

STRAY LIGHT CALIBRATION OF THE ENMAP IMAGING SPECTROMETER MISSION

Andreas Baumgartner¹, Claas Henning Köhler¹, Simon Baur², Richard Wachter²,
Leonhard Polz², Anna Serdyuchenko² and Miguel Figueiredo Vaz Pato¹

¹German Aerospace Center (DLR)

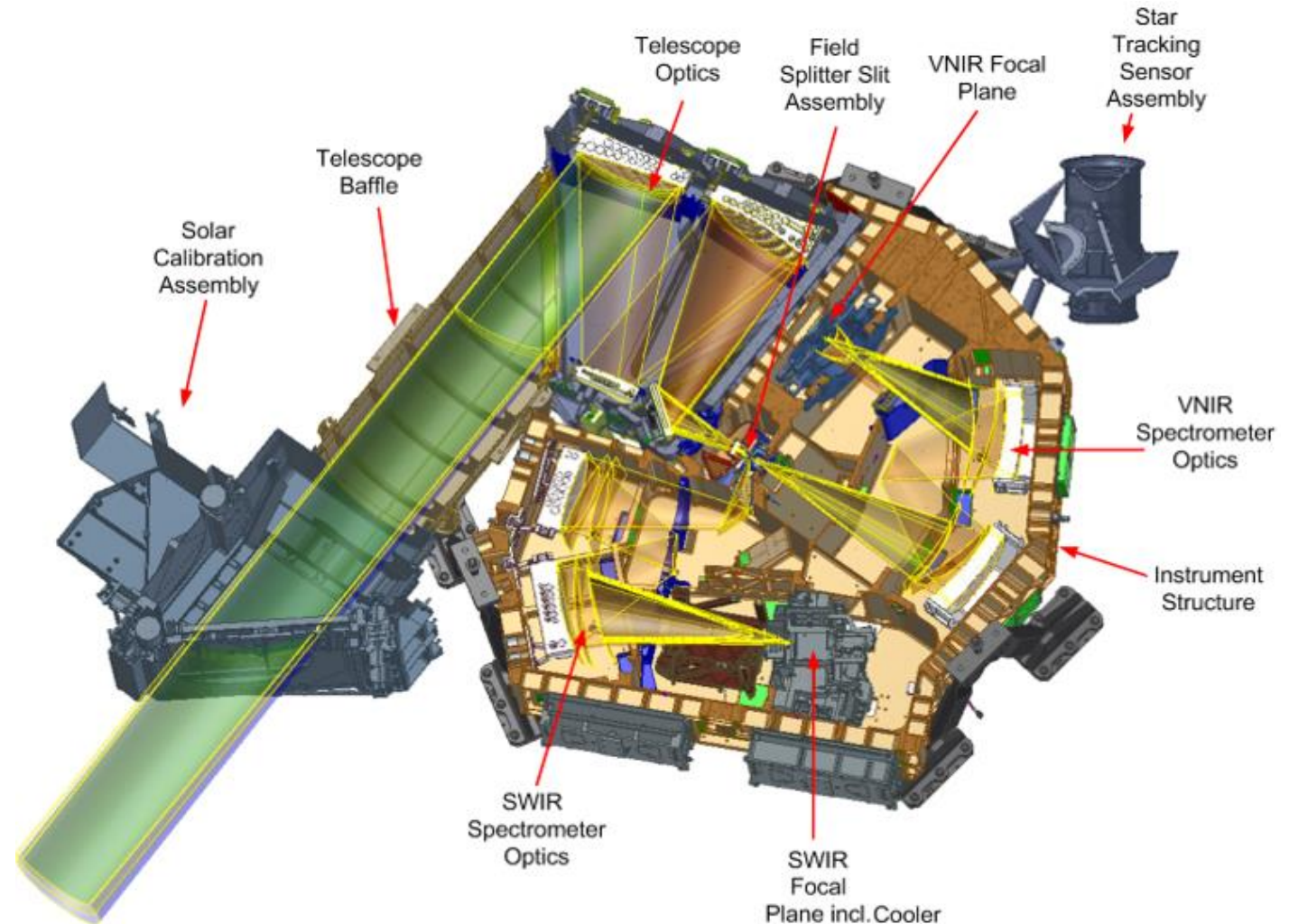
²OHB System AG



EnMAP



- Two pushbroom imaging spectrometers:
 - VNIR:
 - Detector: Silicon CMOS
 - Spectral range: 420 – 1000 nm
 - Spectral sampling: 4.7 – 8.2 nm
 - SWIR:
 - Detector: MCT + ROIC
 - Spectral range: 900 – 2450 nm
 - Spectral sampling: 7.5 – 12.0 nm
 - Ground sampling: 30 x 30 m
- Built by OHB System AG
- Calibration supported by DLR
- Launched 1 April 2022
- Operational 2 November 2022



Stray light Measurements

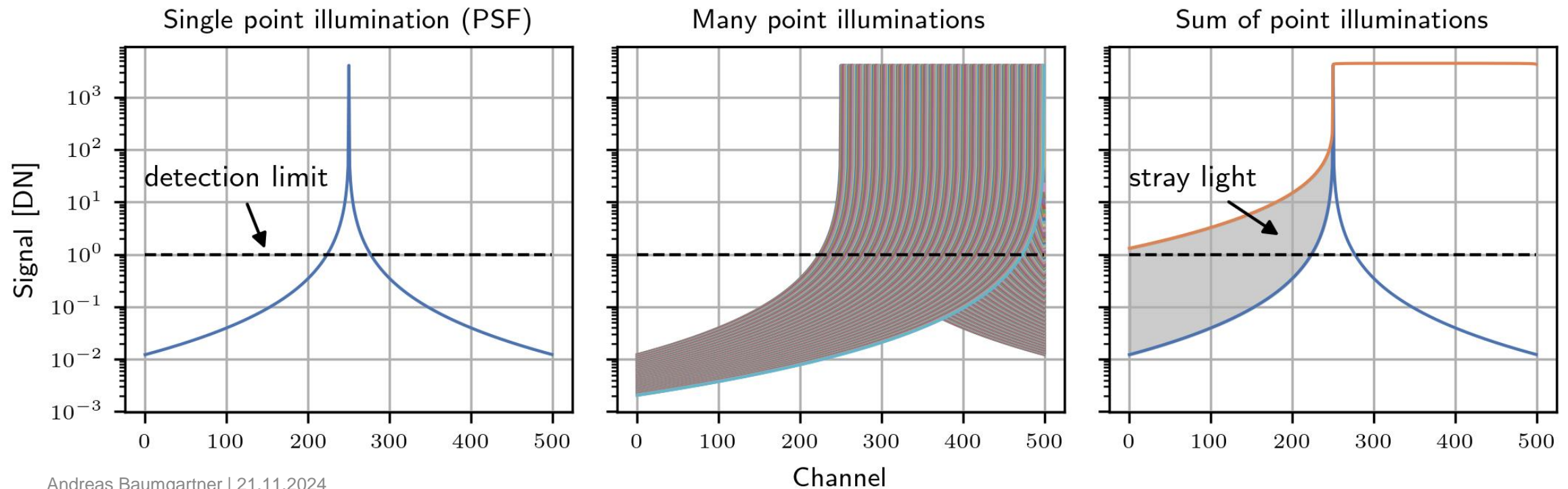


- Performed
 - under DLR lead
 - during EnMAP C&C campaign
 - in clean room @ OHB

- Measured types:
 - Diffuse stray light
 - Along-track out-of-field stray light
 - Across-track out-of-field stray light (below requirement)
 - Ghosts (not detectable)

