BERGISCHE UNIVERSITÄT WUPPERTAL

Stray Light Measurement and In Orbit Validation of an Atmospheric Limb Sounder

25.11.2024 I TOBIAS AUGSPURGER

Metrology for Earth Observation and Climate

EMPIR EURAMET

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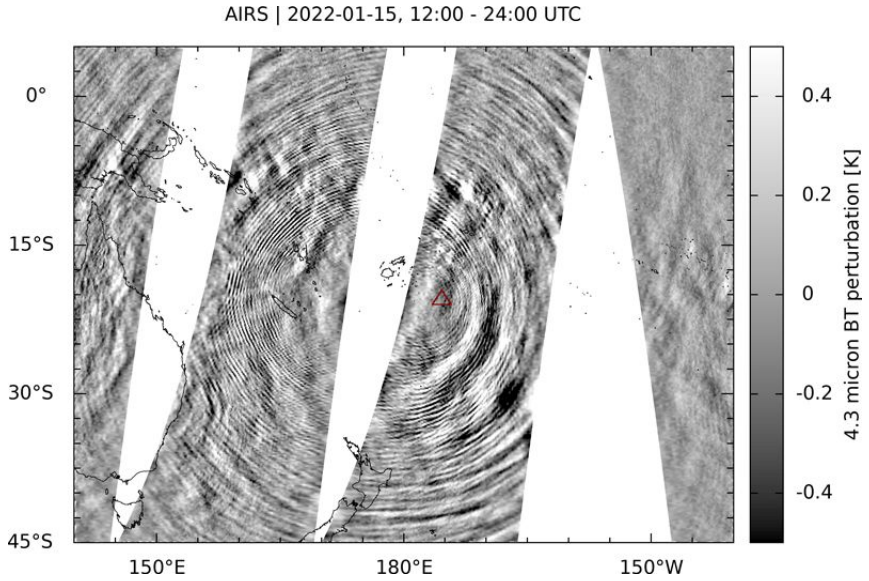
PTB

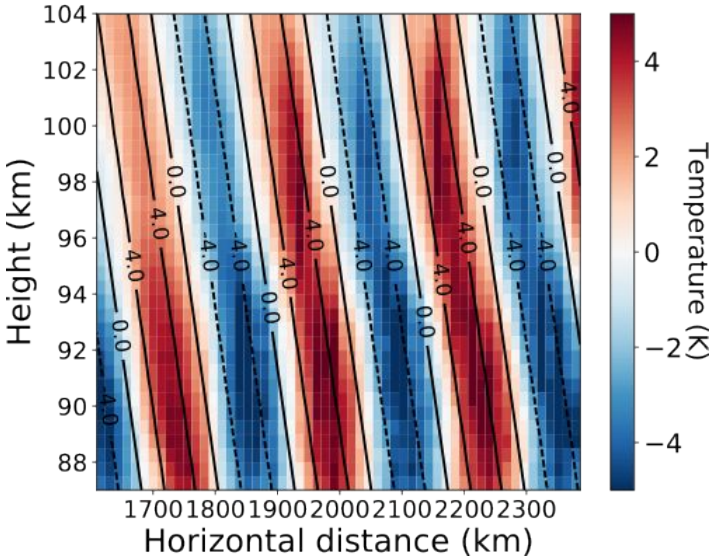
Physikalisch-Technische Bundesanstalt
Nationales Metrologieinstitut

JÜLICH Forschungszentrum

Objective: Observation of Gravity Waves



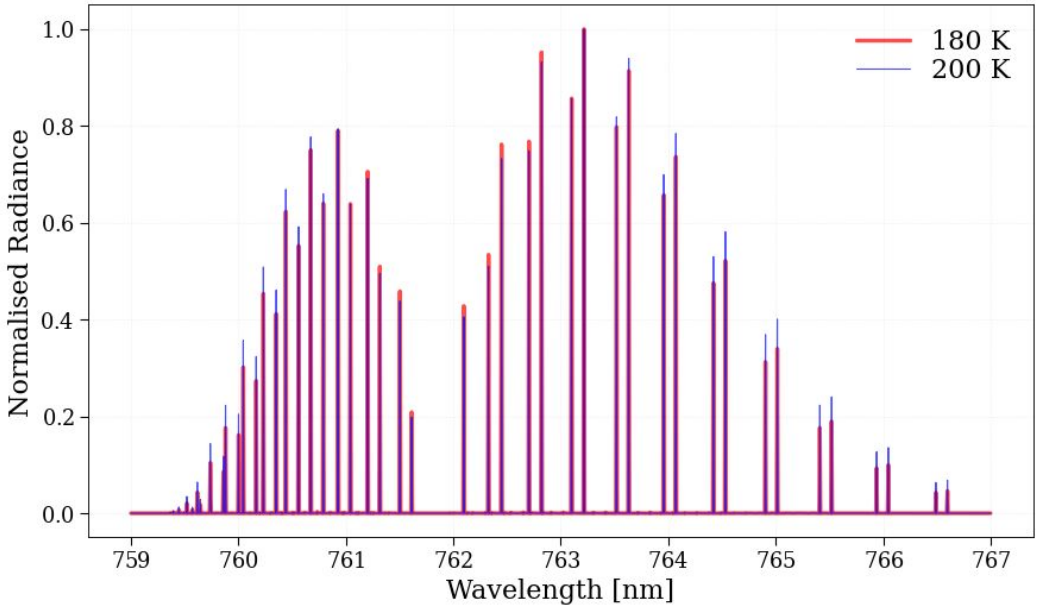
The gravity waves from the Tonga eruption observed by the AIRS instrument on NASA's Aqua satellite.

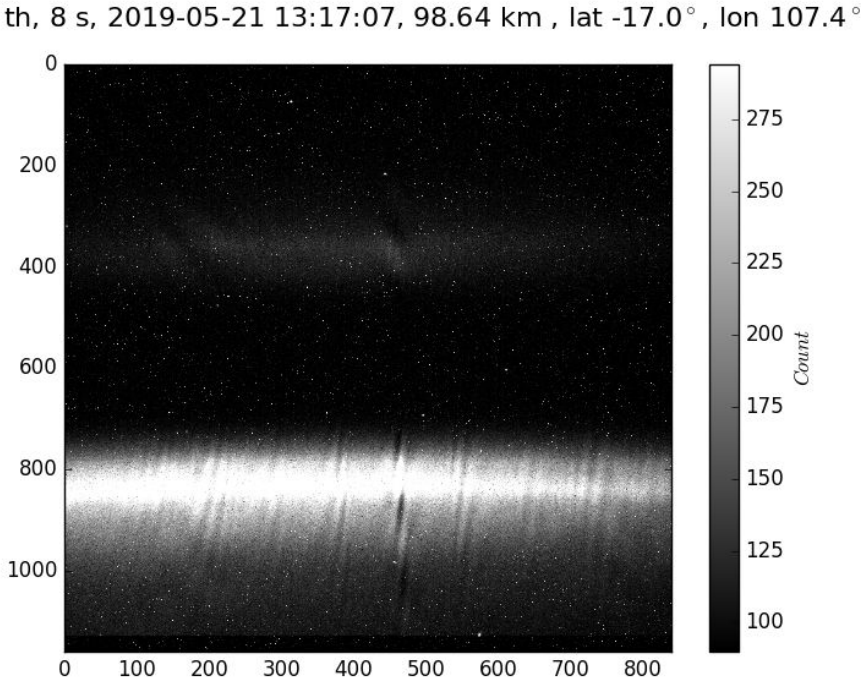


Simulation by Rui Song of a typical temperature distribution generated by a gravity wave between 86 and 104 km

The transfer of momentum by gravity waves is a principal driver of the large-scale dynamical features in the higher atmosphere.

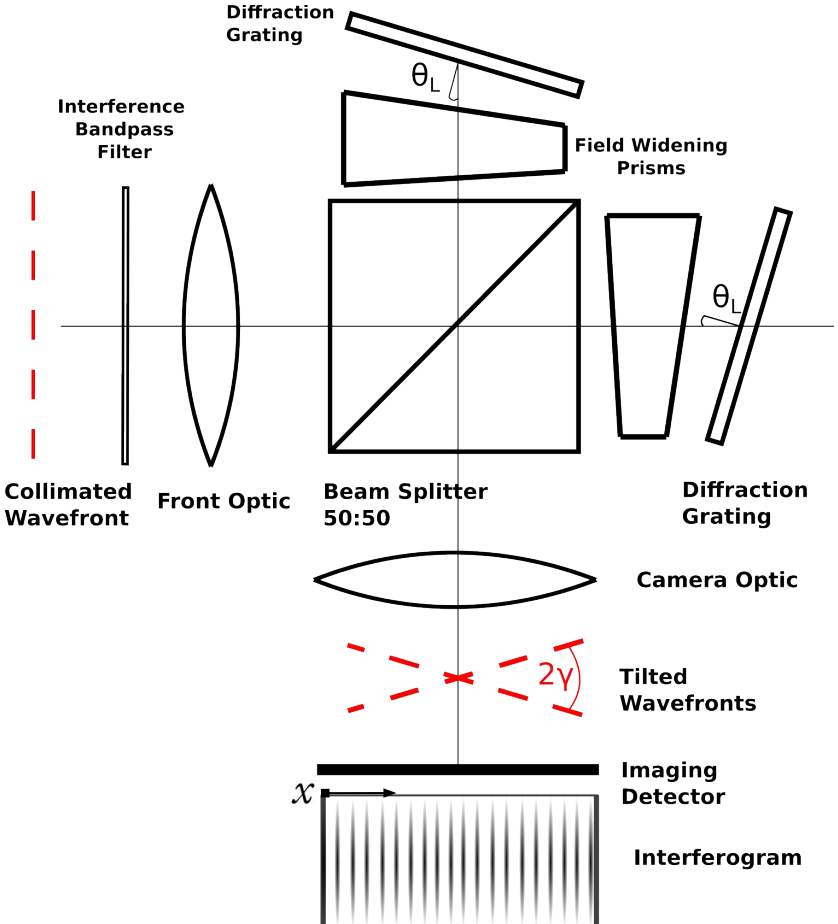
O_2 A-band emissions of the Earth's airglow





Measurement of temperature gradient by spectral shifts of O_2 A-band emissions with an limb sounder instrument

