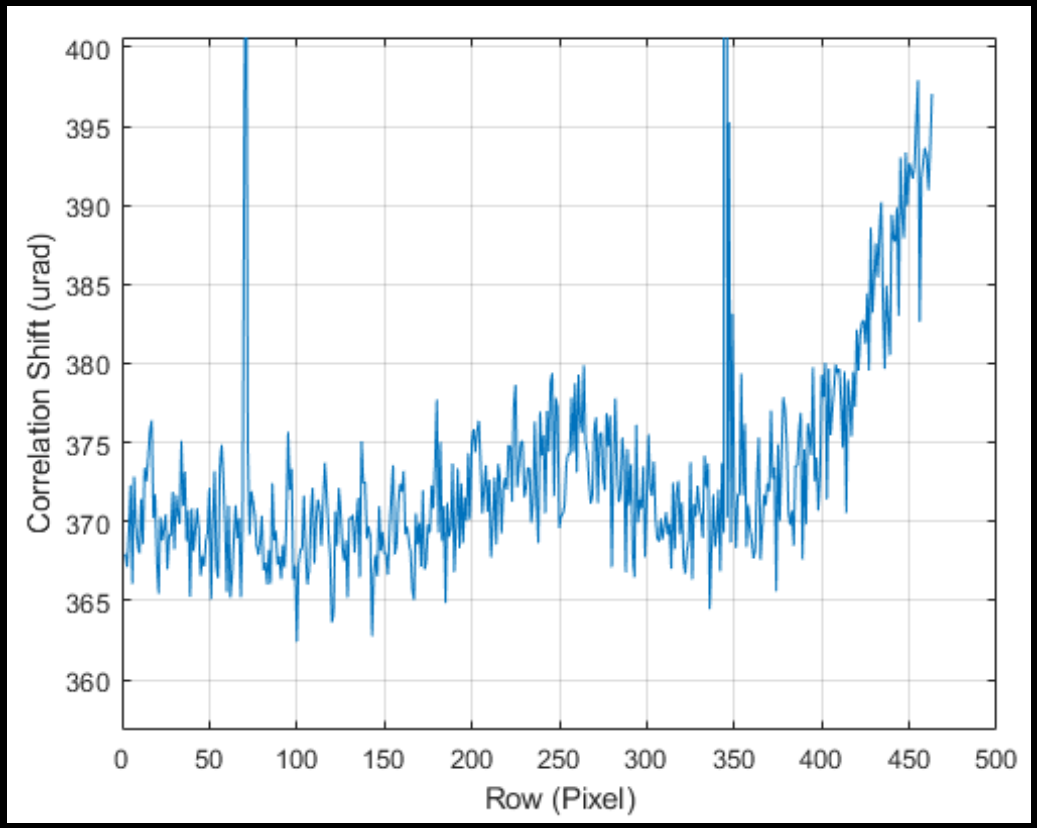
Large-to-Intermediate Aperture Throughput Ratio



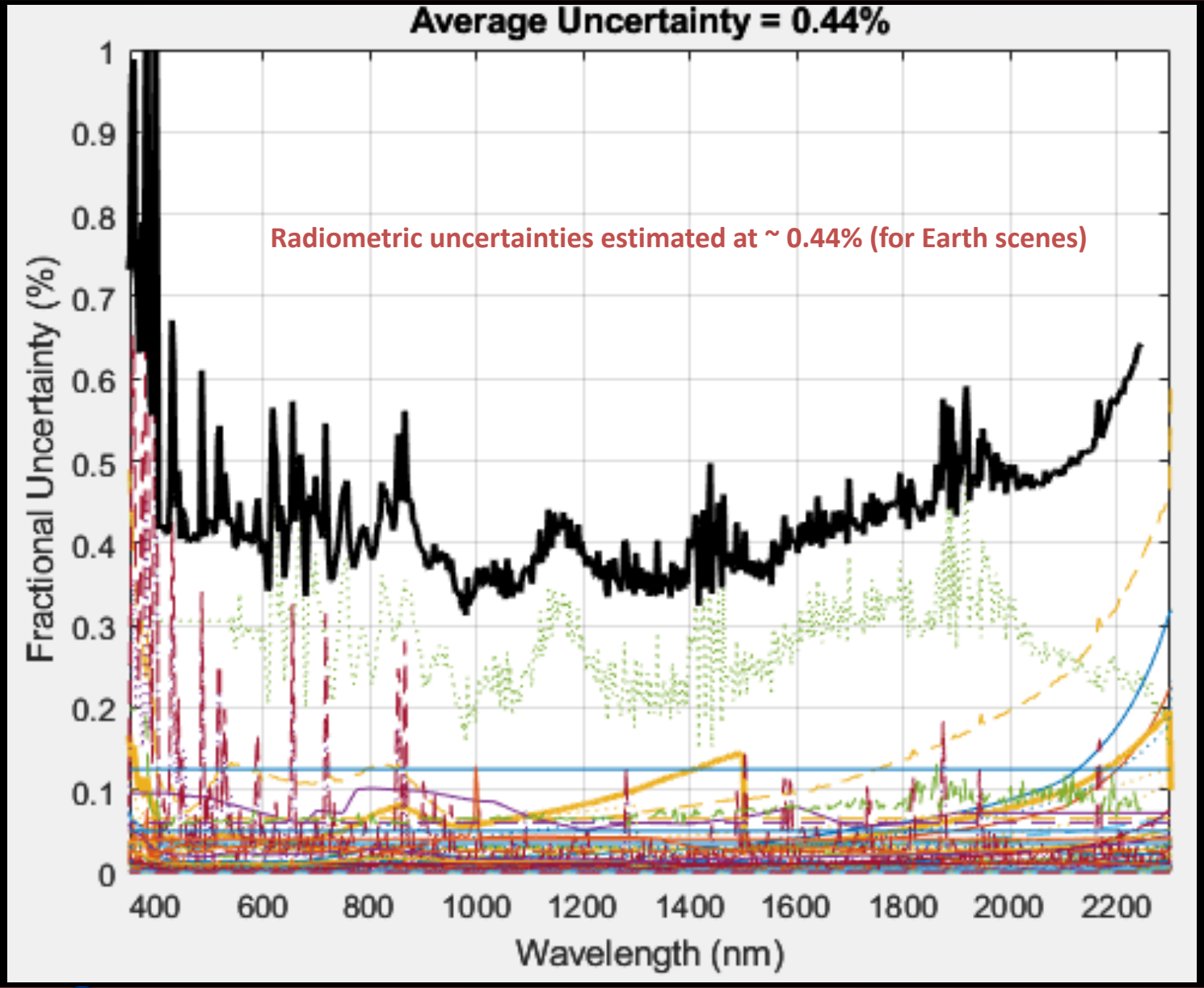
HySICS Calibrations – Field-of-View Measurements

- Per-pixel, both along and across slit, and full-range field-of-view measured at two discrete wavelengths
- Instrument pixel-FOV (IFOV) range: 370 – 390 urad (76 – 80 arcsec)
  - Knowledge is needed for determining irradiances via spatial over-sampling
- Full range (480 pixels) is 10.311 degrees
  - Usable range is between 9.945 and 10.075 degrees
- Per-pixel solid-angle uncertainties ~ 0.06%

