ALTIUS Level 1 Calibration Activity

Topic: B3.01 ALTIUS

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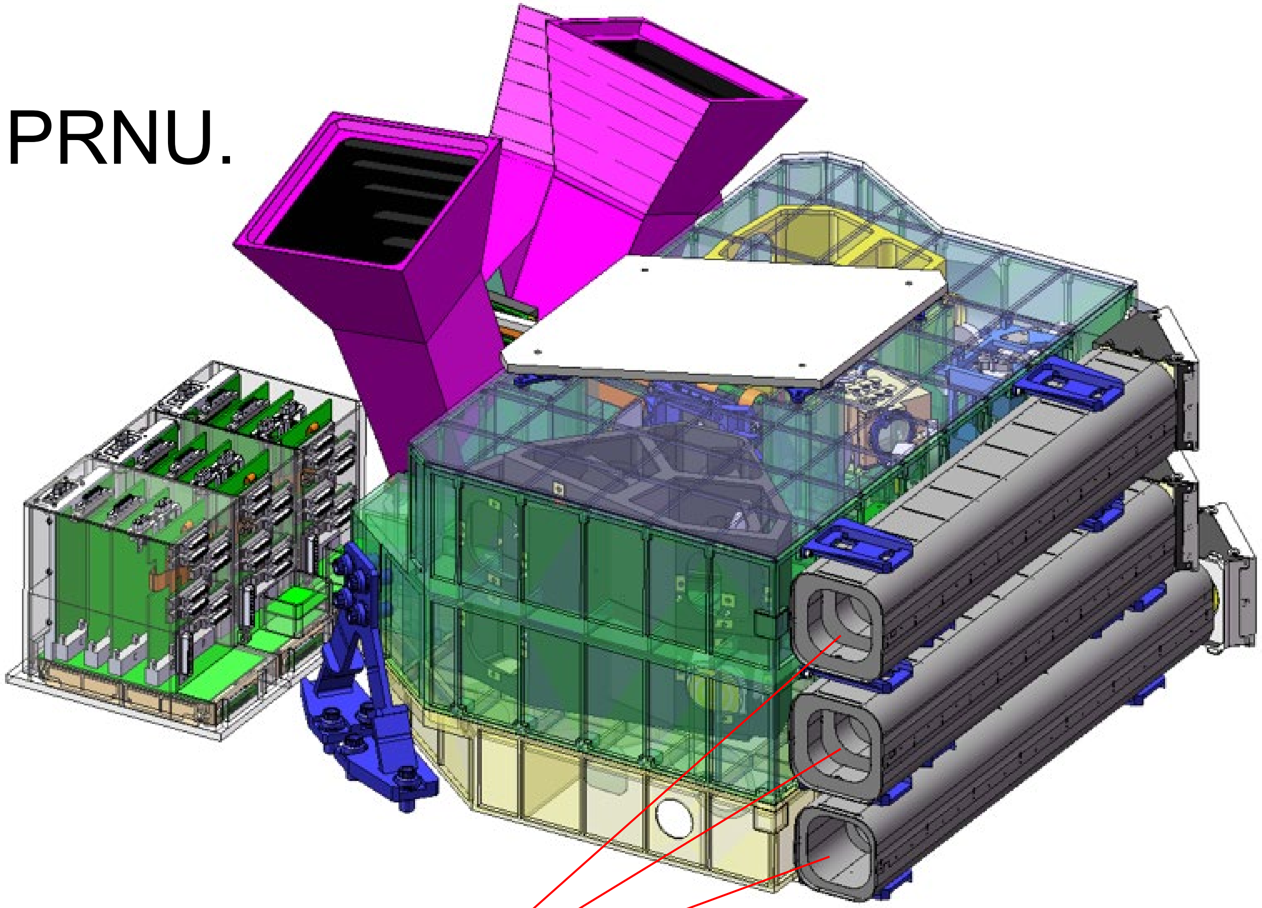
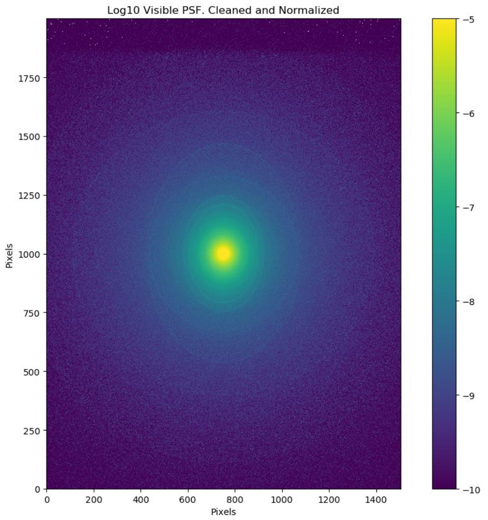
- Stray light.
- Photo-response non-uniformity, PRNU.
- Wavelength Registration.
- Polarization.

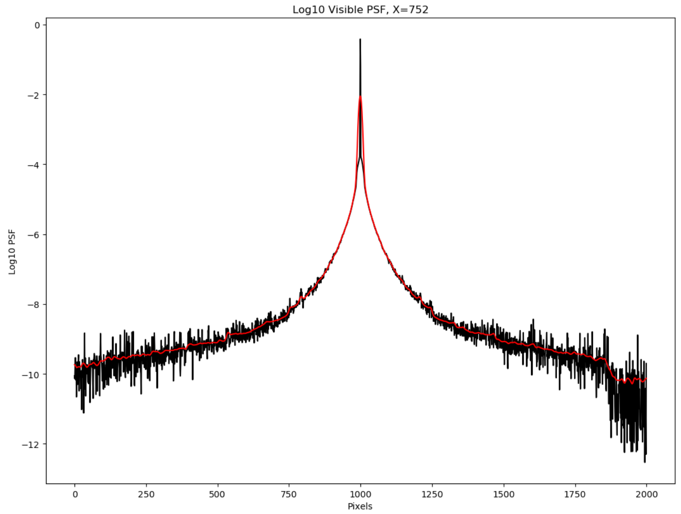


3 channels. UV, VIS, NIR

Stray light algorithm

VIS Channel at 550 nm





- The PSF of the three channels has been estimated with Zemax for a selection of wavelengths.
- The PSF is spatially variant and has a wide range of influence. This is problematic for limb observations.
- Simple deconvolution is not valid. Instead, the observed signal, S(**x**), at position **x** is an integral of the incoming scene, R(**x'**), convolved with a spatially variant point spread function, **P**.