Imaging Spatial Heterodyne Interferometer (ISHI)



$$f_x = 4\theta_L \tan(\sigma - \sigma_L)$$

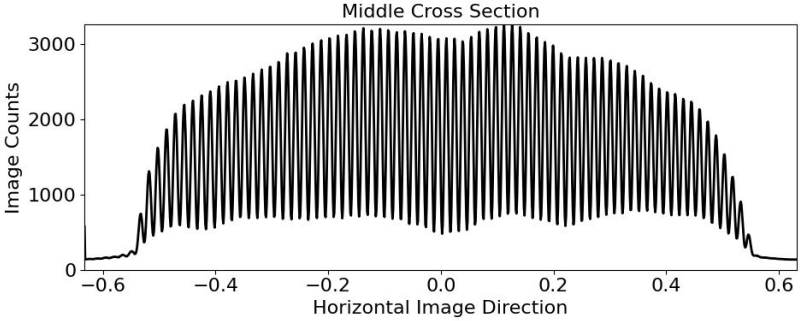
$$I(x) = \int_{\sigma_{min}}^{\sigma_{max}} B(\sigma)[1 + V(x,\sigma)\cos(2\pi f_x + \delta(x,\sigma))]d\sigma$$

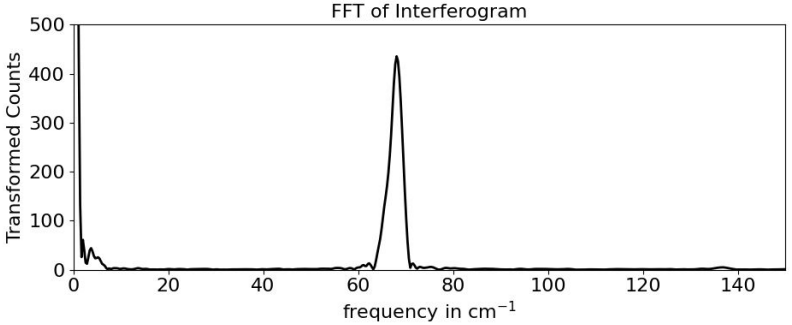
Visibility! $\longrightarrow$ $$V = \frac{I_{max} - I_{min}}{I_{max} + I_{min}}$$

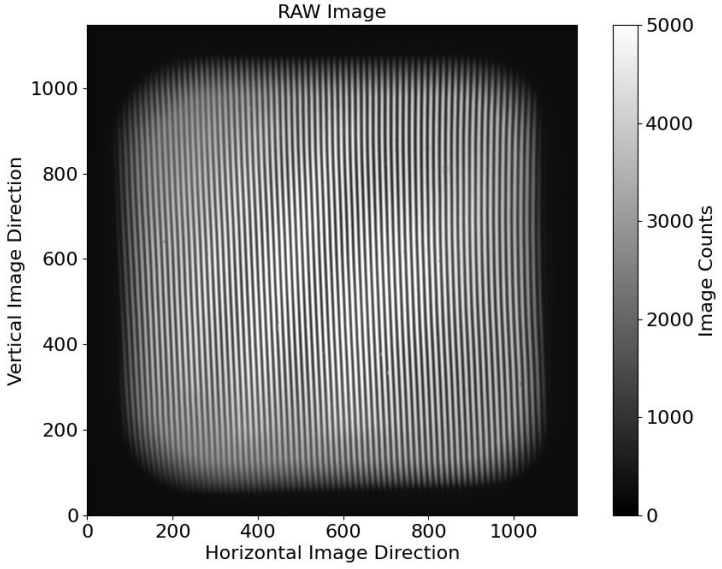
Measures spectral information horizontally and spatial information both horizontally and vertically simultaneously in a single frame with a very high étendue.

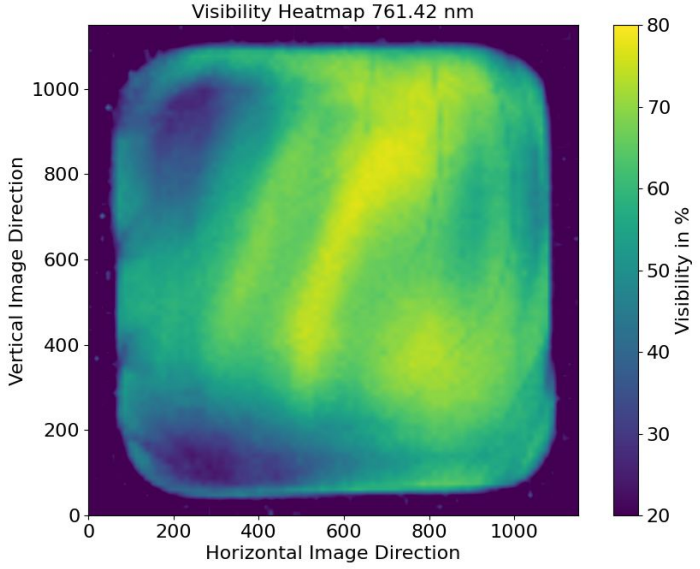
No moving parts and extreme compact.

Pre-Flight Calibration in the Lab

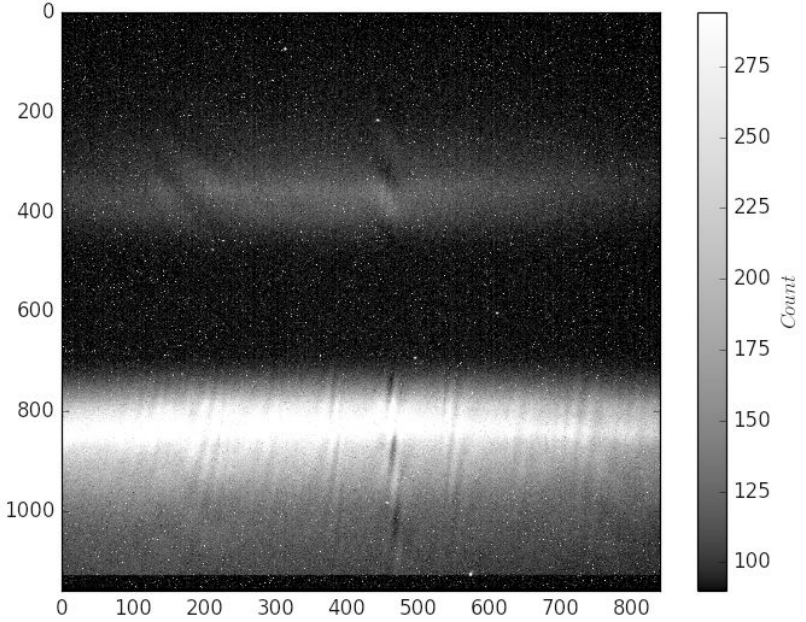




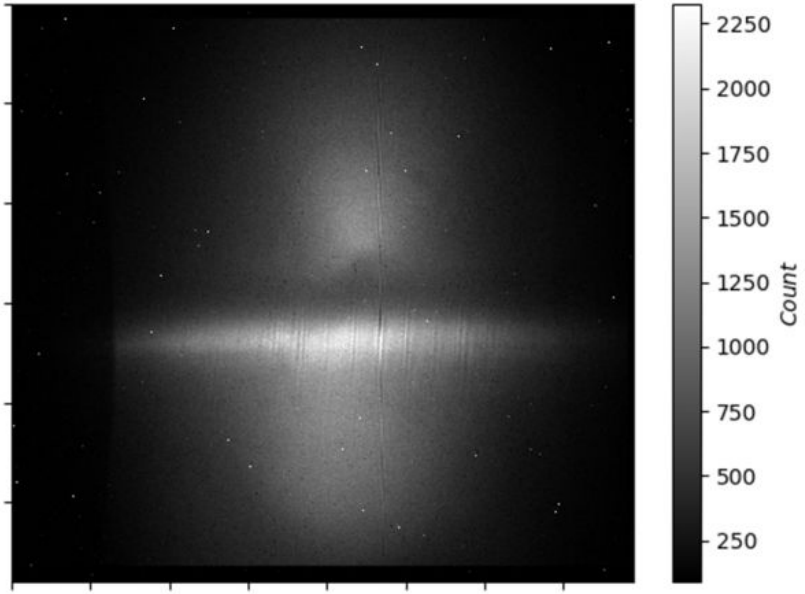




Challenges Experienced In-Orbit



In-Field Stray Light and Ghost Artefacts



Out-of Field Stray Light

Stray Light

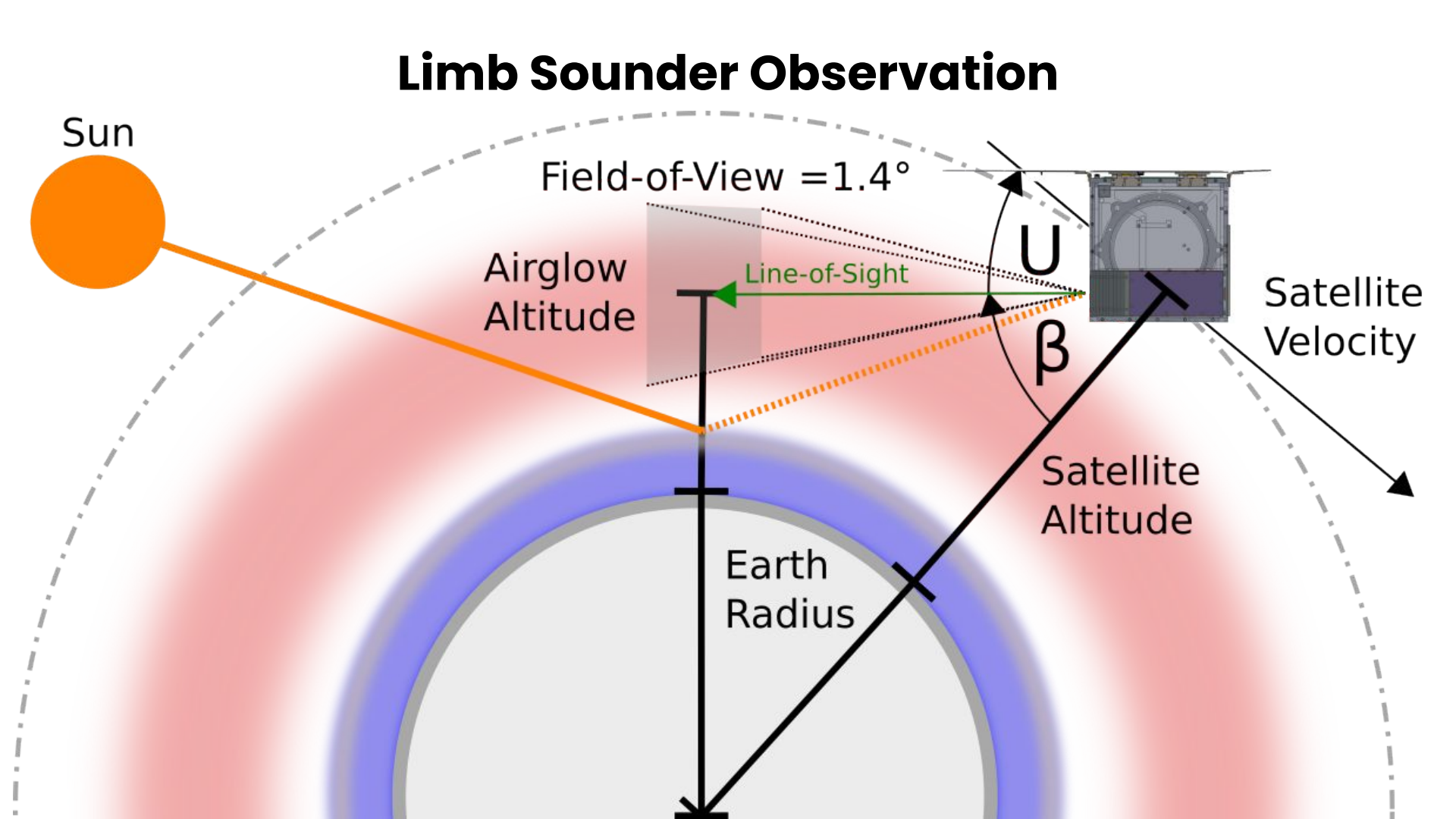
~~Stray light is defined as unwanted light that reaches the focal plane of an optical system.~~
(Stray Light Analysis and Control from Eric Fest)