IFOV



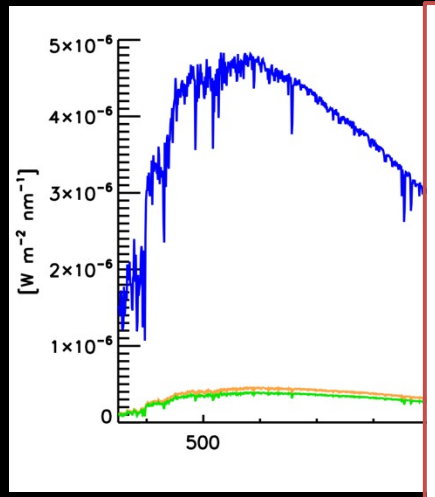
HySICS Calibrations

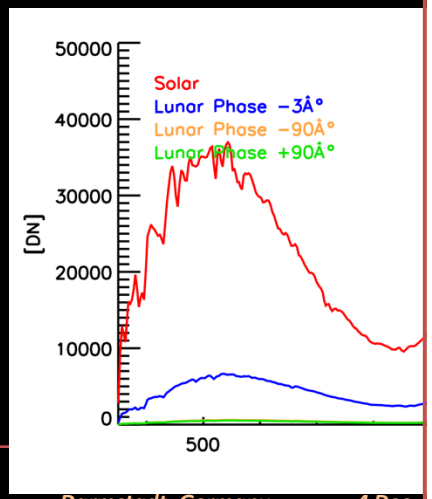


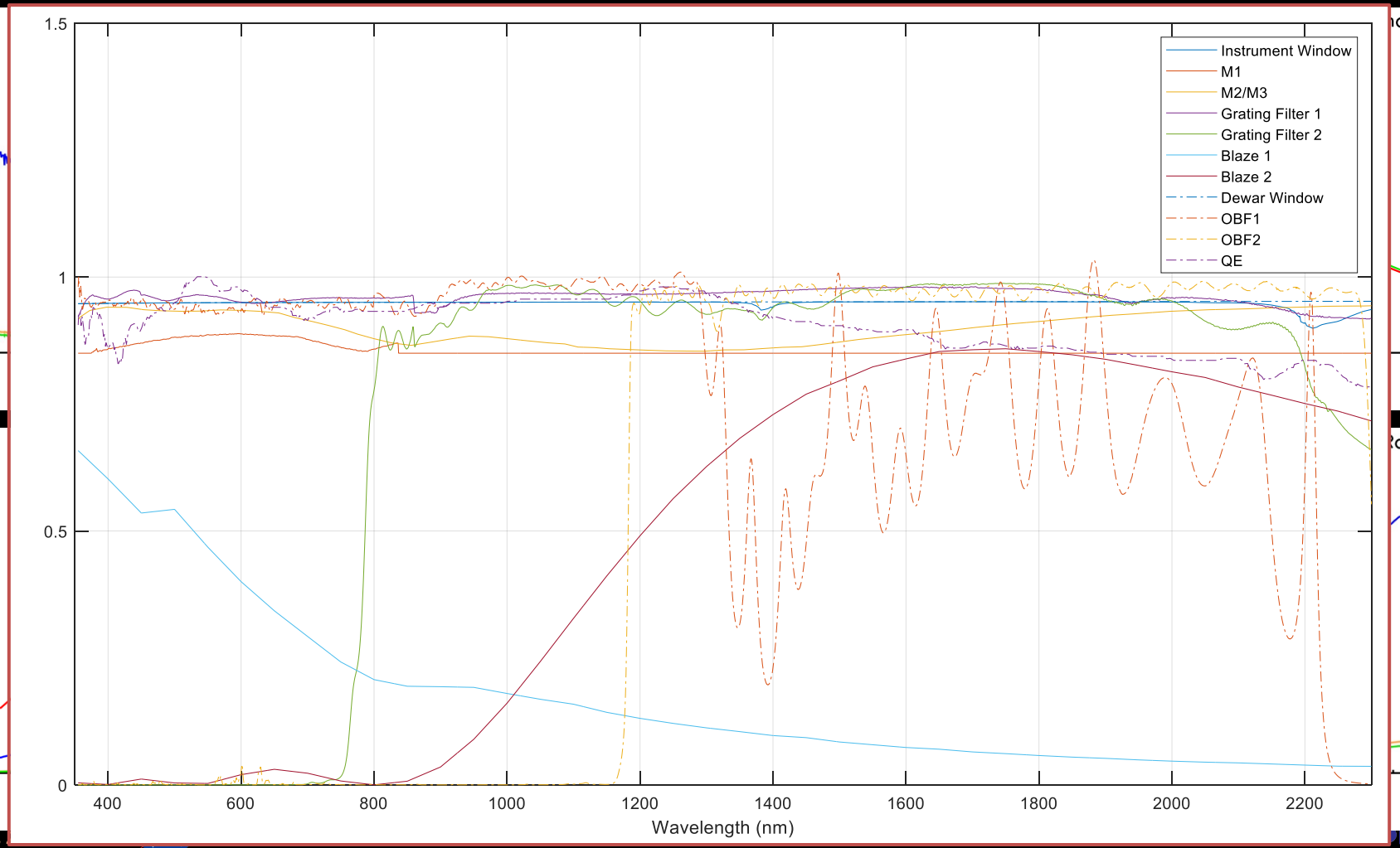
Calibrations Completed on Prototype ARCSTONE Instrument

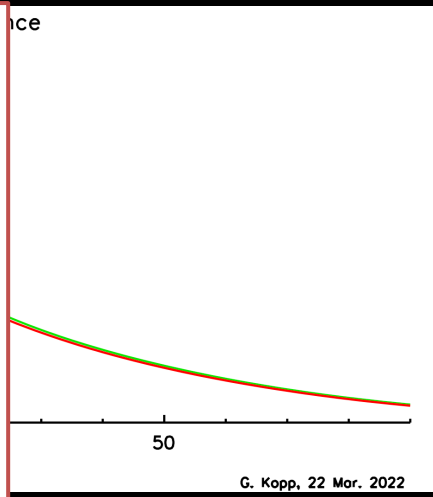
Expected Instrument Signal Levels

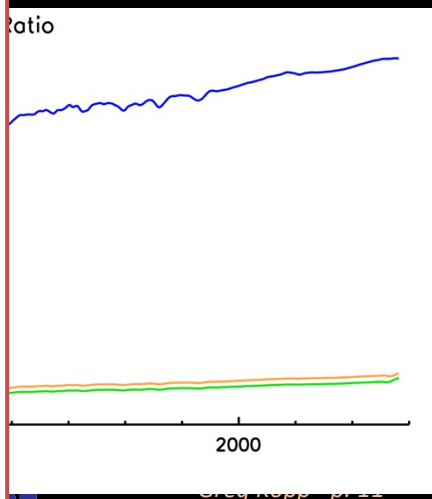
- **Integration Times:** 40 µs solar & 3 sec lunar (75,000 x)
- **Lunar Phases:** -3˚ , ±90˚ (InVEST goal ±135˚ threshold ±90˚)
- Includes ILS sensitivities to position for binary maps of the Sun and Moon in each phase





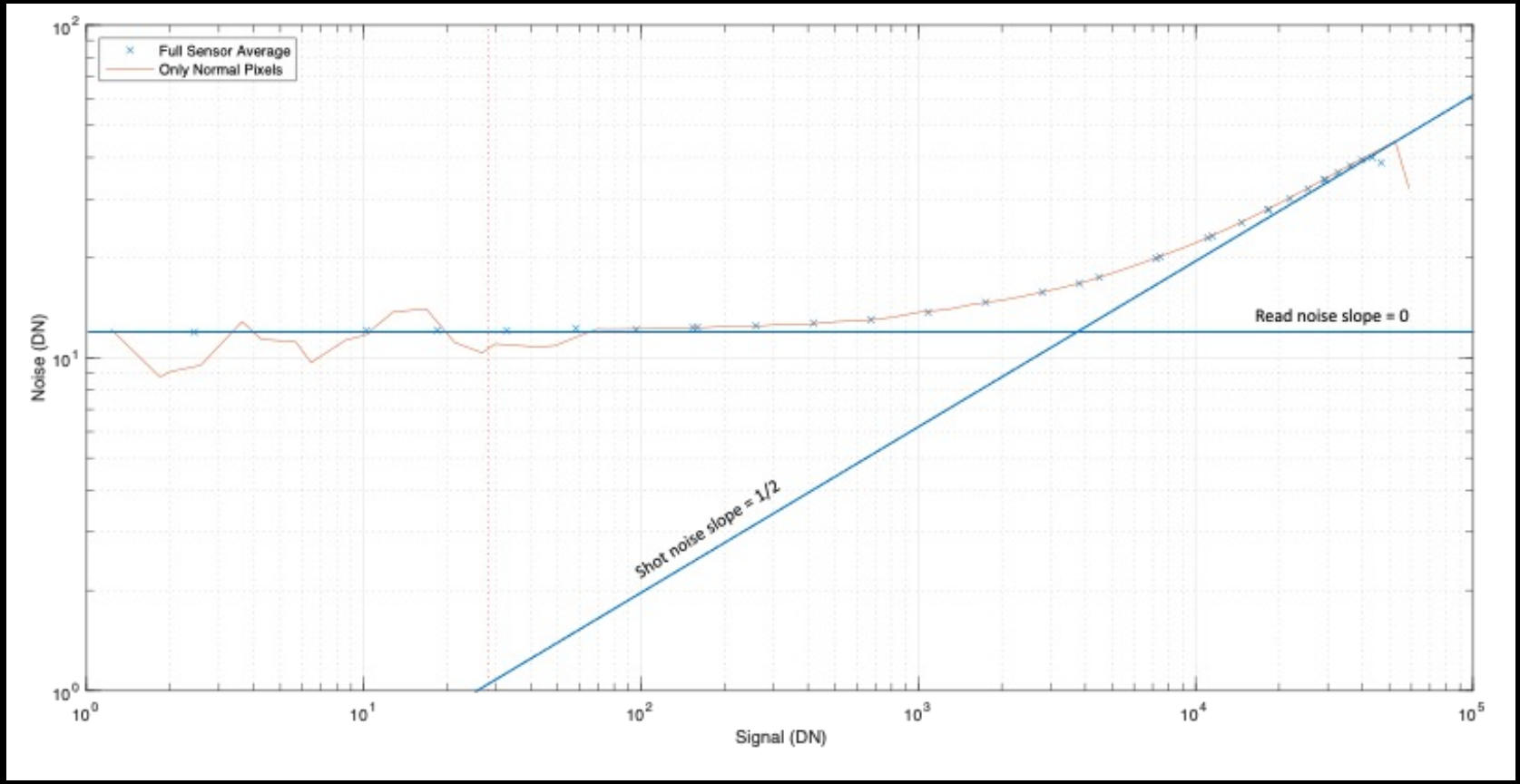


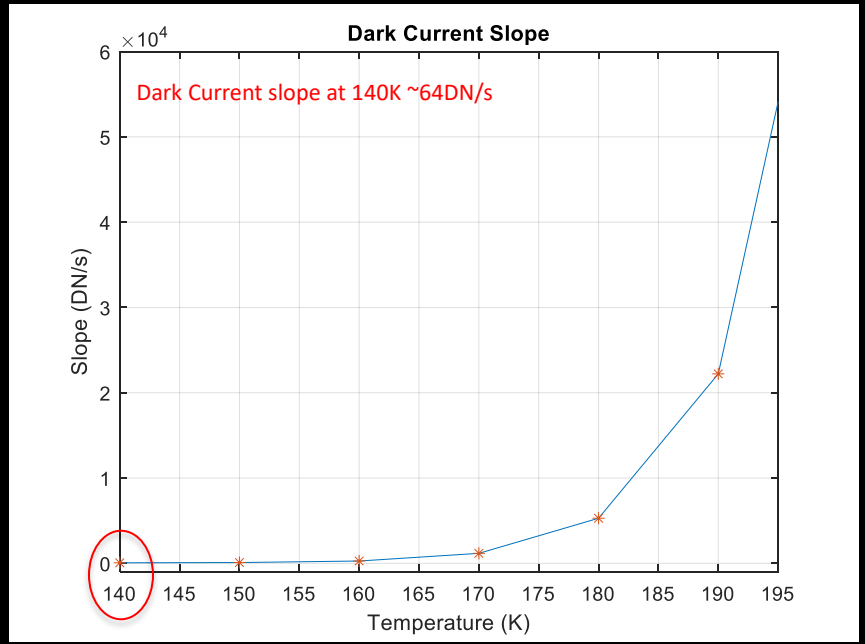




Component-Level Characterizations: Focal Plane Array (FPA)