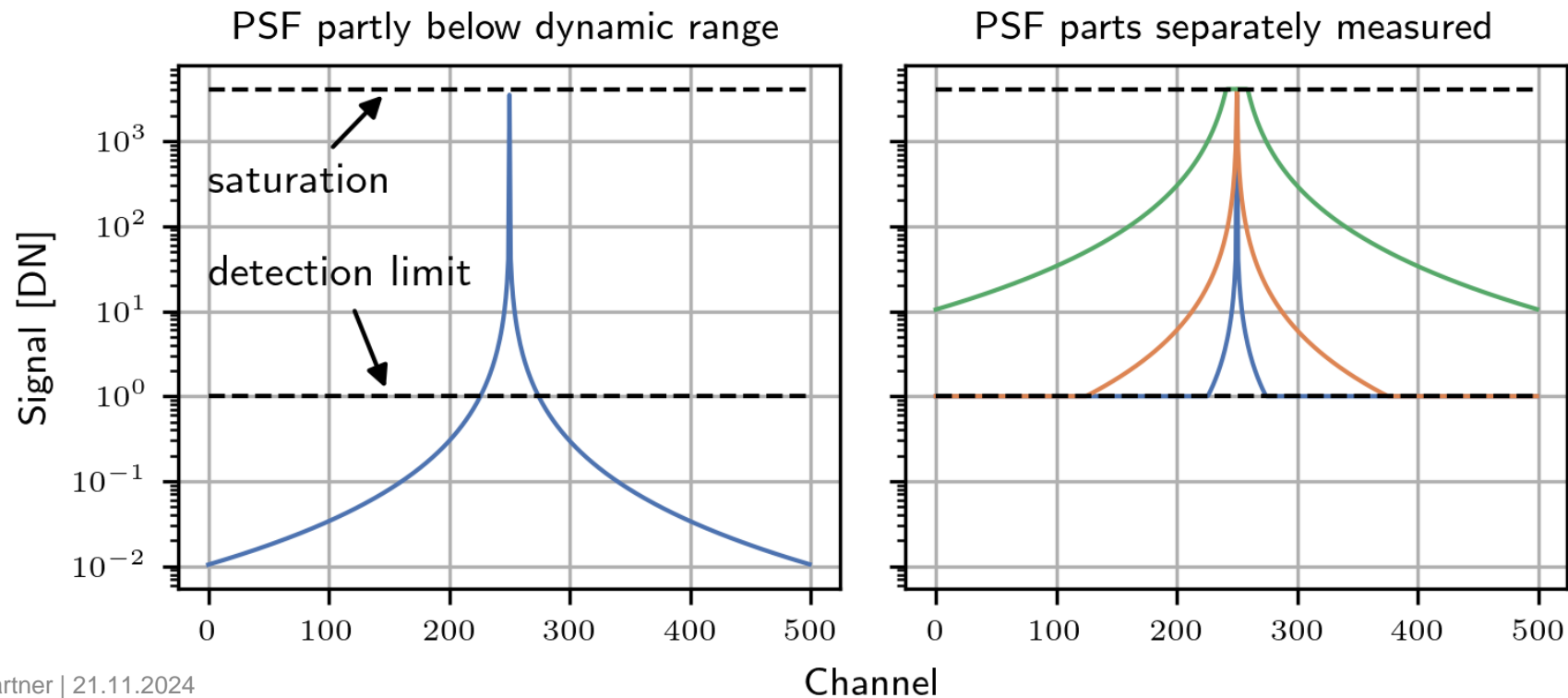
Diffuse Stray Light

- Described by High Dynamic Range (HDR) Point Spread Function (PSF)
- Illumination of single point → HDR-PSF flanks below detection limit
- Illumination of many points → Sum of HDR-PSF flanks detectable → stray light

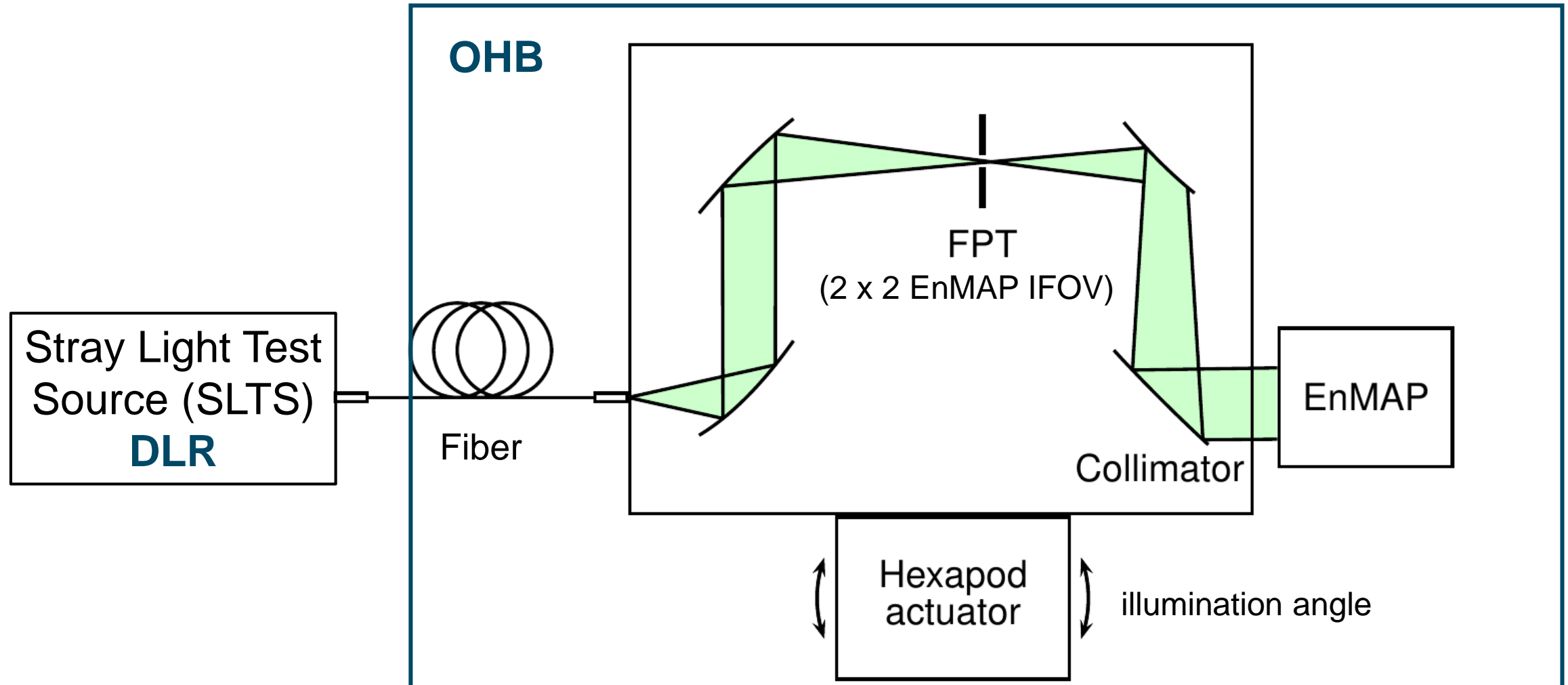


HDR-PSF Measurement

- High intensity monochromatic point illuminations
- No Saturation: far wings are below detection limit
- Saturation of center: measurement of wings