$$S(\mathbf{x}) = \int_{\mathbf{X}'} \int R(\mathbf{x}') P(\mathbf{x}, \mathbf{x} - \mathbf{x}')\, \mathrm{d}\mathbf{x}'$$

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Stray light algorithm

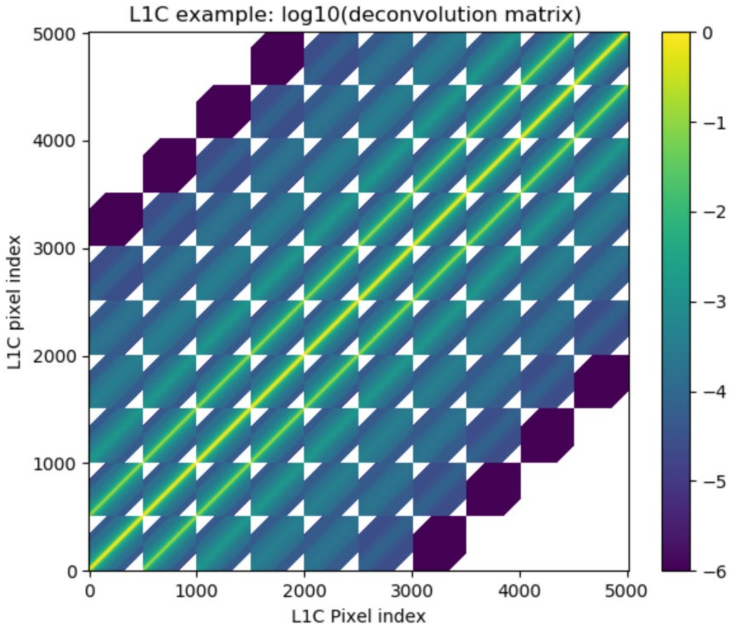
The integral equation can be approximated as a matrix equation. The blurred image, S, is generated by summing all elements of the true profile, R, that contribute to each element of S, weighted by the appropriate weight, P, from the point spread function.

$$\mathrm{S} = PR$$

The true profile, R, can be immediately calculated by taking the inverse.

$$\mathrm{R} = P^{-1}S$$

Example matrix: P



1. Full resolution Altius images (512 x 514) generate very large matrix arrays (of the order 250,000 by 250,000) which are not manageable on standard computer systems.
2. We assume horizontal homogeneity and horizontally bin in 50 pixel steps. Reduces the image to (10 x 514) which is manageable.
3. Generating matrix P takes 4-12 hours on a modern, multi-core, desktop machine: the code is not complicated but has to perform trillions of floating-point calculations. It is a one-time calculation.
4. Application of P^{-1} is quick and takes a fraction of a second.
5. The matrix inverse is stable and accurate. It does not (yet) require more sophisticated methods, e. g. regularization.

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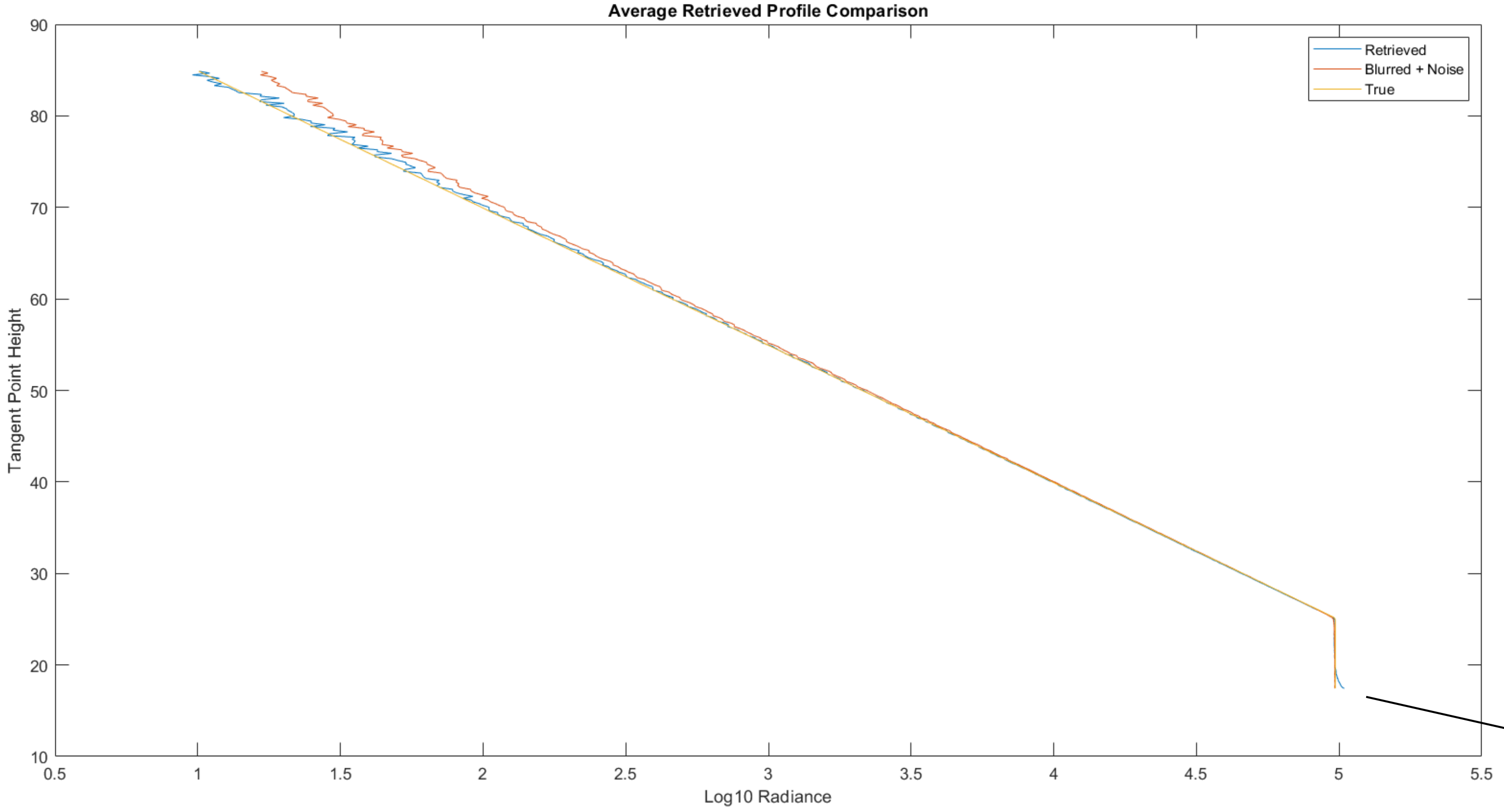
Stray light algorithm

An example in the presence of noise. Works well



The stray light at high altitude due to bright signal at low altitude is removed.