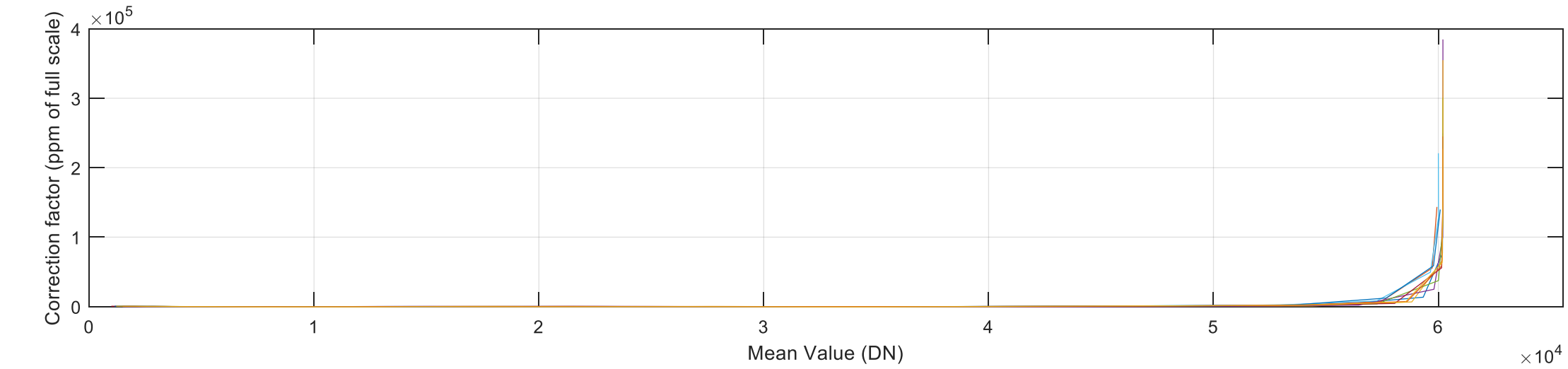
- **FPA:** AIM SWIR MCT 640x512 15 µm
- **Read Noise:** 12.06 ± 0.0207 DN
- **Gain:** 26.2 e^- DN^{-1}

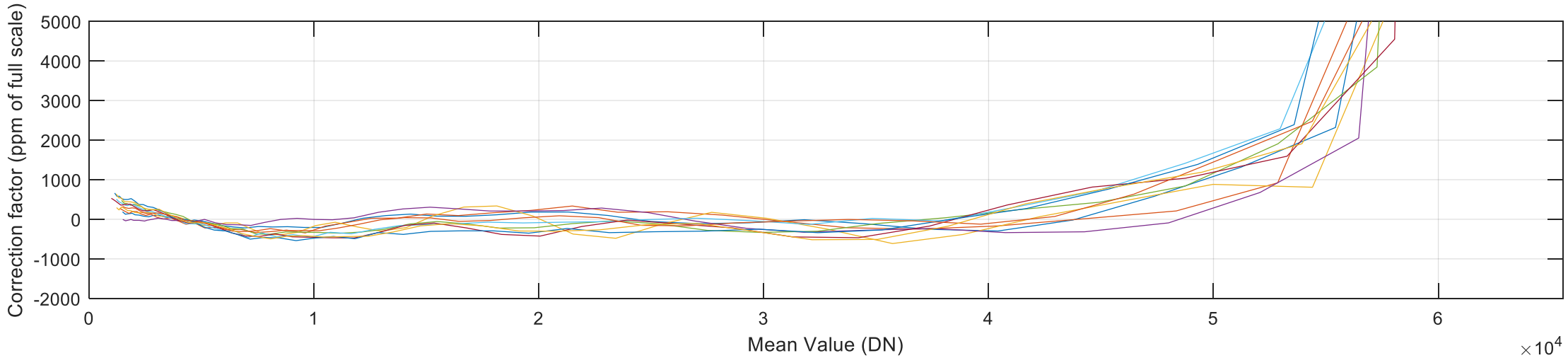




Component Level: FPA Non-Linearity Corrections and Uncertainties

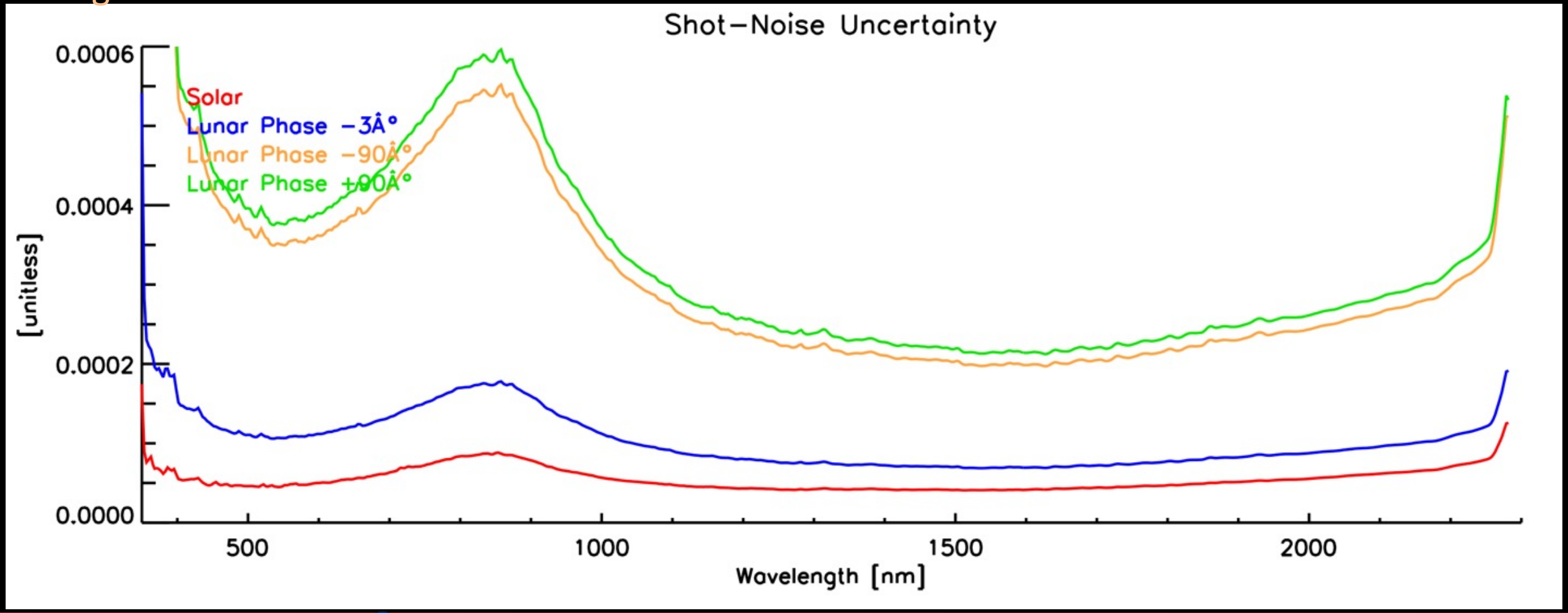
- Low for signals < 50 000 DN





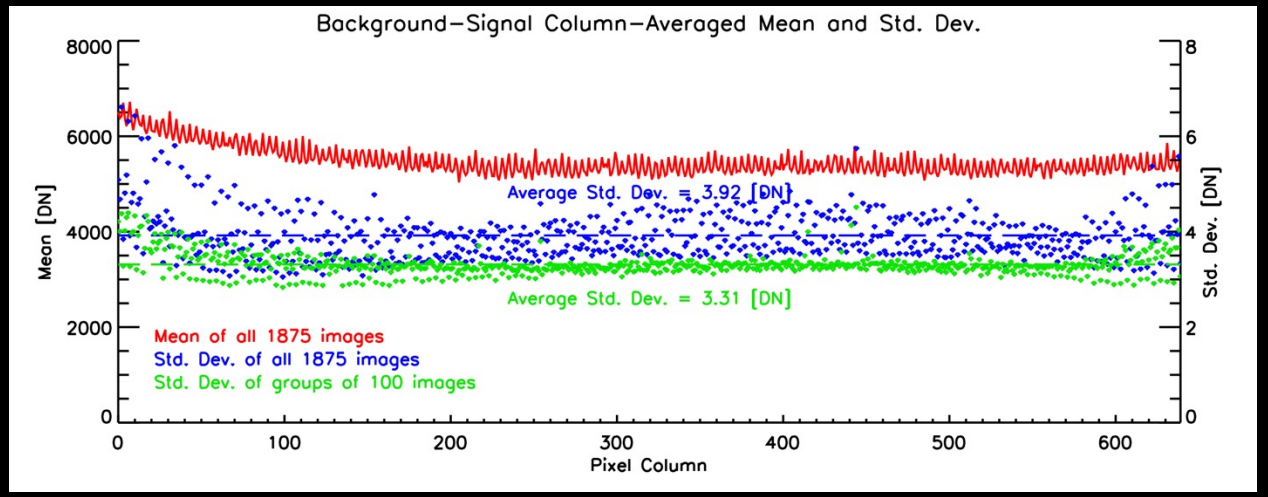
Instrument Level: Shot-Noise Uncertainties – Signals

