ICON
Ionospheric Connection Explorer

The ICON FUV Instrument

S. B. Mende, H. Frey, C. Chou, K. Rider, S. Harris, C. Wilkins, W. Craig – UCB SSL

J. Loicq, P. Blain – Centre Spatial de Liege (CSL)

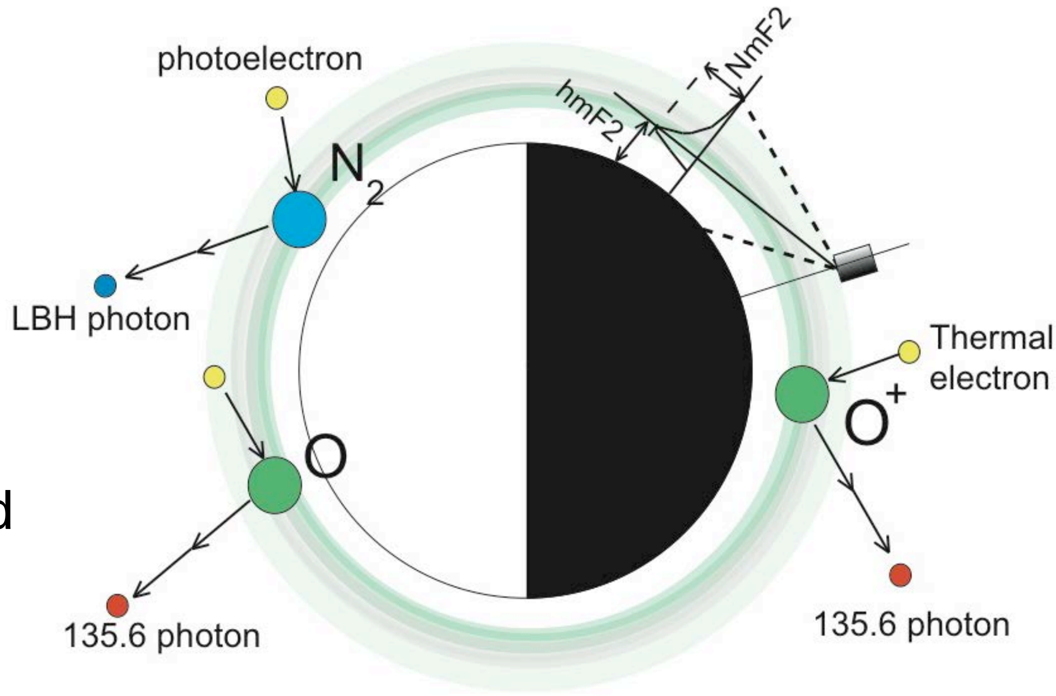
S. Ellis – Photon Engineering

Agenda

- ICON FUV Science
- Key requirements
  Sensitivity.
  Stray light rejection.
- Description of the Instrument
- Calibration Test Setup
- Calibration Results
- Instrument Performance

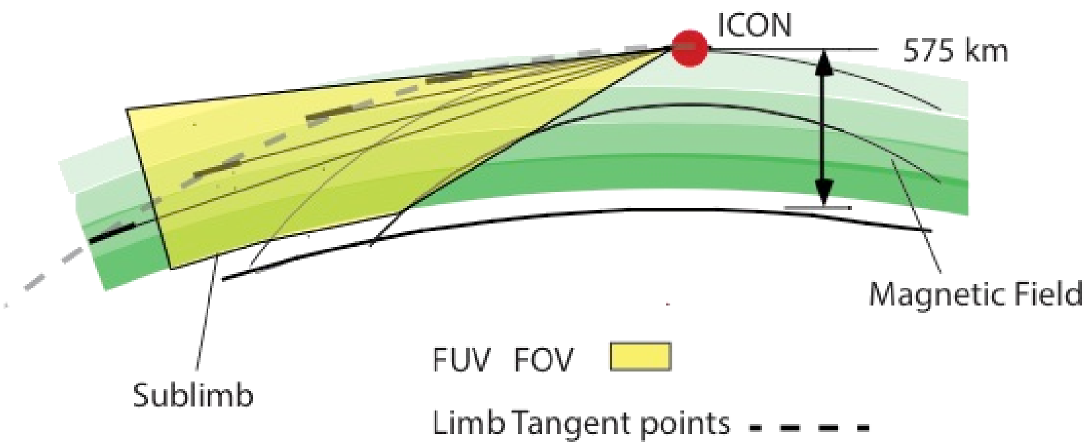
Far Ultra Violet Imaging Spectrograph - FUV

- FUV is a two channel spectrographic imager that measures the intensity and spatial distribution of atomic oxygen (135.6 nm) and molecular nitrogen (157 nm) (Lyman-Birge-Hopfield, LBH) emissions on the limb.
- Daytime photoelectron excited neutral O and N_2 atmosphere.
- Nighttime recombining O^+ ionosphere



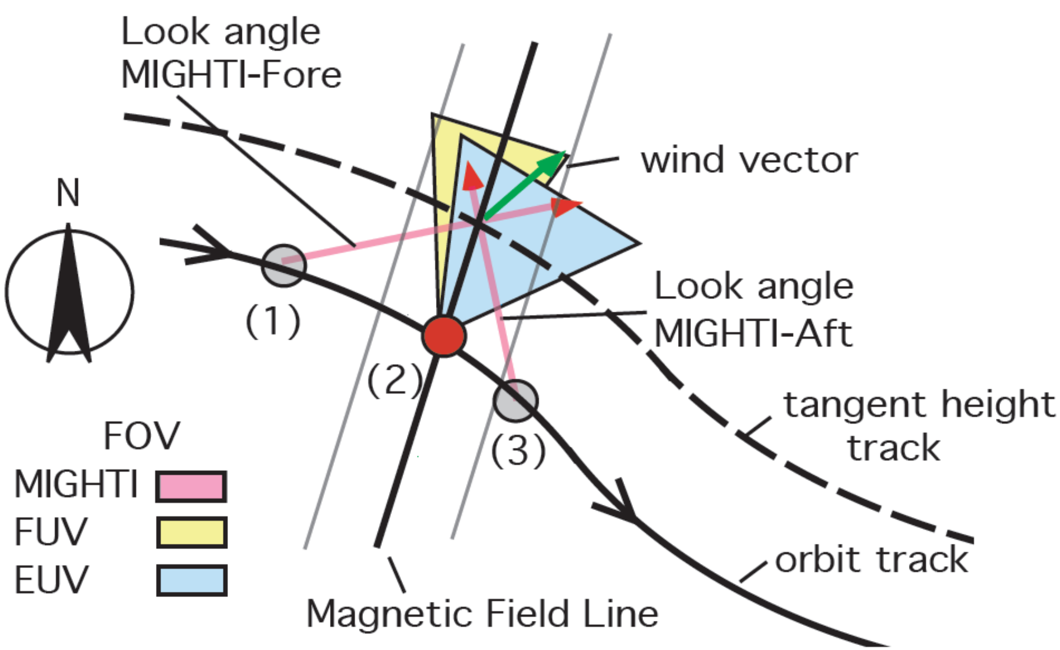
- Optical design based on IMAGE FUV (developed by UC Berkeley and CSL), detectors based on ISUAL.
  - Grating spectrometer
  - Intensified CCD detectors

• Illustration of ICON operations



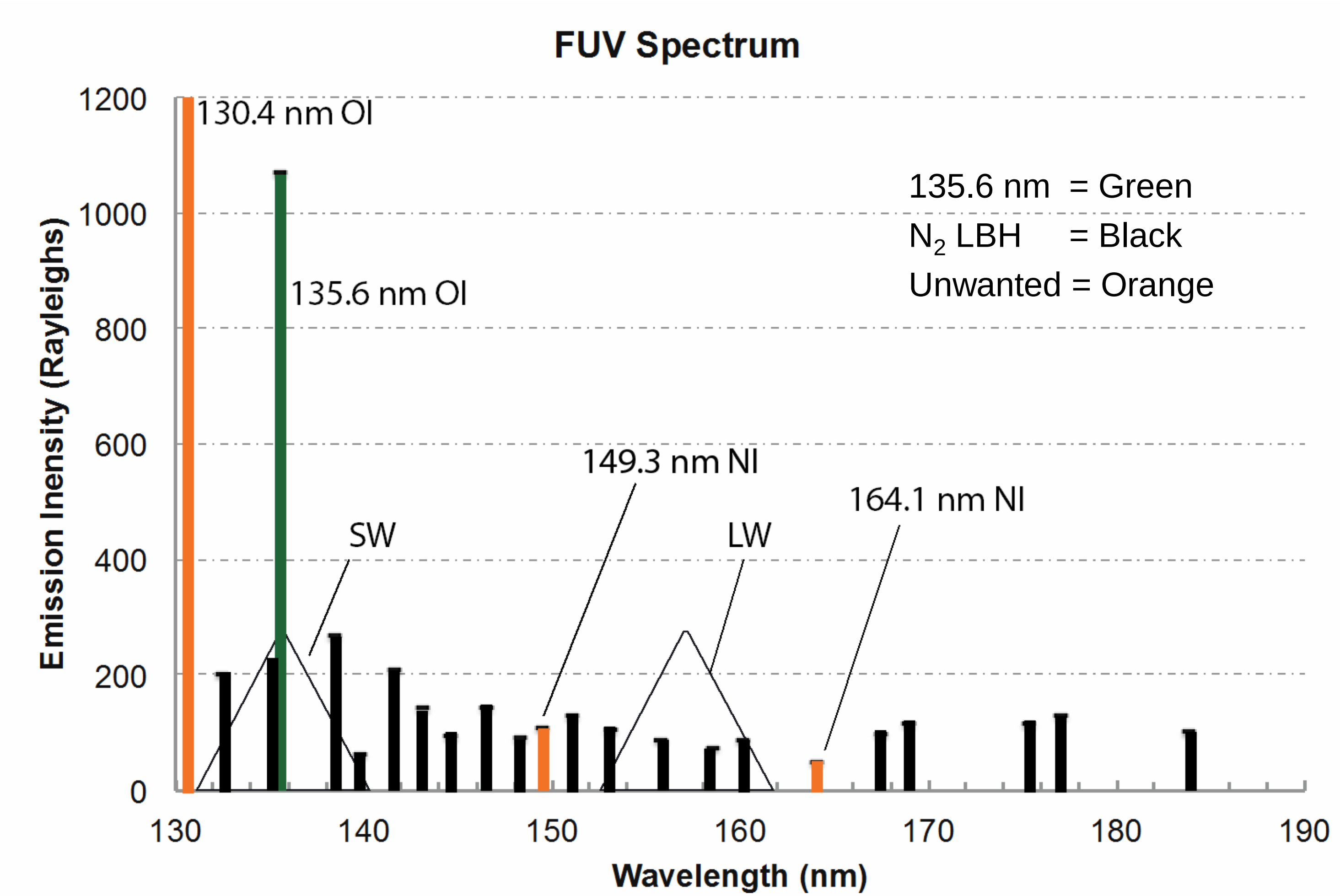
FUV observes on the left (port) side of ICON. On the limb the maximum emission is seen at the tangent point.

At sub limb height integrated emissions are observed



- At night FUV will point along the magnetic field to observe the intensity distribution of the ionospheric O^+ ions.

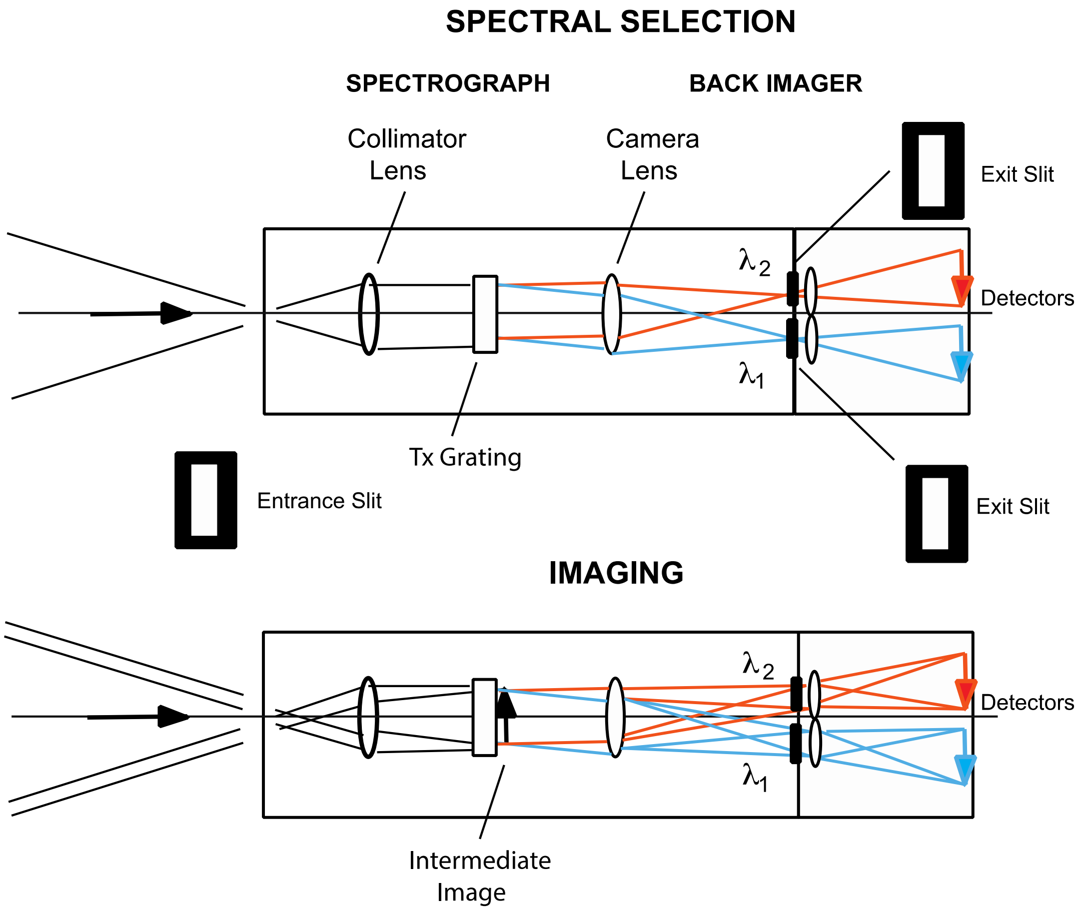
FUV Spectrum



- Spectral distribution (midday nadir) in wavelength range of interest for ICON FUV [Meier, 1991]

ICON FUV Instrument Functional Layout

Functional explanation of the Spectrographic Imager concept.



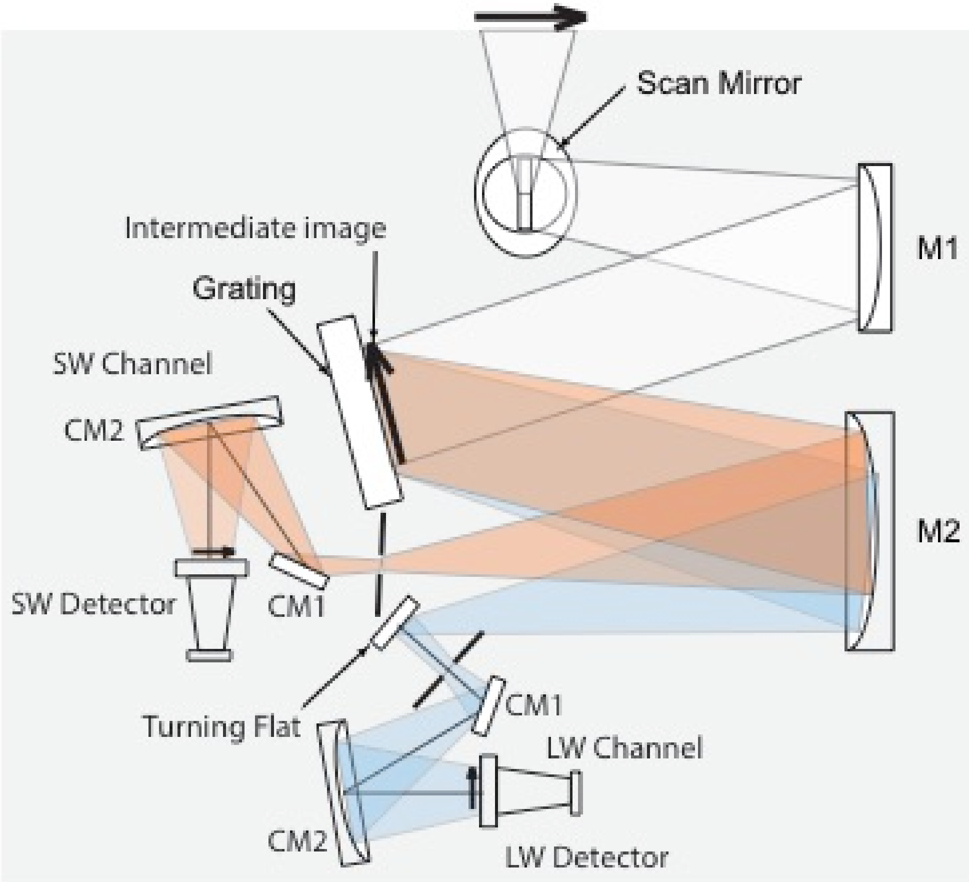
In a spectrographic imager type of instrument, the spectral dispersion and the imaging are in "quadrature," i. e. separate and independent of each other. The top diagram describes the spectral wavelength selection while the bottom explains the imaging operation of the same instrument. These diagrams show lenses as the optical elements for simplicity however in the FUV region it is necessary to use mirrors instead.

Spectral selection. Light enters through entrance slit. Collimator lens provides parallel light for grating. Tx grating disperses the light according to wavelength (red-blue). Exit slit defines the spectral profile of the transmitted light. Detectors pick up light arriving from exit slit.

Imaging. Collimator lens acts as an objective focusing the scene on the grating as an intermediate image. Camera lens combined with back imager small lenses re-image intermediate image on detectors.

•6

ICON FUV Instrument Functional Layout

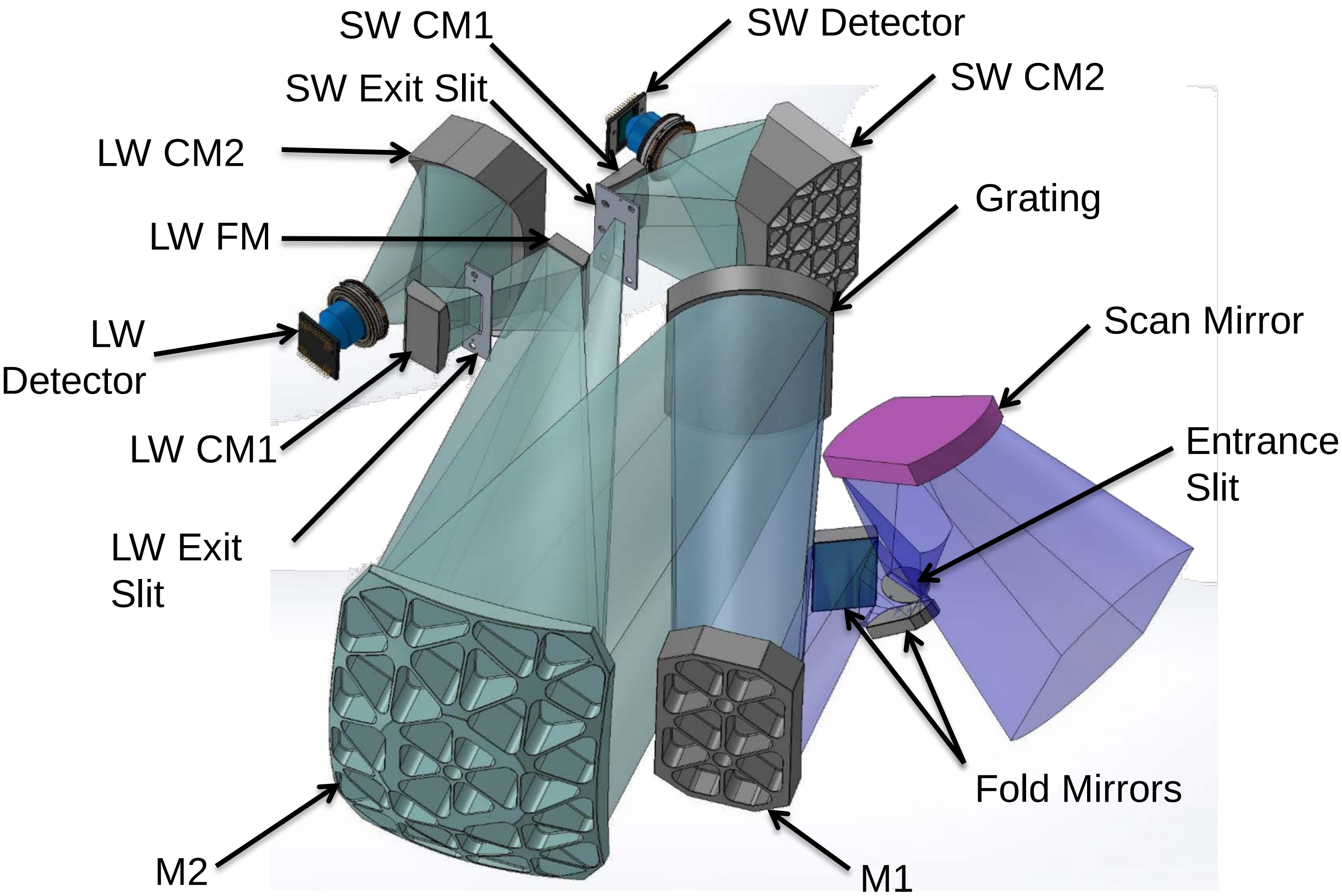


ICON FUV is a Czerny-Turner spectrographic imager. Turret contains a movable steering mirror and a fixed entrance slit.