Stray light is defined as radiance on a detector due to undesired scattering, reflection or diffraction effects within an optical system. (Tobias Augspurger)

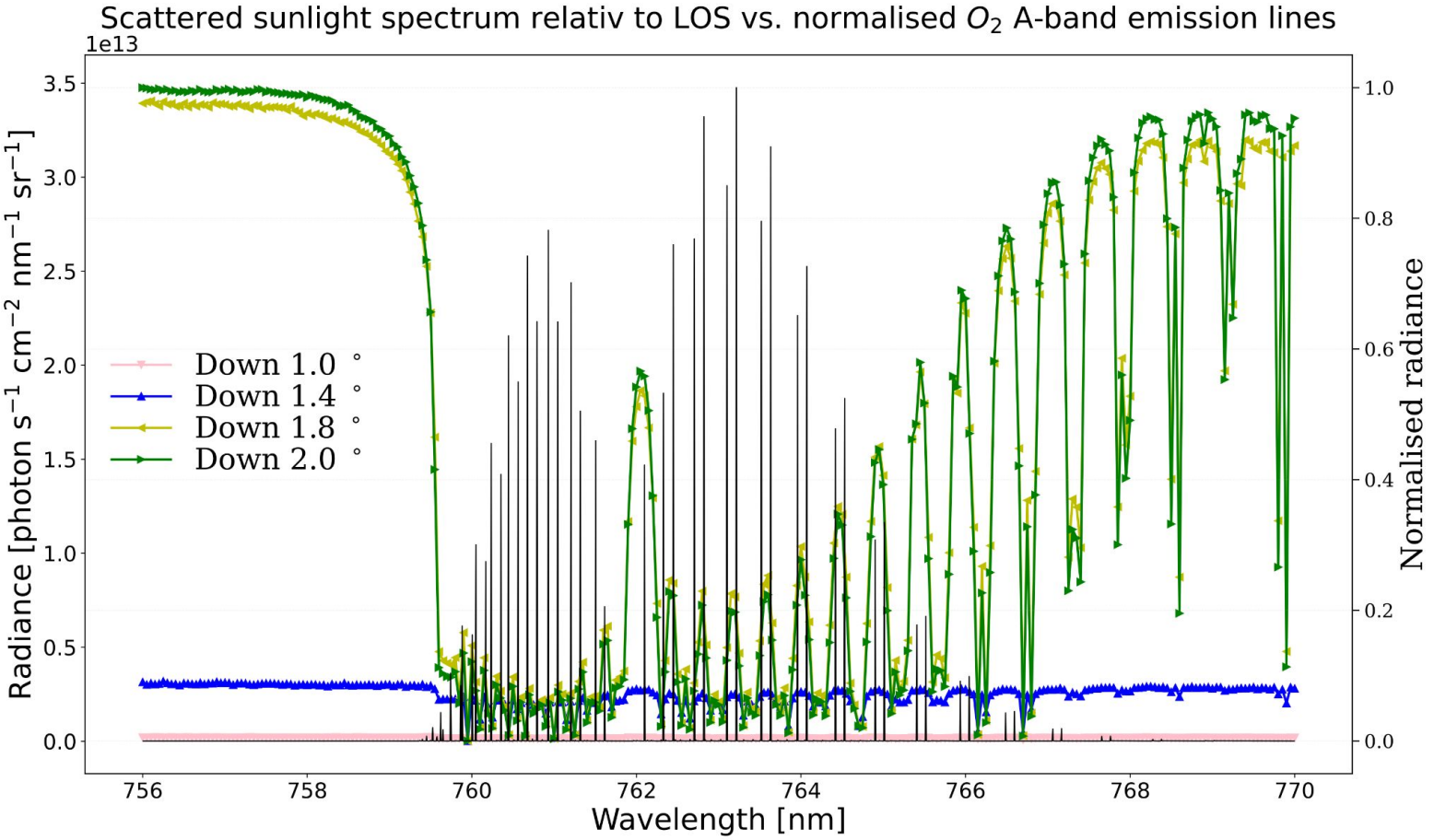
Objectives of Thesis:

1. **Research into existing end-to-end stray light measurement methods.**
2. **Creation of a traceable test bench for stray light measurement of limb sounders**
3. **Perform measurements to evaluate instrument and test bench performance.**
4. **Simulation and research for in-orbit validation experiments.**

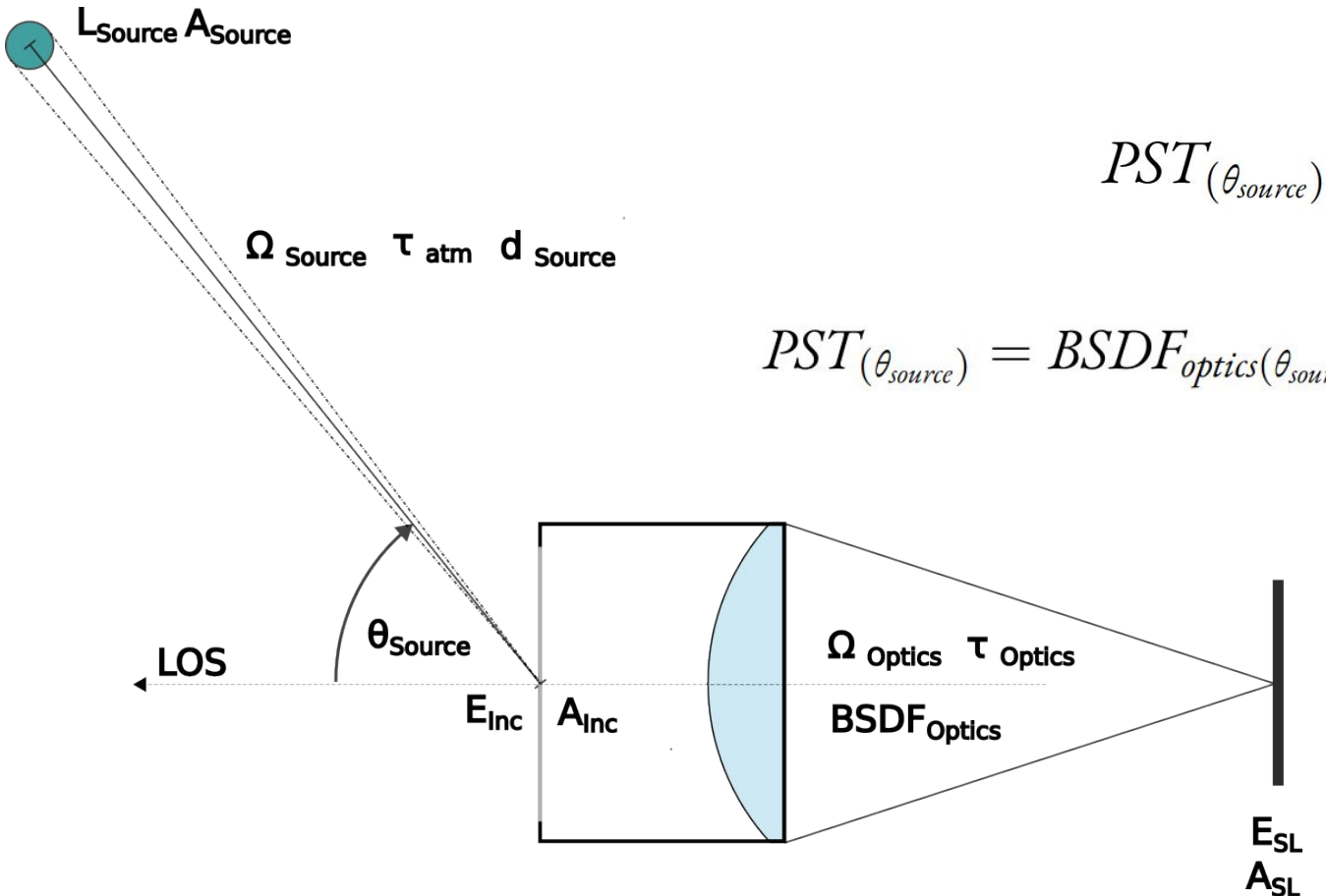
Limb Sounder Observation



O_2 A-band emissions vs. Out-of-Field Stray Light



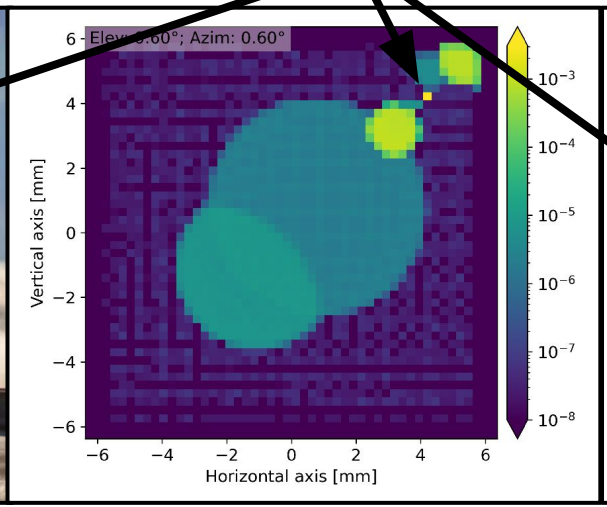
Point Source Transmittance (PST)