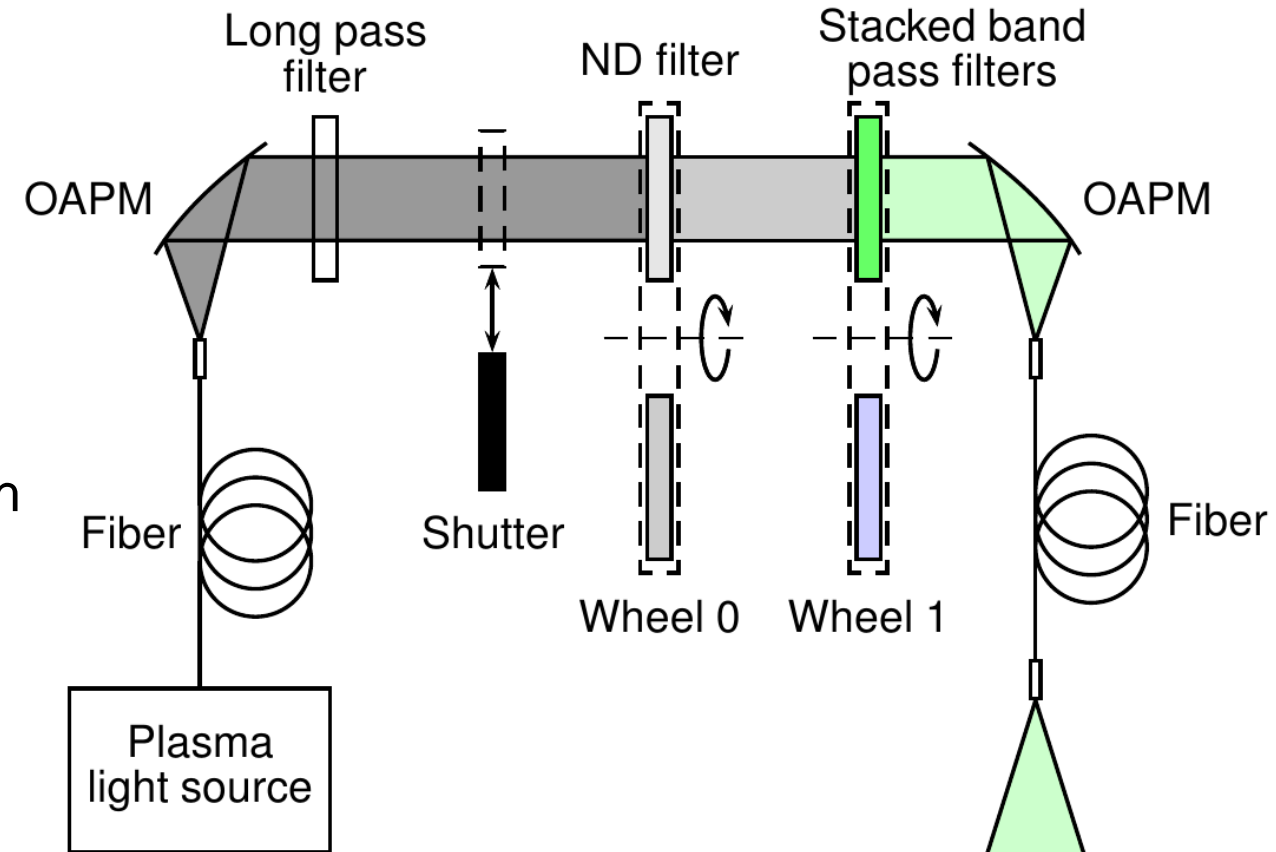


Measurement Setup



Stray Light Test Source (SLTS)

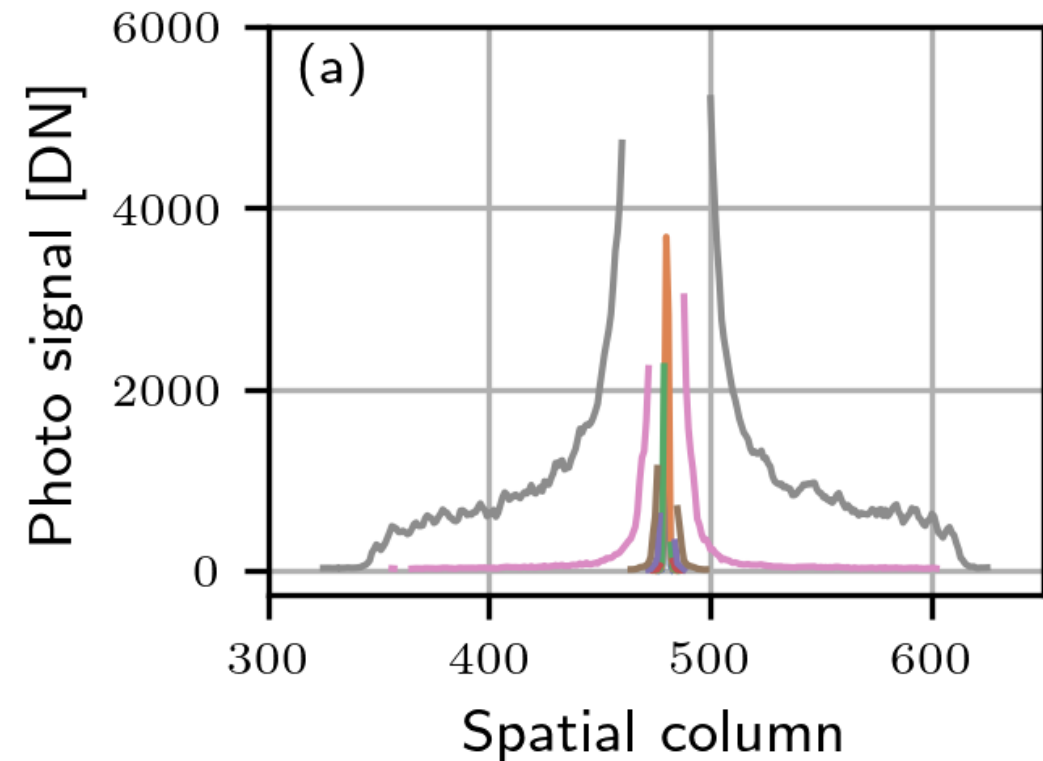
- Custom built by DLR
- Fiber coupled plasma light source
- 15 wavelengths (bandpass filters)
 - 11 VNIR (COTS)
 - 4 SWIR (custom made)
 - 2 – 4 filters stacked
 - Angled to compensate center wavelength inconsistencies
 - Out-of-band suppression $> 10^9$
- 11 ND - filters (OD 0.5 – 5.5 | 0.5 steps)
 - Calibrated in combination with BP filters