M1 focuses the object viewed by the instrument on the grating as an intermediate image. This image is then re-imaged on the detectors by M2 and by the back imager optics consisting of two mirrors CM1 and CM2 in each channel. There are two wavelength channels short (SW) and long (LW) wavelength.

The two wavelength channels are handled by separate exit slits, back imager optics and detectors.

ICON FUV Instrument Functional Layout



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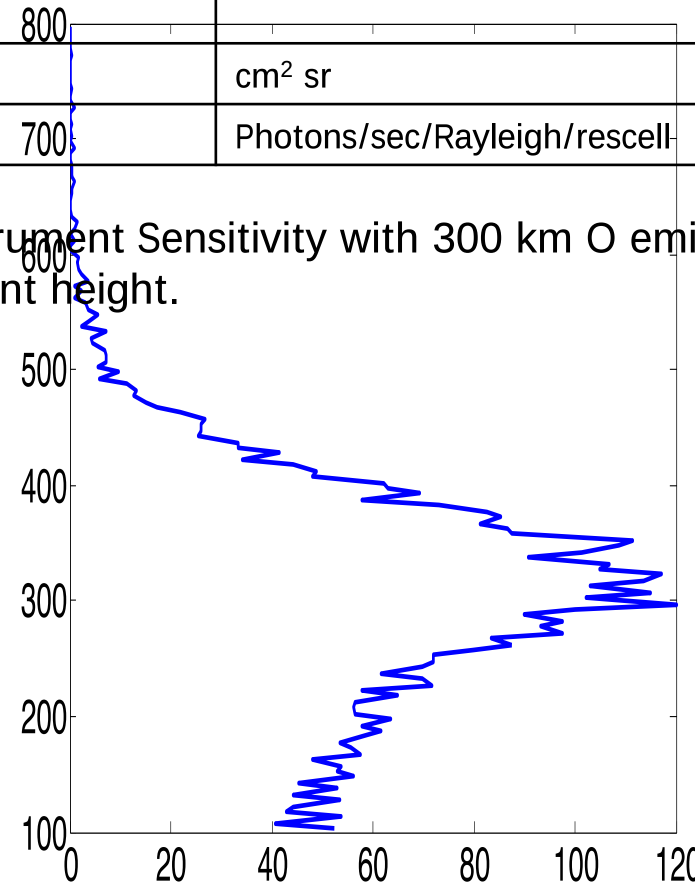
Level 4 Requirement: Instrument sensitivity

Slit area 5mm x 32 mm	1.6	cm^2
Field of view 24º x 18º	0.14 (truncated circle) Equivalent F No. = 2.3	sr
Étendue per science rescell	6.85e-05*	cm^2 sr
Photon collection rate	5.45 (Single stripe)	Photons/sec/Rayleigh/rescell

	135.6	157
Scan Mirror	90.00%	90.00%
Turret Fold 1	90.00%	90.00%
Turret Fold 2	92.00%	90.50%
Spectrograph M1	92.00%	89.00%
Spectrograph M2	91.00%	91.00%
Back Imager SW CM1	80.00%	
Back Imager SW CM2	93.00%	
LW fold		90.50%
Back Imager LW CM1		88.40%
Back Imager LW CM2		82.00%
Total Reflective Efficiency	46.42%	38.95%
Grating eff	17.50%	30.00%
Quantum efficiency	11.00%	7.00%
Efficiency Predicts BOL	0.54%	0.47%
Efficiency Predicts EOL	0.46%	0.40%
Total efficiency measured	0.45%	0.16%
Total Counting Rate/kR/rescell/sec	147	52

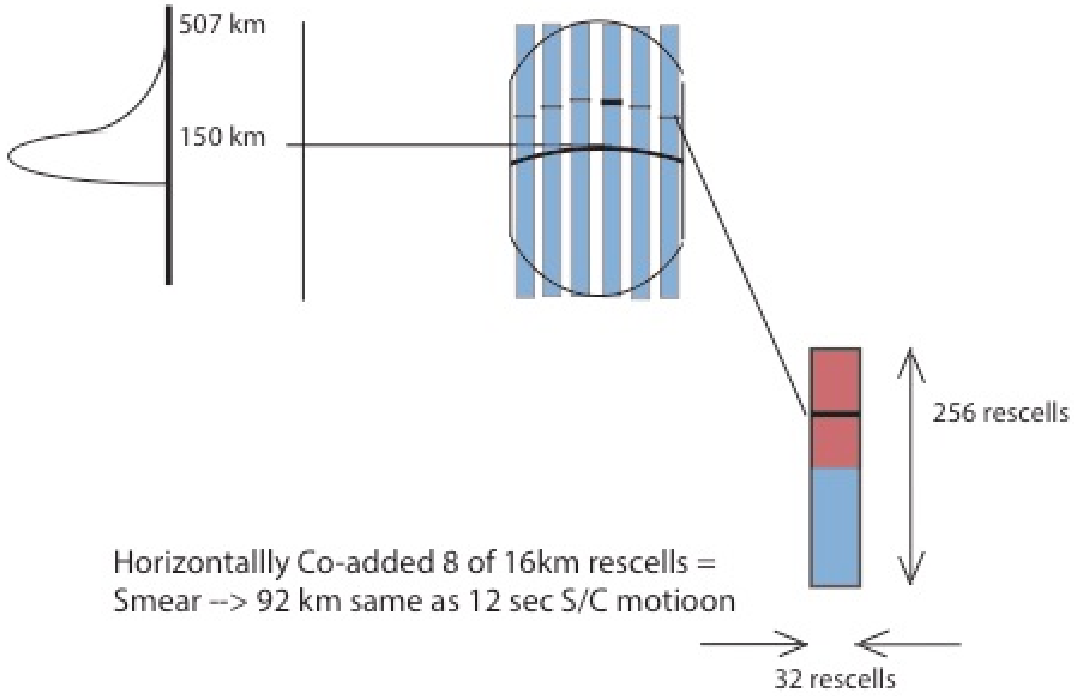
*Instrument Sensitivity with 300 km O emission tangent height.



Key Requirements and Design Considerations

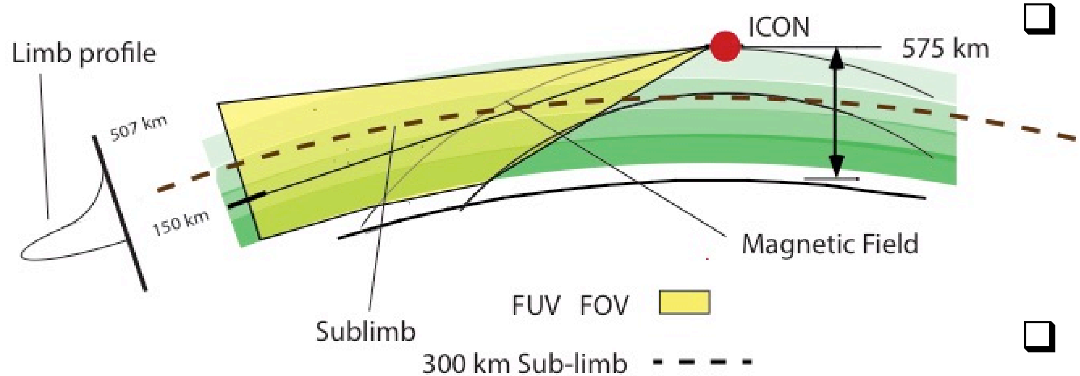
	L4 Requirement	Capability	Implementation
Spectral Resolution	Image OI 135.6 and N2 LBH bands	Complies	**2 channel grating spectrograph**
	Suppressing 130.4 to < 2%	<1%	**Grating line density, slit width**
Radiometric Performance	Sensitivity of: >13 counts/sec/res-el/kR @135.6	147 @ 135.6 night 6 stripes co-added)	**Large étendue, high reflectivity coatings, high QE UV converter, contamination control**
	>8 counts/sec/res-el/kR @LBH	52.3 @ 157 (6 stripes can be co-added)	
Spatial coverage, FOV and Resolution	Field aligned observations	Steerable FOV with range +/- 30º	**Steerable baffle (turret)**
	Vertical FOV of > 20º	Vertical 24º Horizontal 18º	**Wide field collimator – Czerny-Turner Spectrograph**
	Vertical spatial resolution <9km	Vertical 8 km (0.18º) Horizontal 16 km (0.37º)	**Optical Design, Tolerance Analysis, Detector Selection**
Dynamic Range	Dynamic range of 1,000	10,000	**UV converter with fast frame read out rate camera and subsequent digital co-add**
Motion Compensation and Data Compression	Maintain spatial resolution from moving spacecraft. Fit in allocated ICON data budget	TDI motion Compensation	**TDI algorithm - LUT instrument and geographic distortion correction, digital co-adding with address offset**

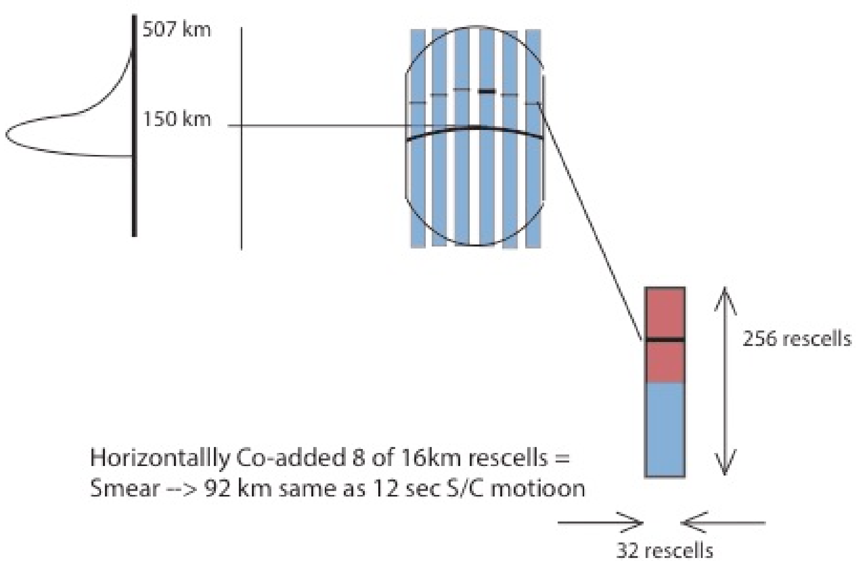
•Data Type 1: Limb Altitude Profiles.



•Illustration of limb altitude profiles. There are 6 vertical strips. In each strip the pixels are co-added horizontally. During daytime data is taken for both channels. For nighttime for the 135.6 nm channel only. Below 150 km altitude there is substantial O_2 absorption and it is not possible to get limb views of the atmosphere.

Limb Altitude Profiles

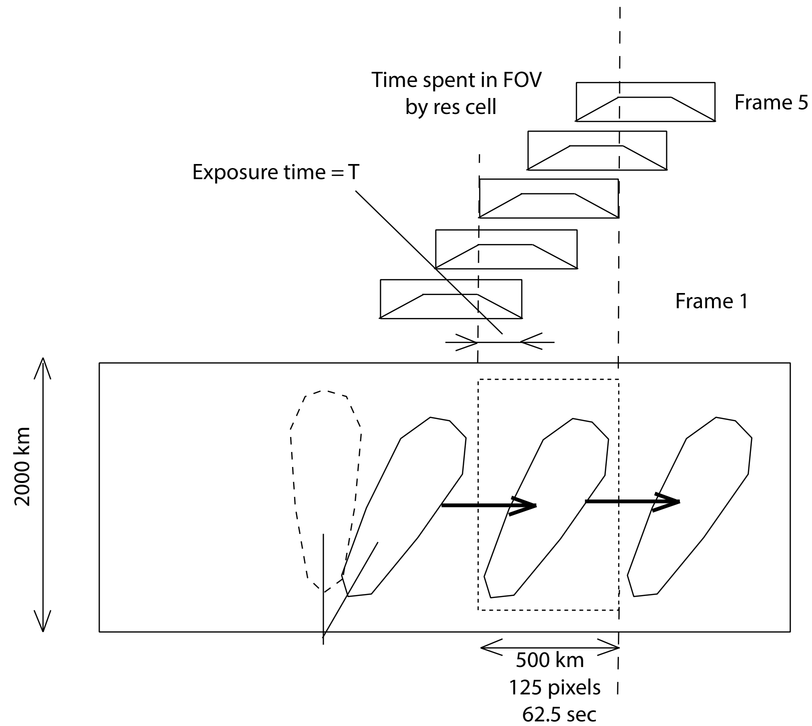




- Daytime for both channels. Nightime 135.6 nm only. Below 150 km altitude there is substantial O_2 absorption and it is not possible to get limb views of the atmosphere.
- ICON prime science is measuring the altitude distribution of the thermosphere/ionosphere on a spatial scale of ~ 500 km.
- The nighttime equatorial ionosphere is often unstable producing small scale structures.
- ICON will have the capability of monitoring the ionosphere to detect ionospheric irregularities on a spatial scale of 10-20 km.
- ICON FUV has the capability of recoding images using Time Delay Integration (TDI)

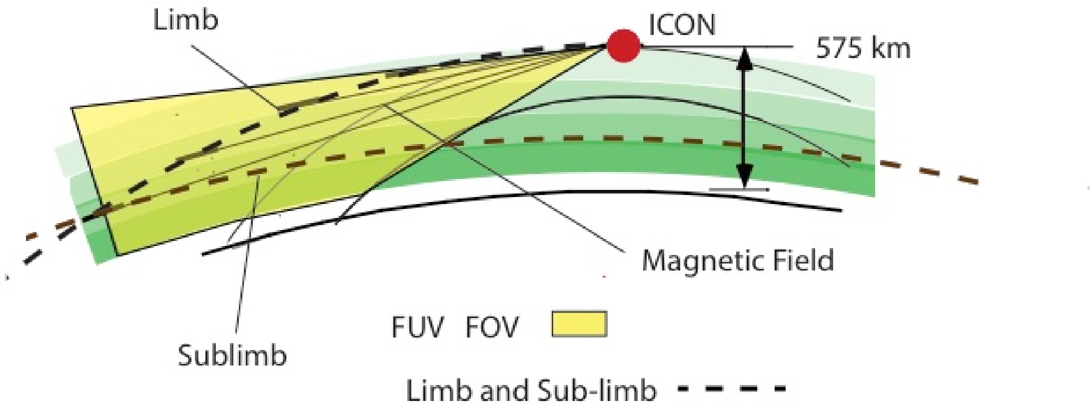
Data Type 2: TDI-ed emission maps

(Nightime only)



This treatment assumes that the emissions are mapped either on the sub-limb at a constant altitude at 300 km or on the limb view tangent point associated with the elevation of the view angle.

•Illustration of ICON operations (Side View)



FUV observes on the left (port) side of ICON. On the limb the maximum emission is seen at the tangent point.

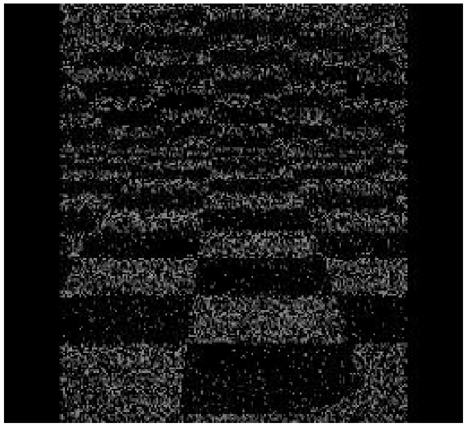
At sub limb height integrated emissions are observed

•During daytime-

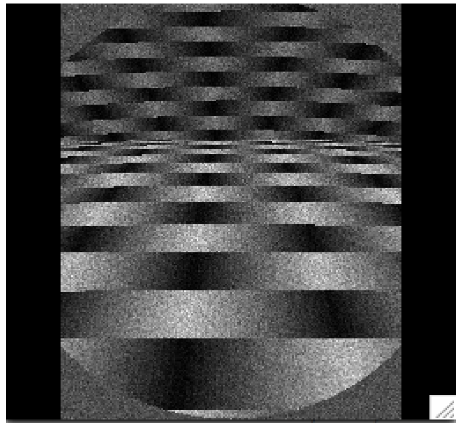
- ICON FUV takes only altitude profiles at limb tangents (no sub-limb).
- ICON looks perpendicular to the orbit plane
- Exposures are 12 seconds long.
- In 12 sec exposure ICON travels 96 km and the curvature of the Earth will provide less than 1 km altitude error.

TDI imaging 0 turret angle

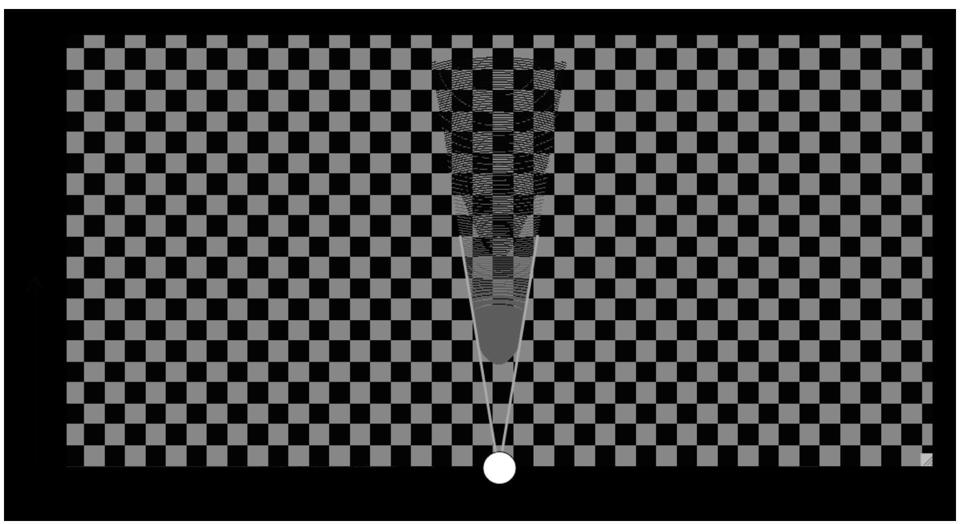
Raw images white checks 0.6 counts per res cell per frame. Black 0.03 counts per frame.