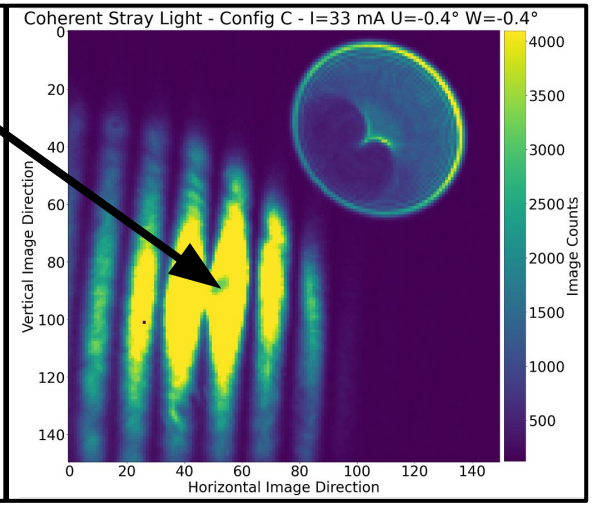


$$PST_{(\theta_{source})} = \frac{E_{SL}}{E_{inc}}$$

$$PST_{(\theta_{source})} = BSDF_{optics(\theta_{source})} \cdot \Omega_{optics} \cdot \tau_{optics}$$

Stray Light From Point Sources





RGB Photography

Broadband Light Source

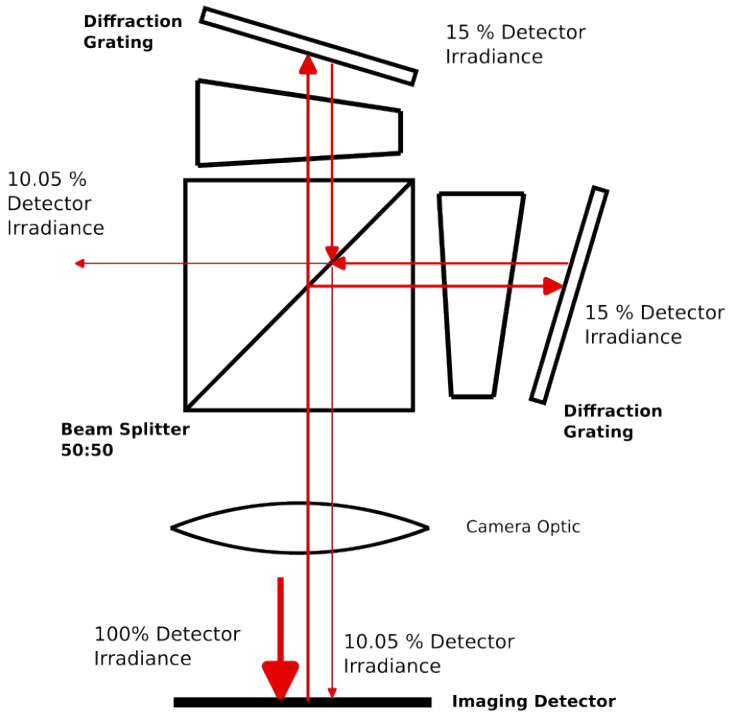
Simulation of SHIS Stray Light

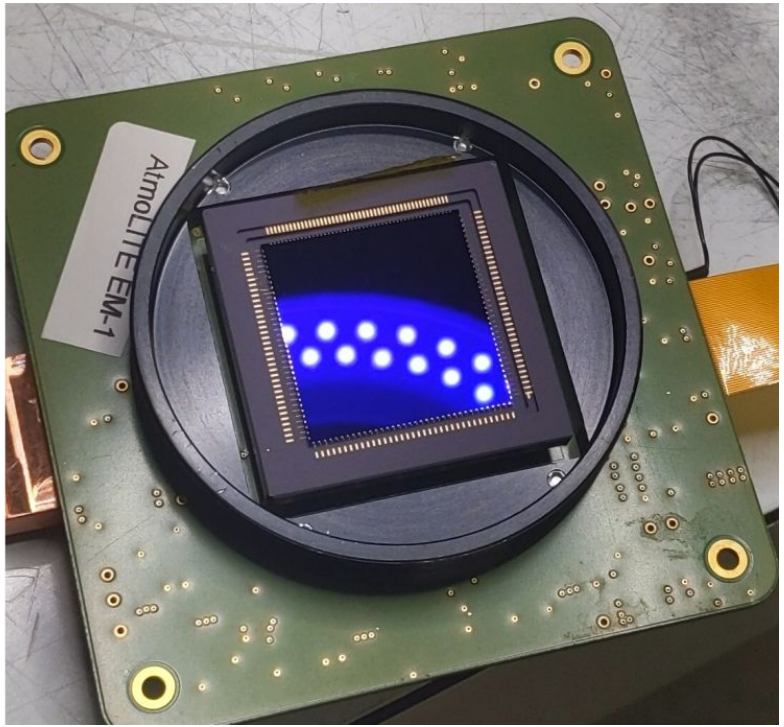
Broadband Light Source

Measurement of SHIS Stray Light

Narrowband Light Source

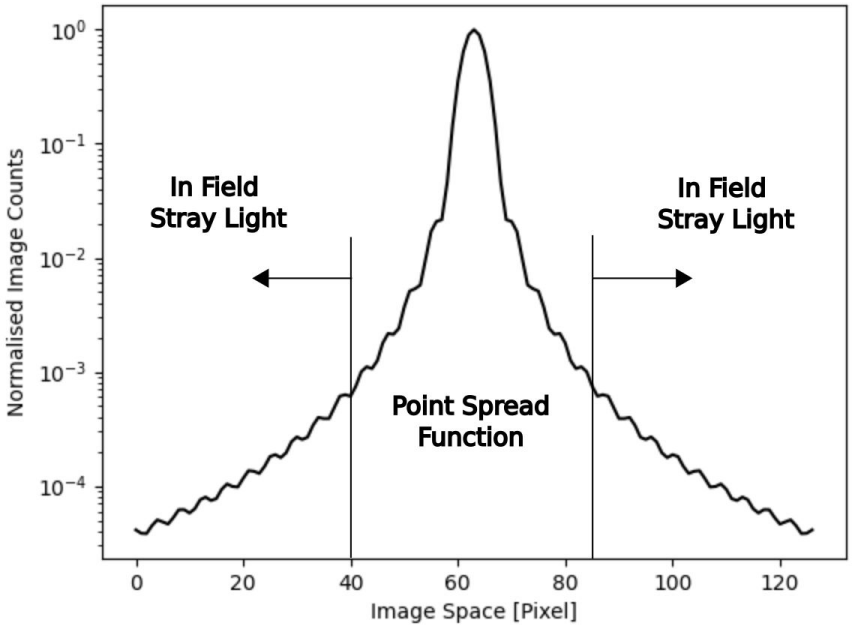
Ghost Artefacts causing Parasitic Interference

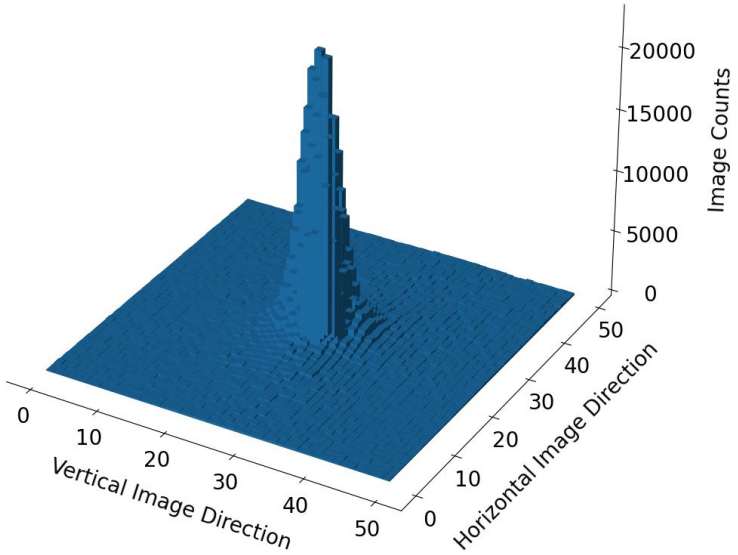




Parasitic interference is an inherent measurement artefact that is visible in all instruments that are similar to Michelson interferometers.

[Incoherent] Point Spread Function (PSF) and In-Field Stray Light

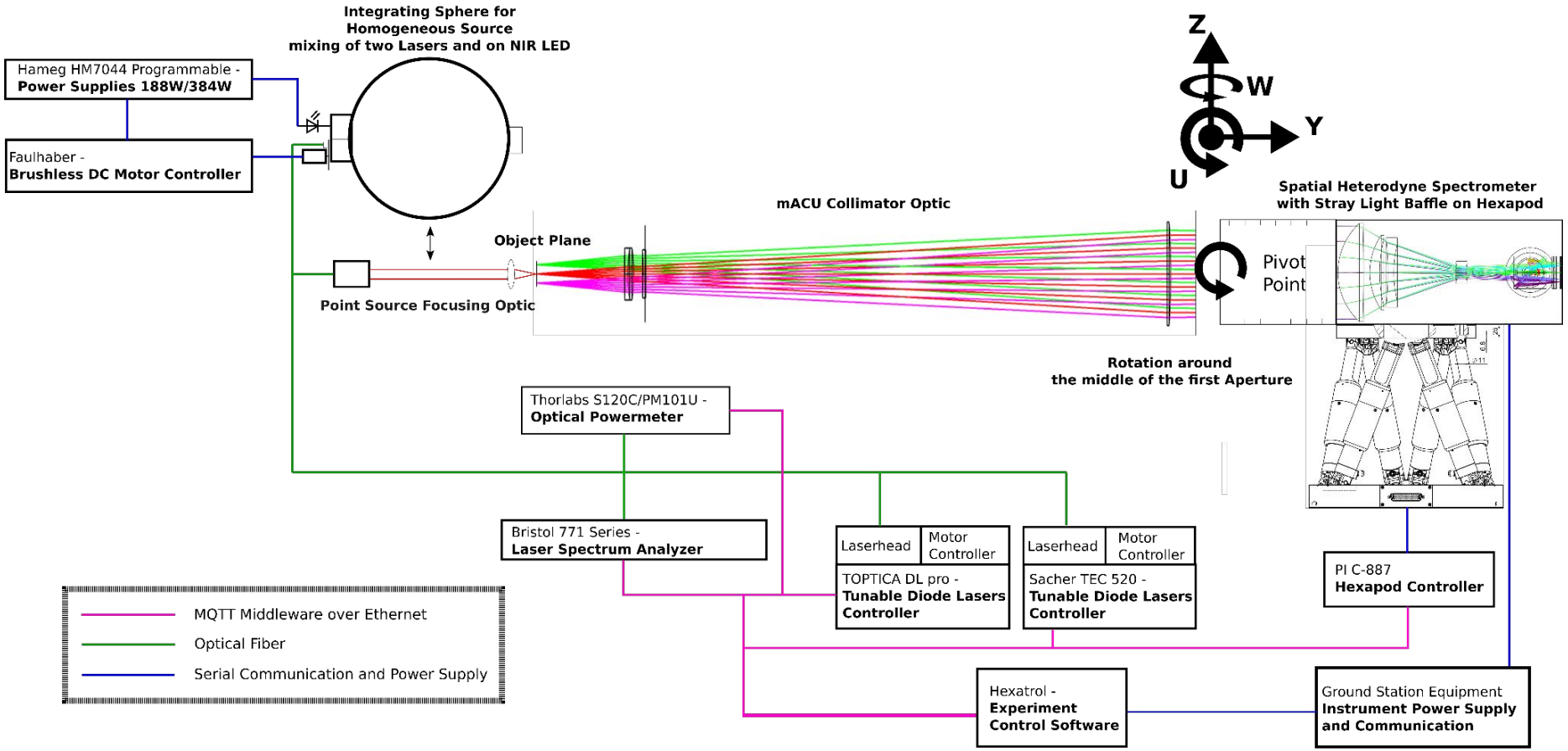




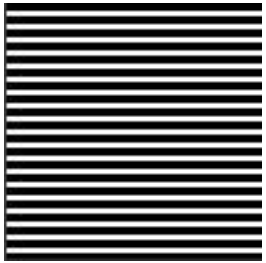
Extended PSF in size and dynamic range represents the [Incoherent] Stray Light Kernel

$$\text{In-Field Stray Light} = \frac{E_{Detector\ Exluding\ Signal}}{E_{Signal}}$$