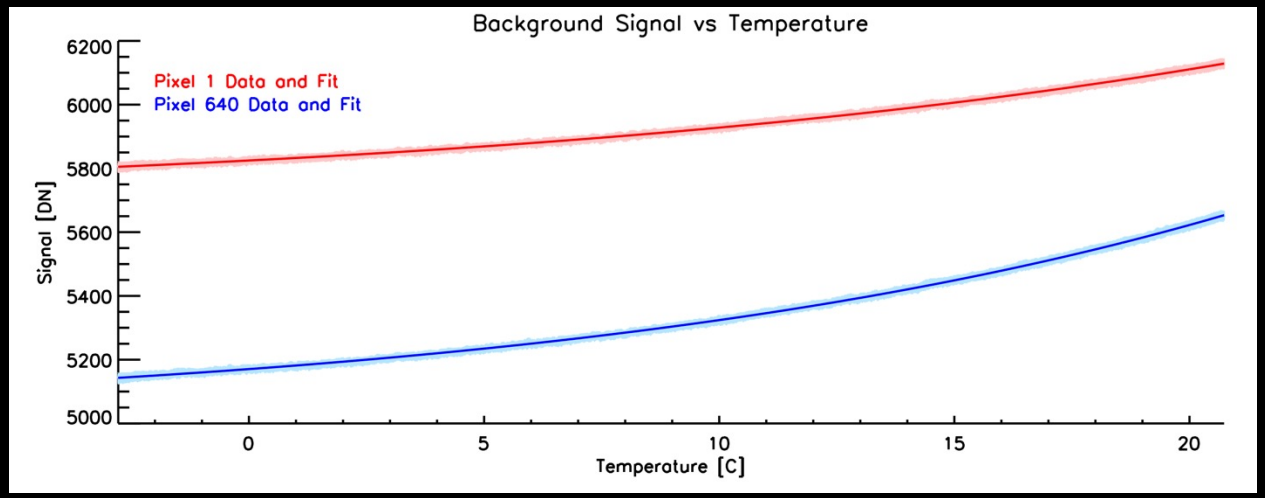
- Has been reduced by 512-pixel spatial-column RSS average for a single image
- Will be reduced further by the multiple images to be acquired to reduce the background-signal uncertainties

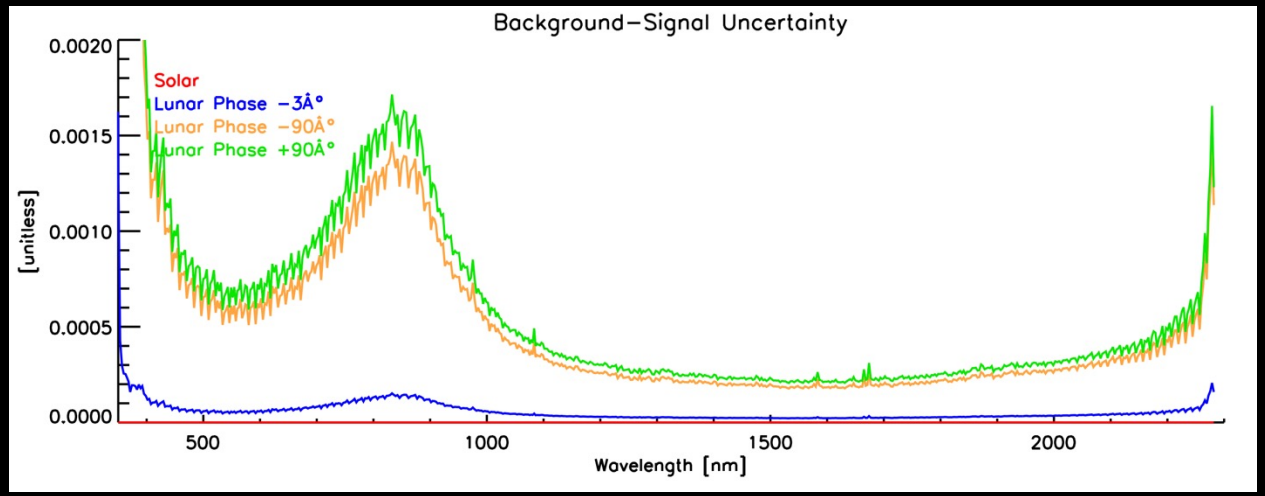


Instrument Level: Background-Signal Uncertainties

- Subsumes read-noise and dark-current uncertainties as well as shot-noise uncertainties due to background
- Estimates assume 500 sec of measurements

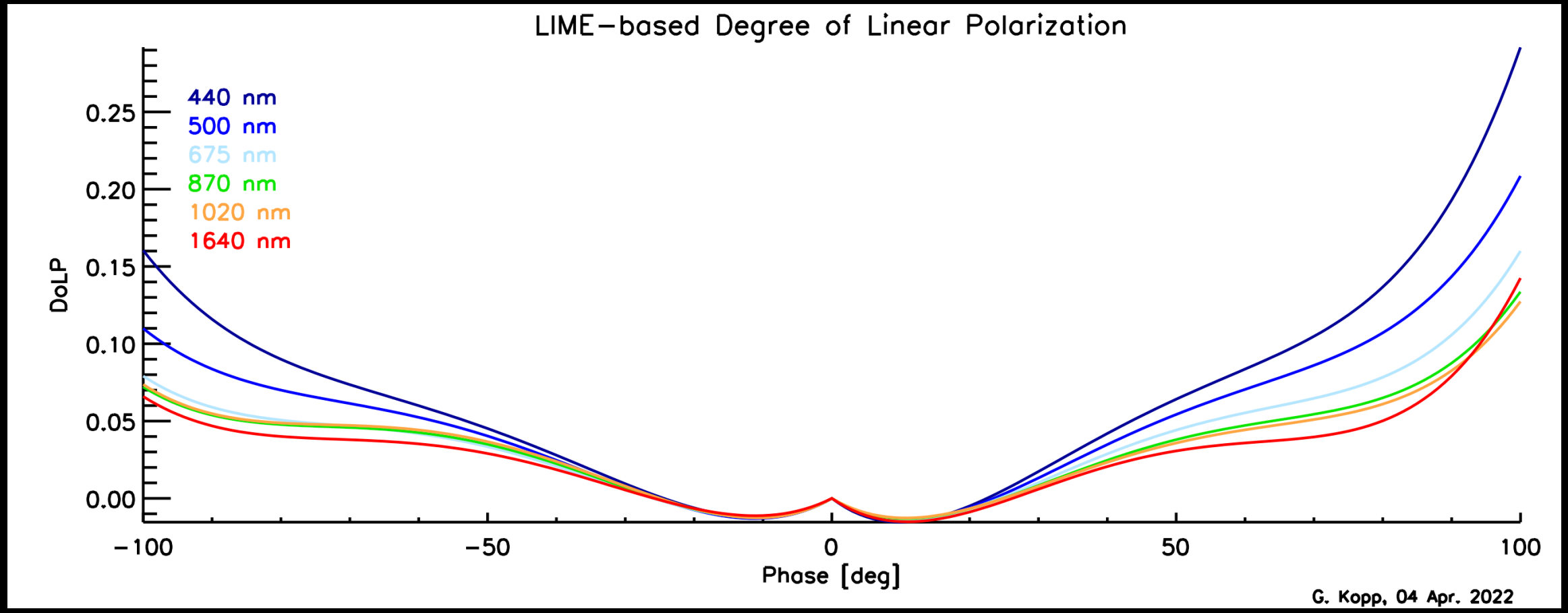






Instrument Level: Lunar-Polarization Uncertainties – Causes

1. Instrument's inherent polarization sensitivity (~ 8 % at 633 nm)
2. Lunar signal's inherent polarization
   - Varies with both wavelength and lunar phase



Lunar-Polarization Uncertainties – Reduction Approaches

1. Do not attempt to correct (Table 1)
2. Correct via lunar-polarization model
   - 0.455 % model uncertainty x 0.5 % instrument-polarization uncertainty = **~ 0.0023 %** uncertainty
   - Will characterize wavelength dependence
3. Measure on-orbit via orthogonal orientations