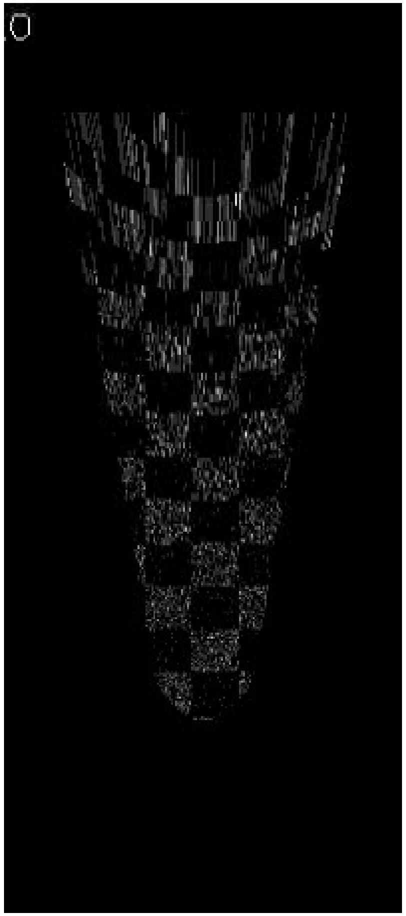


Movie of uncorrected frames

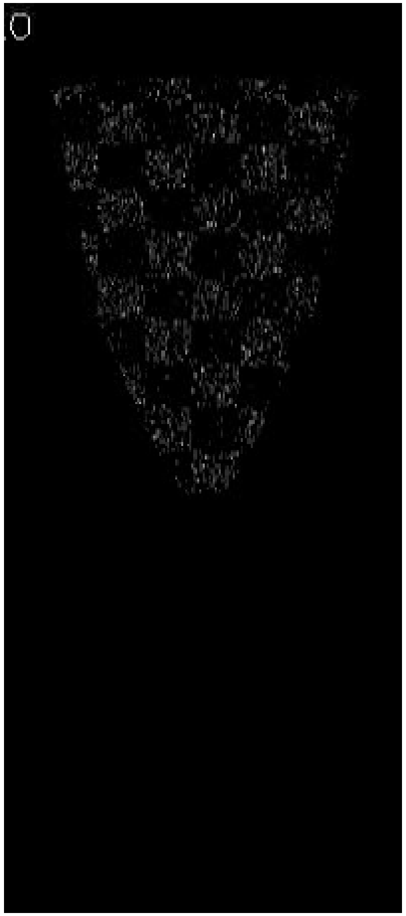


Co-added uncorrected images





Sub Limb

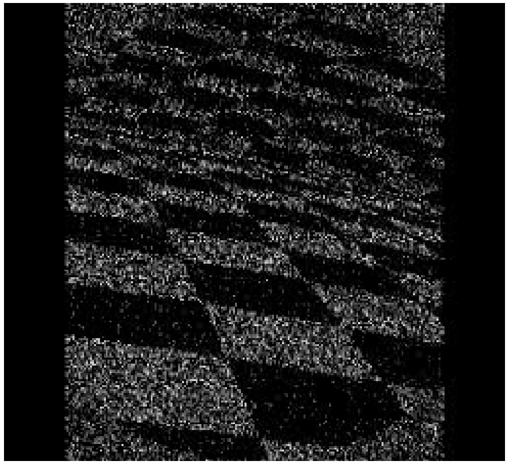


Limb Tangent

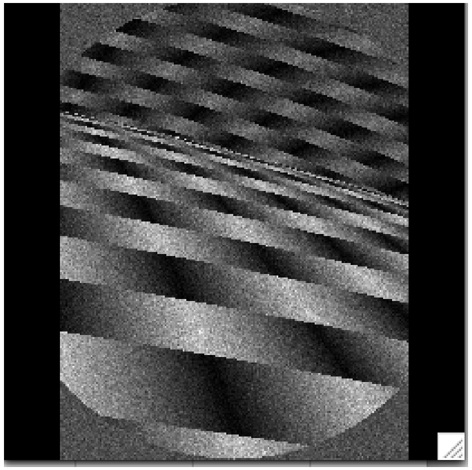
TDI mapped images with motion compensation co-added

TDI imaging 15 degree turret angle

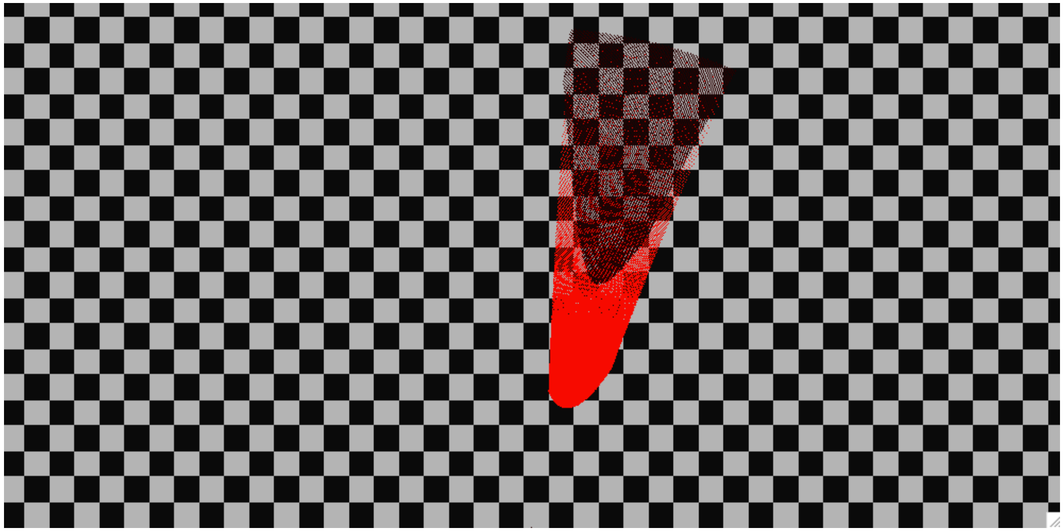
Raw images sublimb white 0.6 counts per res cell per frame. Black 0.03 counts per frame.

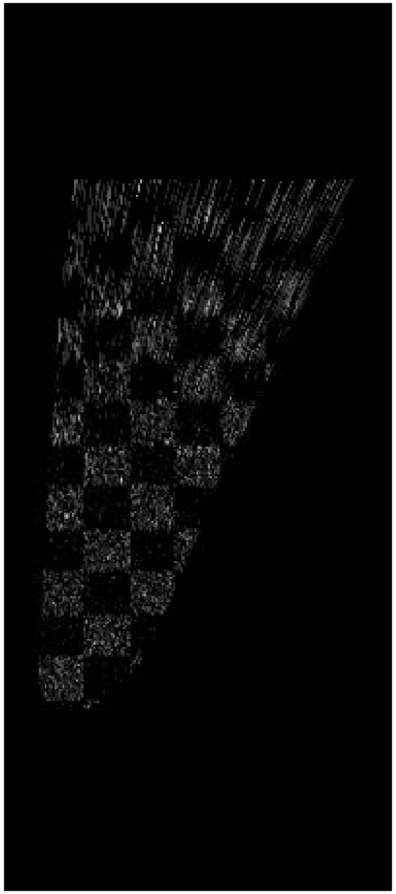


Movie of uncorrected frames



Co-added uncorrected images



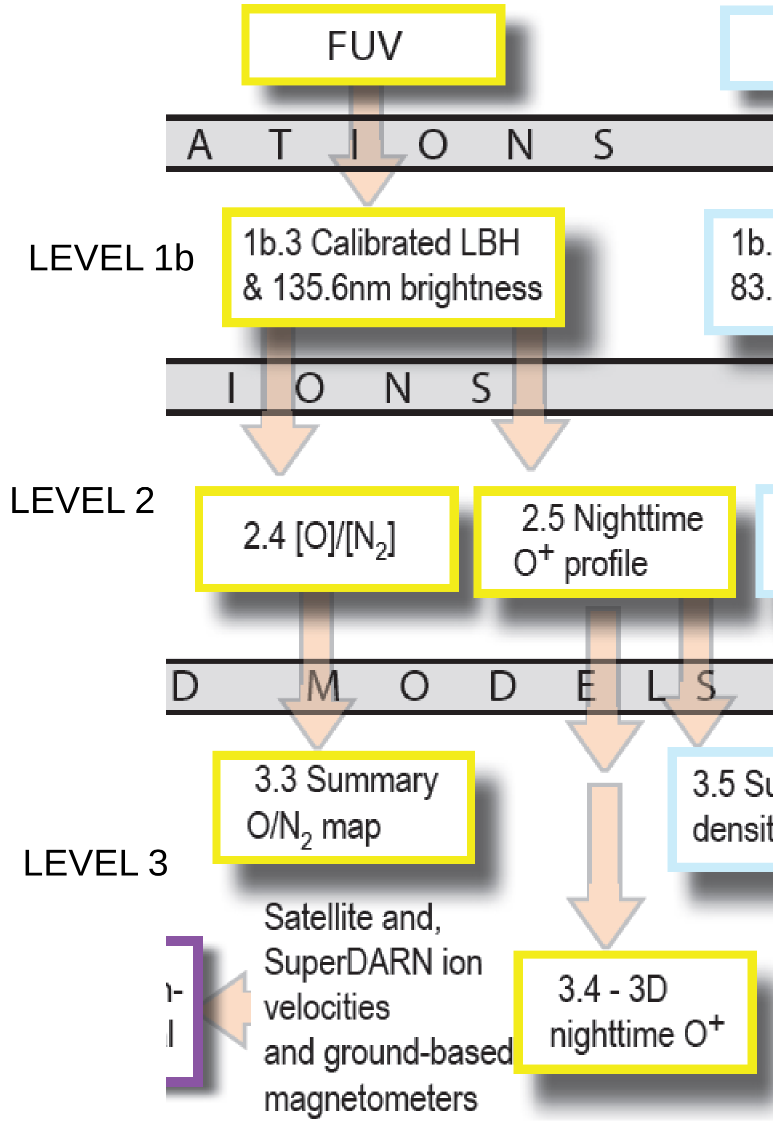


Sub Limb

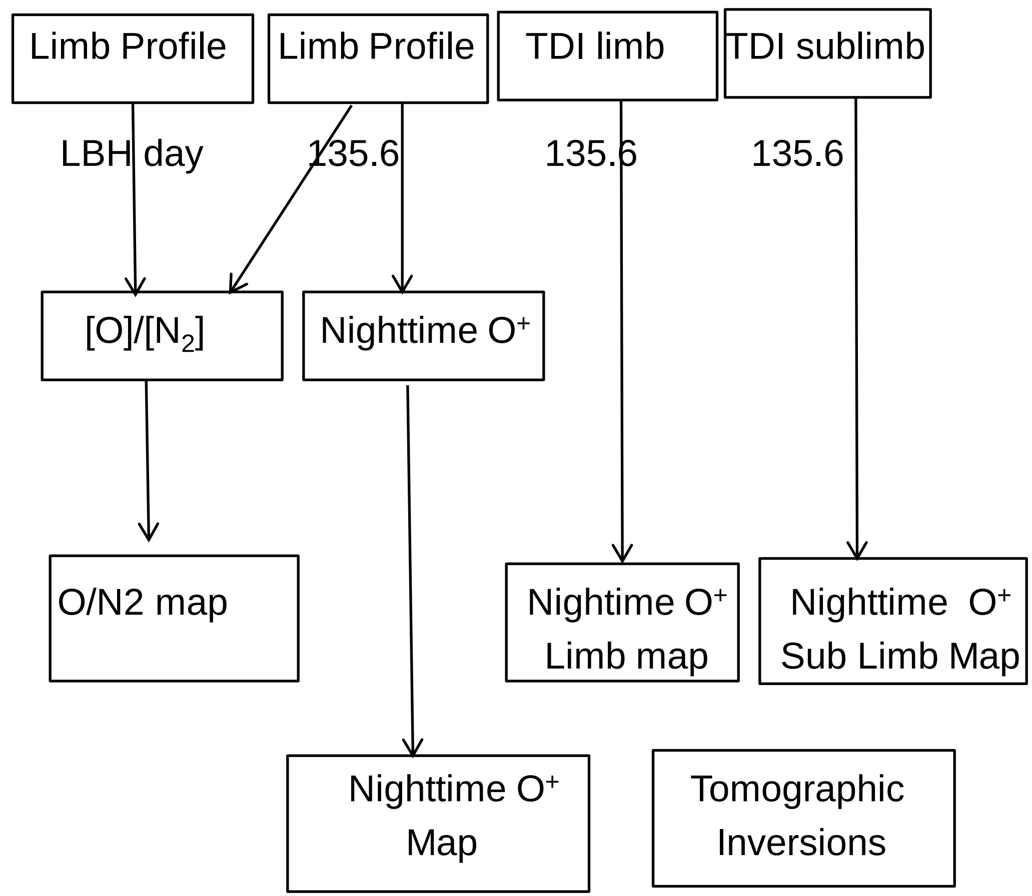
Limb Tangent

TDI mapped images with motion compensation co-added

FUV Data Products



Calibrated LBH & 135.6 intensities

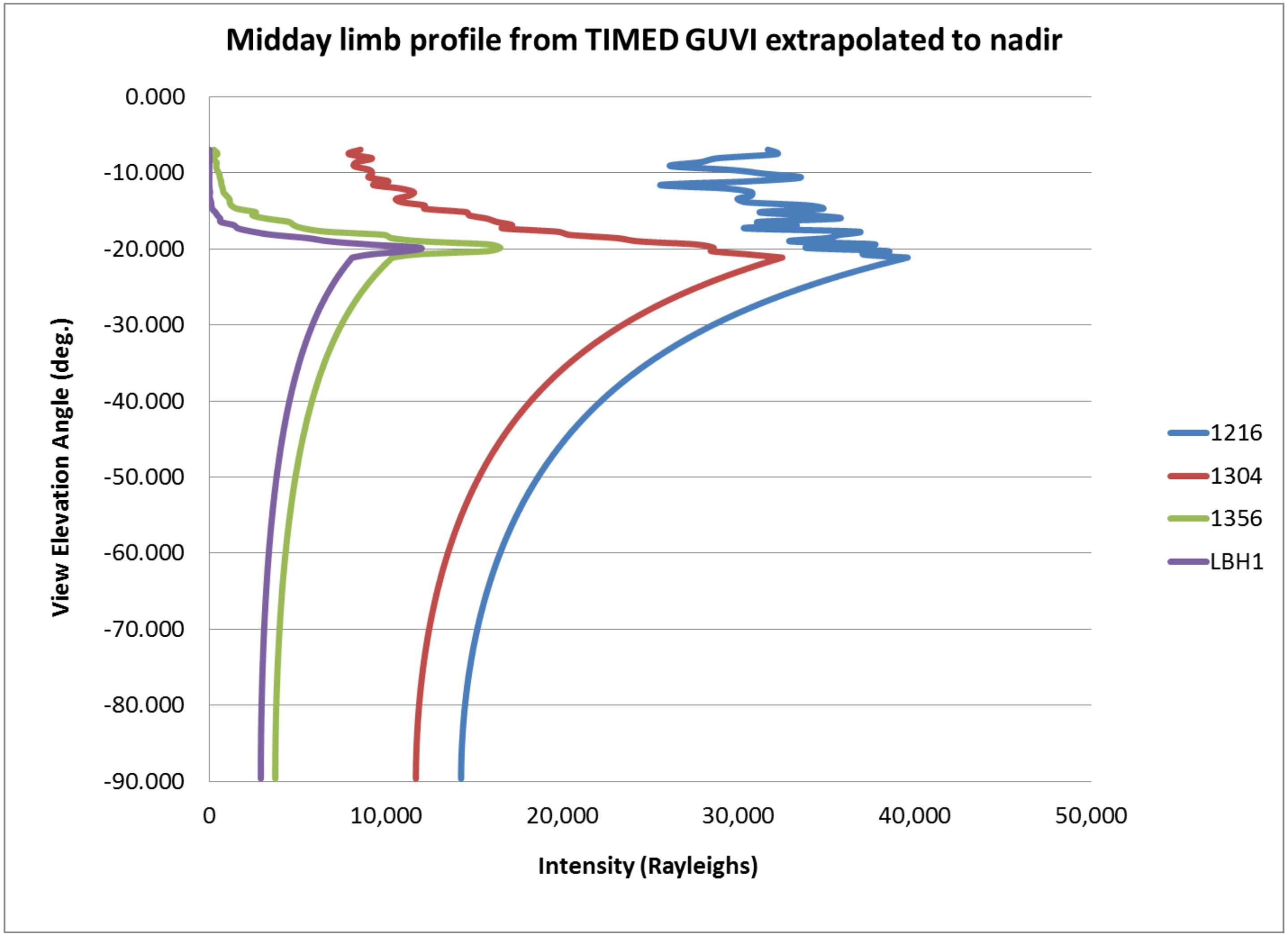


Atmospheric model for straylight calculations.

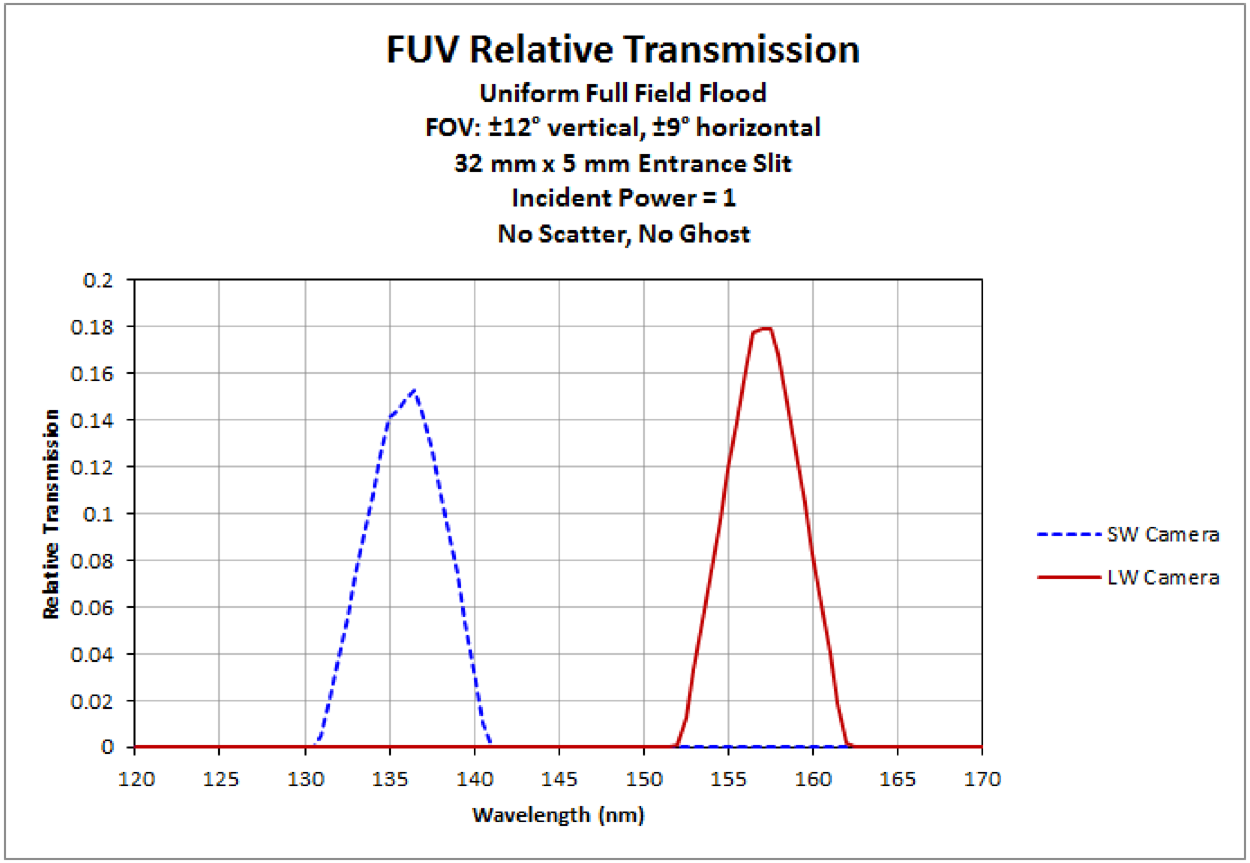
- Constructed source models for limb emission derived from GUVI from measurements from atmospheric vs. altitude for 121.6 nm, 130.4 nm, 135.6 nm, 157 nm

- Completed preliminary atmospheric limb irradiance calculations for both cameras at 121.6 nm, 130.4 nm, 135.6 nm, 157 nm
  - 157 nm source model used LBH lines at 153.1 nm, 155.8 nm, 158.6 nm, 160.2

GUVI data of the key day-glow features.