C. T. Pope et al. (2019) DOI: 10.1117/12.2531264

HDR-PSF Measurements

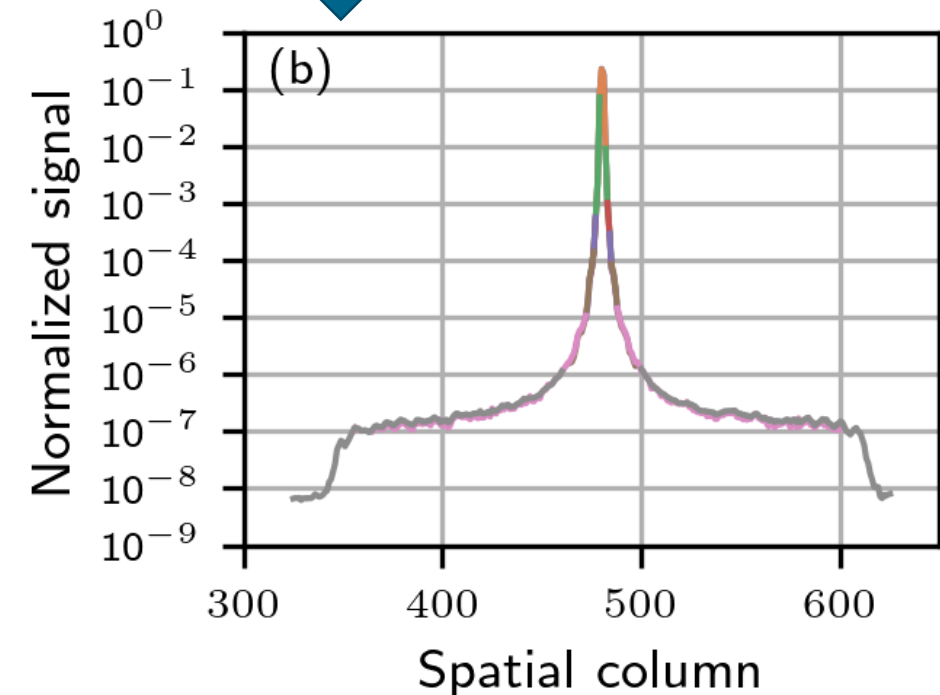
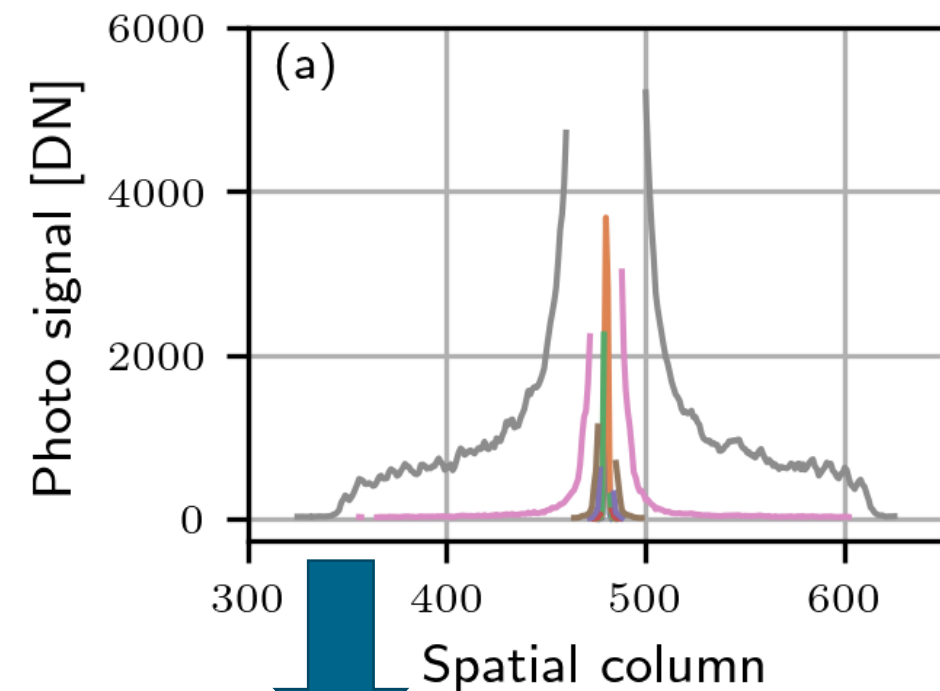
- 12 spatial positions
- 11 (VNIR) + 4 (SWIR) spectral positions
- 8 intensity levels (8 sub-PSFs)
 - Combination of
 - integration time
 - ND-filter transmission
 - gain
 - Chosen to cover entire PSF (no gaps)



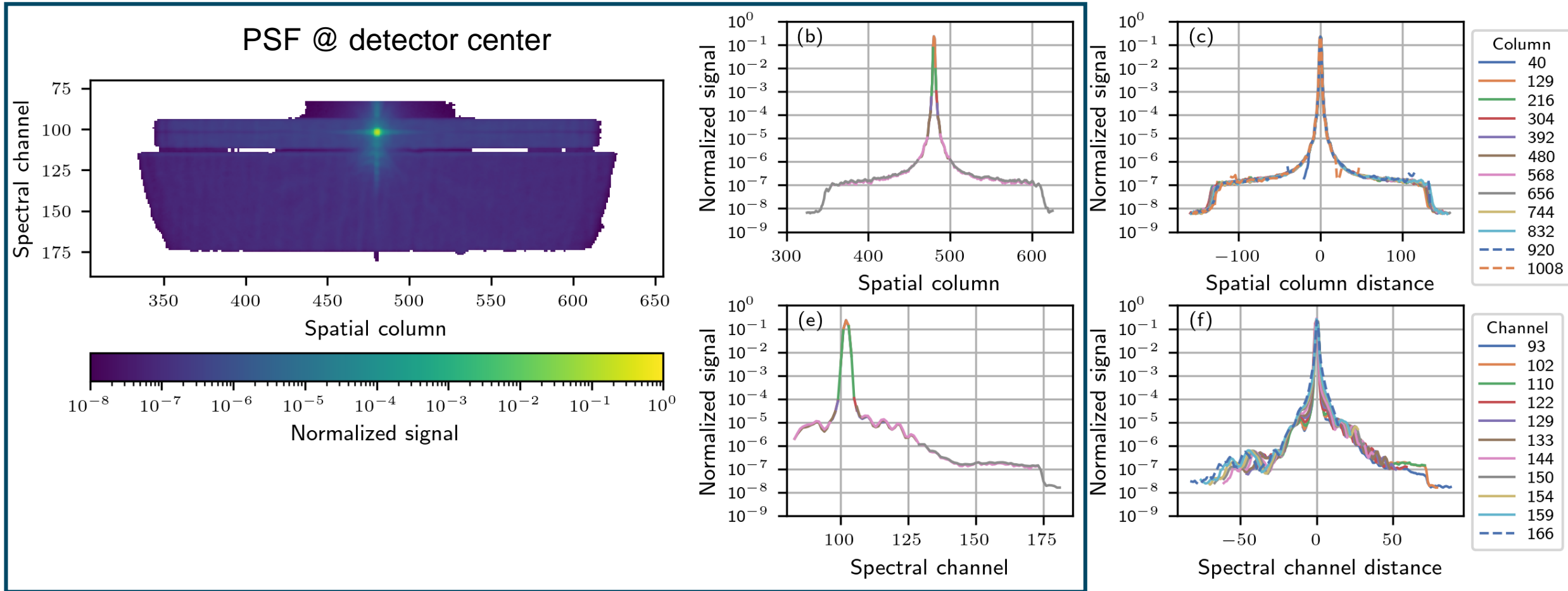
HDR-PSF from Sub-PSFs

- Correct non-linearity
- Correct response non-uniformity
- Mask bad pixels
- Mask saturated pixels + neighbors (blooming)
- Subtract dark signal
- Mask low signal + low SNR pixels
- Scale by integration time * ND-filter-transmission * gain
- For pixels with >1 values: use highest photo signal value