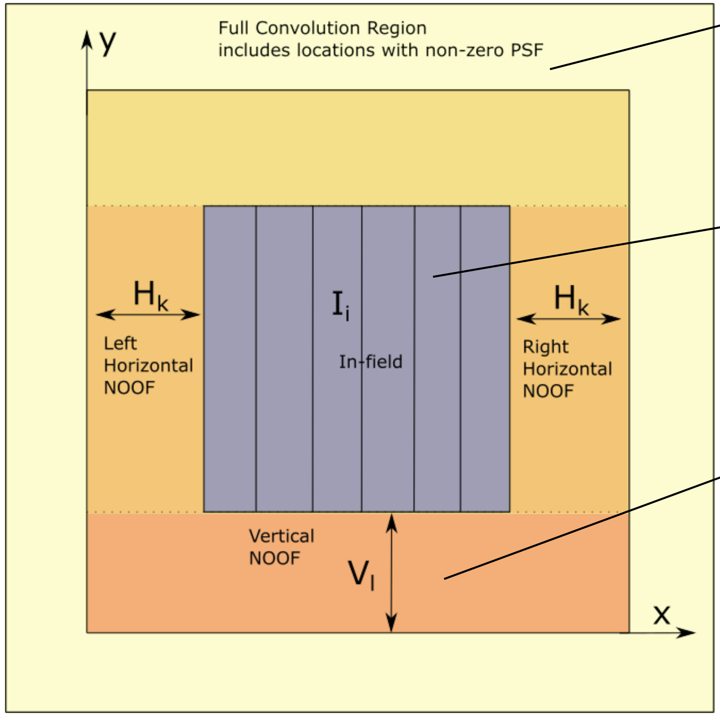
The orange curve is the "measured" signal. The "blue" curve is the retrieved signal.

Its difficult to see, but the "retrieved" blue line is on top of the "yellow" true line.

Small edge effect at low altitude. Needs a bit more tweaking

Stray light: Out-of-field

- The preceding algorithm is only for “in-field” stray light, where we can generate a consistent set of relationships between measurement and incoming signal.
- There is significant stray light from out-of-field sources. These are more complicated as there are no direct measurements of the out-of-field region. We cannot solve the matrix equation $R = P^{-1}S$ for these regions as the measurements, S are not available.



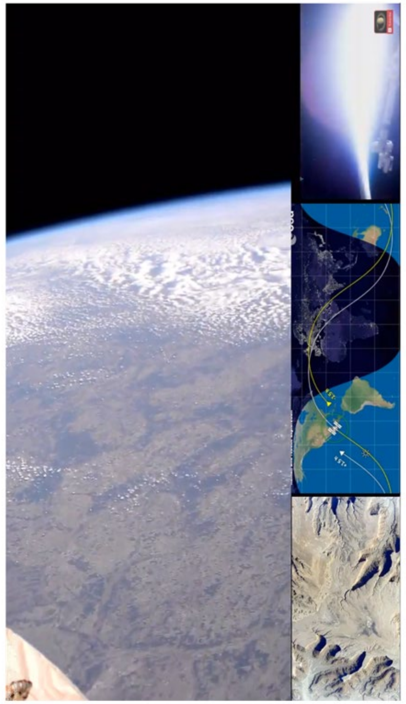
Far out-of-field regions (FOOF). Rays from the out of field scene are not imaged on the detector plane. Light scatters off front-end optical surfaces

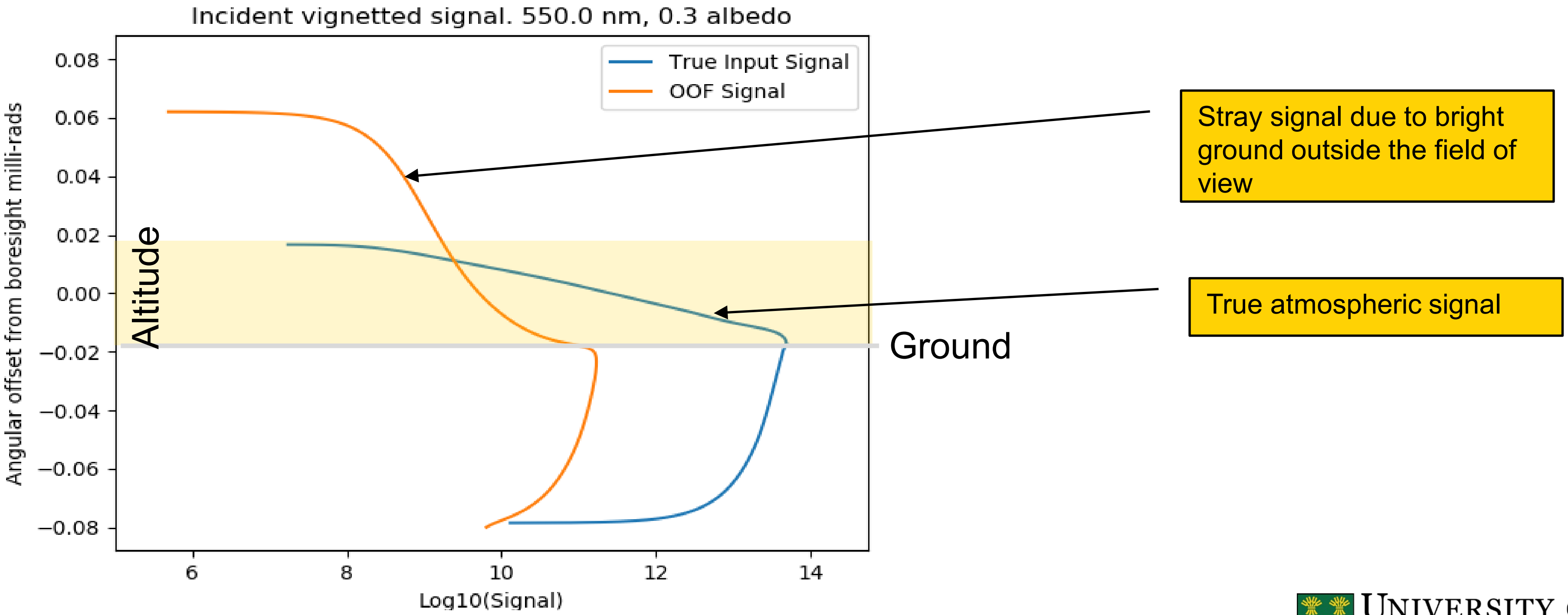
In-field region. Stray light can be managed in a quasi-self-consistent manner.