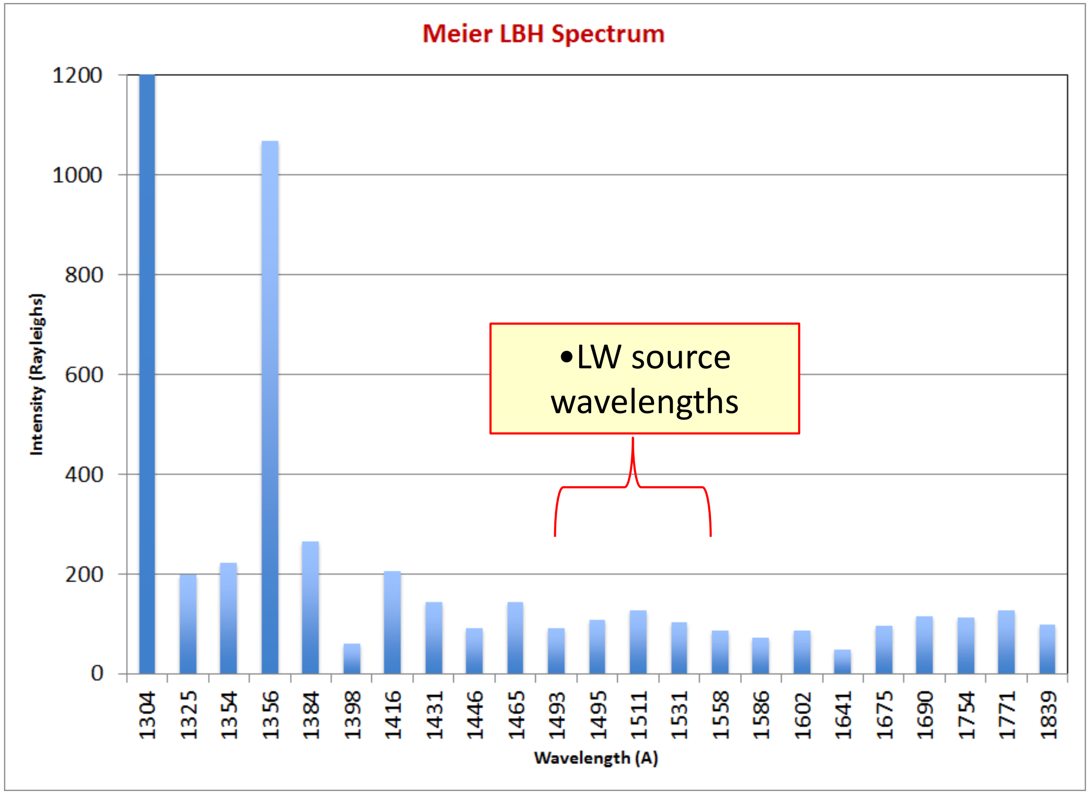


FUV Relative Transmission Analysis



Integrated power vs. wavelength, no ghost, no scatter

Reference Intensity vs. Altitude



Notes

- GUVI data was used for the 121.6 nm, 130.4 nm, and 135.6 nm source models (all traced monochromatically)
- The 157 nm (LW) source model is polychromatic, with in-band wavelengths selected from the Meier spectrum data. It uses the LBH1 limb profile.

Backgrounds

Modeling of stray light.

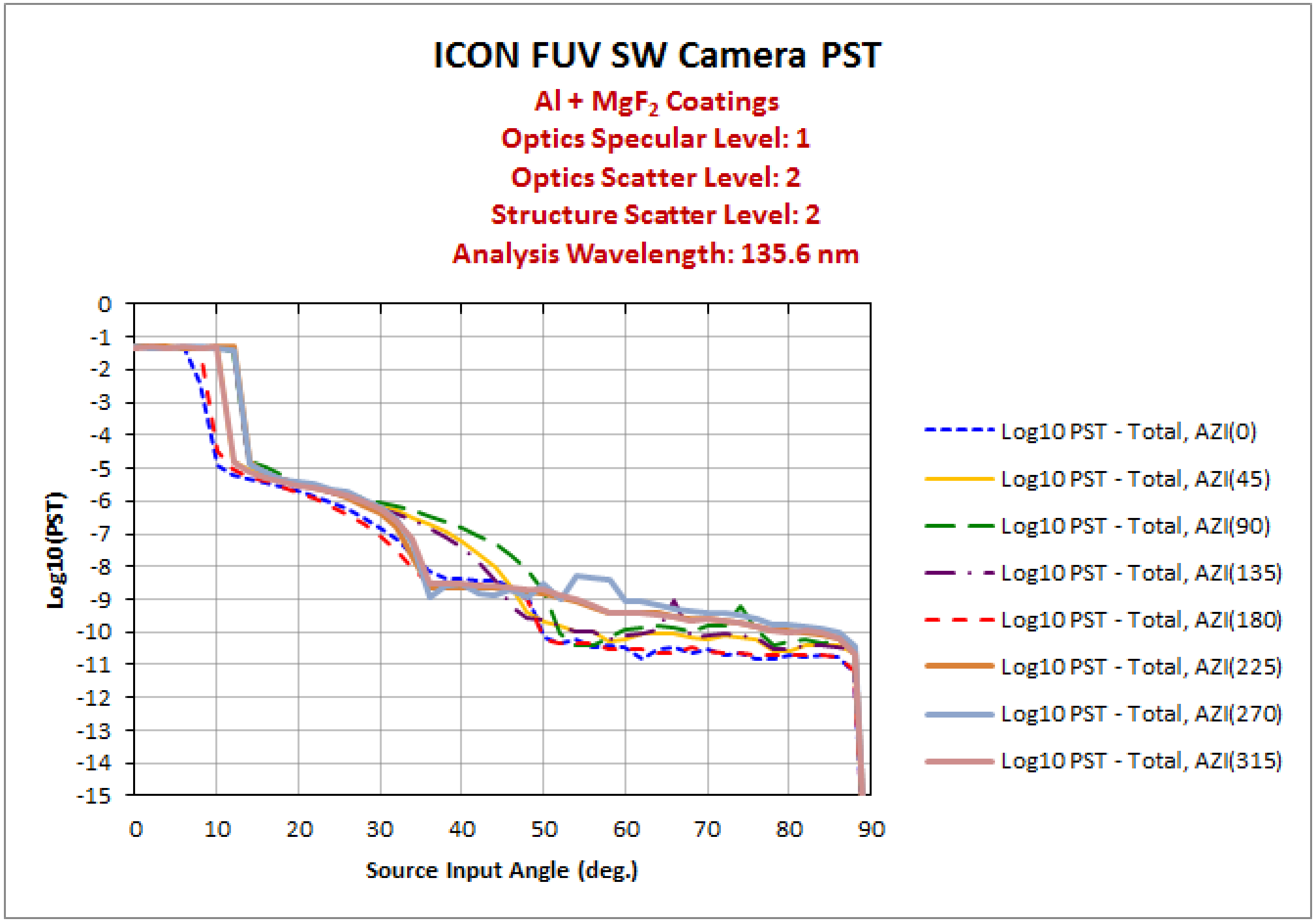
Step 1. Performing PSD computations.- Instrument Response to parallel incoming radiation as a function of the angle of arrival at the aperture of the instrument.

Step 2. Modeling the Limb. - Calculating the integrated stray light energy using the the PSD combined with the distribution of photon fluxes arriving at the aperture of the instrument.

2 component to stray light:

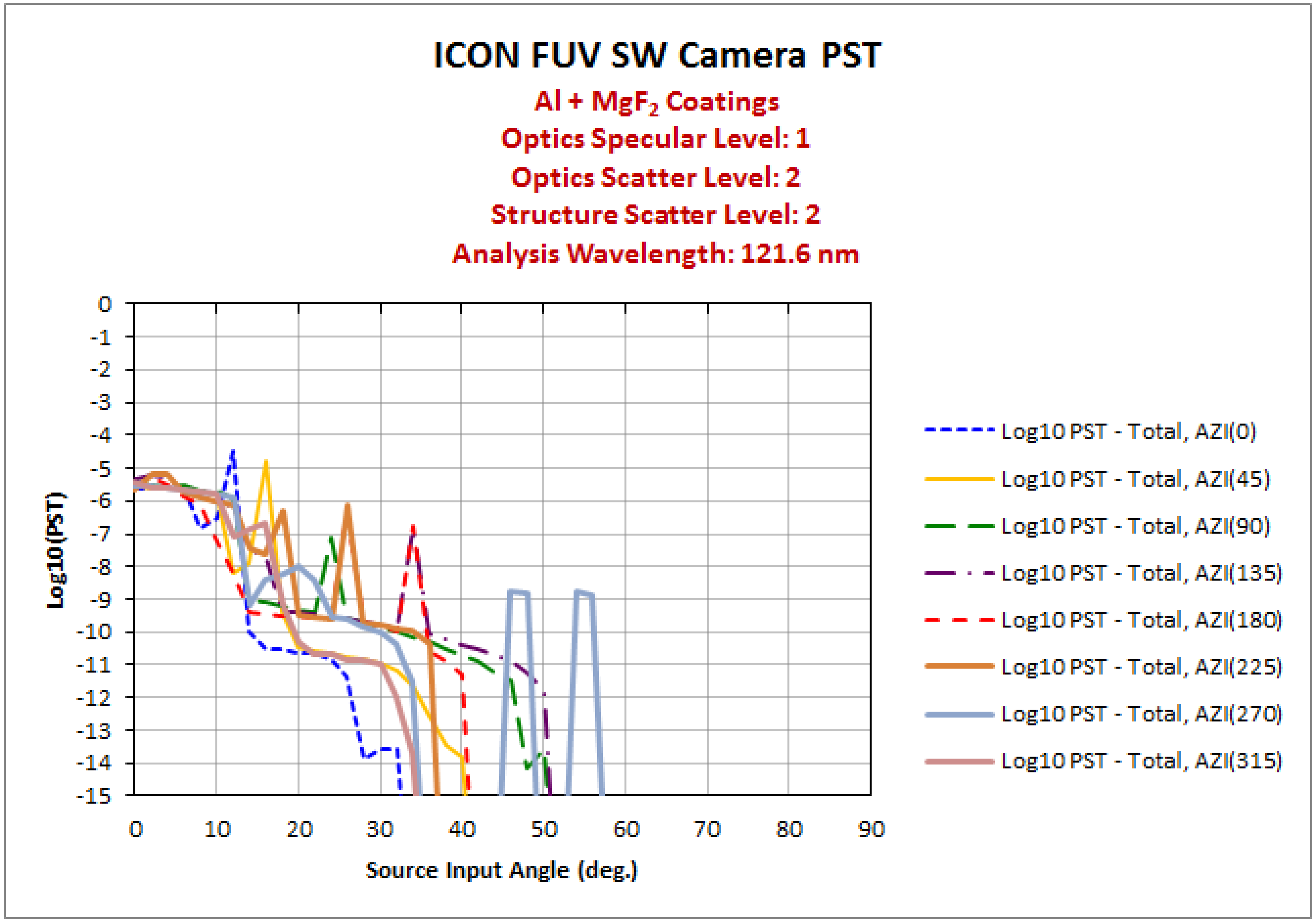
1. Out of wavelength band radiation originating in the FOV
2. In wavelength band radiation originating outside the FOV.

SW Camera PST (135.6 nm)

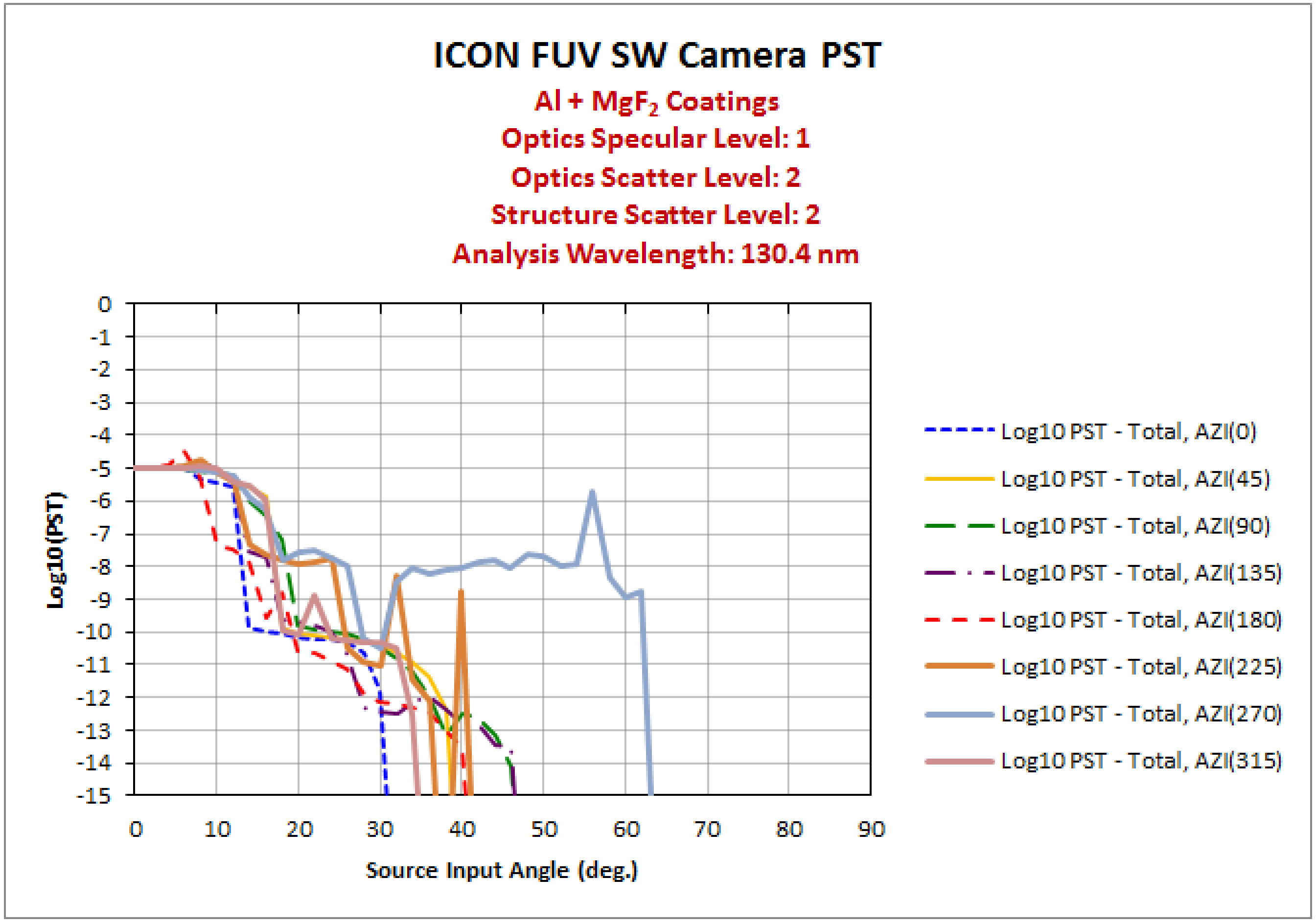


- Design wavelength

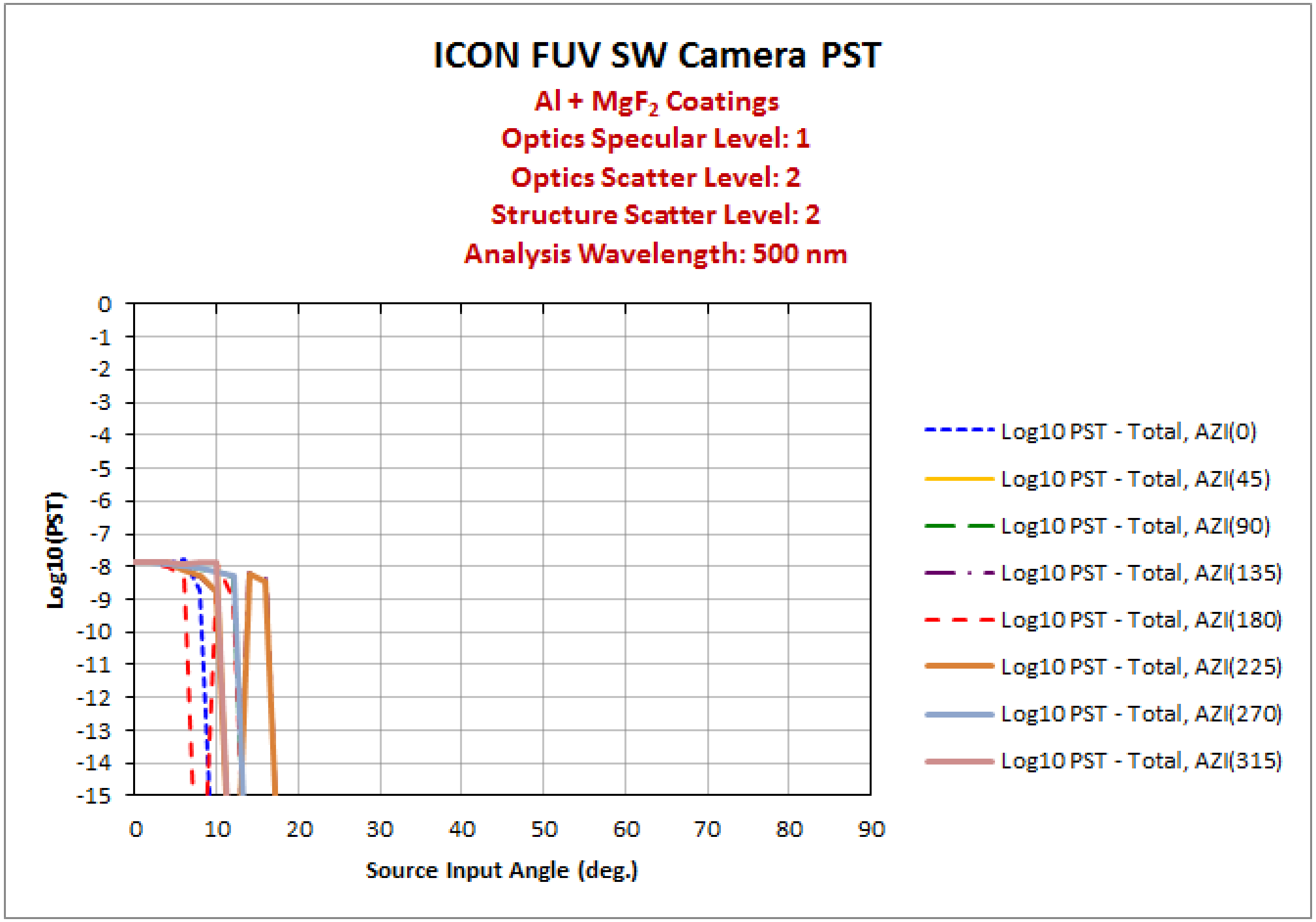
SW Camera PST (121.6 nm)