Fully Automated Limb Sounder Test Bench

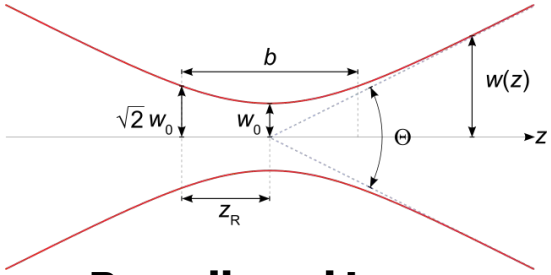


Calibration Targets

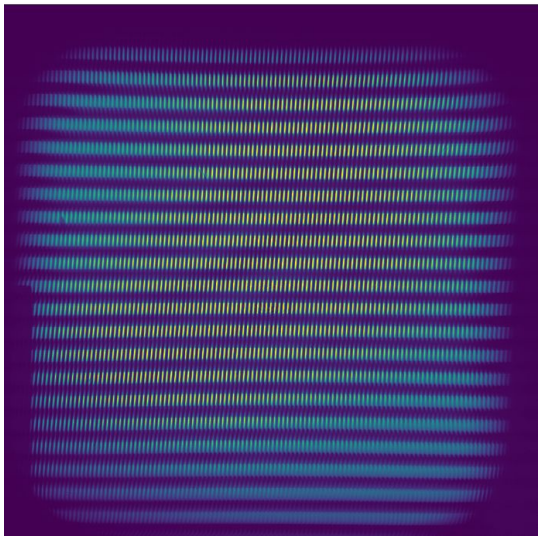


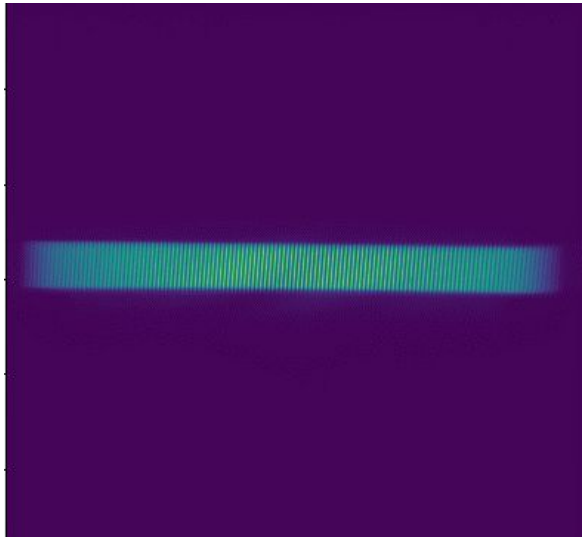
Ronchi Ruling

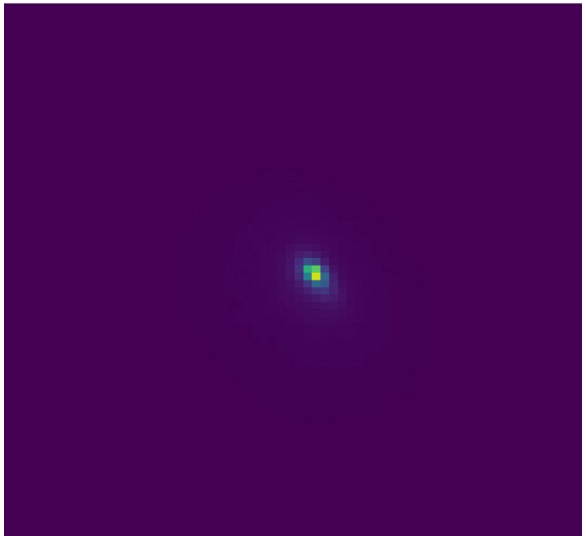
Slit

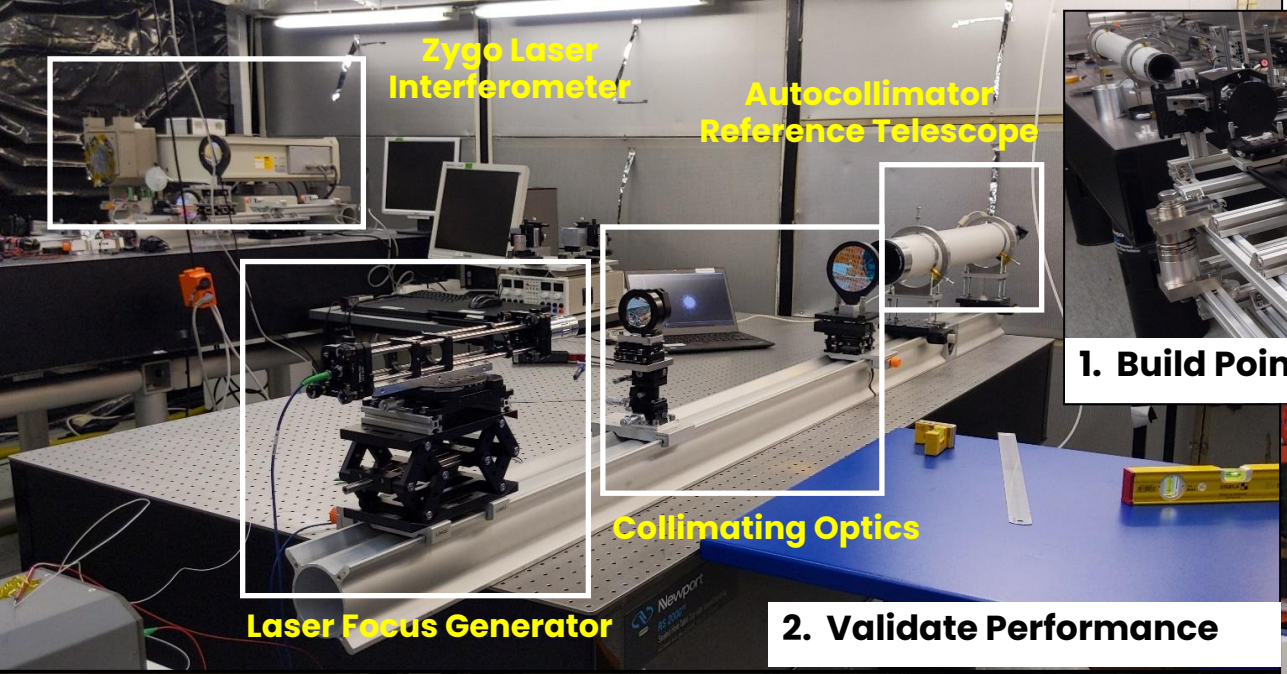


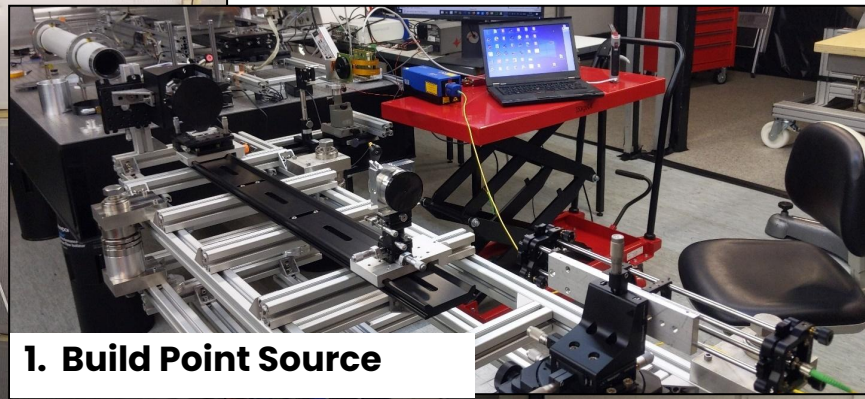
Broadband Laser Beam Waist





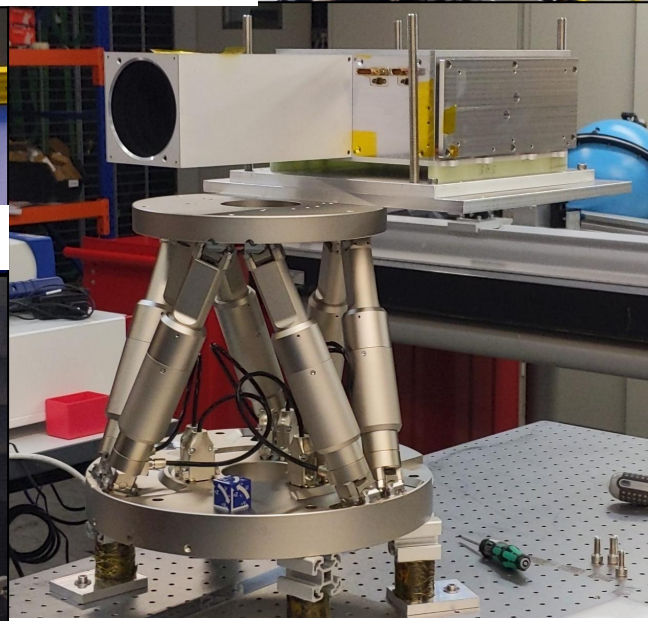




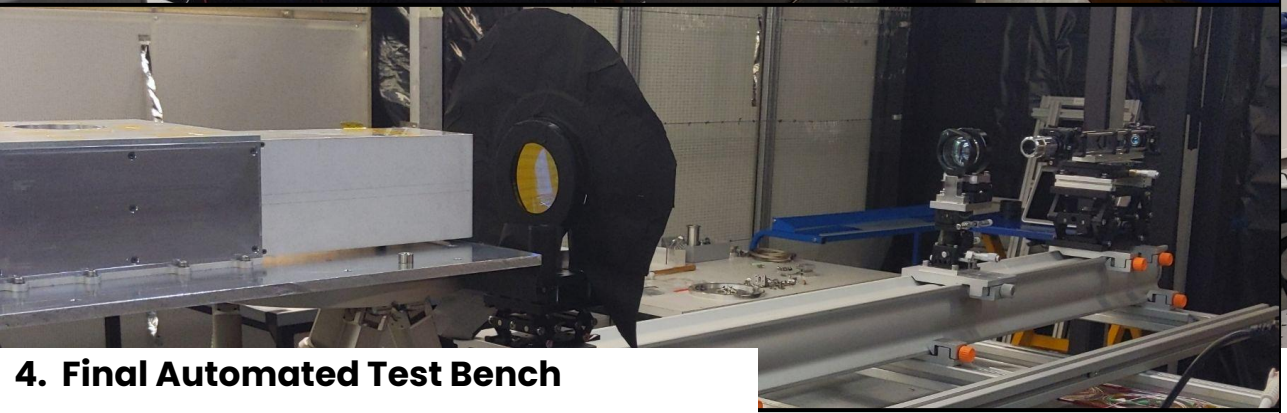


1. Build Point Source

2. Validate Performance

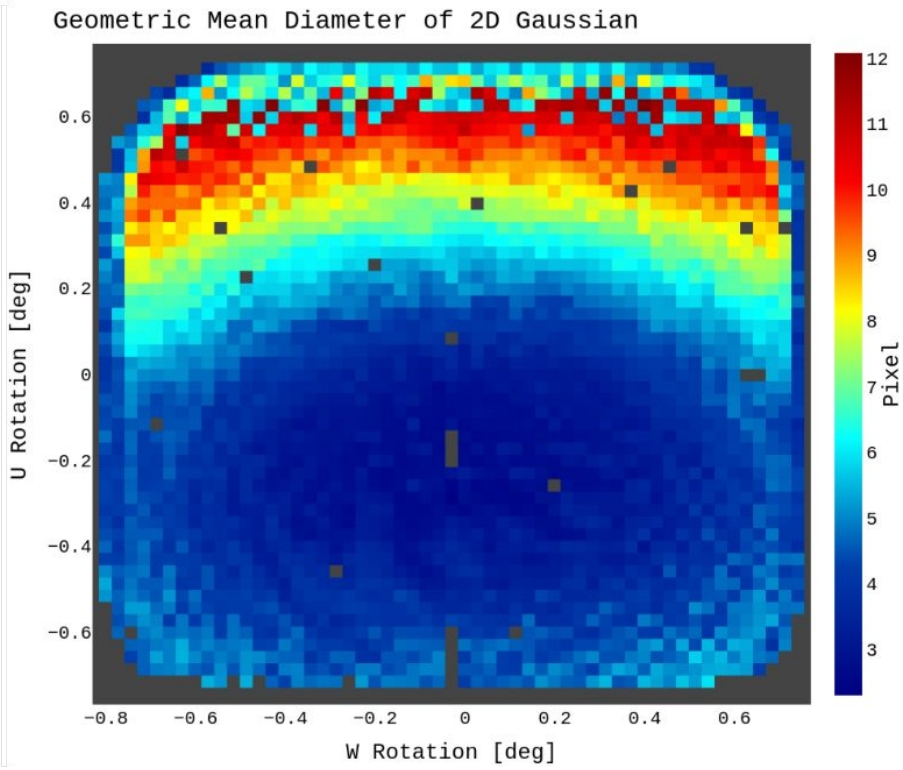


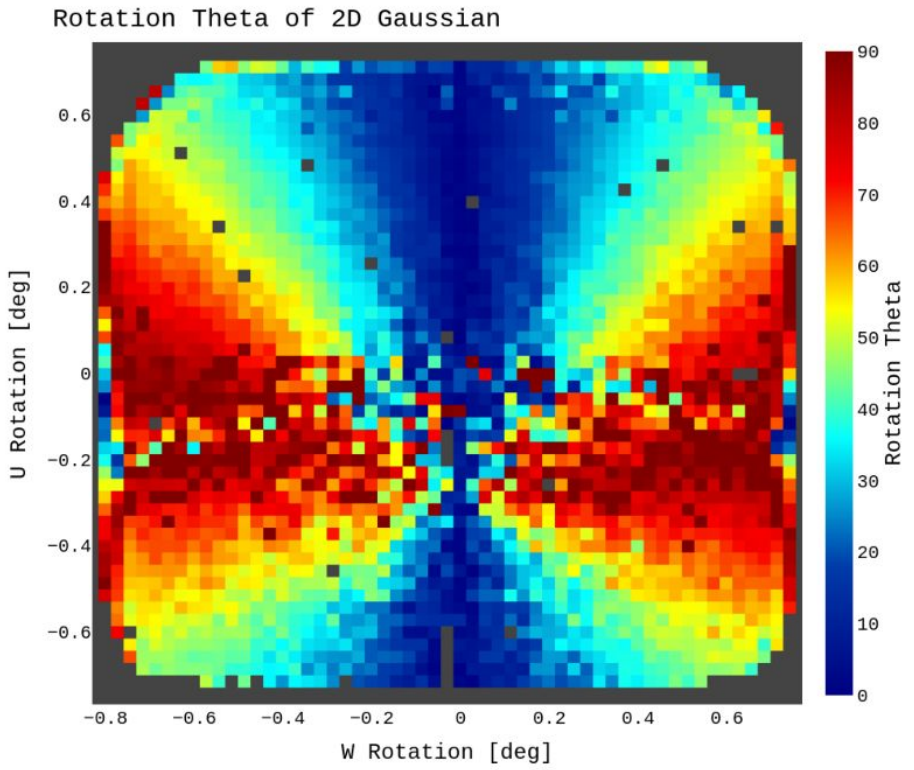
3. Place instrument on hexapod.