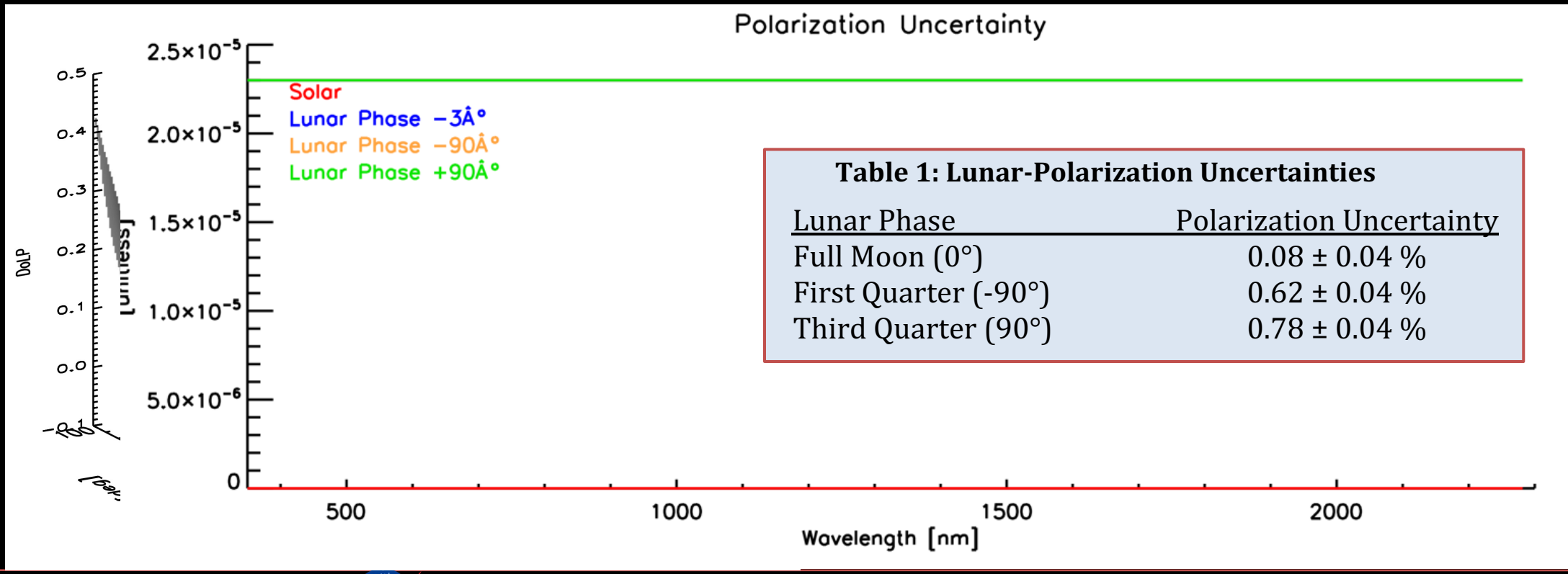
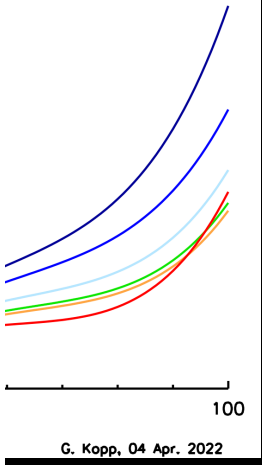


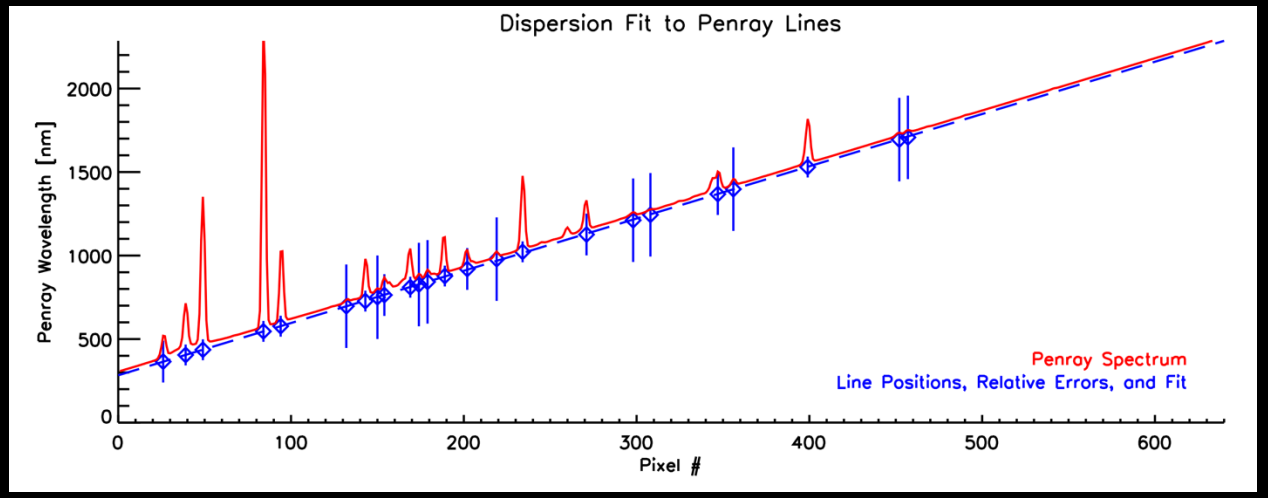
Table 1: Lunar-Polarization Uncertainties

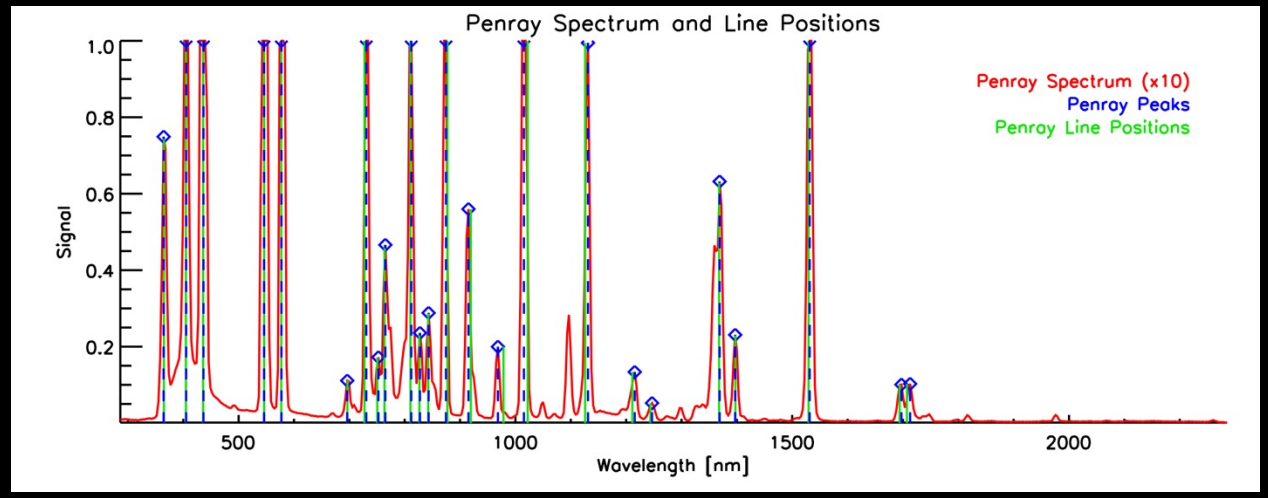
Lunar Phase	Polarization Uncertainty
Full Moon (0°)	0.08 ± 0.04 %
First Quarter (-90°)	0.62 ± 0.04 %
Third Quarter (90°)	0.78 ± 0.04 %



Instrument Level: Dispersion

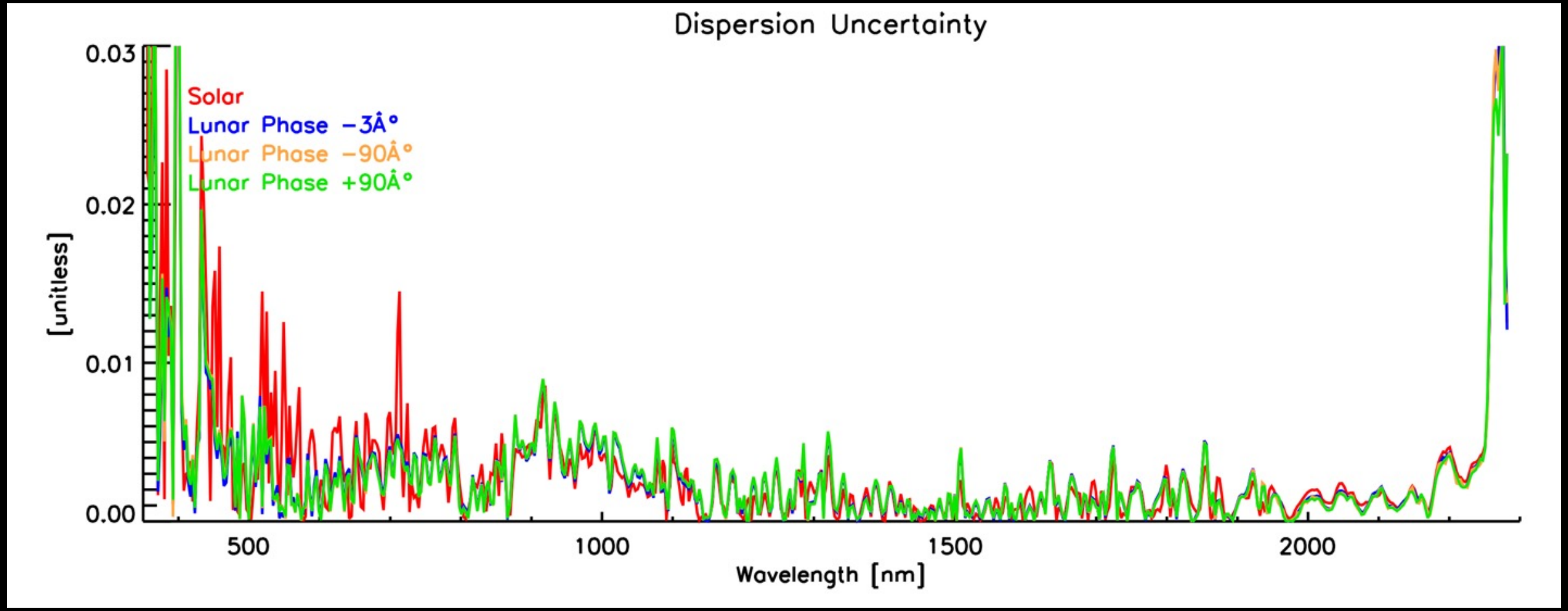
- Achieved wavelength range: **286.31** to **2285.54 nm**
- Dispersion: **3.1287 nm pixel^{-1}**
- Std. dev. of mean: **0.732 nm**