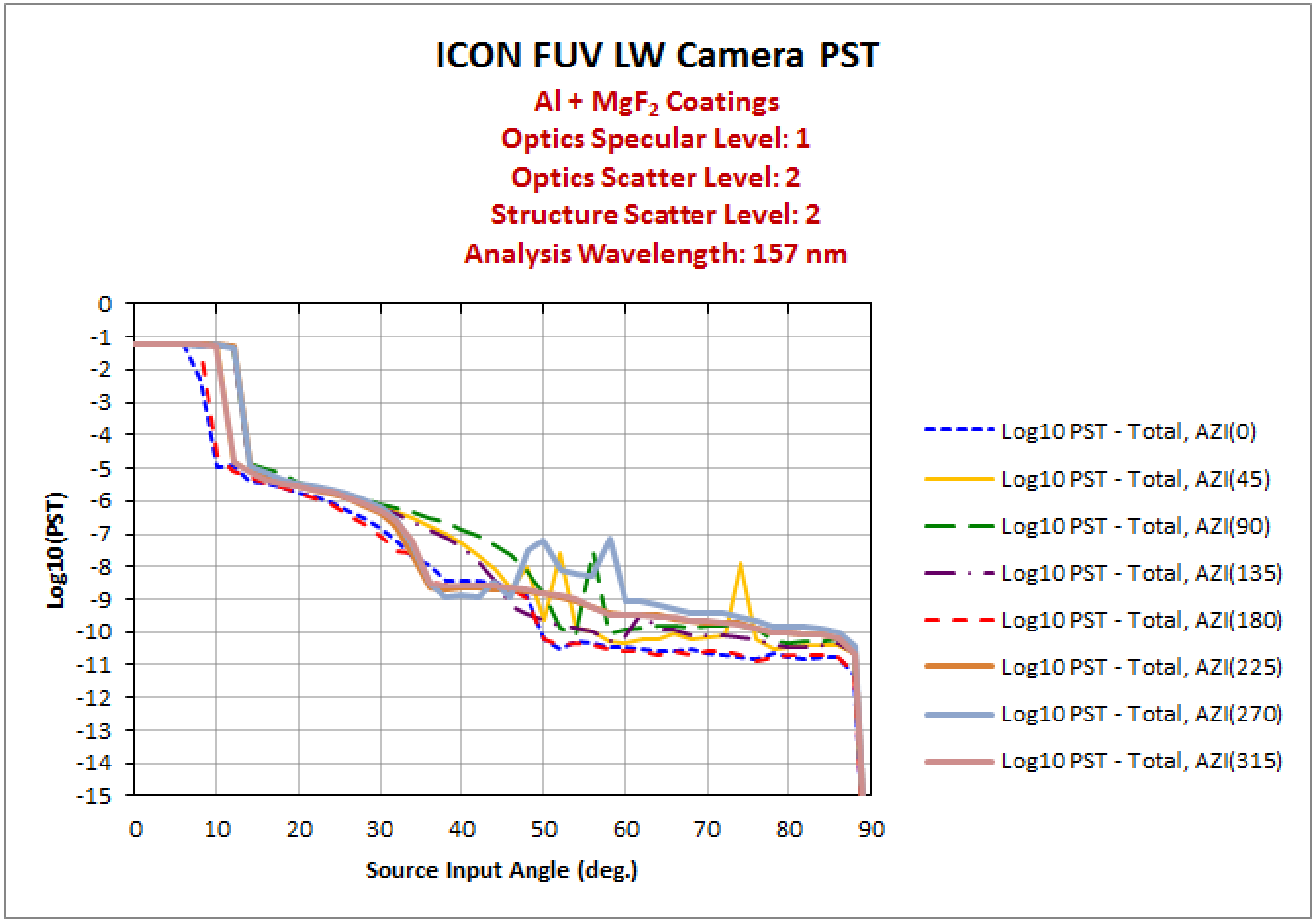
SW Camera PST (130.4 nm)



SW Camera PST (500 nm)

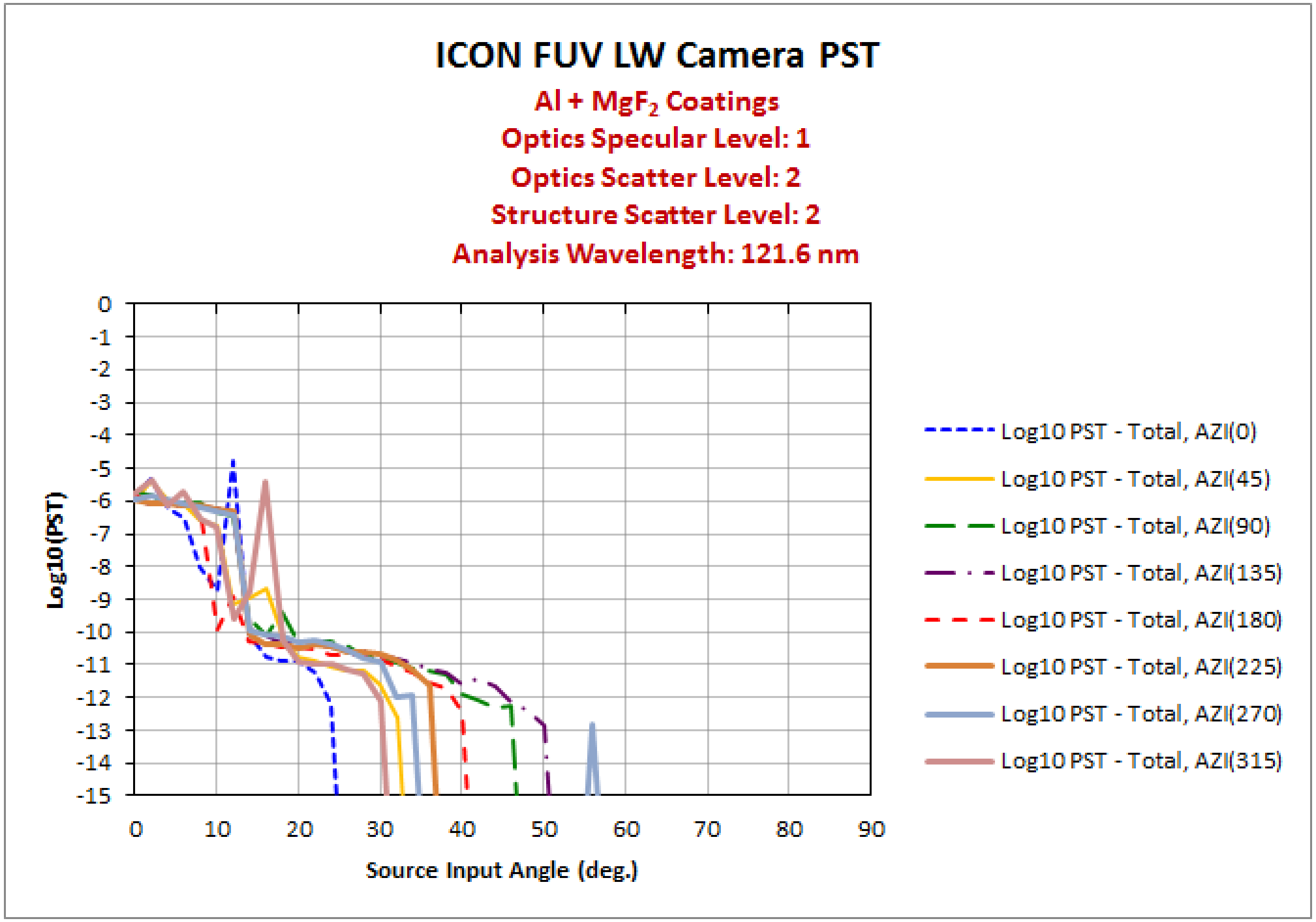


LW Camera PST (157 nm)

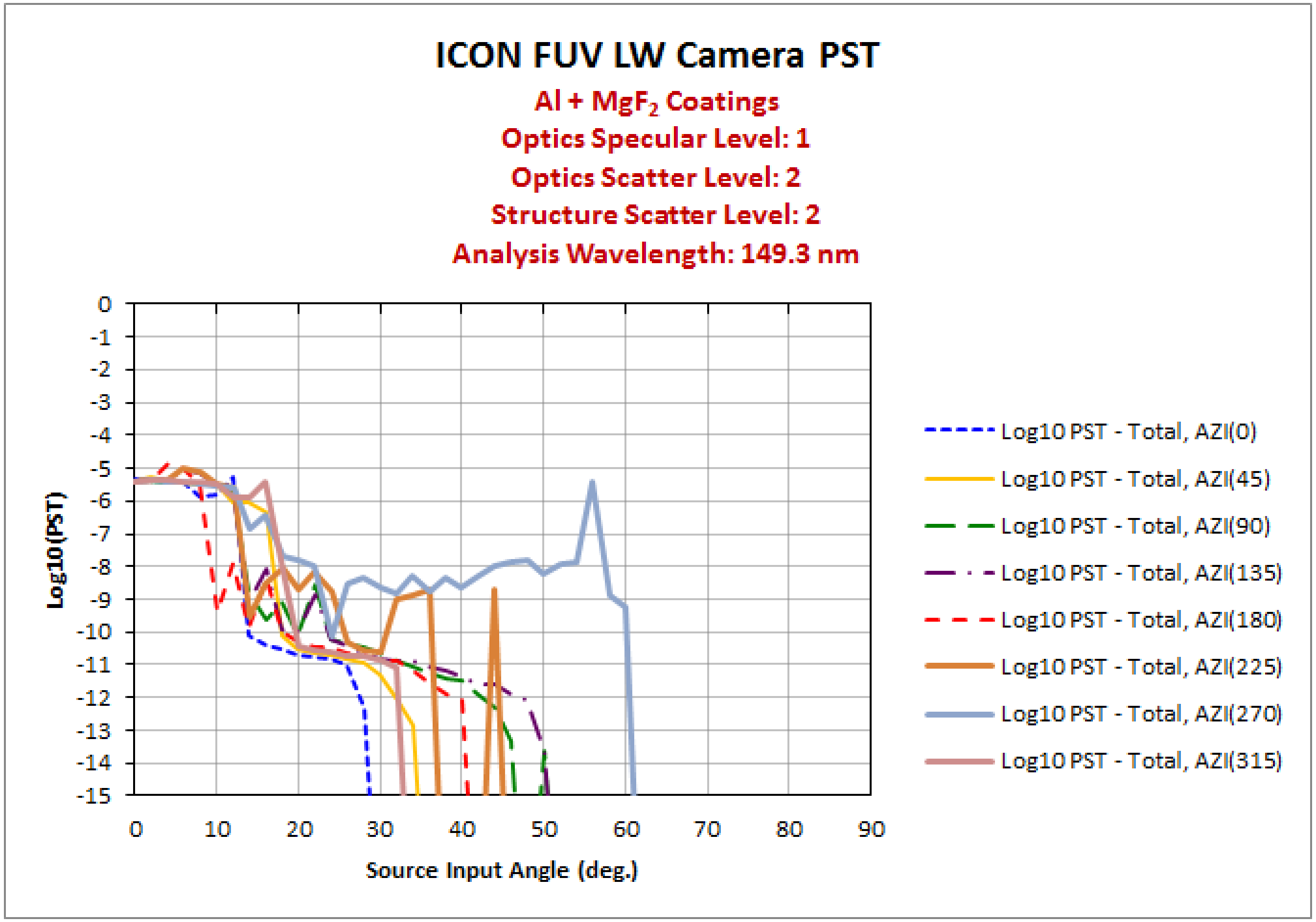


- Design wavelength

LW Camera PST (121.6 nm)



LW Camera PST (149.3 nm)



Modeling the Limb

- Source radiance models are converted to intensity (flux/steradian) via ray tracing
- The trace algorithm divides the atmosphere into a series of earth-centric annular rings corresponding to different altitudes
- Each ring is oriented so that it is tangent to the line of sight for a known altitude
  - For reference the center of the field of view is tangent at an altitude of approximately 155 km
  - As the altitude increases, the ring rotate away from the spacecraft → equivalent to increasing the vertical field angle
- Ray powers are computed using the limb radiance and line of sight projections onto the baffle input
- Rays are traced to the aperture and the intensity values are computed on polar grids that are subsequently used to in the source models for the detector irradiance computations

Comments

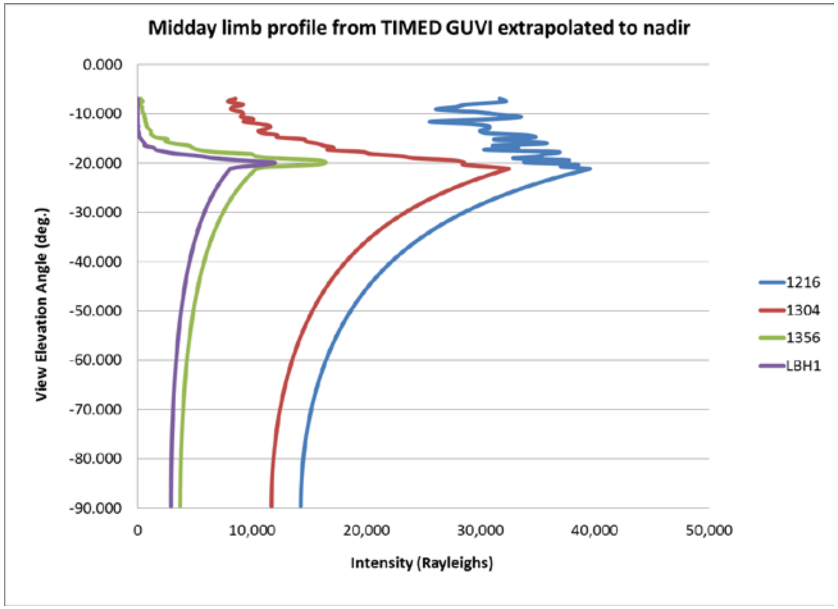
- Visible light analysis (400 nm – 700 nm) shows nearly identical behavior for the two cameras
  - No diffraction: all light is propagated in the direction of the zeroth order (higher orders are evanescent)
  - ~7 orders of magnitude attenuation for objects inside the field of view
  - No contribution outside of the field of view
- Broadband coating results in higher backgrounds for out of band light
  - It remains to be seen if this has a significant impact on the overall performance of the system

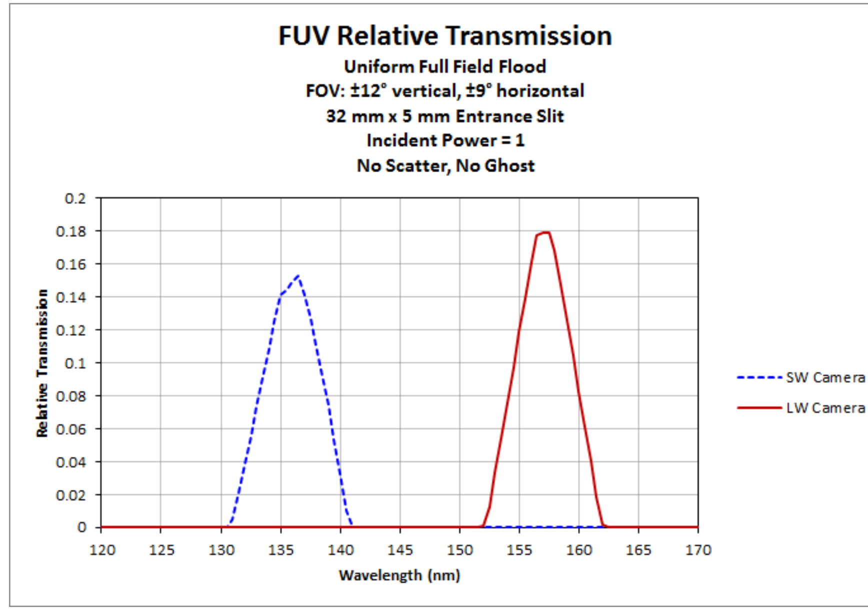
Comments

- ❑ Because the SNR calculations are based on irradiance calculations, they are subject to statistical noise → these data should not be interpreted as absolute, but should provide a good qualitative estimate of performance
- ❑ Integrated flux calculations are more reliable → in a ray trace, power converges more quickly than irradiance
- ❑ Both SW and LW channels are susceptible to direct illumination from sources outside of the design field of view → this contribution is a significant source of stray light
- ❑ Out of band rejection is very good, even for cases in which the line strength is much larger than the intended signal
- ❑ Ghost and scatter events, in and out of band, contribute a small amount to the stray light background
- ❑ The model assumes a diffuse black surface treatment for all opto-mechanical surfaces and structures

Scattering Analysis Summary

Requirement: scattered light all contribution < 2%





- ❑ Model by Photon Engineering
- ❑ Calculated PST based on instrument model
- ❑ Used GUVI measurements for daytime stray light input and integrated PST
- ❑ Results better than 2% peak requirement
- ❑ Very effective out of band rejection especially in the visible ~7 orders
- ❑ Dominant stray light from in band out of FOV

	SW Camera	LW camera
Signal (photons/s)	1.51E+07	9.42E+06
In band SL (photons/s)	1.47E+05	7.92E+04
In band SL (%)	0.98%	0.84%
Out of band SL (photons/s)	4.50E+04	3.43E+04
Out of band SL (%)	0.30%	0.36%
Total SL (%)	1.27%	1.20%

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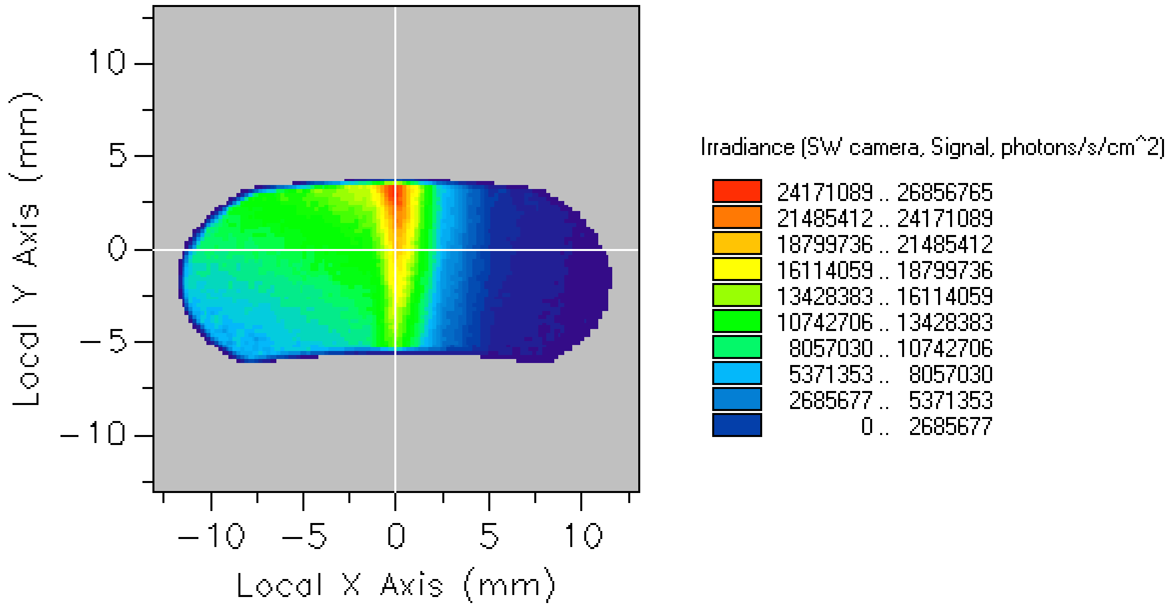
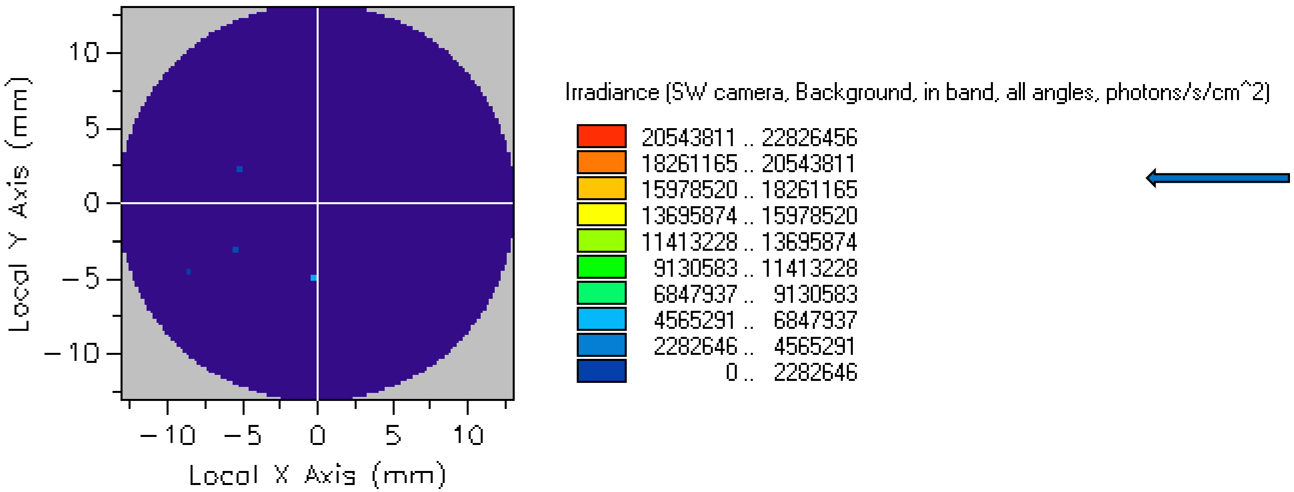
SW Camera: Signal Irradiance