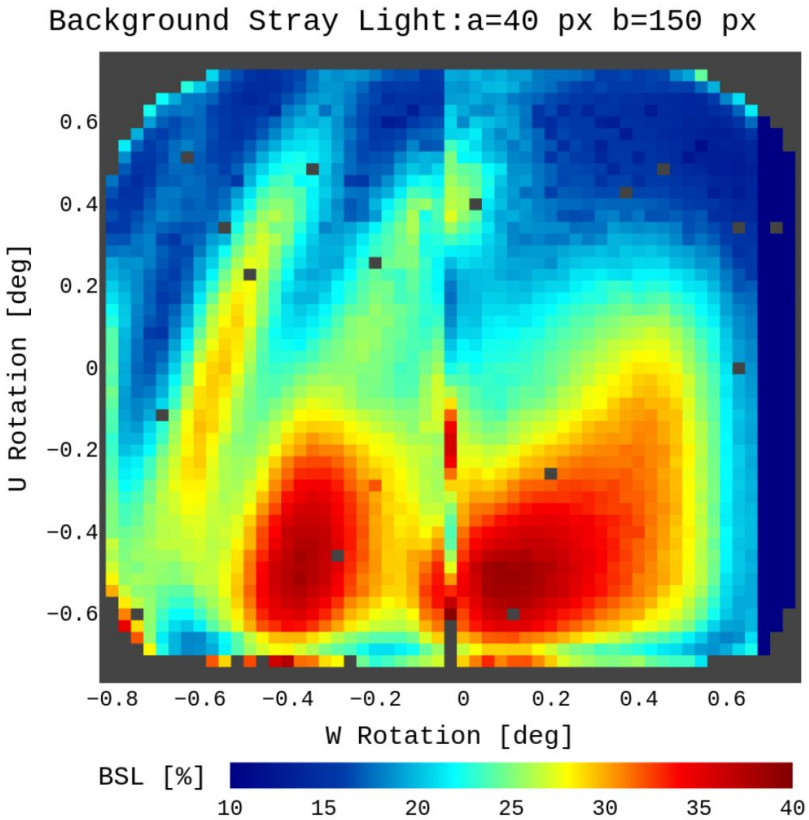
4. Final Automated Test Bench

Point Spread Function and Spatial Resolution

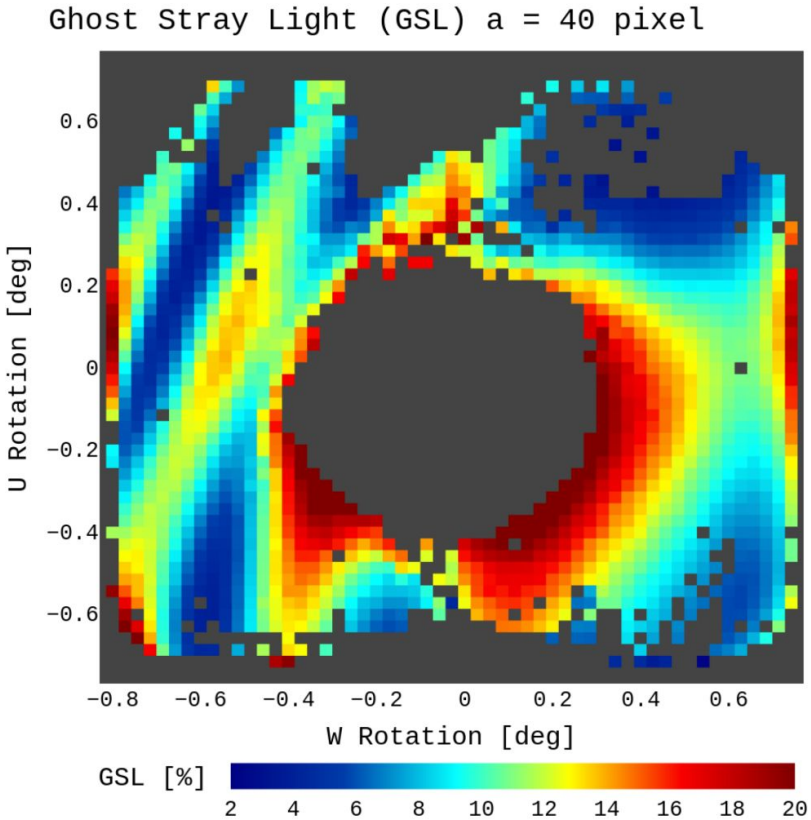




Background and Ghost Stray Light

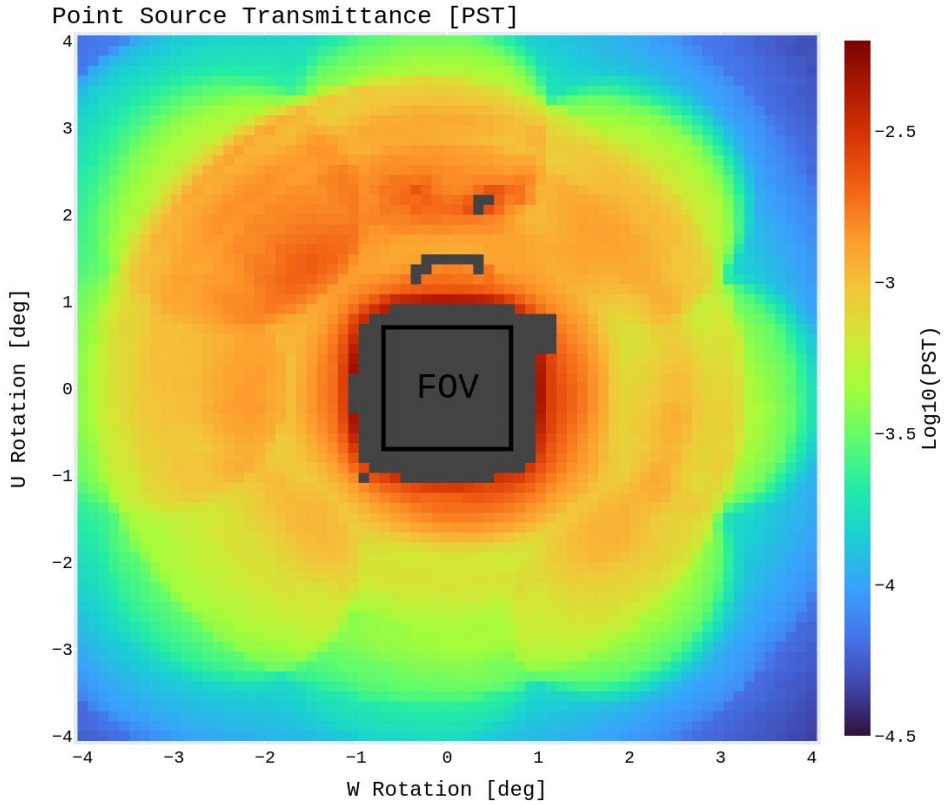


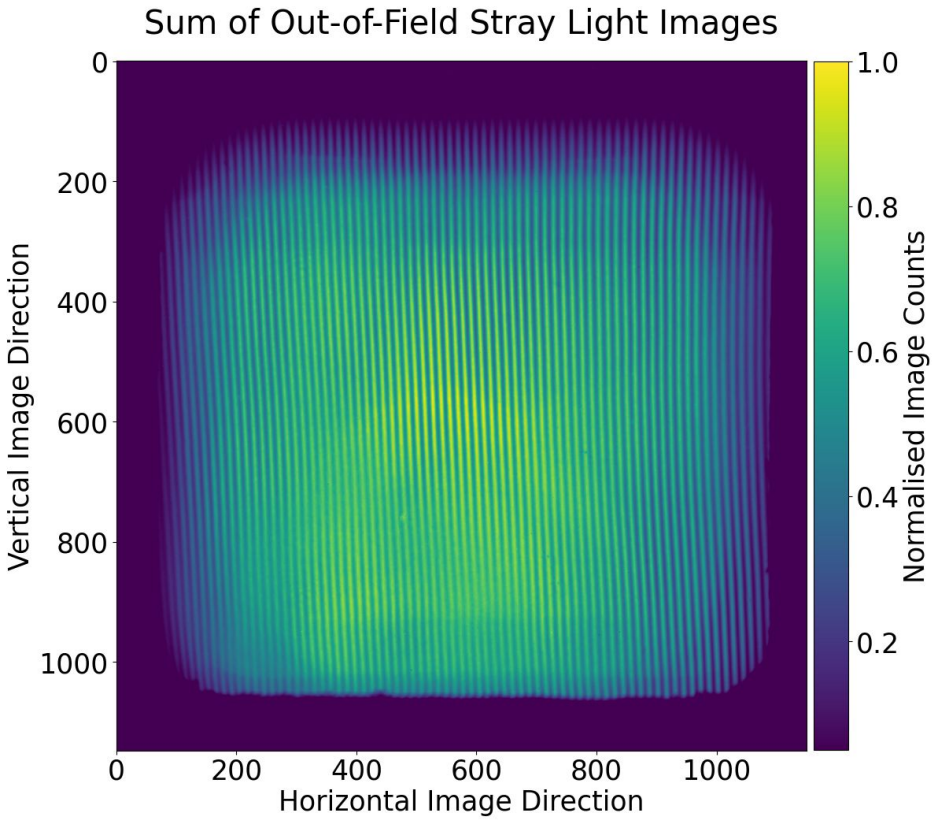