Near out-of-field regions (NOOF). Rays from the scene are imaged on the detector plane but are not collected by the detector

Stray light: Vertical

- The ground is very bright in visible channels. Ten to twenty times more photons enter the front aperture from out of field than in-field.
- The angular fall-off of stray light is slower than the fall of true atmospheric signal for even the cleanest, smoothest optics available.
- There is an altitude at which stray light from the ground will dominate true atmospheric signal.
- This is the basis of the high-altitude proxy algorithm.





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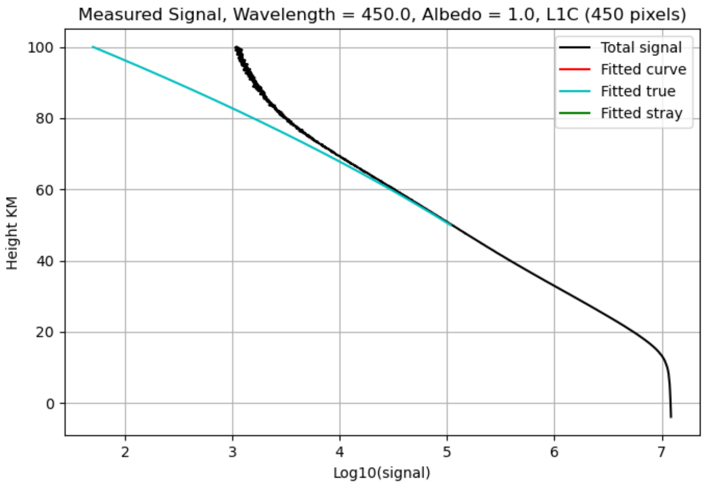
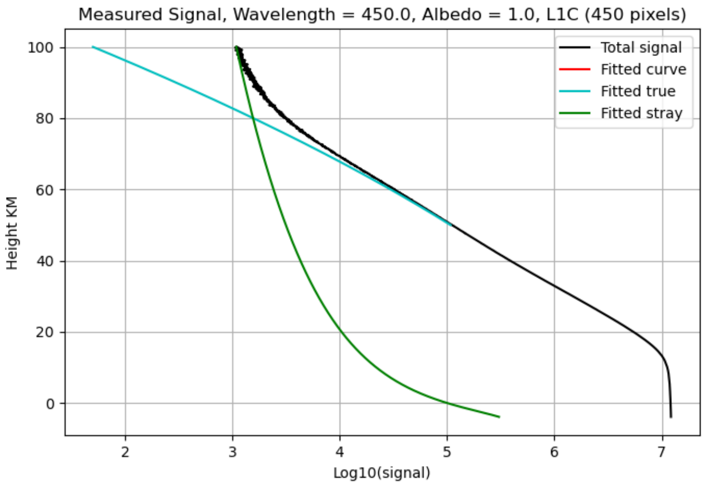
Stray light: Vertical proxy

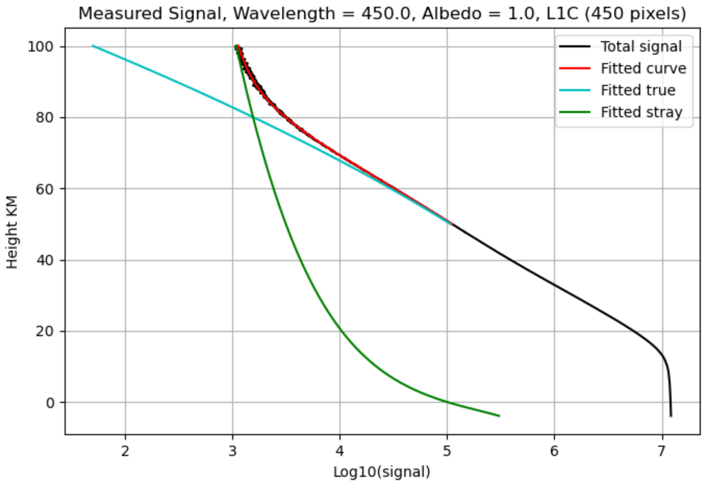
- Represent the far-field stray light PSF as a modified Harvey function (or similar).
- Model the (unknown) out-of-field ground signal as a low order polynomial (e.g. constant or linear).
- Evaluate the PSF integral contributions from the out-field ground region to the measured atmospheric profile. Simple polynomials for the out-of-field signal permit an analytic evaluation.
- Fit PSF integral contribution to the measured high-altitude stray light proxy until there is a good fit (see red curve in right hand figure).
- Algorithms are still under development as they need tuning for each operational wavelength.



1) Model log of true signal above 50 km as a 3-term quadratic (cyan).



2) Model straylight as the PSF convolved over the out-of-field region and multiplied by a constant (green)



3) Adjust 4 parameters in non – linear fit until a good fit. (red)