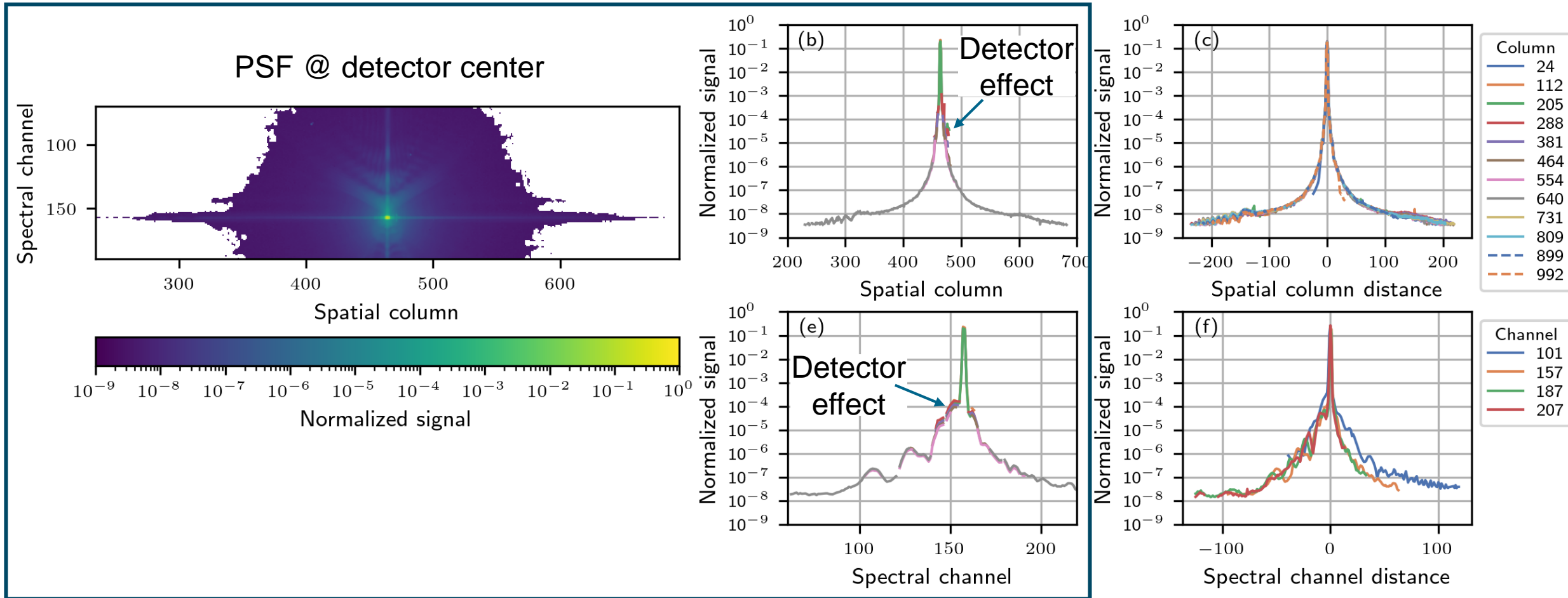
- Subpixel center determination with Gaussian fit
- Linear interpolation to shift HDR-PSF center on nearest pixel center



VNIR spectrometer results



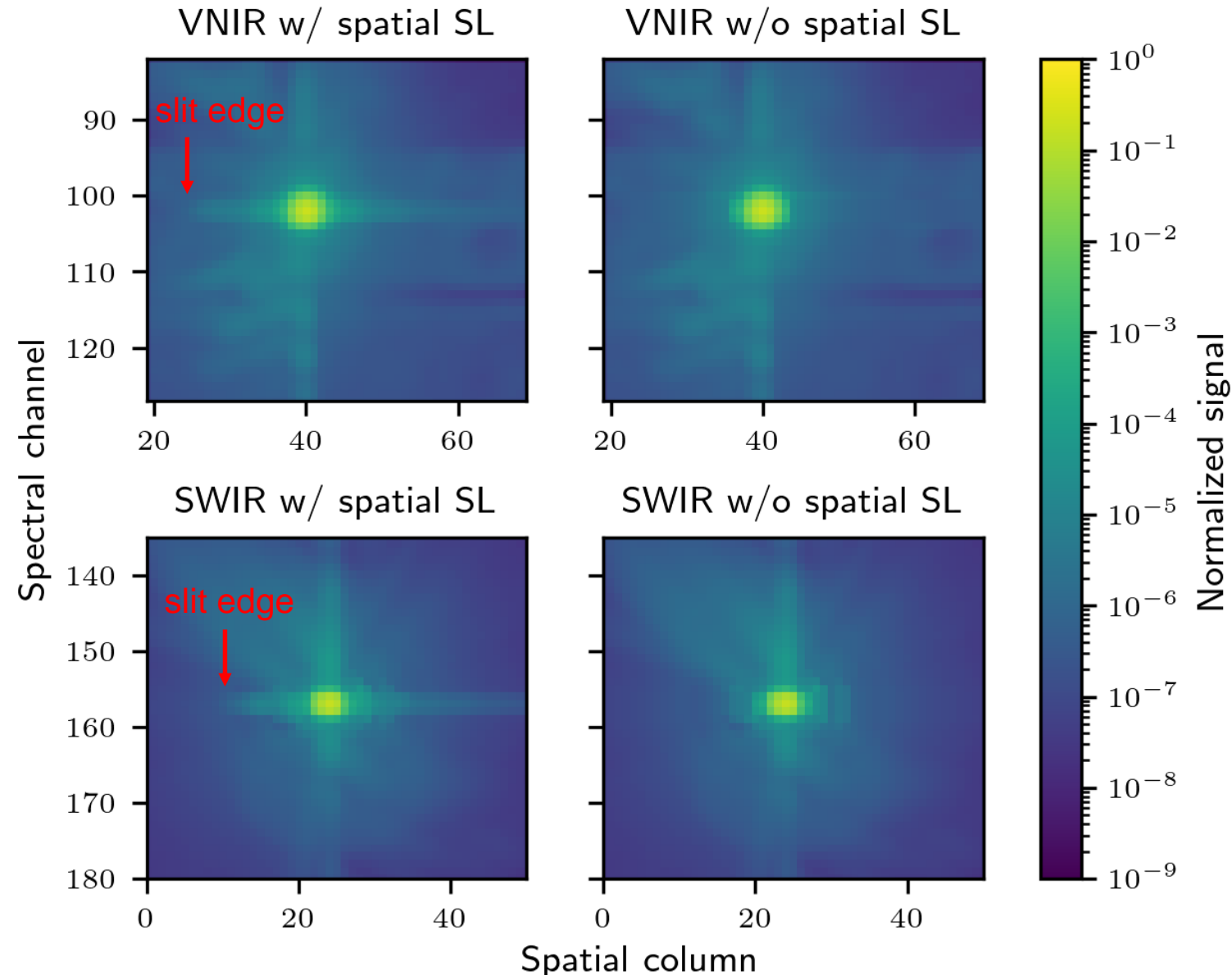
SWIR Spectrometer Results



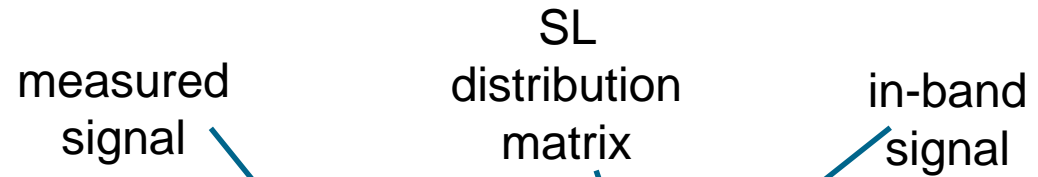
Estimation of Collimator Stray Light



- Some stray light is not visible under pixels covered by instrument slit
- Assumption: this SL originates before the slit
- Before slit (“spatial”) SL = Collimator + EnMAP telescope SL
- Estimation of “spatial” stray light: interpolating ± 2 channels from center axis
- For each PSF 3 variants:
 - 0% spatial SL
 - 50% spatial SL (used)
 - 100% spatial SL