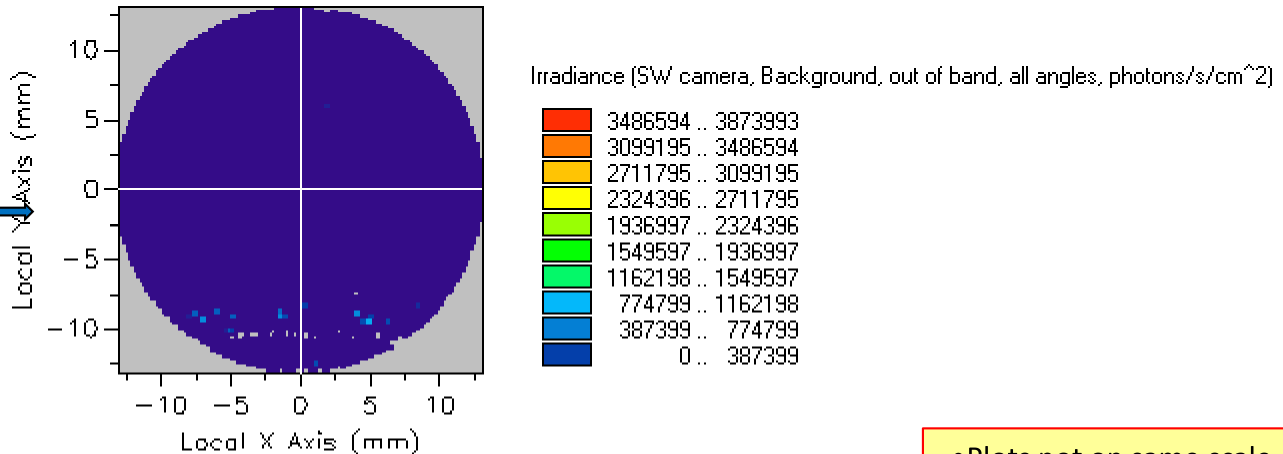


SW Camera: Background Irradiance



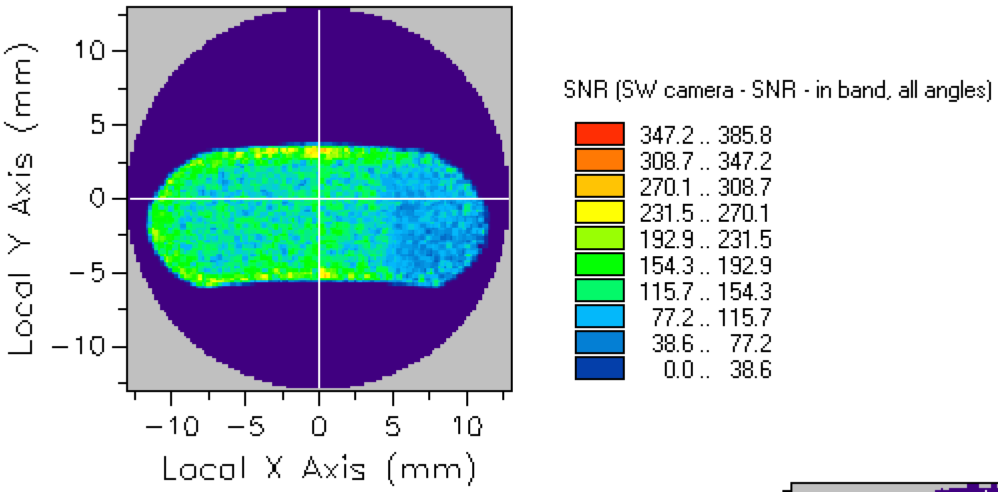
- In band stray light, all angles

- Out of band, all angles



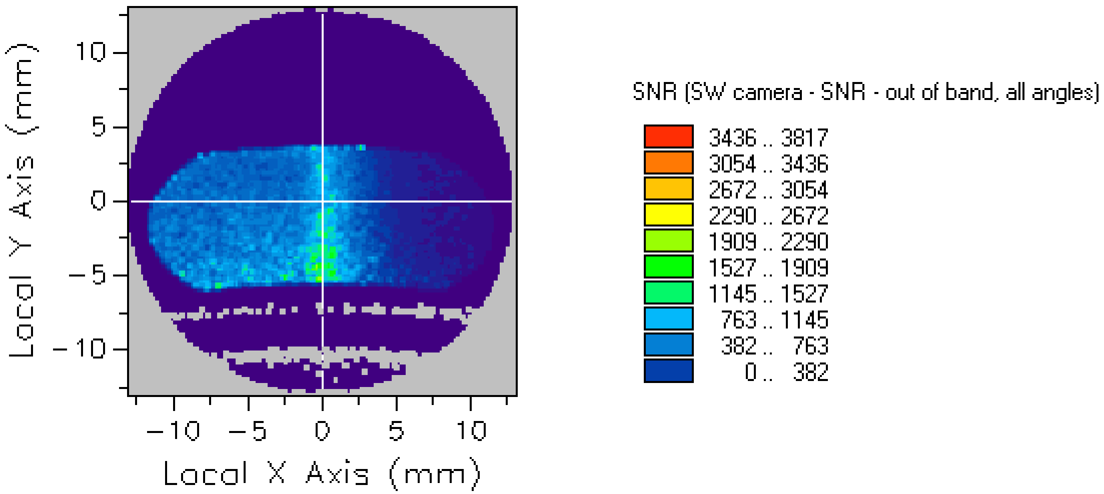
- Plots not on same scale

SW Camera Signal-Background

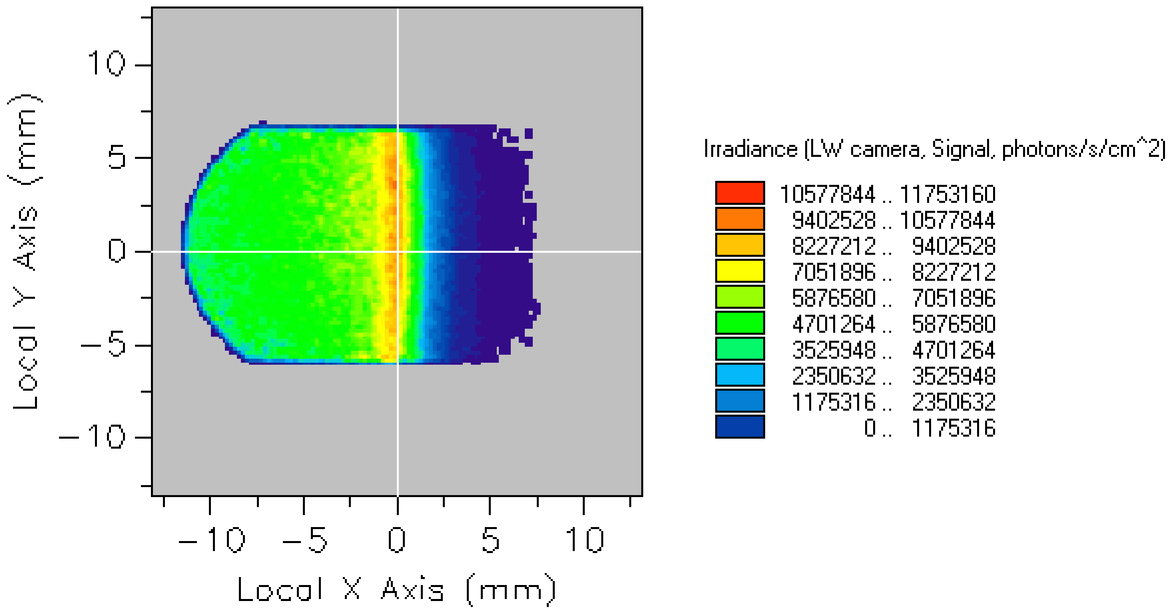


• In band, all angles

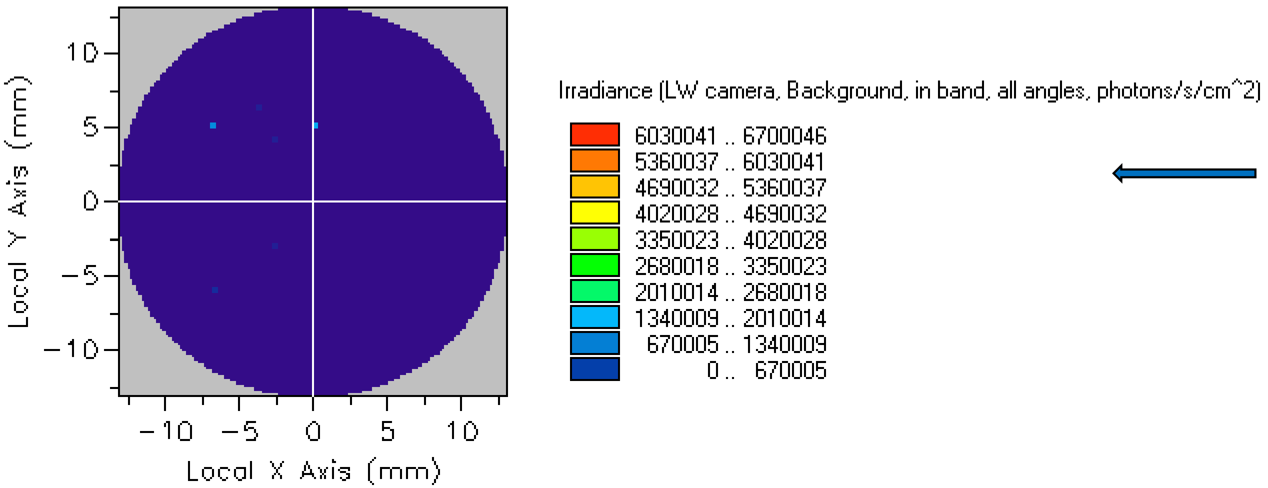
• Out of band, all angles



LW Camera: Signal Irradiance

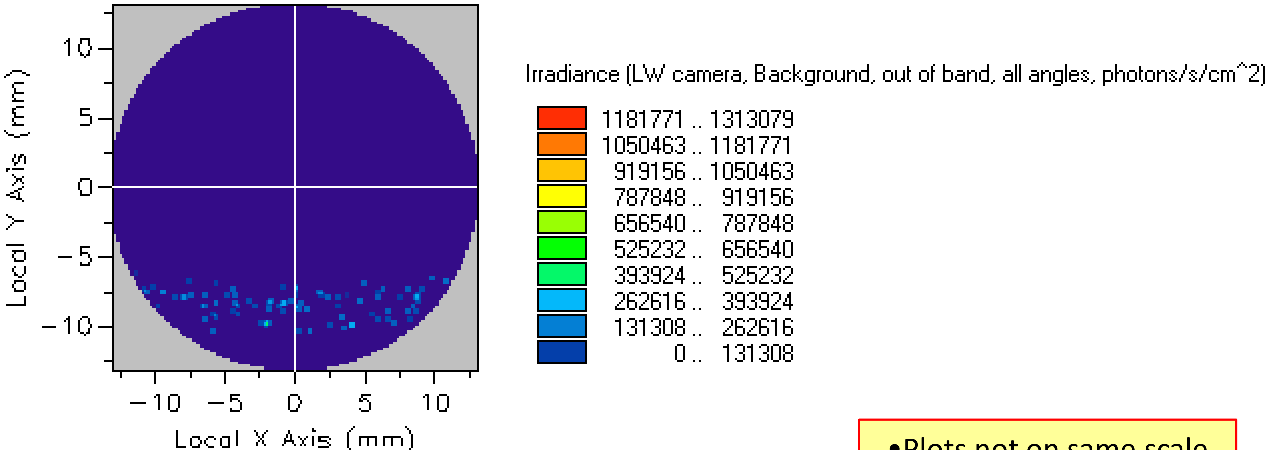


LW Camera: Noise Irradiance



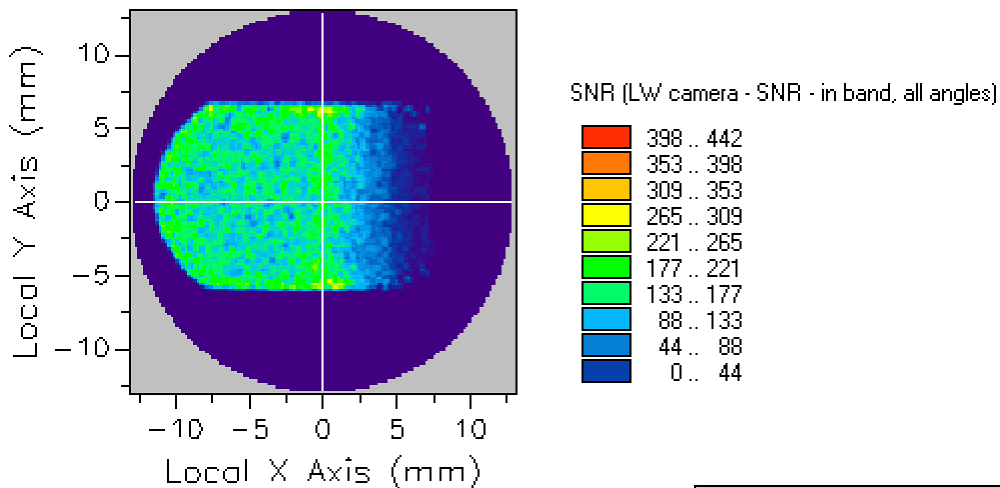
- In band stray light, all angles

- Out of band, all angles



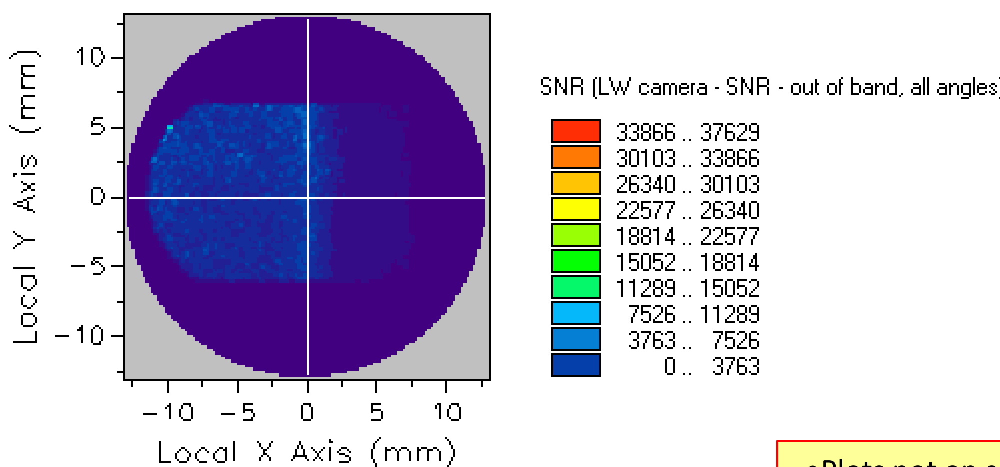
- Plots not on same scale

LW Camera Signal-Background



- In band, all angles

- Out of band, all angles



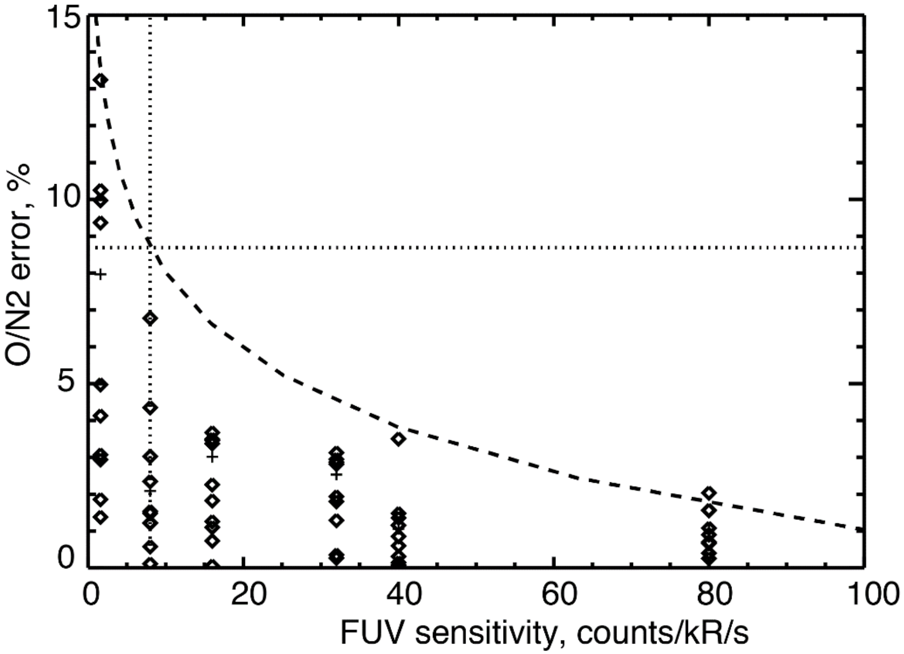
- Plots not on same scale

Comments

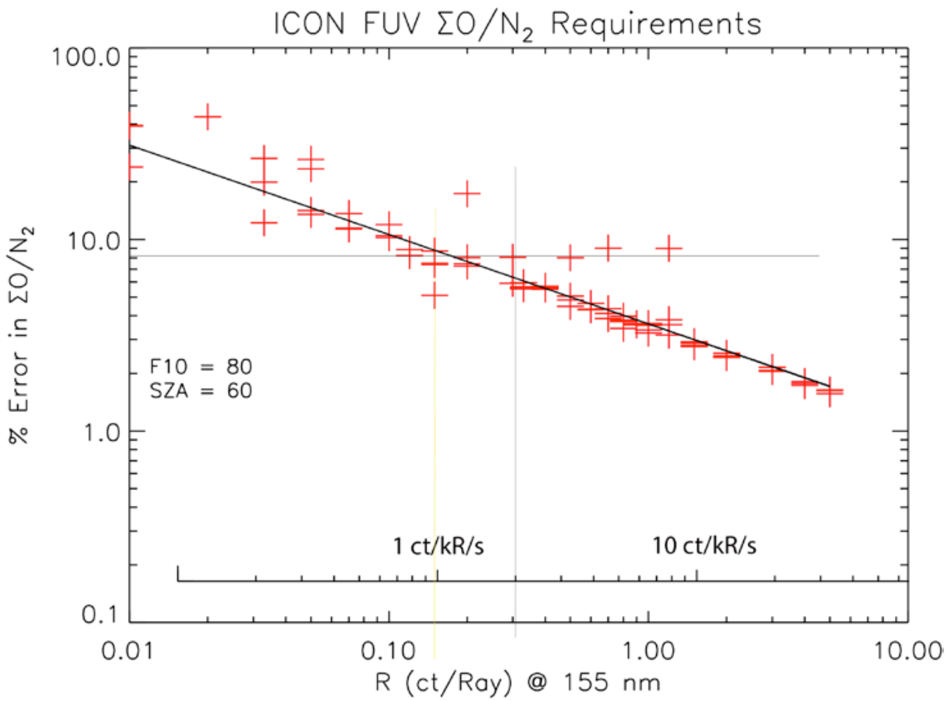
- Because the SNR calculations are based on irradiance calculations, they are subject to statistical noise → these data should not be interpreted as absolute, but should provide a good qualitative estimate of performance
- Integrated flux calculations are more reliable → in a ray trace, power converges more quickly than irradiance
- Both SW and LW channels are susceptible to direct illumination from sources outside of the design field of view → this contribution is, by far, the most significant source of stray light
- Out of band rejection is very good, even for cases in which the line strength is much larger than the intended signal
- Ghost and scatter events, in and out of band, contribute a small amount to the stray light background
- The model assumes a diffuse black surface treatment for all opto-mechanical surfaces and structures

Daytime O/N2 Ratio LW Sensitivity Requirement

- Prior estimates (ICON CSR) the requirement S-3 needs an instrument of sensitivity 8.3 counts/kR/sec.