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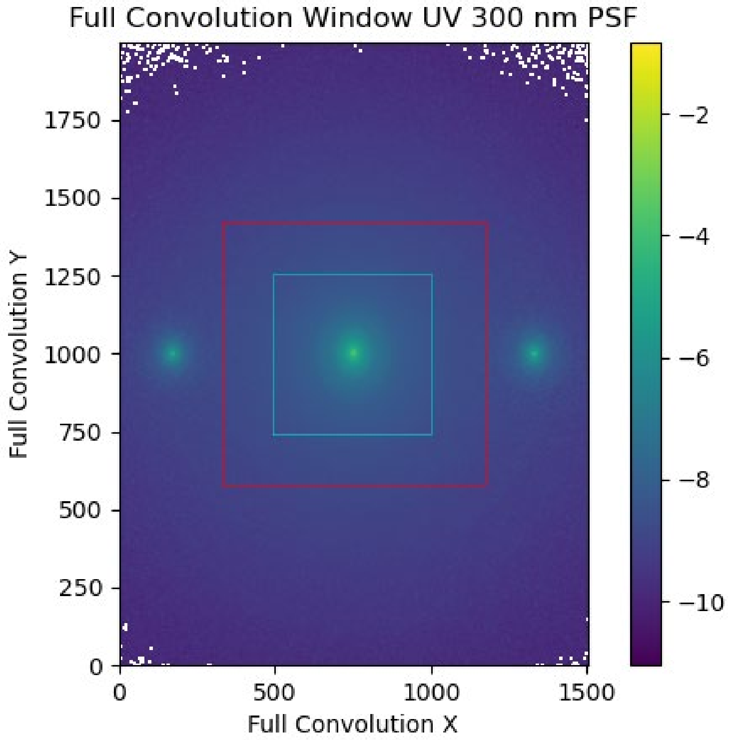
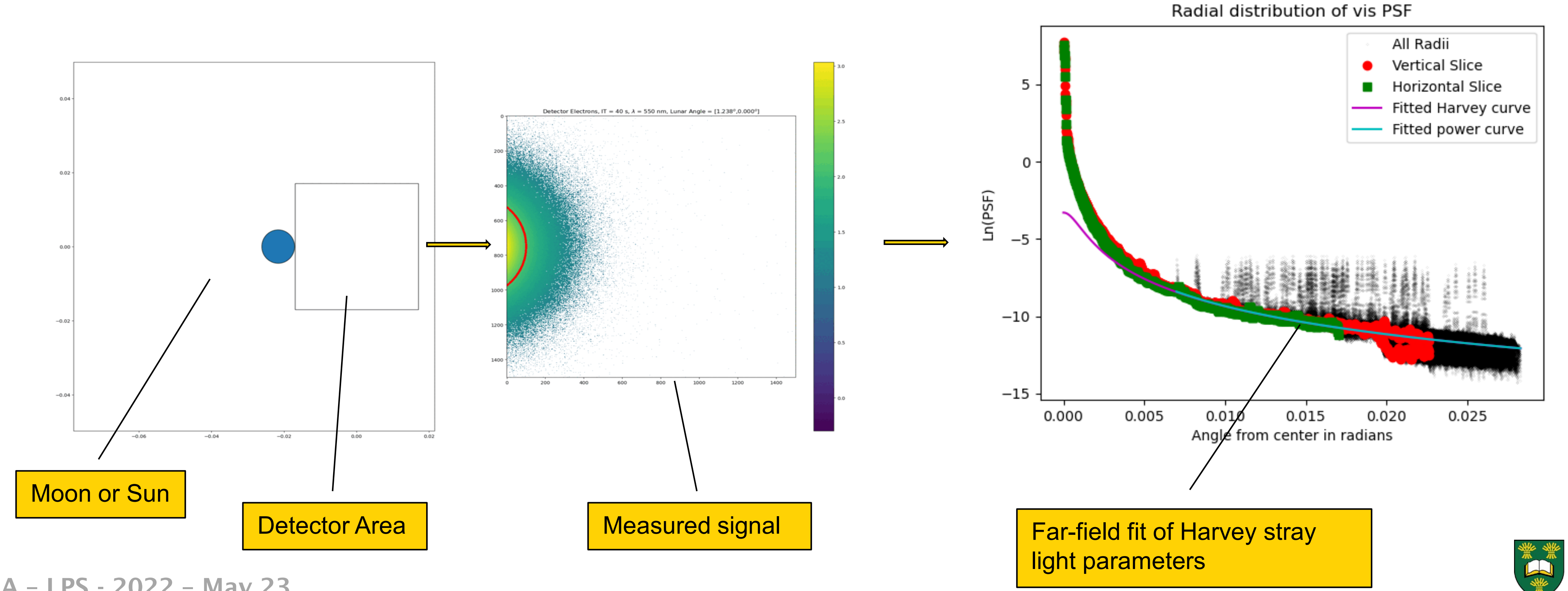
Stray light: Ghosts

- The UV channel has the additional complexity of a couple of ghosts due to reflections within the internal Fabry-Perot complex.
- The ghosts are located outside the near-out-of-field region (shown in red) but are able to contribute a non-negligible signal to the edges of the in-field region.
- In limb mode, we estimate the value of the incoming radiance, S, at the ghosts (in $\mathrm{R} = P^{-1}S$) by assuming horizontal homogeneity in the atmospheric signal.



Stray light: Inflight Measurement

- Goal is to measure the far-field stray light response.
- Stars are excellent point sources such but are far too dim.
- Sun and moon are bright extended sources that will create a measurable signal without needing to image the disk on the detector. This is our default inflight measurement technique.
- Also, possible to use the vertical stray light observed in the Earth's limb.



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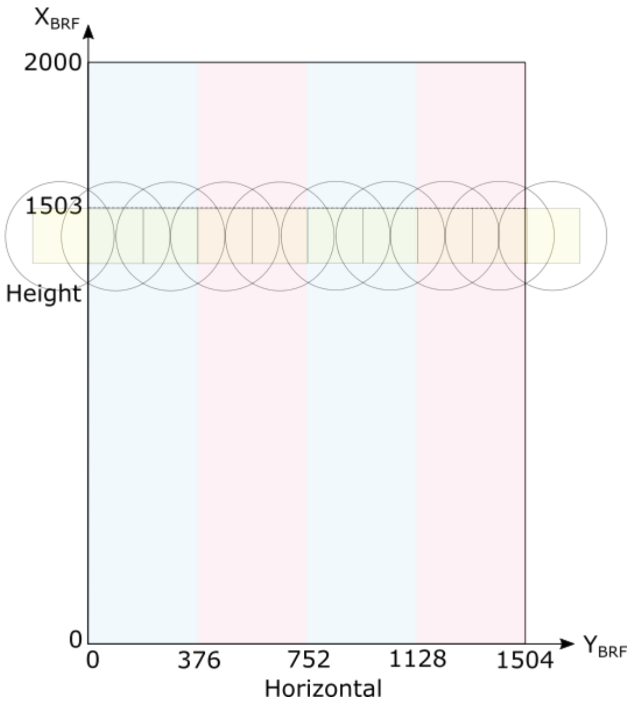
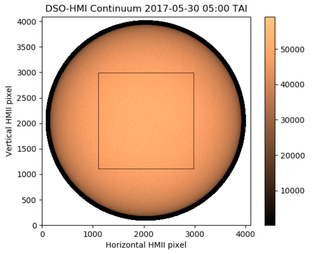
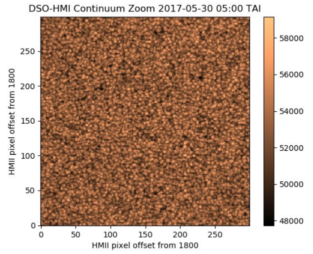
PRNU