Correction Method



- Measurement equation

$$y_{meas} = [I + D] y_{ib}$$

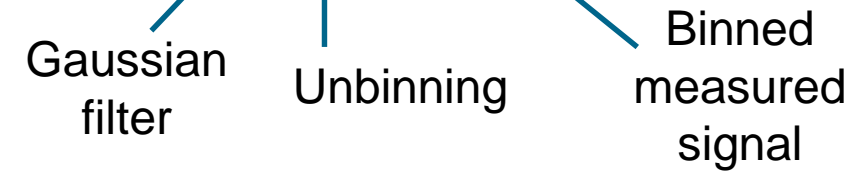
- Method based on Zong et al. (2006)

$$y_{ib} = [I + D]^{-1} y_{meas}$$

- Our approach: Using SL extraction matrix \bar{E}

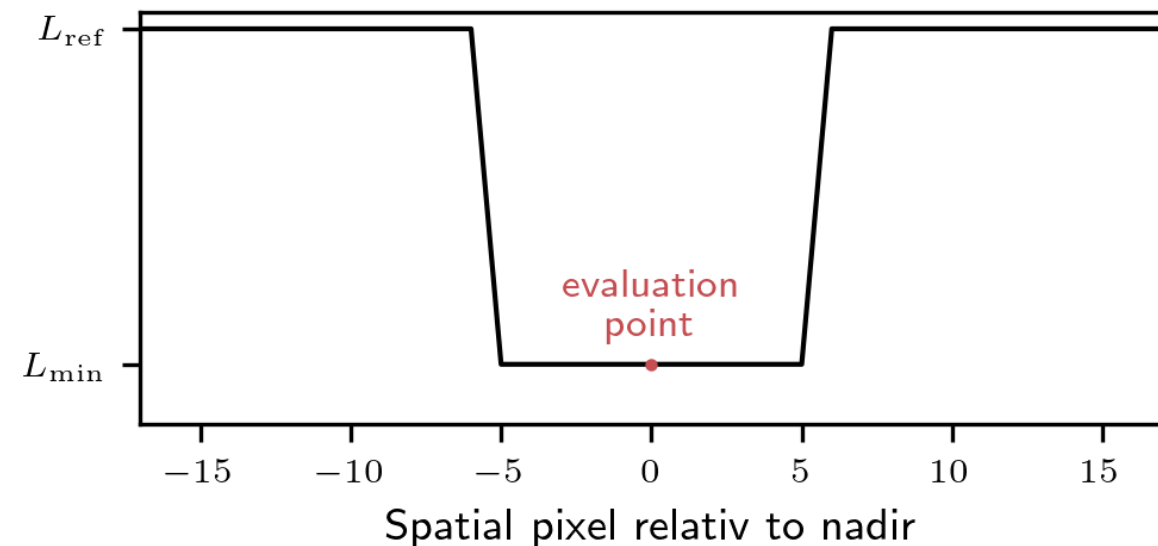
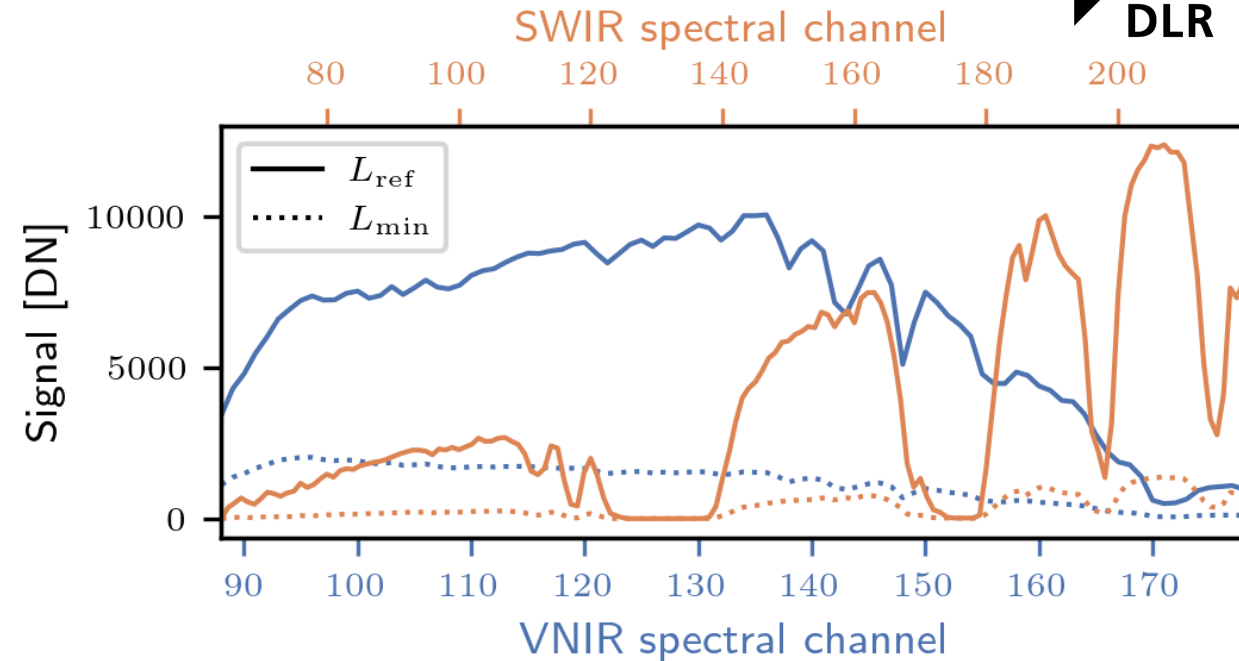
- In-band area: 9x9 pixel
 - Stray light: Light outside in-band area
- 3 x 3 pixel binning
 - 81 x smaller stray light matrix
 - Processing time ↓
- Nearest neighbor interpolation from measured HDR-PSFs

$$y_{ib} = y_{meas} - f(B^+ \bar{E} \bar{y}_{meas})$$

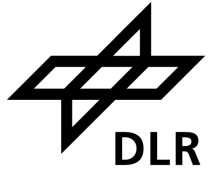


Stray Light Reference Scene

- Reference for stray light measurement and correction methods
- Uniform scene with radiance L_{ref}
- Cutout of 5 pixels around evaluation point with radiance L_{min}



Simulation



Simulation of stray light reference scene at evaluation point

SL Requirements:

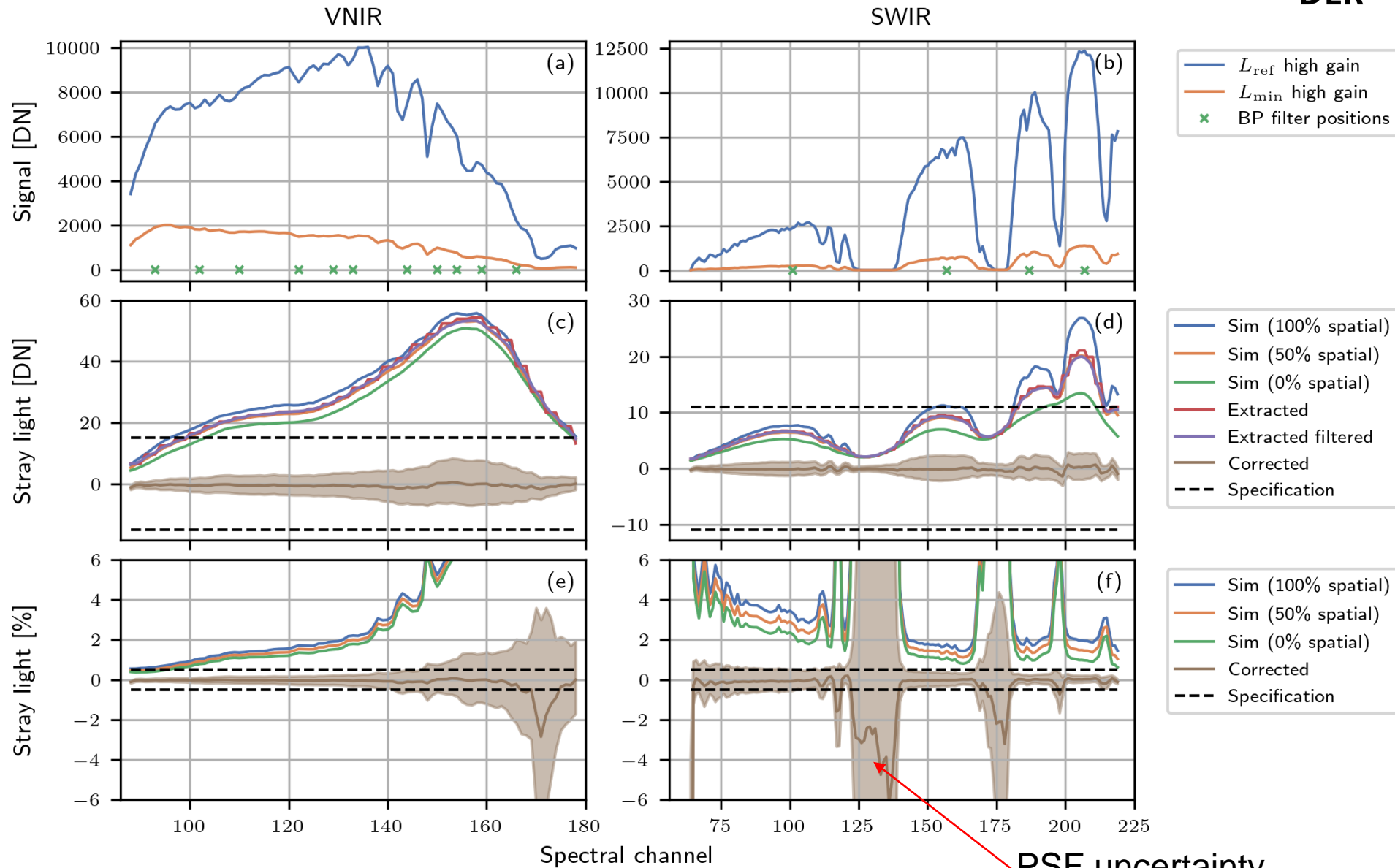
Absolute (high gain):