Config C: Median BSL of 23.61 %



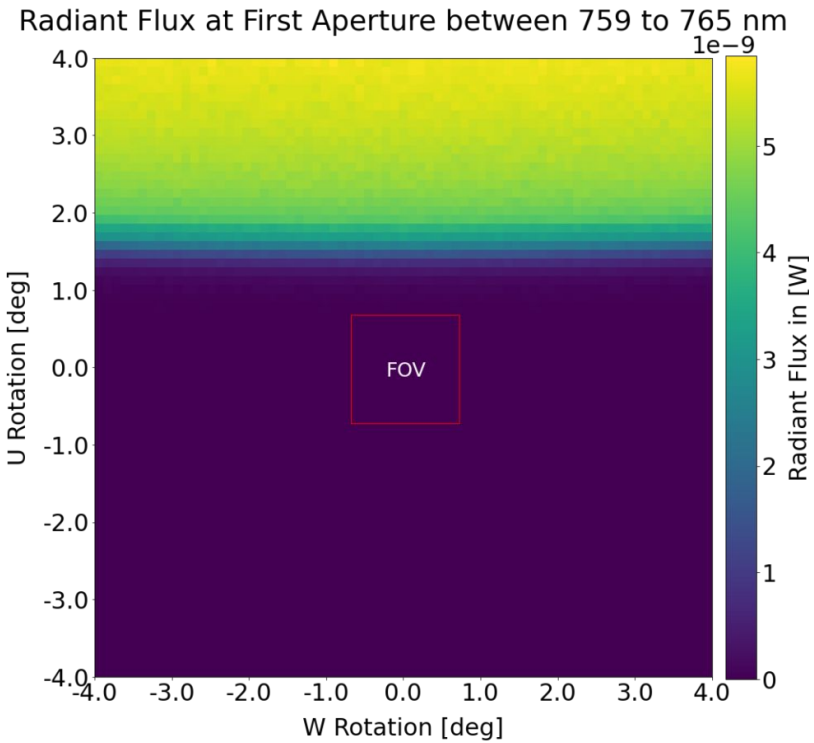
Config C: Median GSL of 9.98 %

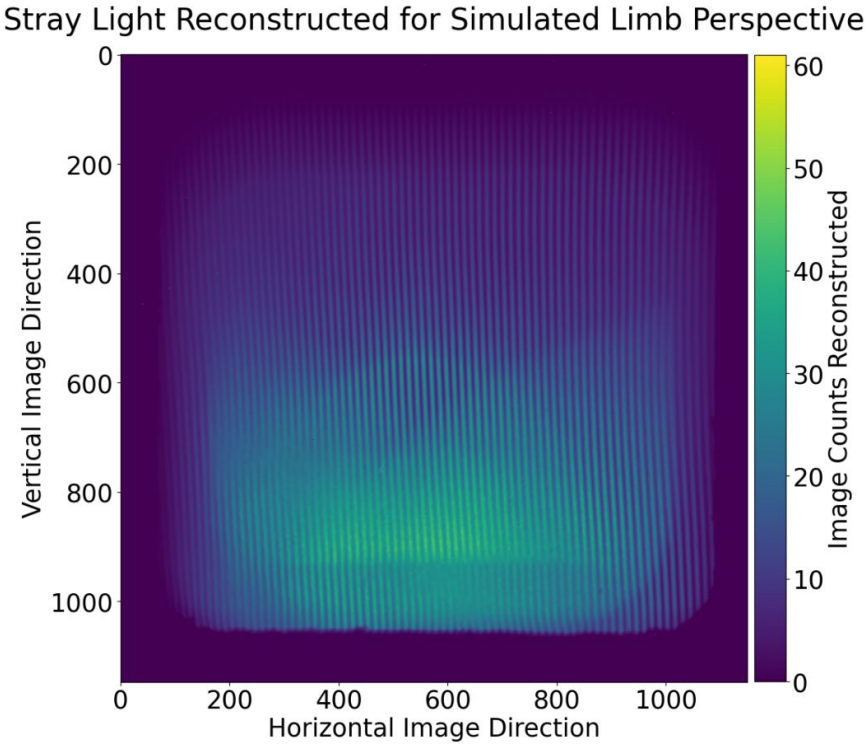
Out-of-Field Stray Light





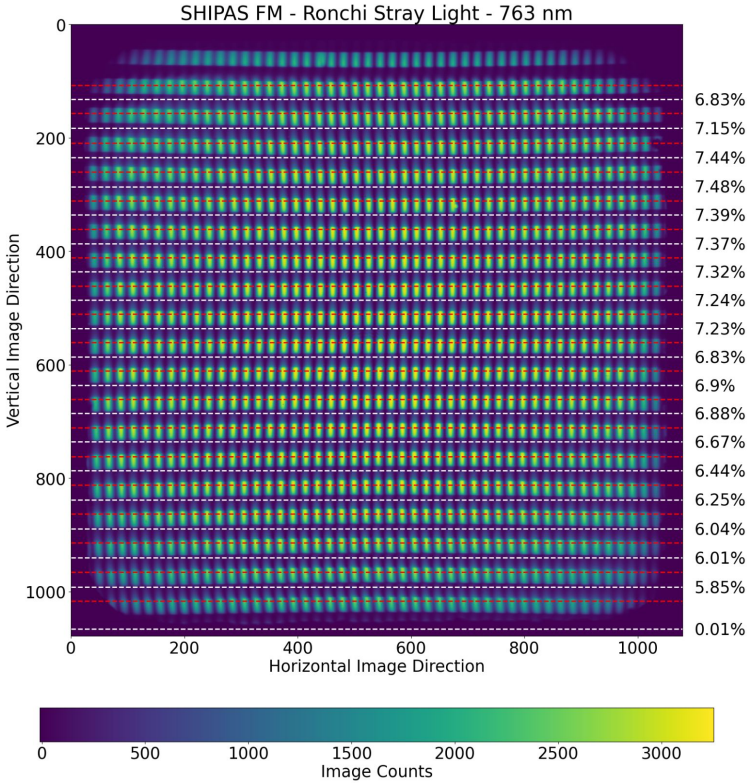
In Orbit Stray Light Image Reconstruction