- The task is to provide a relative (and absolute) calibration of the 250,000 pixels of each detector at each operational wavelength.
- There is no onboard source or diffuser plate. Calibration solely depends upon natural extended sources accessible from low earth orbit. i.e. Sun, Moon, Earth.
- The Sun is a good candidate as it the most uniform of all three targets. It is very stable if we ignore sun-spots and brief periods of activity (CME etc.). High resolution databases of solar spectra exist (e. g. SAO 2010).



- Baseline plan is to raster scan the solar disk (circles) across ALTIUS field of view in a 10x10 grid. This allows us to only use the central section of the solar disk where limb darkening is well-understood.
- ALTIUS pixels are big enough that solar granulation is not a big issue.
- Full disk measurements of lunar irradiance (similar to Sea-Wifs) allow for calibration of the neutral density filter used to observe solar disk.
- Also considering other flat-fielding algorithms e.g. Kuhn and Lin 1991, but suspect we will always need ~100 images to calibrate each operational wavelength.





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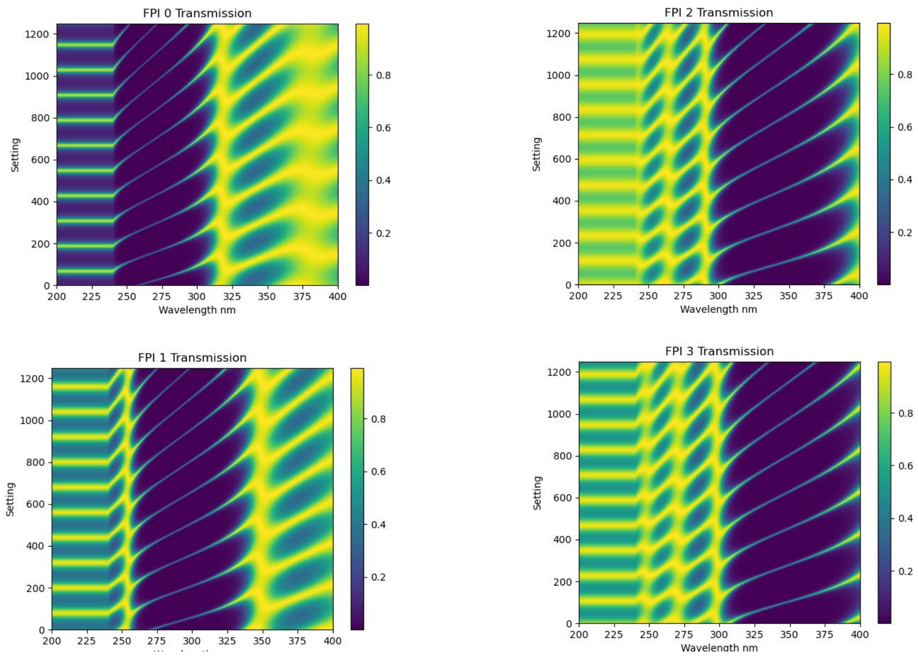
Wavelength Registration: UV

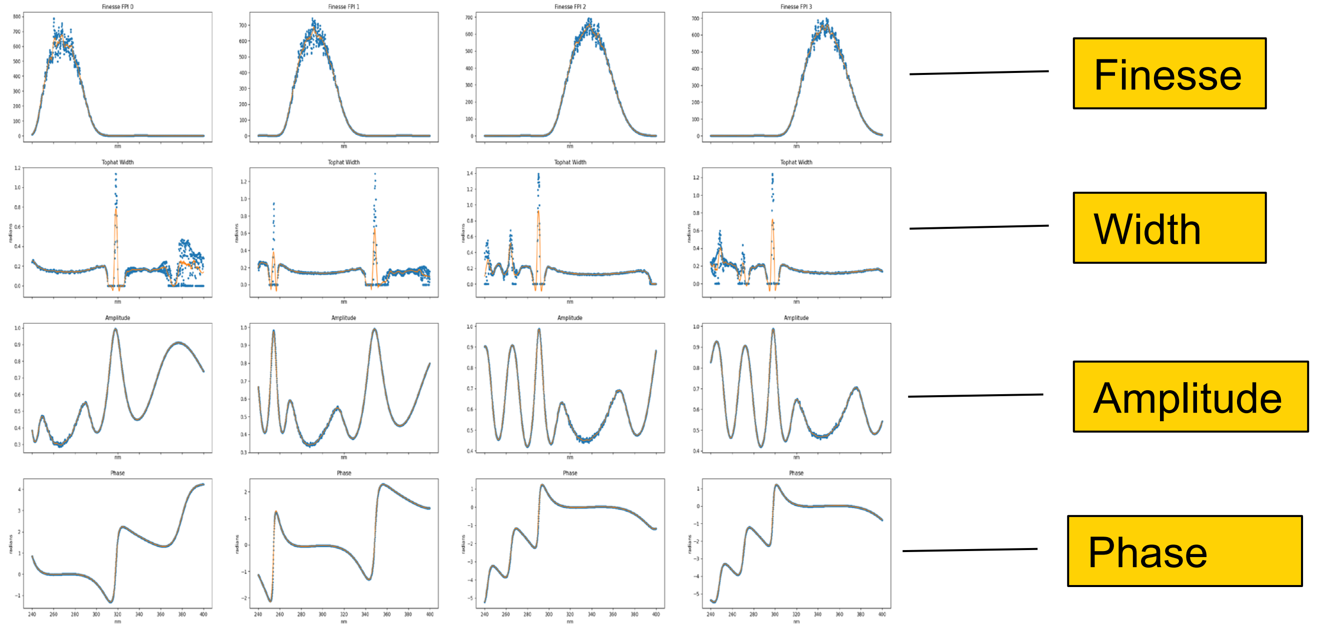
- The ALTIUS UV channel consists of 4 stacked Fabry-Perot interferometers.
- The gap of each FPI can be accurately set to any air-gap value between ~400 nm and 1800 nm.
- The coating of each FPI is carefully designed to give the desired transmission properties.
- The total transmission is the product of the transmission of each FPI.
- The transmission of each FPI is accurately described for all air gaps using a 4 parameter, wavelength dependent fit.
- At any wavelength only two FPI units are spectrally active. The other two are closer to passive colored glass.