- <15 DN (VNIR)
- <11 DN (SWIR)
- ~noise level

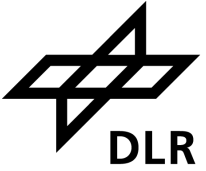
OR

Relative:

- <0.5% signal level



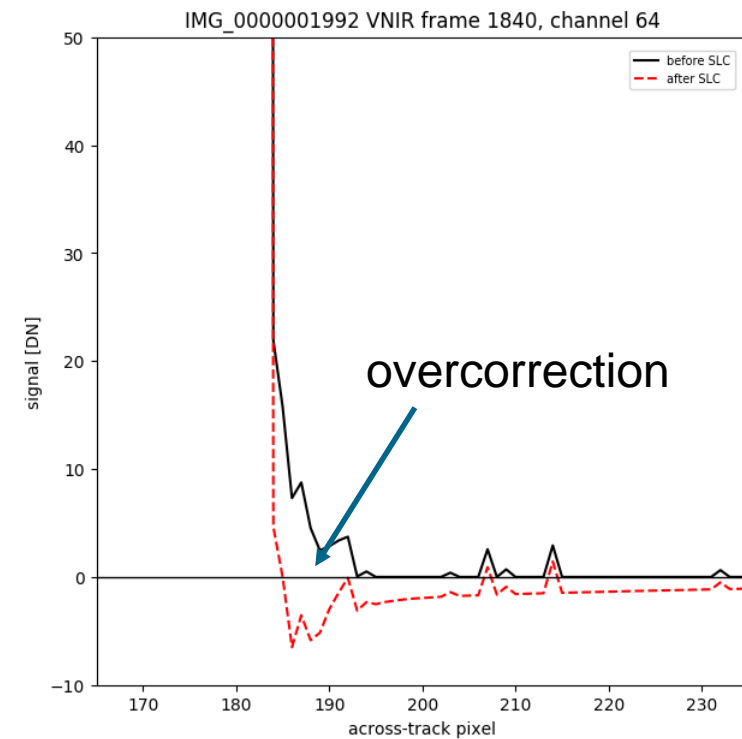
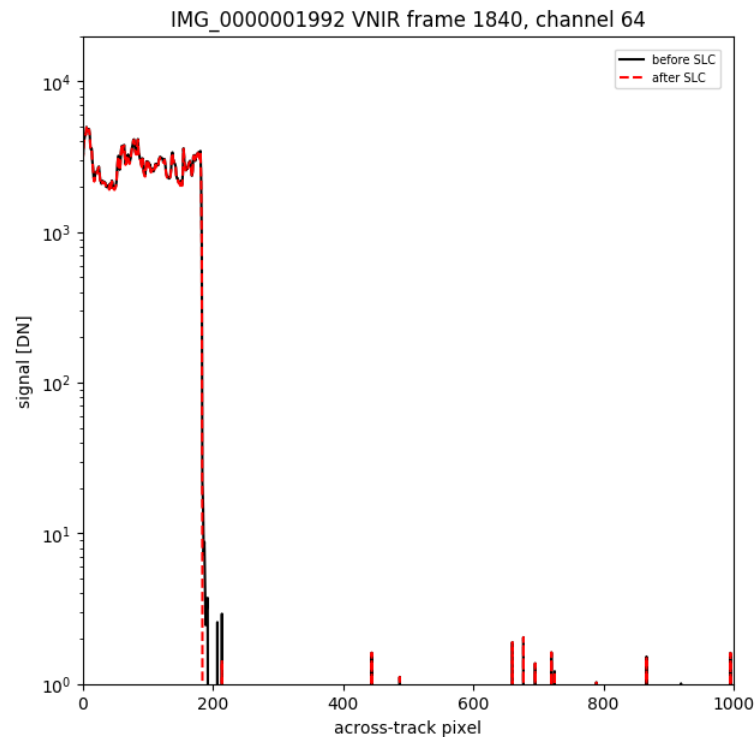
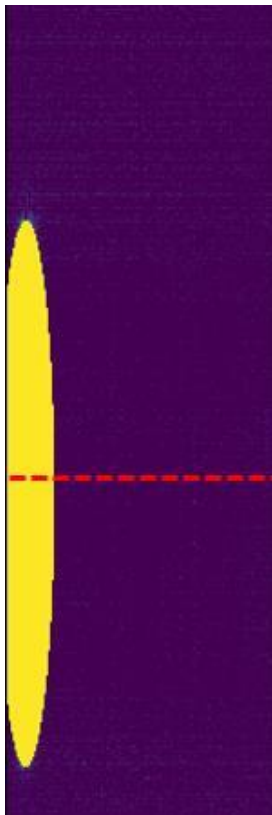
PSF Uncertainty



- Detector effects (small signal non-linearity, pedestal offset, ...)
 - Determined from ratios of overlap of sub-PSFs
 - Upper bound limit
 - VNIR (11% - 15%)
 - SWIR (19%, 27%, 17%, 10%)
- ND-filter transmissions (2%)
- Collimator stray light (50 % of before slit stray light)
- Response non-uniformity (<0.9%)
- SNR (negligible)