- The analysis of the O/N2 requirements was revisited since PDR (R. Meier private communication) preliminary results show that the L4 requirement is conservative.



- New analysis includes (1) Slit widening, and (2) Recalculated effective N_2 branching ratios (3) More realistic error assessment.

Signal to Noise

•**Area**: A res cell is equivalent to 4 km altitude and 128 km horizontal. CCD is read out in a 512 x 512 raster - res cell is equivalent to 2 x 64 CCD binned pixel.

• **Time**: We will consider a 12 second exposure.

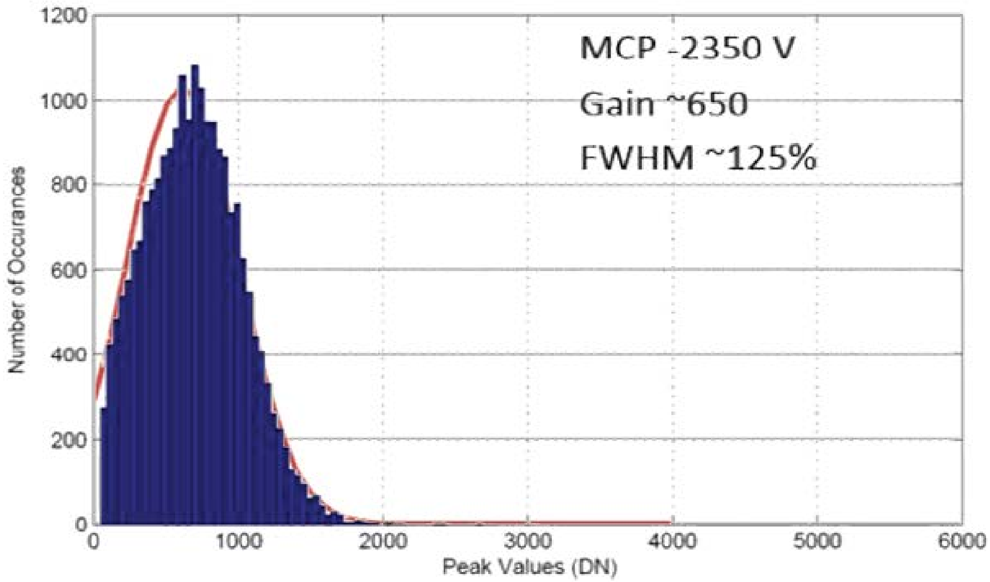
• **Reference point.** Signal and Noise reference point is at the CCD before the A-D converter and unit is electron which is 1/16th of the A-D in the SDL GSE.

$$SNR = \frac{P \times \bar{g}}{\sqrt{\left(P \times \overline{g^2} + I_p \times \overline{g^2} + \Sigma N_r^2 + \Sigma N_{dc}\right)}}$$

•Where P = *Signal in counts in the area collect during exposure time.*

- g = *gain of the intensifier*
- I_p=*stray light induced in counts*
- N_r=*read out noise*
- N_{dc} = *dark current of CCD*

•Most quantities are measured using the detector prototype.



Mean Gain =645   Mean square = 734

y=40*(20+x/100)*EXP(-(((x/100-5.5)/5.5)^2))

Signal to Noise Ratio Summary

Input quantities.				
signal, P	30	Rayleighs	8.82	counts/pixel in stripe
Poisson fluctuations noise =sqrt(P)			2.97	ideal
Gain, g	645	A/D units	1.03E+04	Measured
signal			9.11E+04	elecctrons
Mean square gain			1.17E+04	Estimated
Intensifer background	10	counts/sec/all pixels	0.01953125	electrons
CCD read out noise	40	per frame	1280	electrons

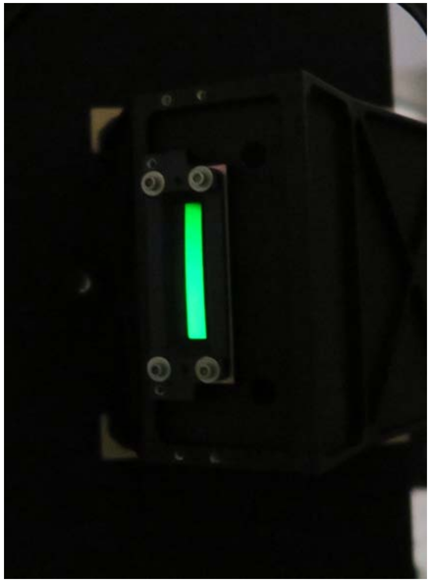
Component	Final Result	No Mult. Noise
Signal	9.11E+04	9.11E+04
P x mean g^2	1.22E+09	9.41E+08
Ip x mean g^2	2.70E+06	2.70E+06
Nr	2.56E+06	2.56E+06
Ndc	3.75E+04	3.75E+04
Dark current fluctuations	9.22E+07	9.22E+07
Mean square	1.31E+09	1.04E+09
RMS noise (CCD els)	3.63E+04	3.22E+04
RMS noise (PE-s)	3.51	3.12

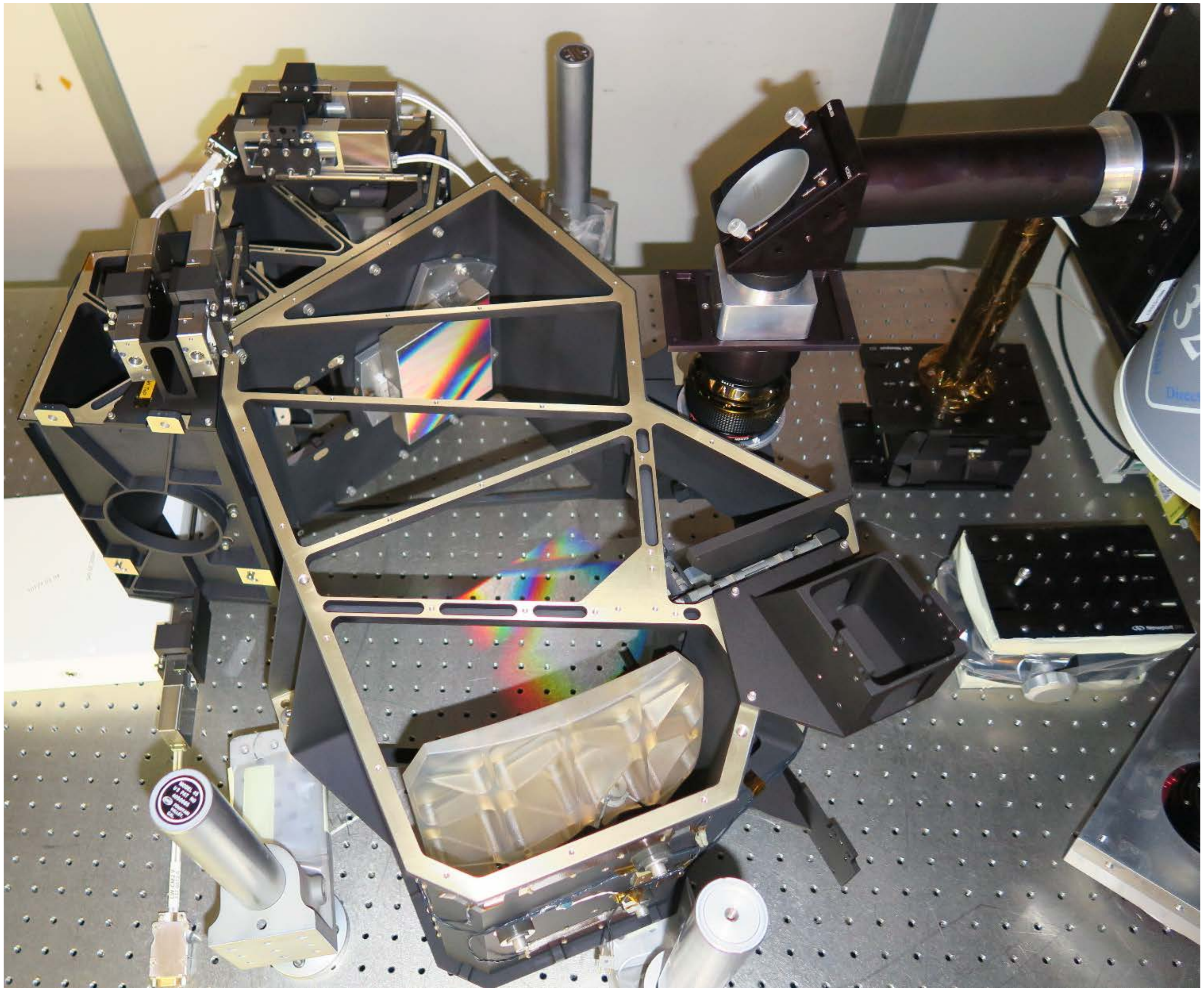
- Nighttime SNR input = 30 Rayleighs.
- Instrument sensitivity 135.6 per stripe = 24.5 counts/sec/kR.
- Signal is amplified by intensifier gain.
- Photo electron noise and backgrounds are amplified by mean square intensifier gain.
- Noise components are summed as squares.
- CCD dark current and CCD read out noise are added.
- The ideal per rescel in each strip noise would be 2.97 but the resulting noise is 3.51.
- The largest contributor is multiplication noise.

Alignment and Calibration Approach

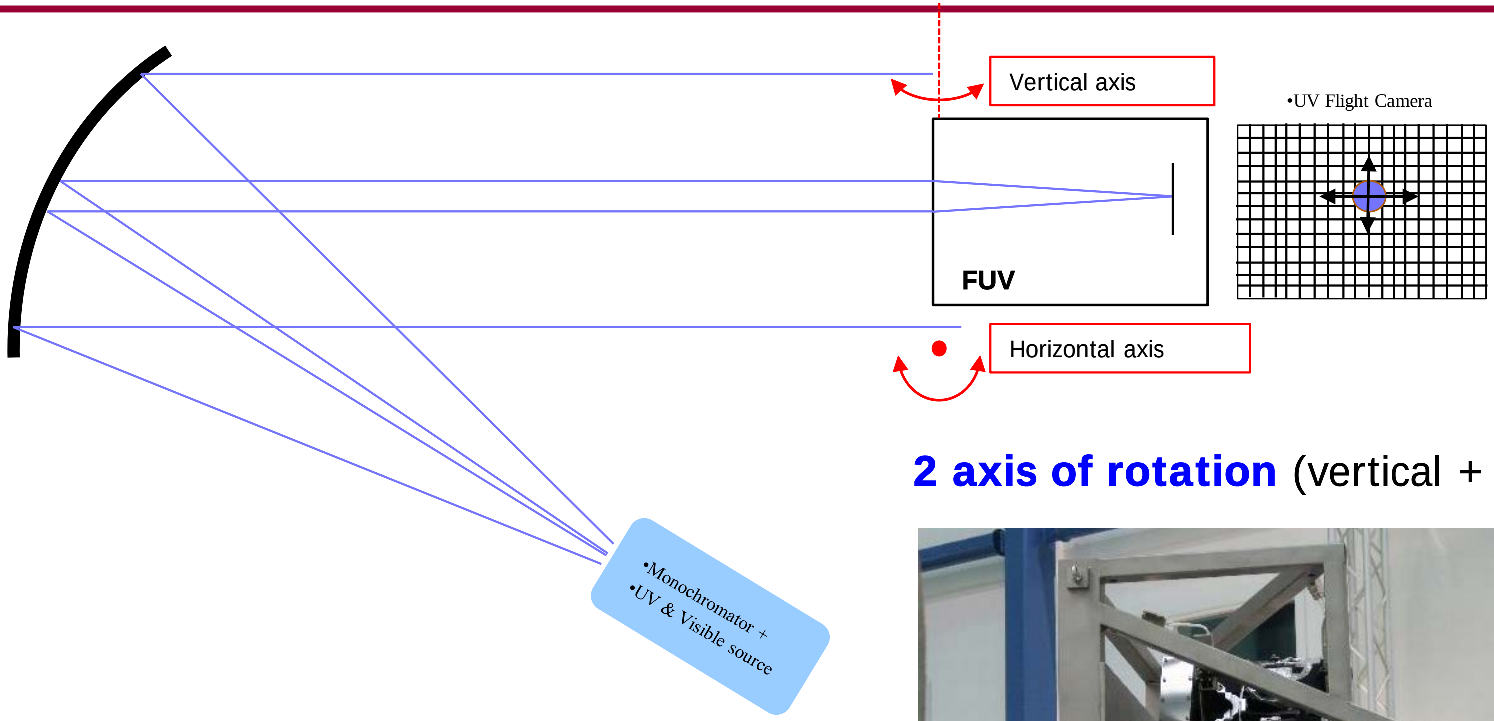
- Coarse mechanical alignment using Faro Arm CMM.
- Benchtop alignment of spectrometer and back imager using a GSE visible grating @ 900 line/mm (UV is 3600 line/mm) and CCD detectors.
  - Initial alignment at Lockheed Martin, Palo Alto
  - Repeat post-ship at CSL in Liege, Belgium
- Alignment of turret to optics package using laser tracker system.
- Visible alignment with turret using CSL OGSE and MGSE.
- UV alignment using CSL OGSE and MGSE.
- UV Calibration at RT, 0C and 40C using CSL OGSE, MGSE, and Thermal Tent.

Benchtop Alignment at LMSAL





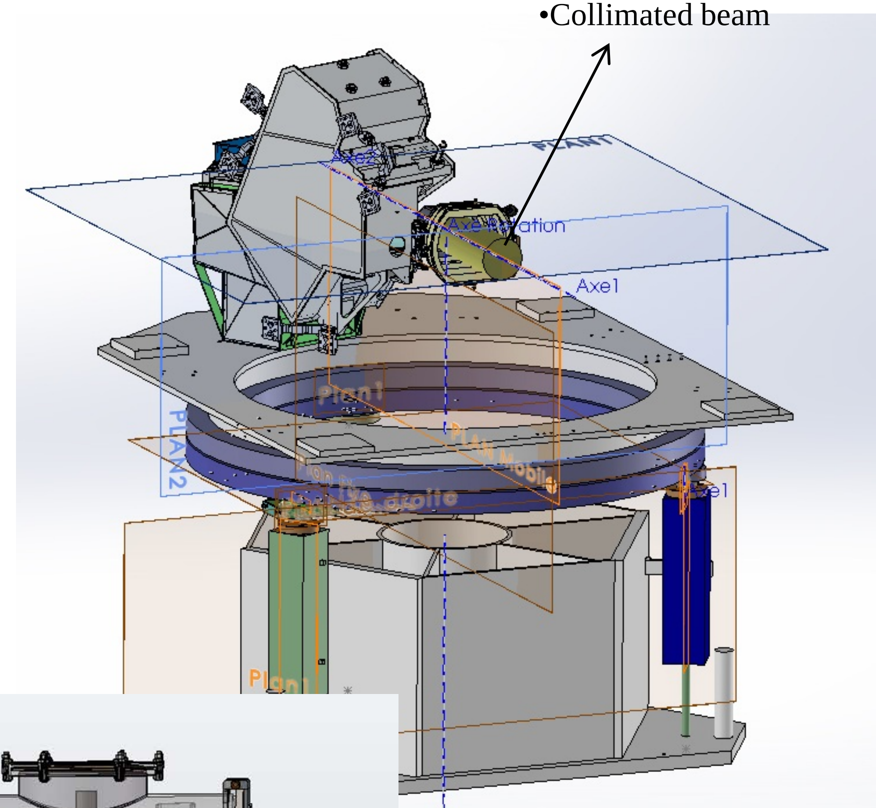
CSL MGSE Overview

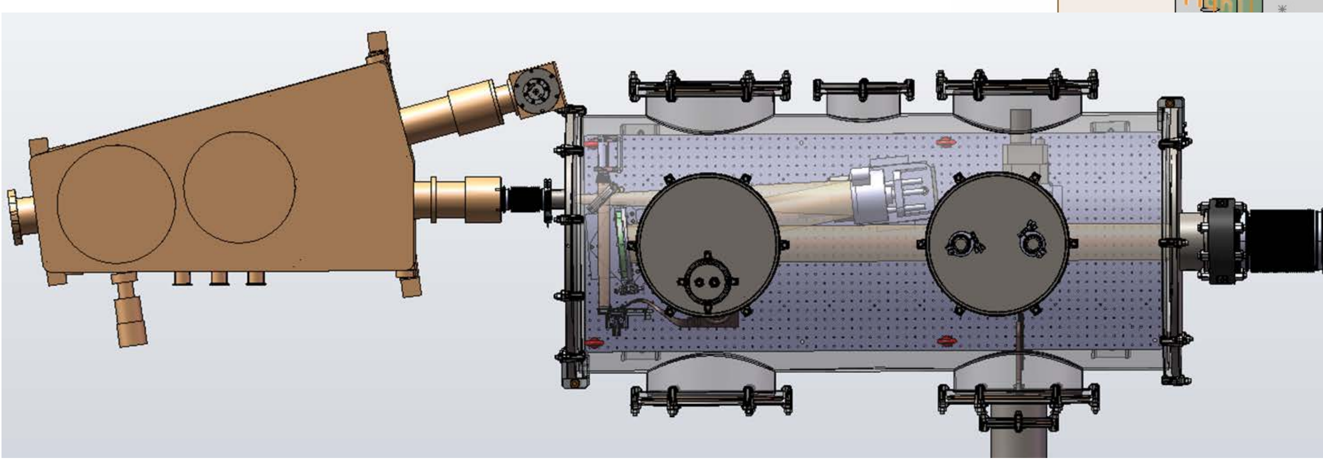


2 axis of rotation (vertical + horizontal)

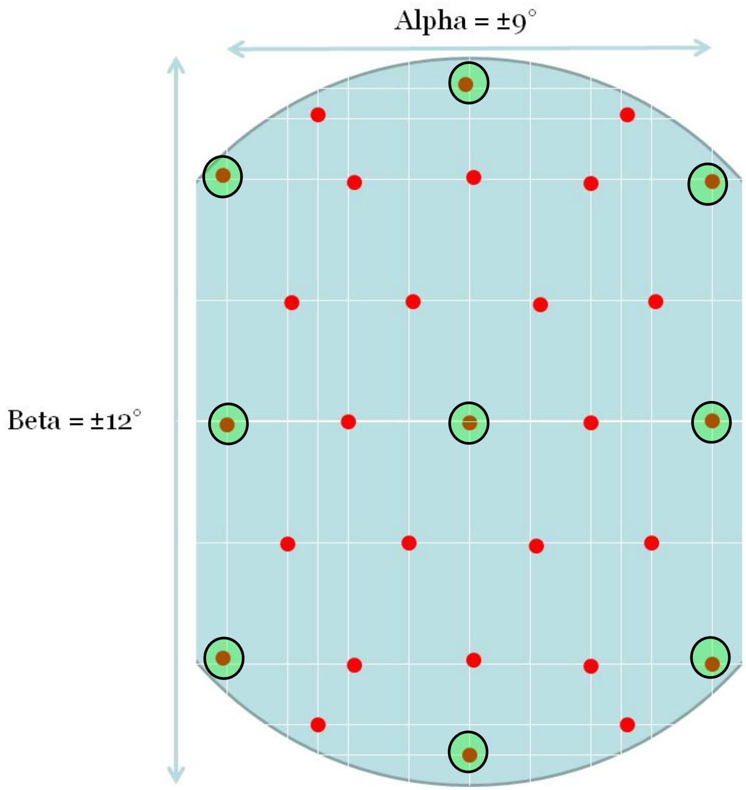
CSL OGSE Overview

- ❑Collimated beam does not cover the entire surface of the scan mirror
- ❑For one specific field, the turret does not need to be fully illuminated
- ❑Collimated beam: 100 mm diameter