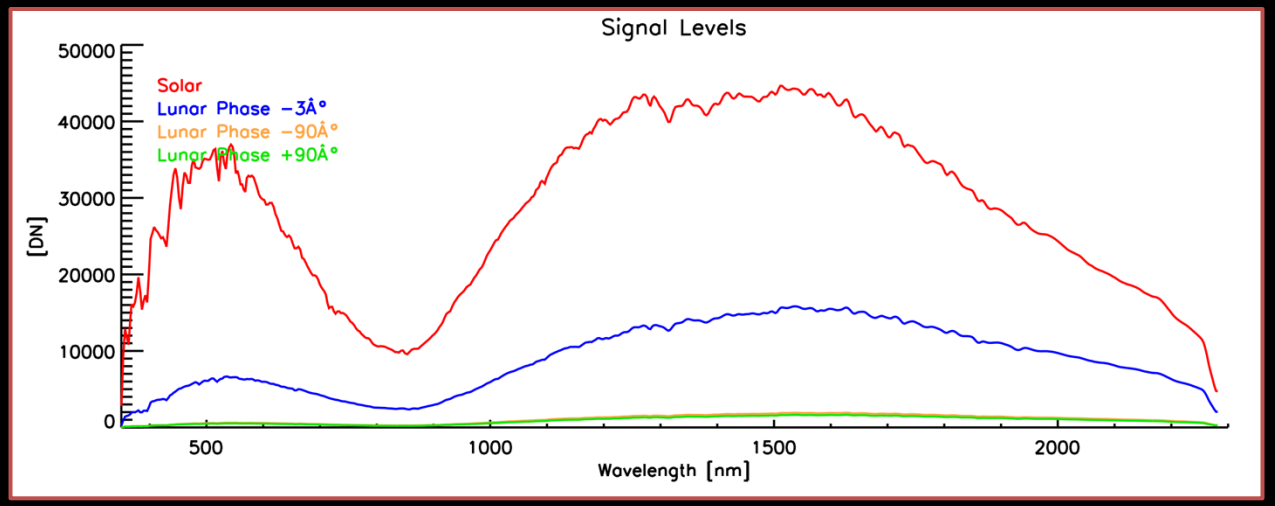
Instrument Level: Dispersion Uncertainties

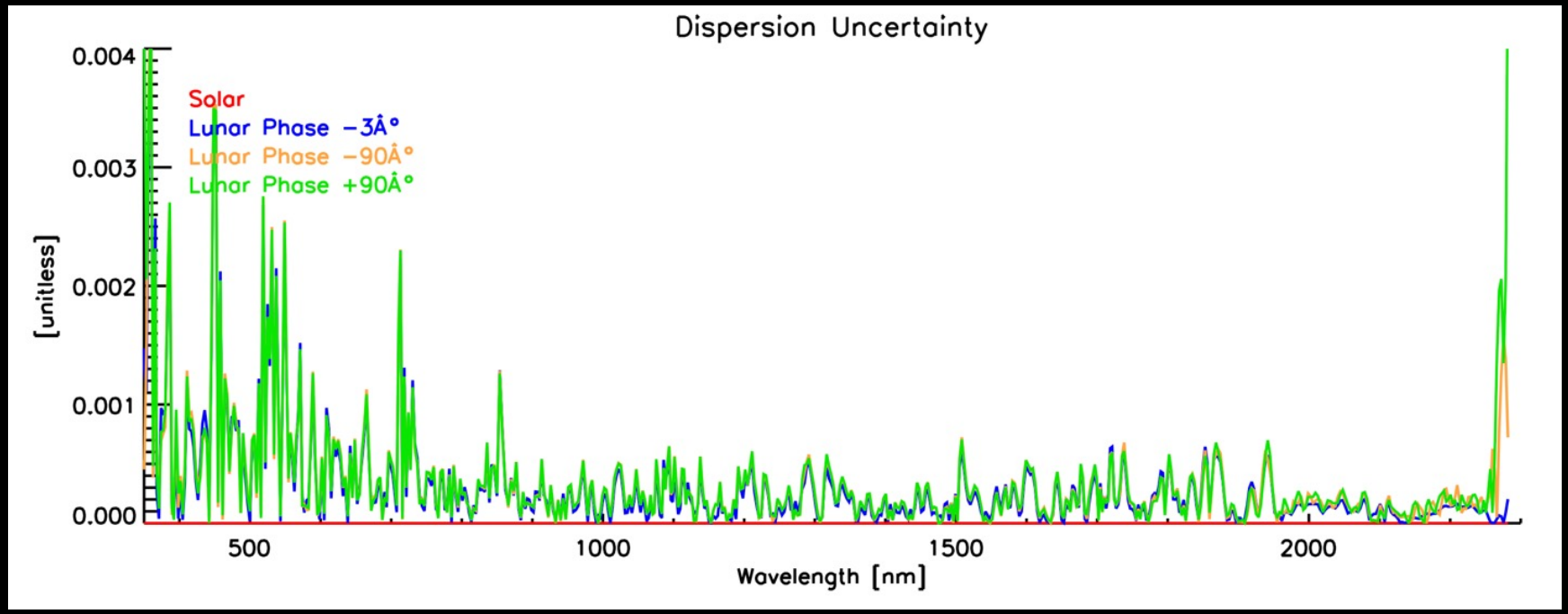
- This exceeds the uncertainty budget
- But...



Instrument Level: Dispersion Uncertainties

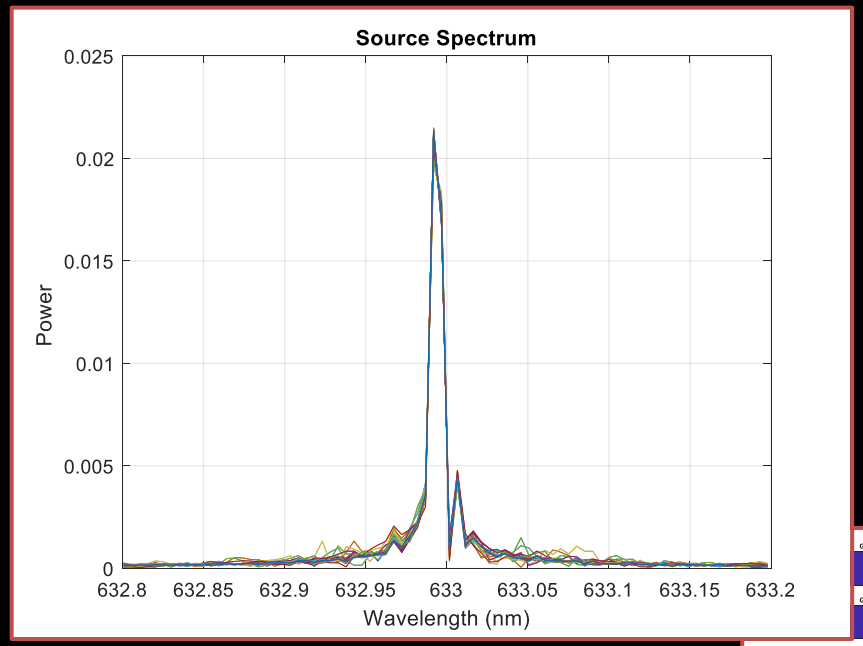
- Dispersion uncertainties are *common mode*
  - This will be applied to CLARREO now too
- Many spikes in results plotted are likely due to lower spectral resolution in ROLO vs. solar model used in these estimates