FPI Transmission



Wavelength 240-400 nm

FPI Parameterization



Wavelength 240-400 nm

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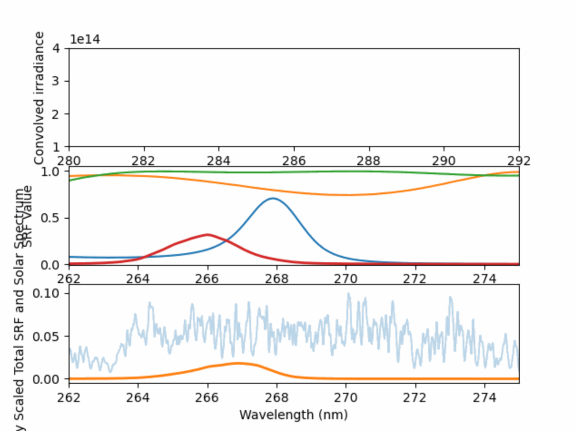
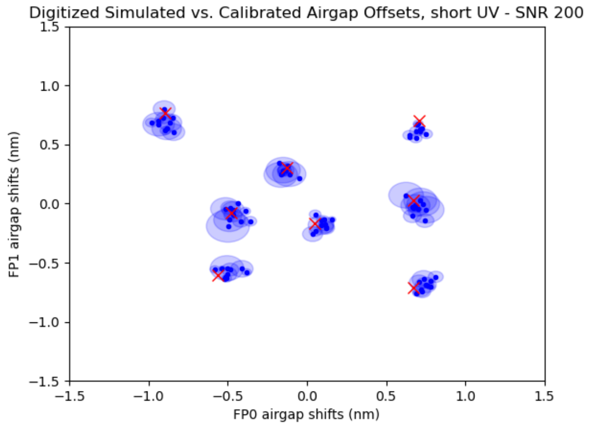
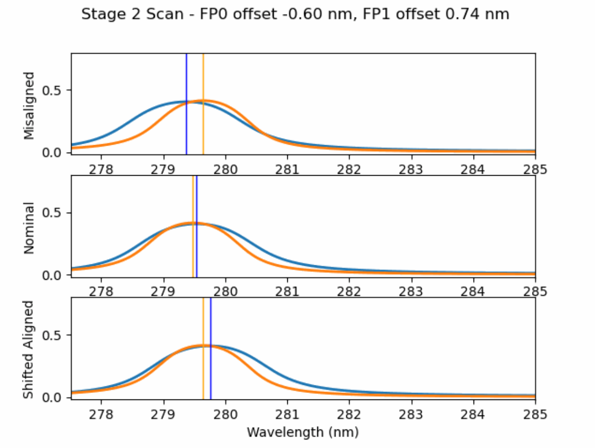
Wavelength Registration: UV

Wavelength registration is determined by fitting observed signals as we spectrally scan across solar Fraunhofer lines. We implement a two-step process.

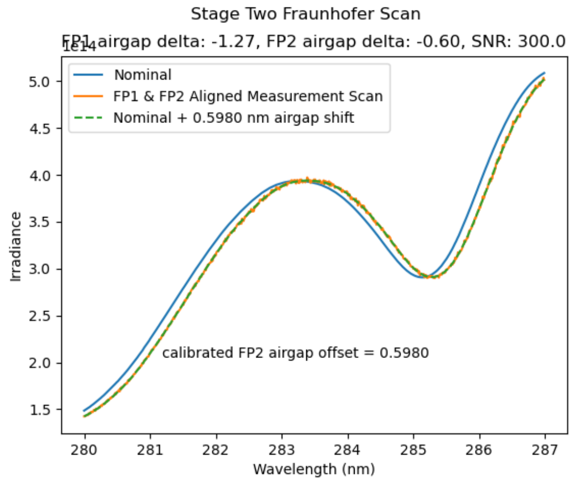


Step 1: Estimate offsets required to align the air-gaps. Hold the air-gap of one active FPI constant in a relatively flat region of the solar spectrum. Scan the air-gap of the other active FPI. Provides the air-gap correction required to align the two active FPI units.