Distortion Map Calibration



Alpha	Beta	Alpha	Beta	Alpha	Beta
0	11	2	4	6	-4
-5	10	6	4	-8	-8
5	10	-8	0	-4	-8
-8	8	-4	0	0	-8
-4	8	0	0	4	-8
0	8	4	0	8	-8
4	8	8	0	-5	-10
8	8	-6	-4	5	-10
-6	4	-2	-4	0	-11
-2	4	2	-4		

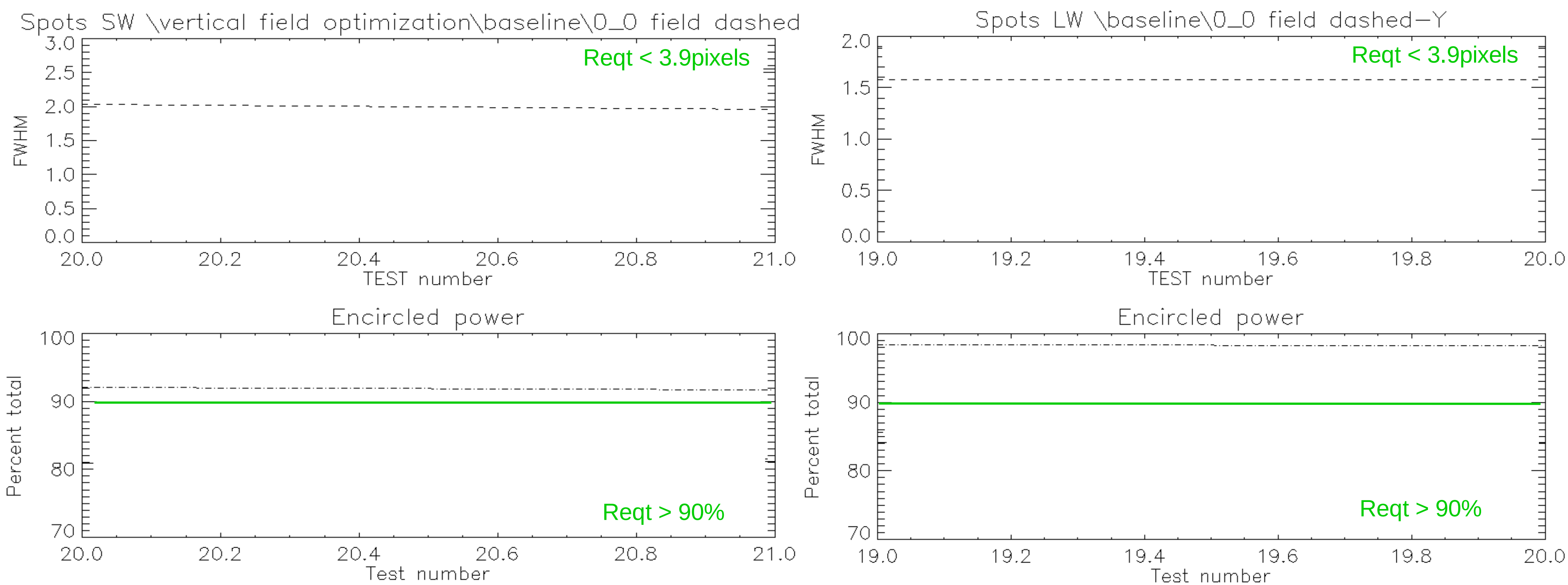
Alpha is the horizontal angle along the spectral direction
Beta is the vertical angle along the slit

Pre environmental calibration map: **9 points**

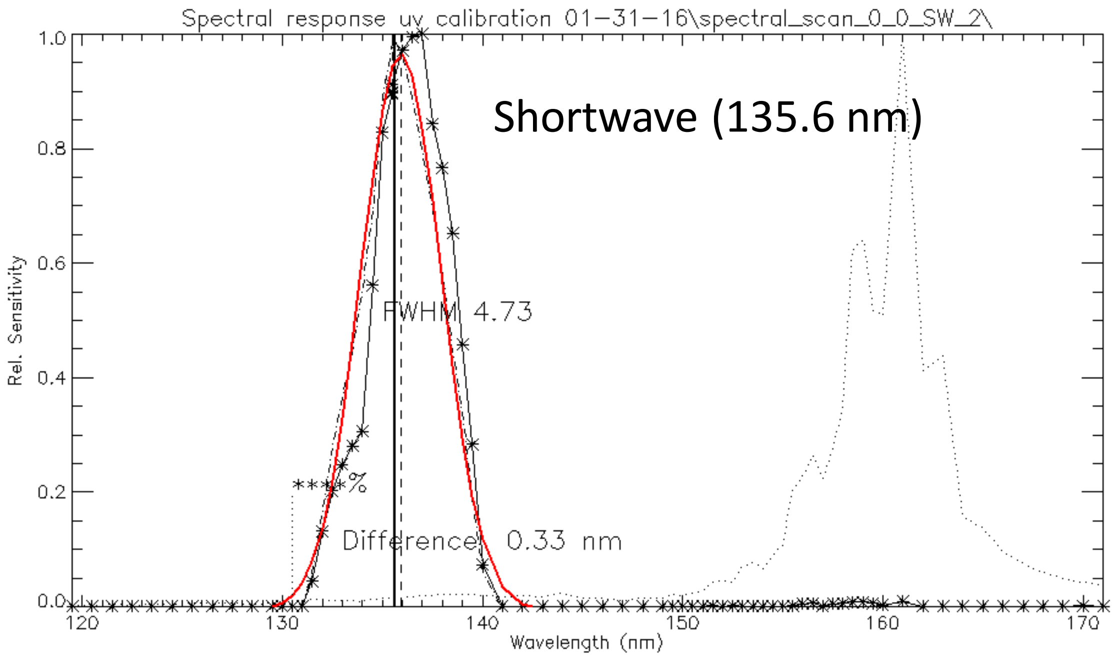
Post environmental calibration map: **29 points minimum**

UV Alignment Results

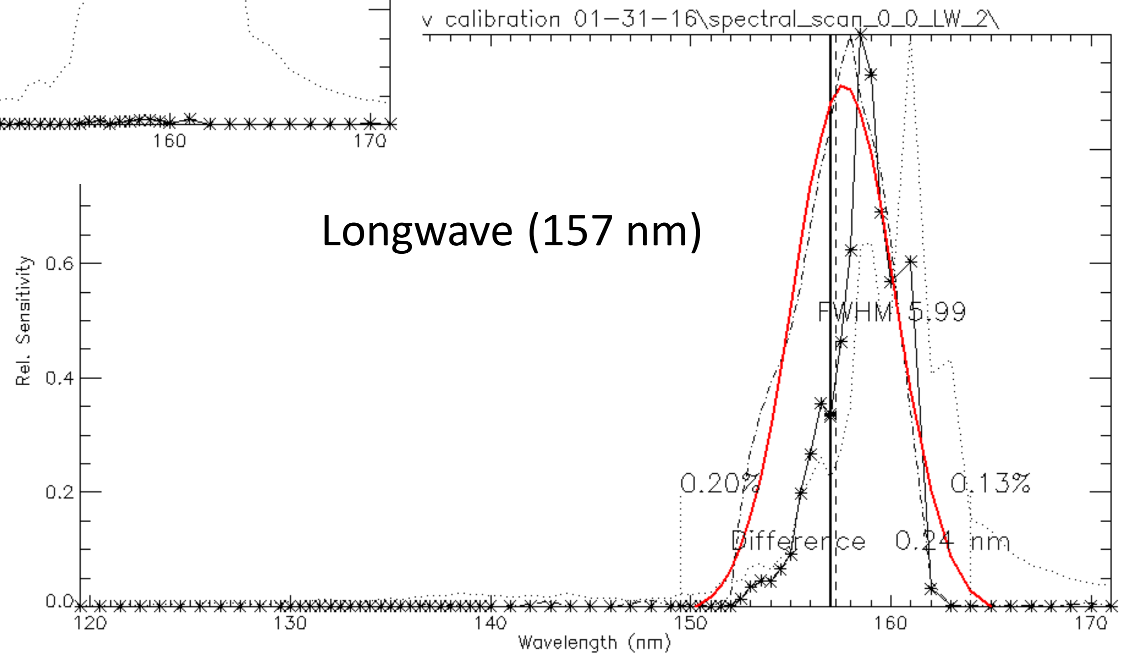
- Spot sized optimized by actuating CM2 mirrors in piston/tip/tilt at the (0,0) field.
- Extreme field angles at FOV edges verified and optimized following (0,0) field optimization.
- All fields show spots meet requirements (<180 microns, >90% encircled energy)



Spectral Sensitivity at 20C

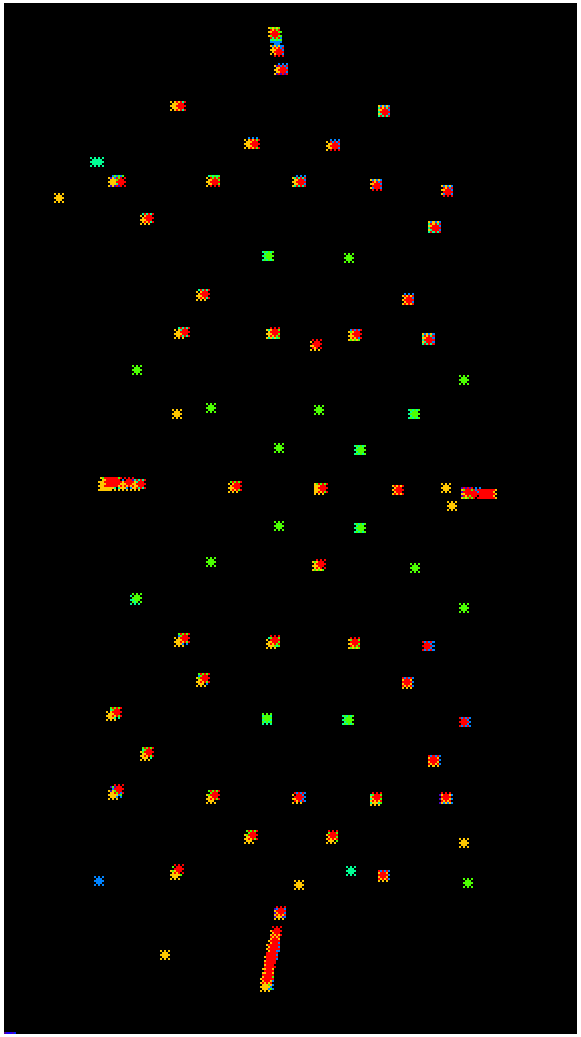


In-Band Suppression of 130.4 line is 100% in SW Channel



In-Band Suppression of 149.6 and 164.1 lines is >99.8% in LW Channel

Distortion mapping



SW field positions measured during tests at different temperatures

Colors denote tests:

Blue: Cold Gradient

Light green: Hot Gradient

Dark green: Room Temperature

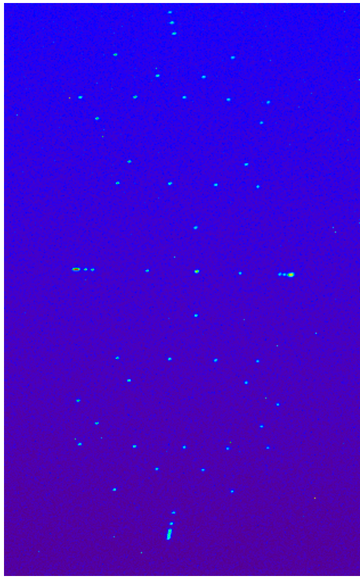
Brown: 0 C

Red: 40 C

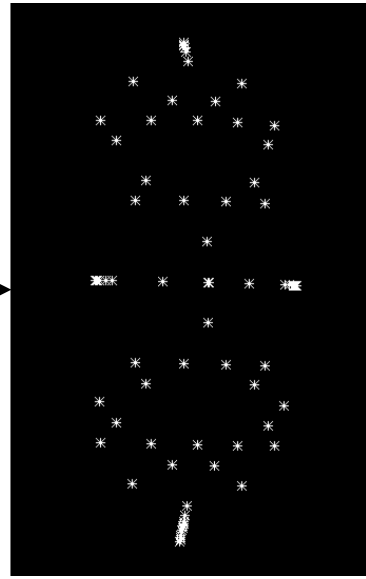
Spots are on top of each other within 2 pixels (1 science pixel in final 256x256 science format)

Distortion Map Determination

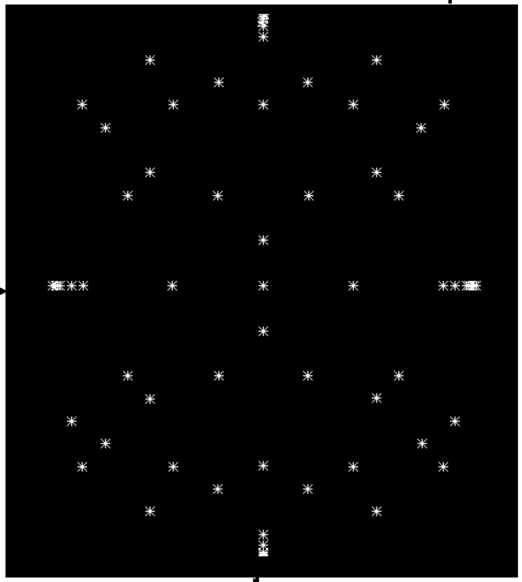
Images at 74 field positions



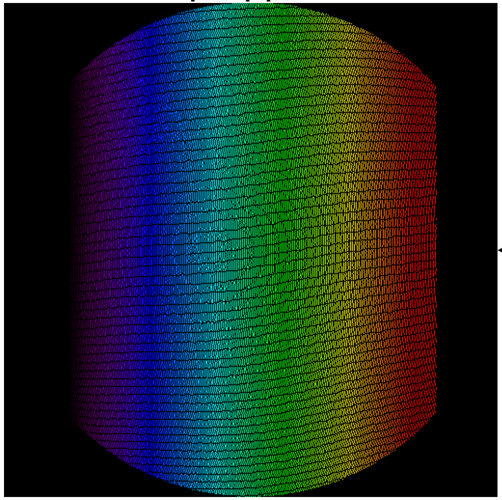
Uncorrected Distortion Map



Corrected Distortion Map



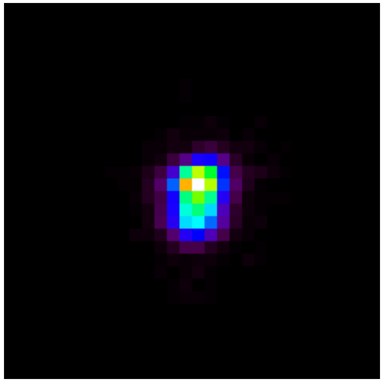
Distortion Map Applied to Entire FOV



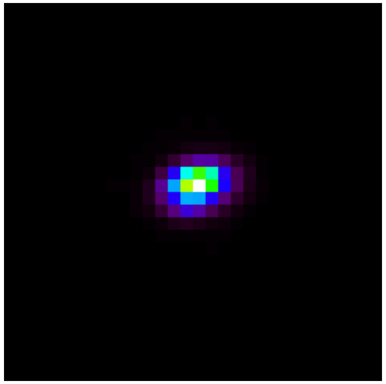
Out of Band Sensitivity at Lyman Alpha (1 of 2)

- Initial out of band sensitivity measurements were performed at Lyman Alpha with high flux from the CSL OGSE. A well focused spot was observed in both channels.
- Expected rejection at this wavelength was 10^5, ~10^3 was observed:

SW



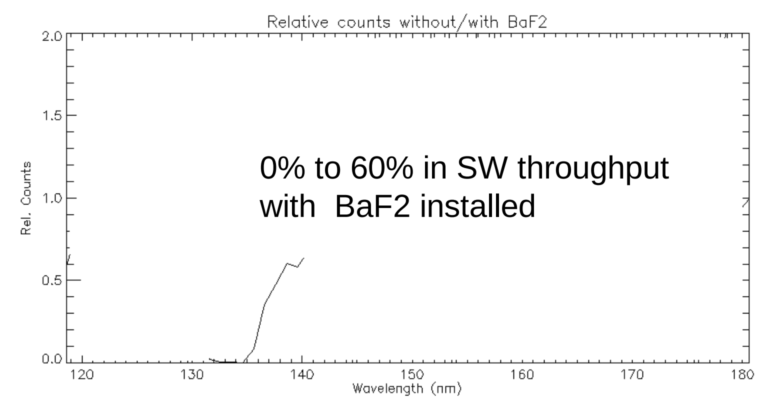
LW

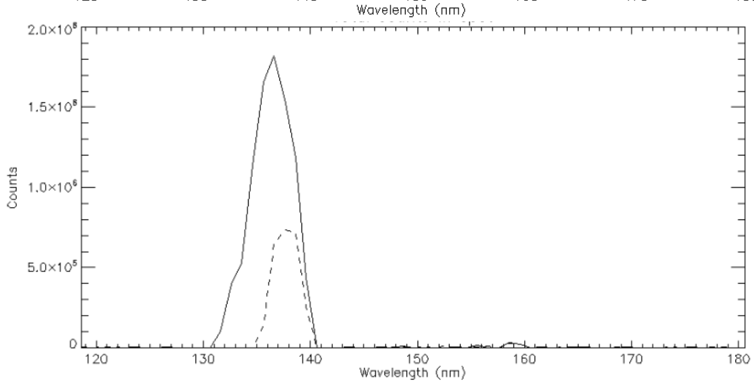


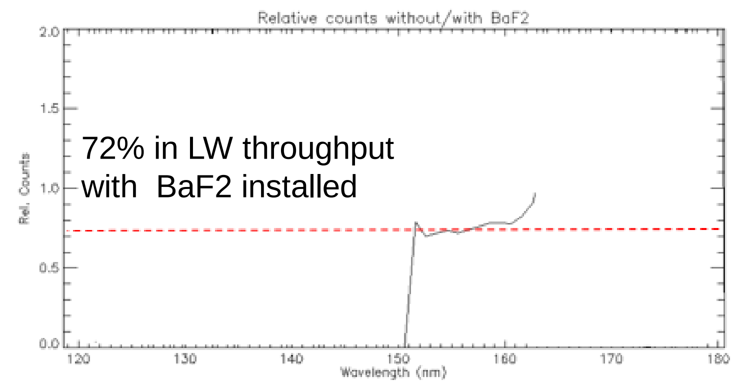
- Following the initial tests, BaF2 windows were installed onto the OGSE. These filters are known to have rejection >90% at wavelengths less than 130nm. Spectral scans were performed with and without the BaF2 windows installed.

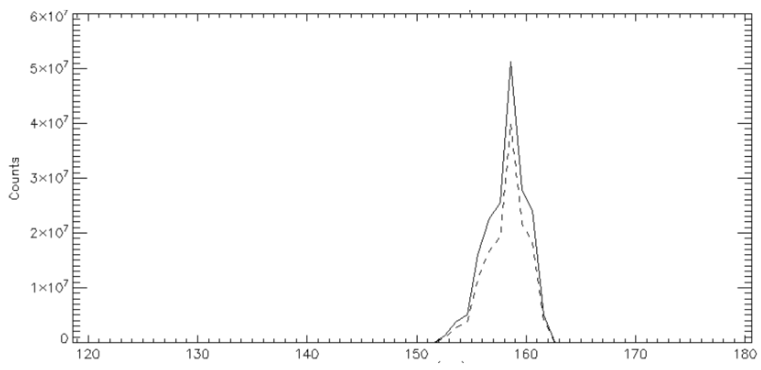
Out of Band Sensitivity at Lyman Alpha (2 of 2)

- Both channels showed a reduction in counts consistent with BaF2 Transmission curves (knee is ~135 nm at room temperature) indicating that in-band light was leaking from the monochromator into the OGSE.









❑ Radiometric performance Summary

Measured instrumental Transmission	0.45%	0.16%	
Count Rate from measured Tx	147.26	52.36	Counts/kR
BOL from measured Tx	88.80	30.21	Counts/kR
EOL from measured Tx	75.84	25.55	Counts/kR
Science Requirments	13.00	8.30	Counts/kR
Margin BOL	583%	264%	Margin
Margin EOL	483%	208%	Margin