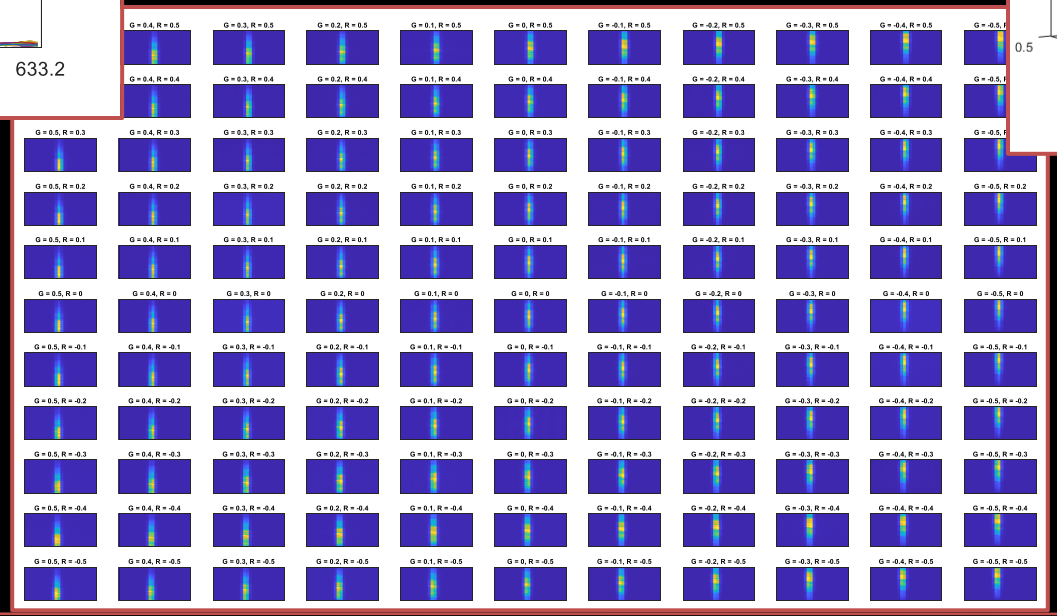


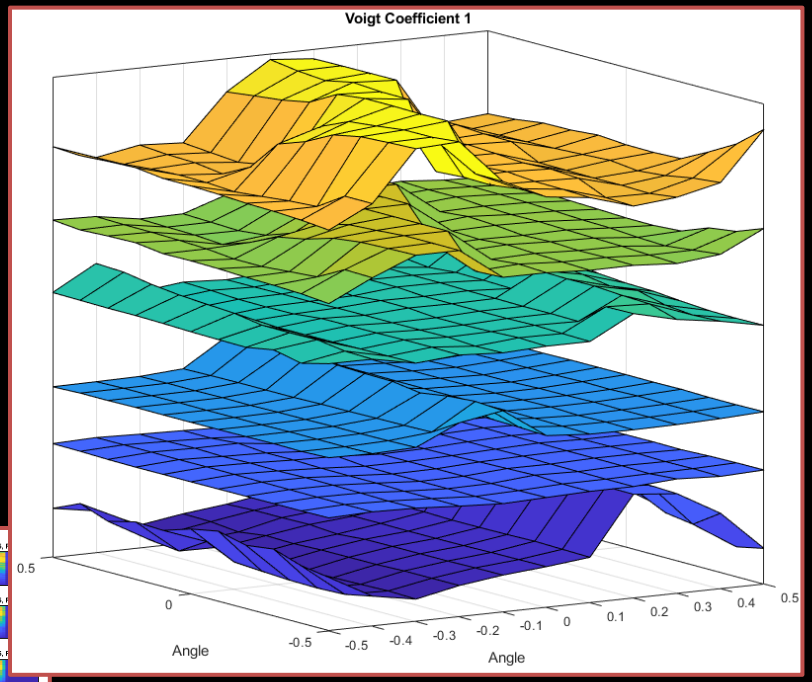


Instrument Level: Instrument Line Shape (ILS)

- ILS is characterized and fitted at multiple wavelengths and angles in both dimensions

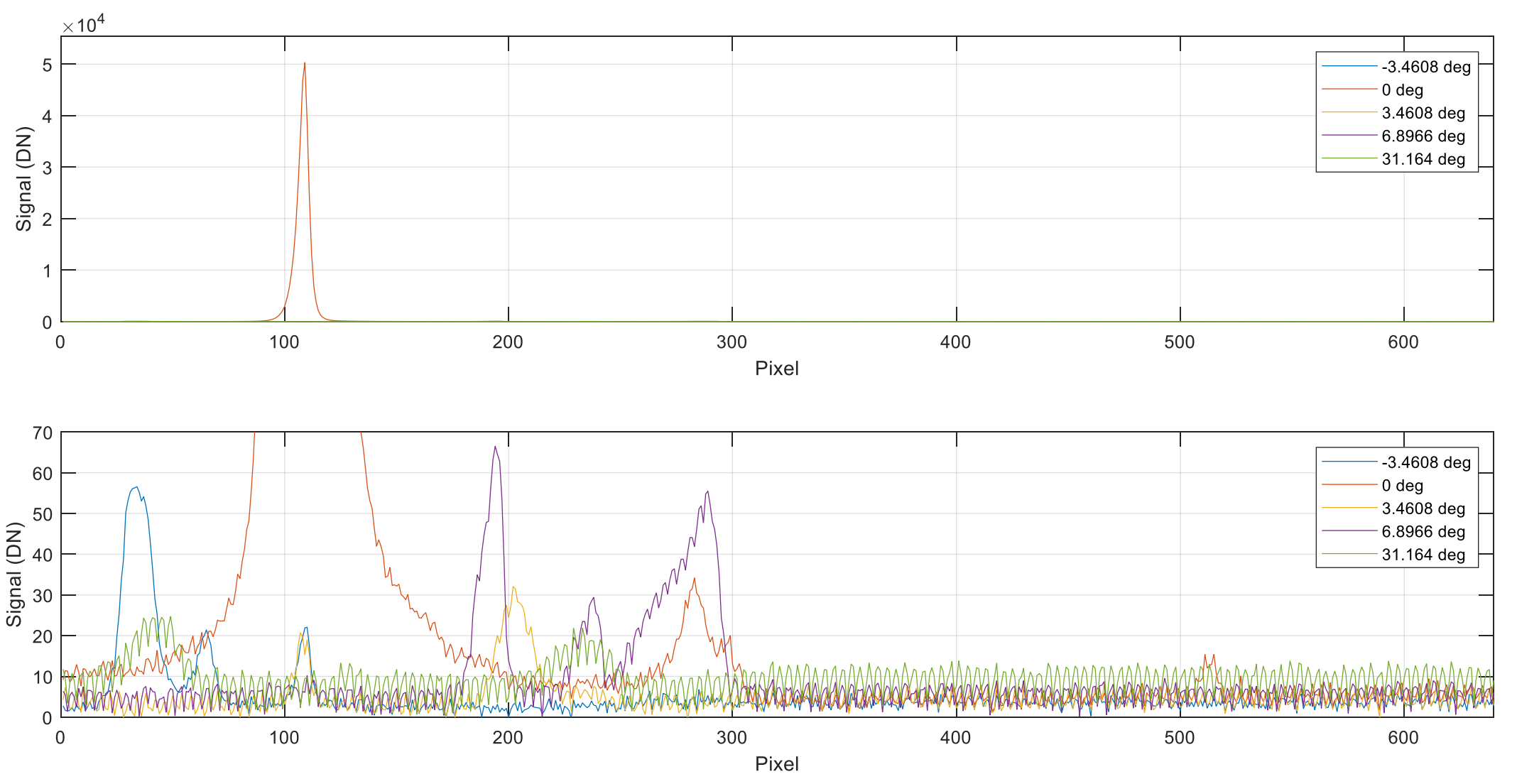




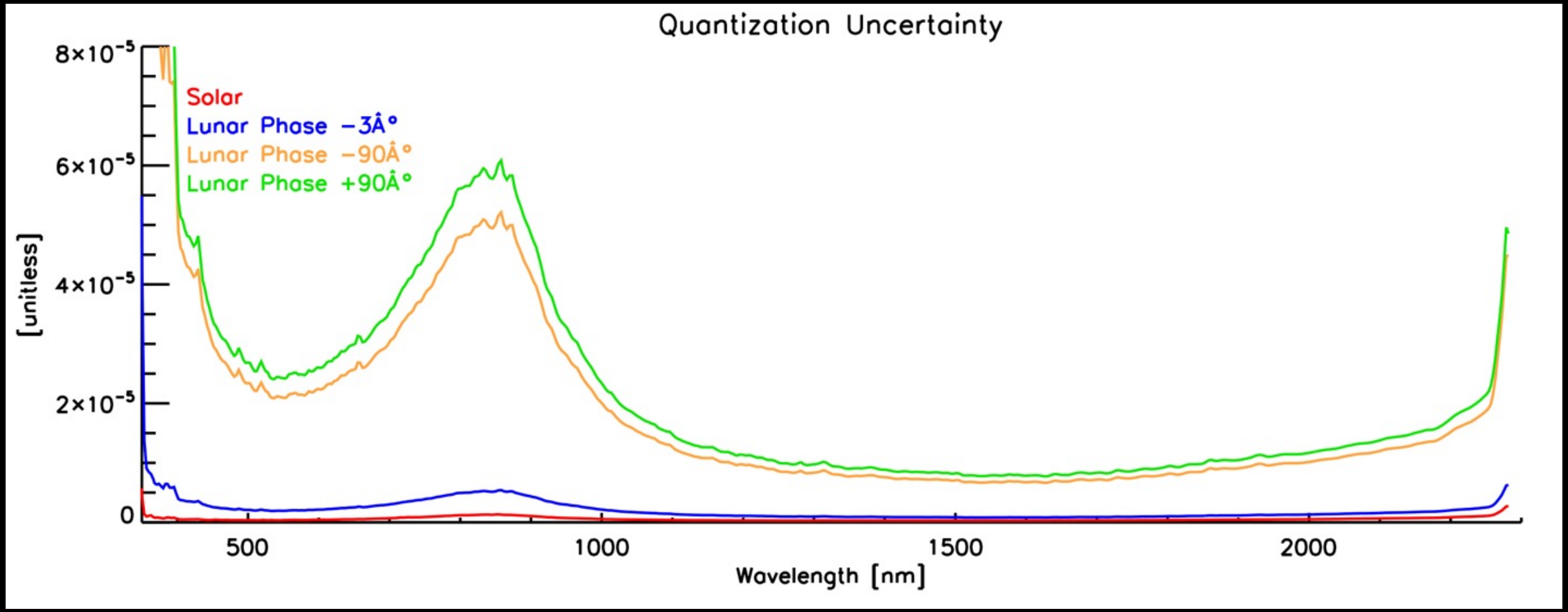


Instrument Level: Stray Light

- Stray light is measured at multiple off-axis angles in both dimensions and is low (~ 10^{-3})



Instrument Level: Quantization Uncertainties



Combined Uncertainties

- With appropriate on-orbit measurements – particularly lengthy background signal measurements, as these are the dominant contributors – *the Intended < 0.5 % (k=1) net uncertainties should be met across most of the instrument's spectral range*