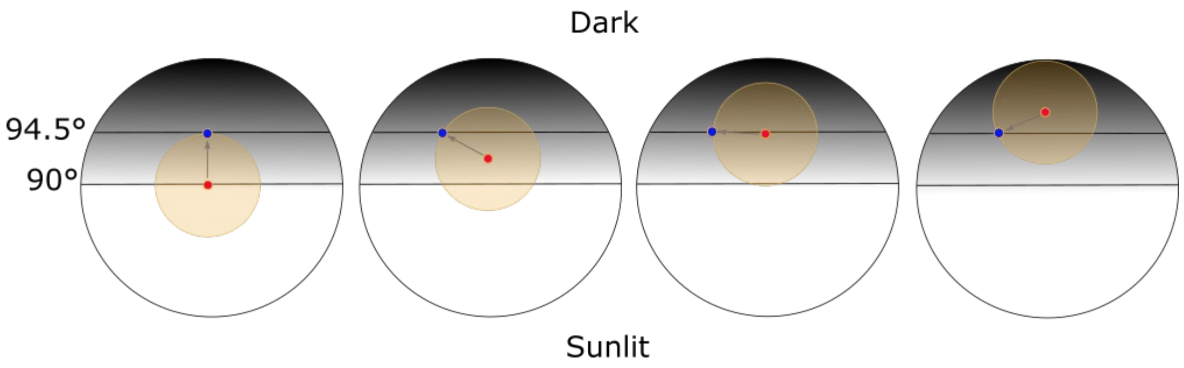


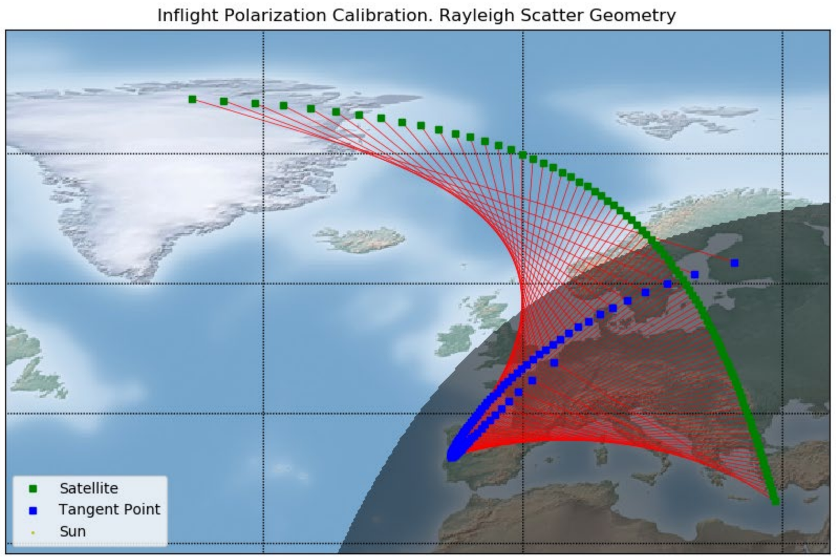
Step 2: Spectrally scan both active FPI units across a spectral region with good variance. Provides accurate wavelength registration when combined with Step 1.



Polarization

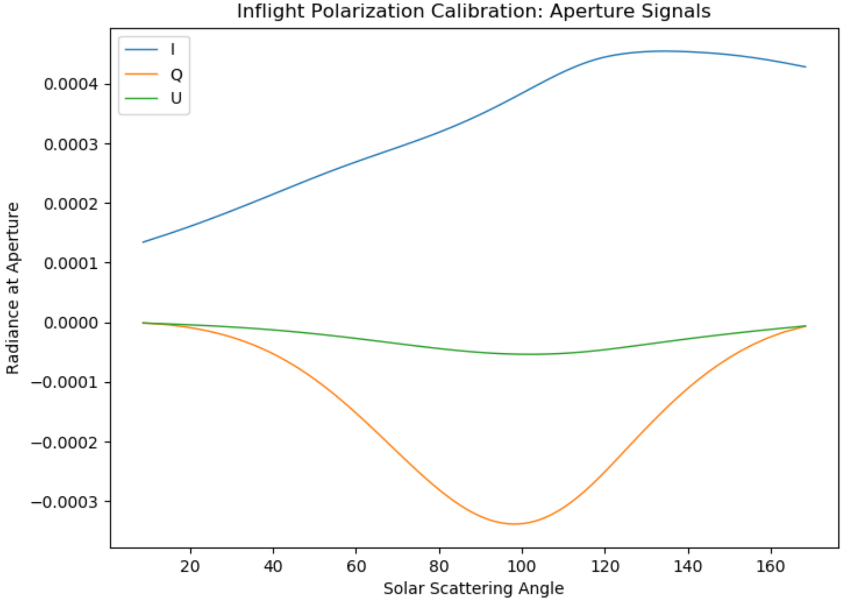
- The NIR and VIS channels use AOTF technology which inherently has a strong linearly polarized response.
- The atmosphere can be used as a source of known polarization state. The trick is to find a geometry that is a good approximation to single scatter by suppressing the upwelling ground albedo signal. This happens at 60 km tangent altitude when that tangent point is at a solar zenith angle of 94.5 degrees.
- As the satellite moves from dayside to darkness (or vice-versa) it is configured to rotate and stare at the tangent point at 94.5 degrees.





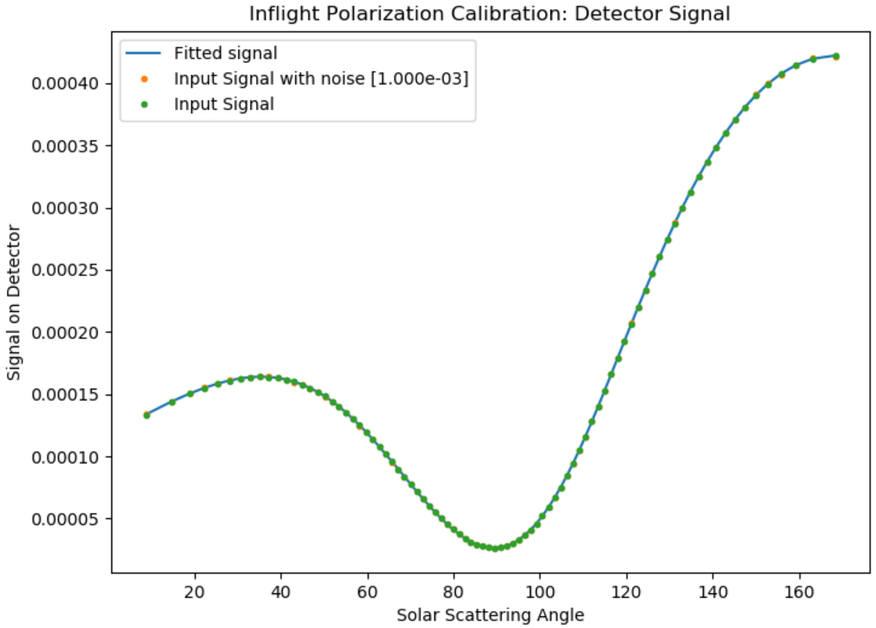
Polarization

Analysis of the measured signals allows estimation of G_{11}, G_{12} and G_{13} for the first row of the polarization (Mueller?) matrix



$$\mathbf{G} = \begin{pmatrix} 1.0 & 0.99 & 0.01 & 0.0 \\ 0.99 & 0.99 & 0.01 & 0.0 \\ 0.01 & 0.001 & 0.001 & 0.0 \\ 0.001 & 0.001 & 0.001 & 0.0 \end{pmatrix}$$

Fitting



- Observation of high altitude (~60km) limb signal allows for reasonable estimation of polarization response. Current simulated scenes work very well.
- In reality, technique requires knowledge of high altitude, atmospheric density variations across region of interest. This will be a limiting factor.
- Current technique can only estimate the polarization response for a small region of detector.

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Summary

- Work on ALTIUS inflight calibration and stray light correction algorithms is on-going.
- Baseline techniques have been established to measure or validate critical instrument parameters during flight using natural sources.
- These techniques will be presented and formally reviewed at an impending Critical Design Review (Fall 2022).

ALTIUS Level 1 Calibration Activity

Thank-you

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