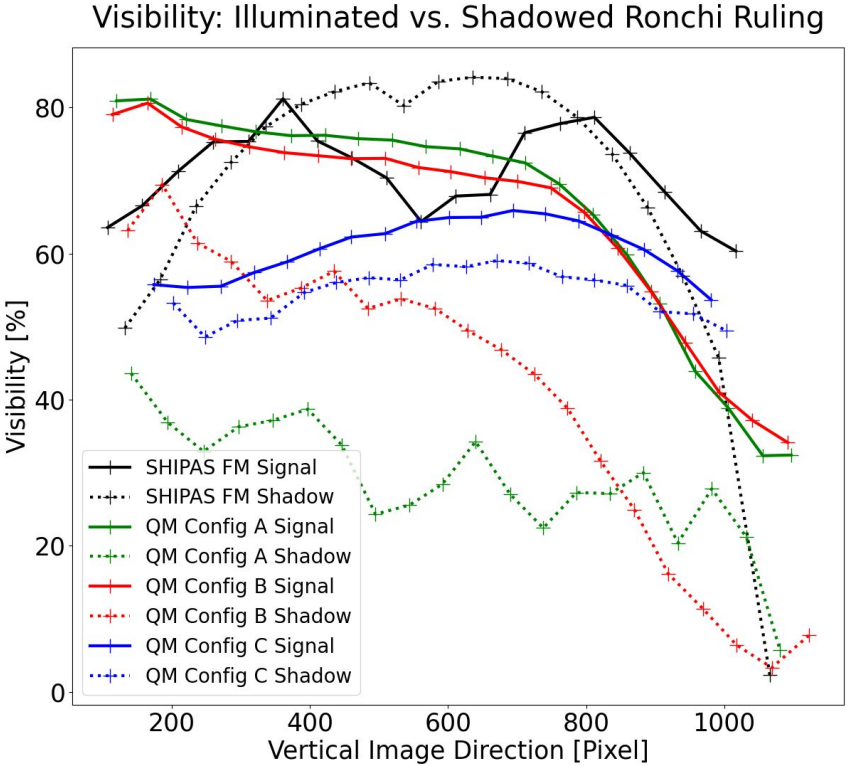




PST measurements combined with 3D radiative transfer simulations allow the reconstruction of the in-orbit stray light image.

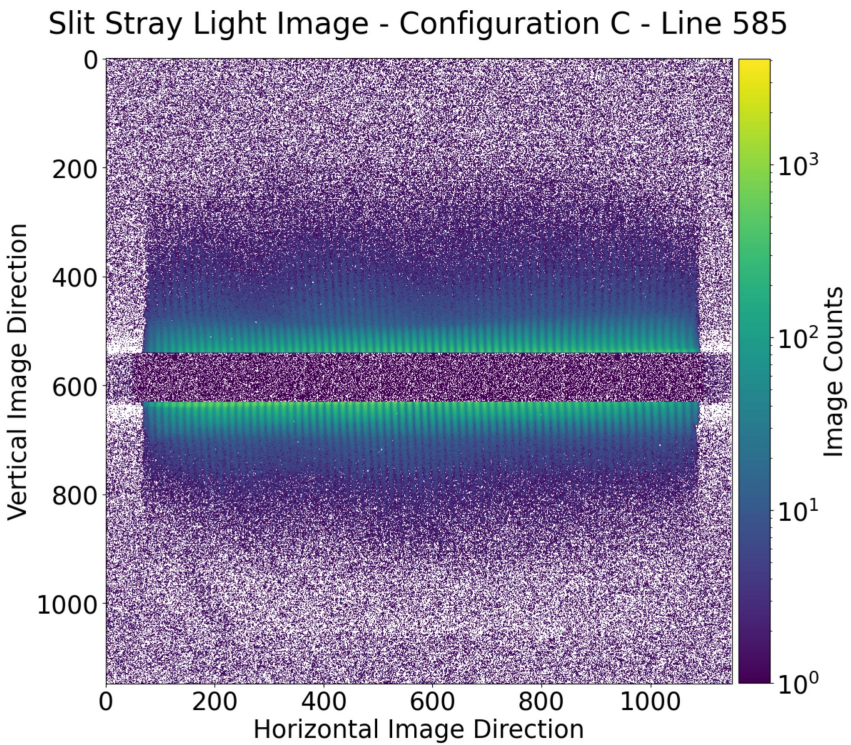
Ronchi Stray Light and Parasitic Interference

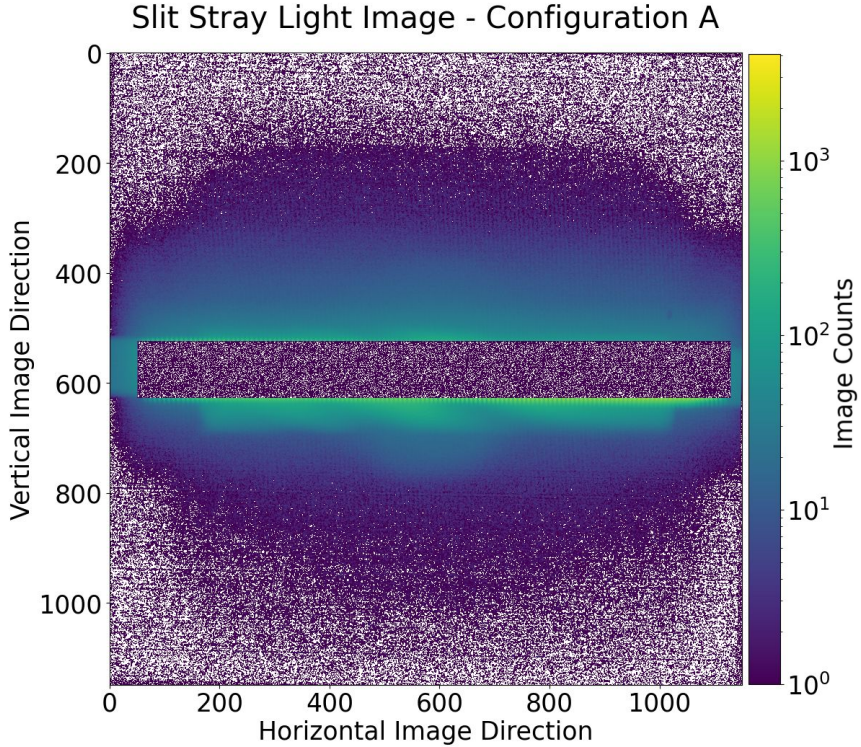




Ronchi Ruling allows the measurement of visibility, in-field stray light, parasitic interference, spatial resolution and spectral variance with a single image over the entire field of view.

Slit Stray Light and Parasitic Interference





Depending on the instrument configuration, in-field stray light causes few parasitic interference and therefore has few effect on the measurement signal.

Interfering Stray Light to Signal Ratio (ISR)

In-Field Stray Light

Out-of-Field Stray Light

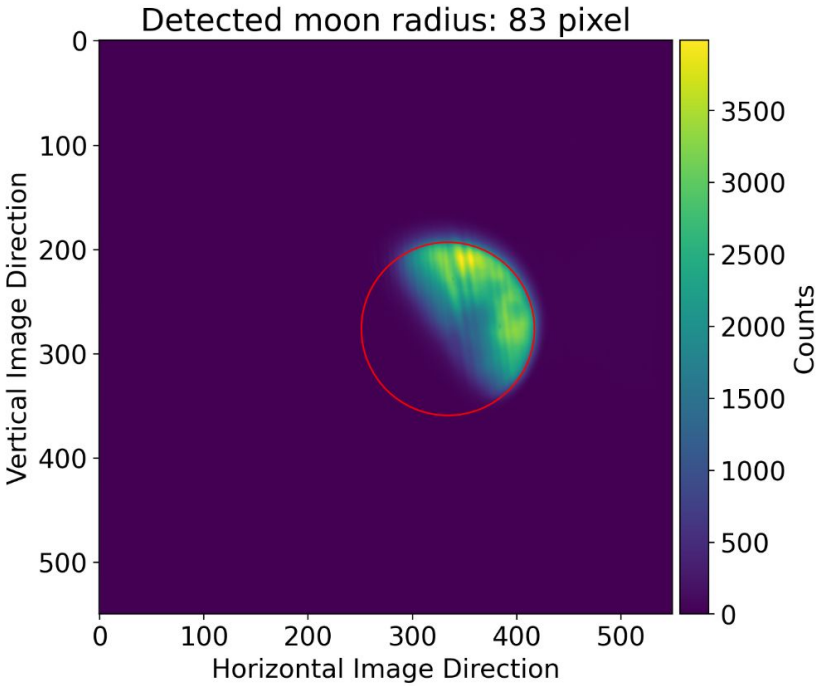
$$ISR_{Config\ A} = \frac{V_{IFSL} \cdot RSL \cdot N_{Signal} + V_{OFSL} \cdot \frac{N_{OFSL}}{\Delta t} \cdot \Delta t_{Integration}}{V_{Signal} \cdot N_{Signal}} = 3.8\,\%$$

Total Signal

Recommendation to reduce stray light and parasitic interference:

1. **Coating or switching of the detector to reduce reflectivity → ISR < 1 %**
2. **Subtraction of the out-of-field interferogram → ISR < 2.7%**
3. **Optimizing stray light and parasitic interference with the Ronchi Ruling → ISR = ?**
4. **Install Field Stop at Intermediate images on detector → ISR = ?**
5. **Install Stray Light Optimized Diffraction grating → ISR = ?**
6. **Deconvolution of In-Field Stray Light using Coherent Point Spread Function → ISR = ?**

In-Orbit Validation Simulated with Skyfield



1. **The Open Source 'Skyfield' project shows great potential for simulating the field of view of instruments in Earth orbit relative to celestial bodies.**

2. **The lunar surface show ideal condition to validate the Line-of-Sight, Point Source Transmittance, In-Field-Stray Light and Spatial Resolution. Recurring observations possible without major rotation of a satellite in a sun-synchronous orbit.**

3. **Pitching the line of sight relative to the airglow is the only way to validate out-of field stray light visibility, as the moon does not cause interference.**

Summary

1. Identification of Parasitic Interference as critical stray light source.
2. Measurement of out-of-field stray light and demonstration of how to apply a stray light correction method using radiative transfer simulations.
3. Identification of the Ronchi Ruling as the ideal calibration target for the alignment of the ISHI instrument.
4. Simulation of multiple in-orbit validation strategies using the Open Source package Skyfield.
5. Multiple design optimizations and correction methods identified to reduce interfering Stray Light to Signal Ratio below 1 %.

Opened up new ways of overcoming and controlling stray light in a traceable way.