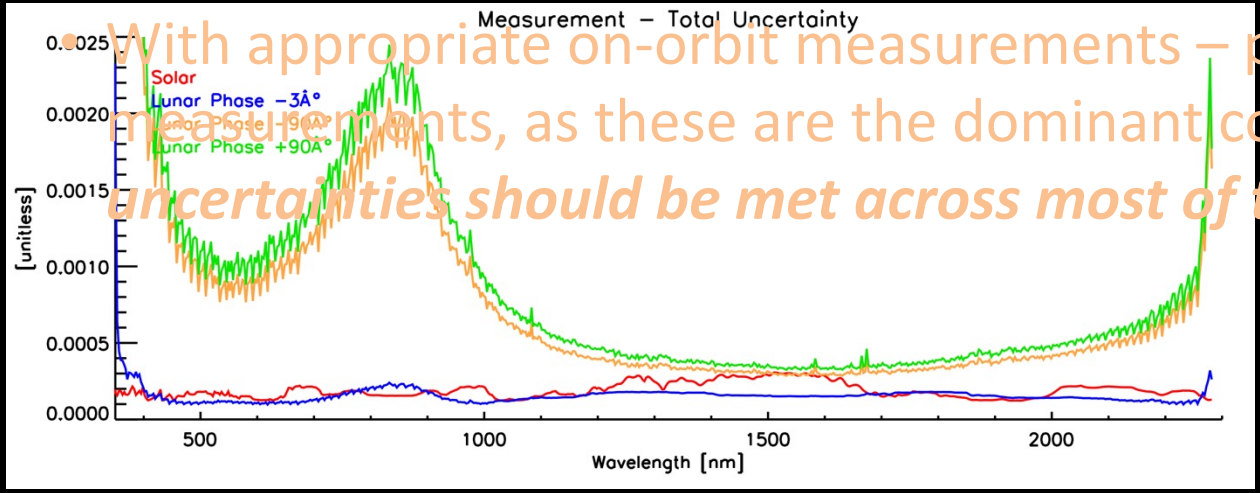
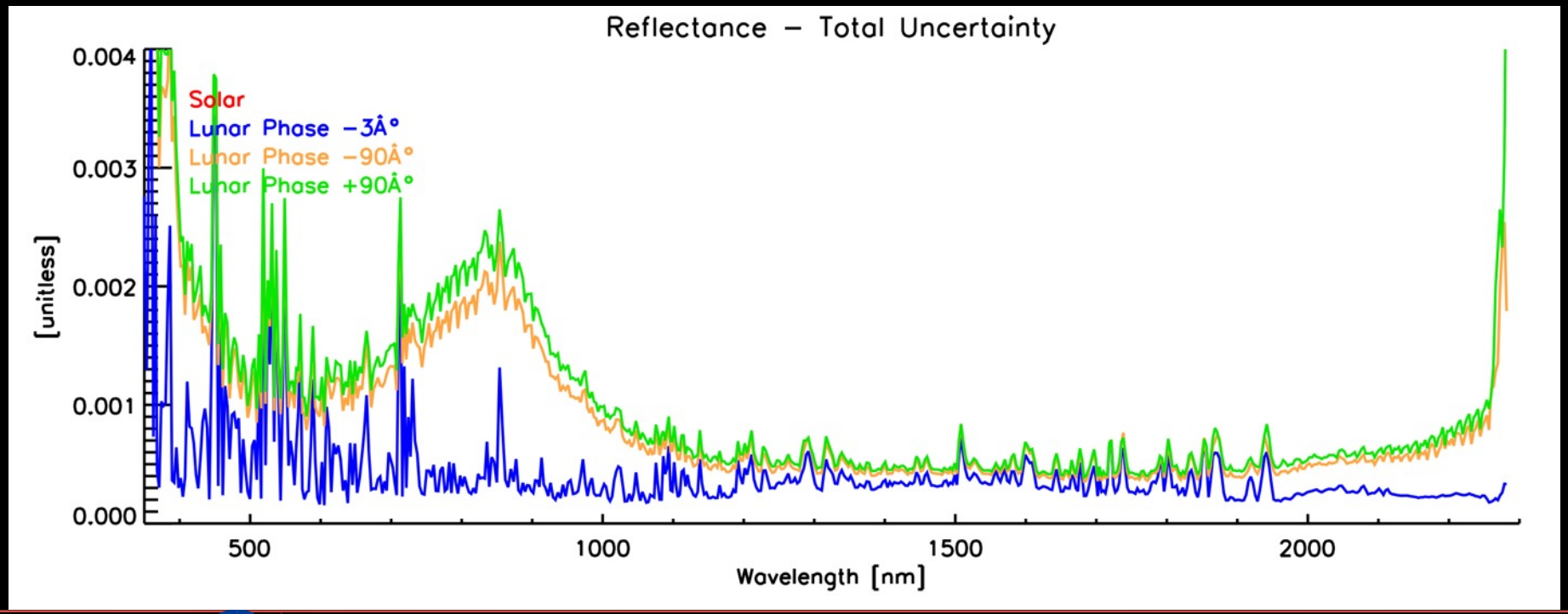


Table 1: Primary Uncertainties Contributing to Measurements

Uncertainty	Solar Meas.	Solar Backg.	Lunar Meas.	Lunar Backg.
Linearity	1x	1x[1]	1x	1x
Backgnd Stability	1x	1x	1x	1x
Shot Noise	1x	2	2	2
Read Noise[2]	-	-	-	-
Quantization	1x	1x	1x	1x
Dispersion[3]	-	-	-	-
Polarization[4]	-	-	1x	1x



ARCSTONE IIP – Issues & Improvements for InVEST

- **Issue**: Requires lengthy background-signal measurements and thermal stability on ~ 20-min timescales
- **Improvements**: Report includes several suggestions for improvements and additional effects specific to InVEST (prioritized)
  1. Verify linearity stability on-orbit
  2. Achieve full spectral range
  3. Correct for lunar-phase (look-angle) changes during lengthy observations
  4. Trade higher uncertainties for shorter background-signal observation times
  5. Include instrument- and lunar-polarization sensitivities at multiple wavelengths
  6. Parameterize dispersion vs. wavelength via optical model to improve dispersion uncertainties
  7. Understand (and measure) stray light and OBF high-order diffraction leakage
  8. Parameterize ILS via optical model to smooth interpolations
  9. Use non-binary lunar-phase and solar masks for ILS sensitivities
  10. Estimate uncertainties from S/C pointing effects in lunar-phase and solar masks
  11. Evaluate downlink vs. on-orbit processing

Improving Calibrations of Lunar Spectral Measurements

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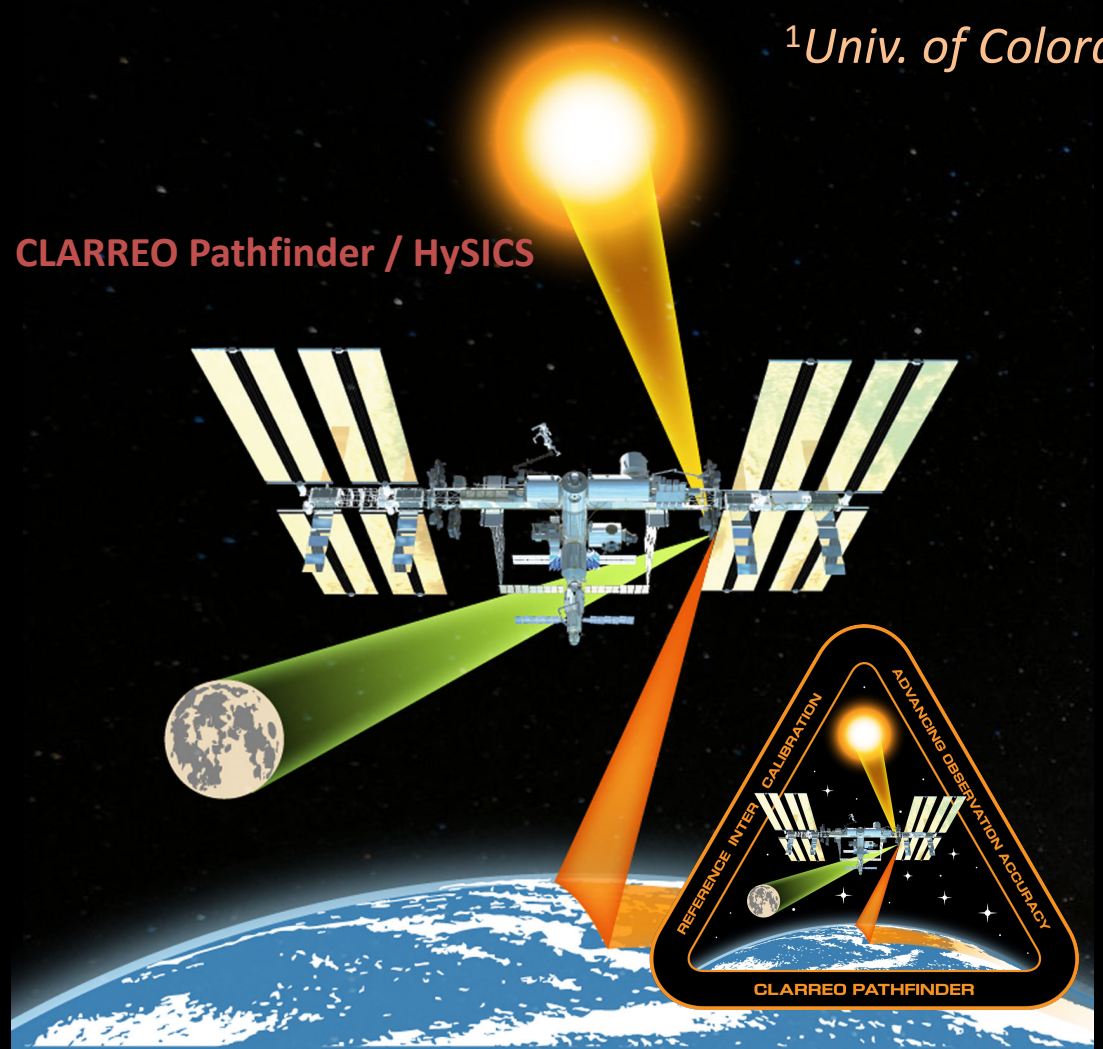
CLARREO Pathfinder / HySICS



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