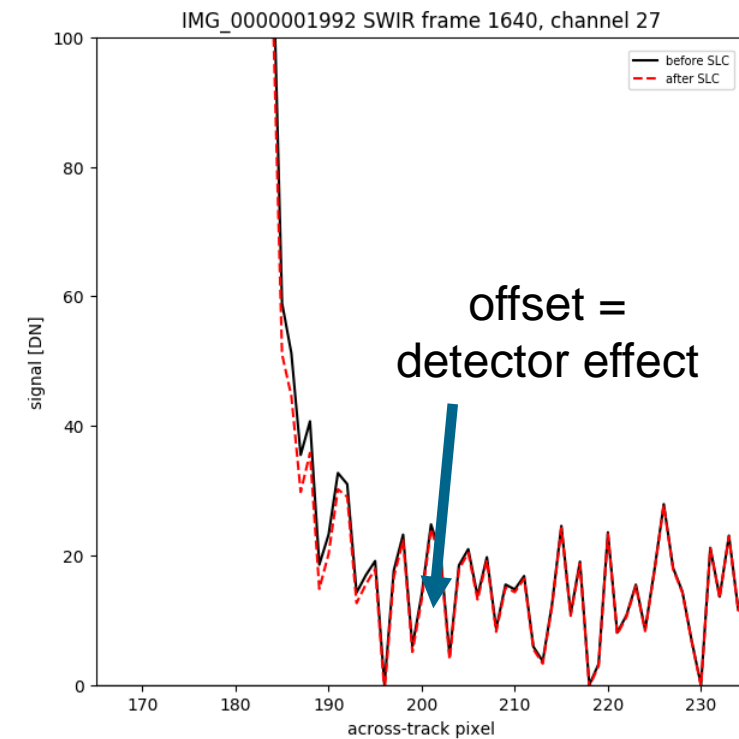
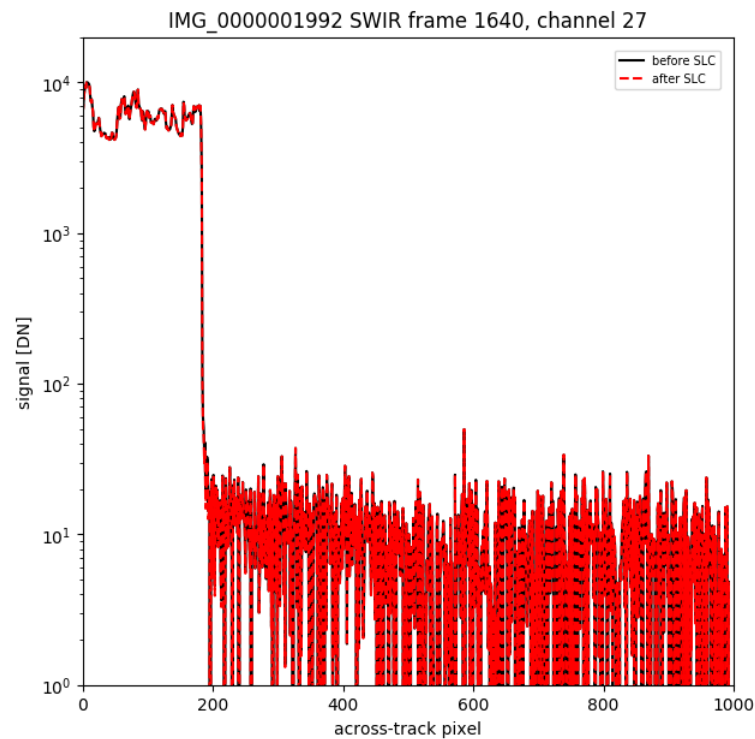
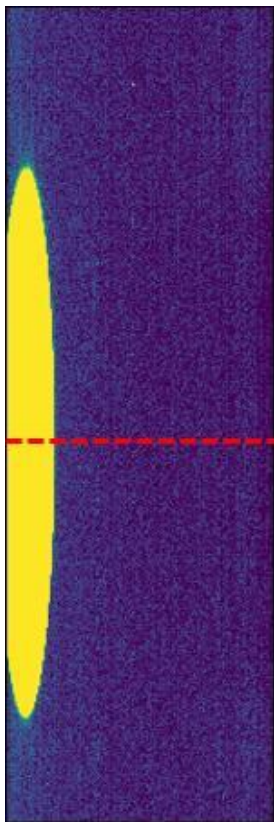
Moon Measurements VNIR

- Performed during commissioning phase
- SL-extraction matrix with 50% spatial stray light (other matrices not tested by commissioning team)
- Overcorrection most likely due to spatial OGSE stray light



Moon Measurements SWIR

- Performed during commissioning phase
- SL-extraction matrix with 50% spatial stray light (other matrices not tested by commissioning team)
- Detector effects hard to separate from stray light



Along-track Out-of-field Stray Light

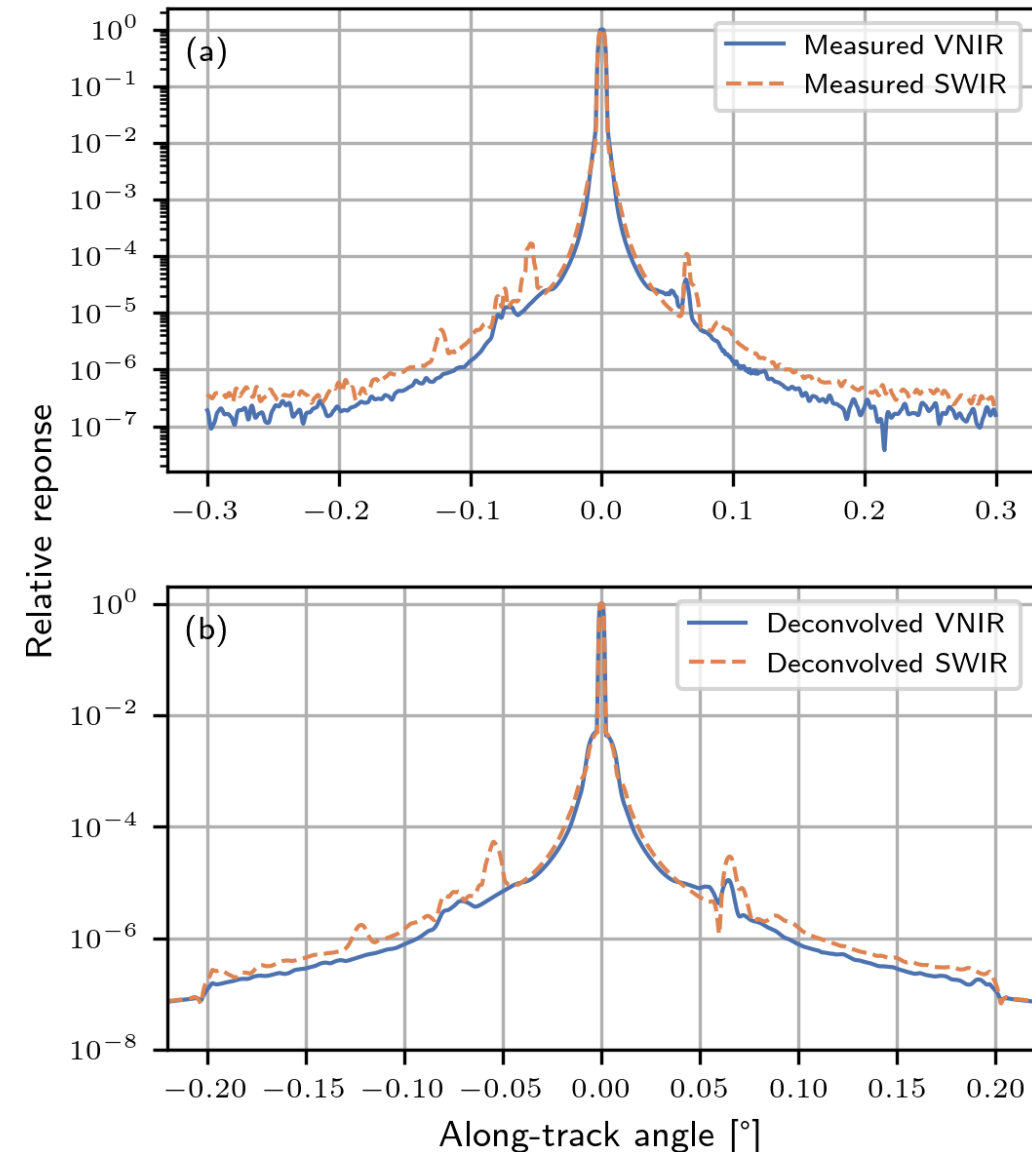


Measurements:

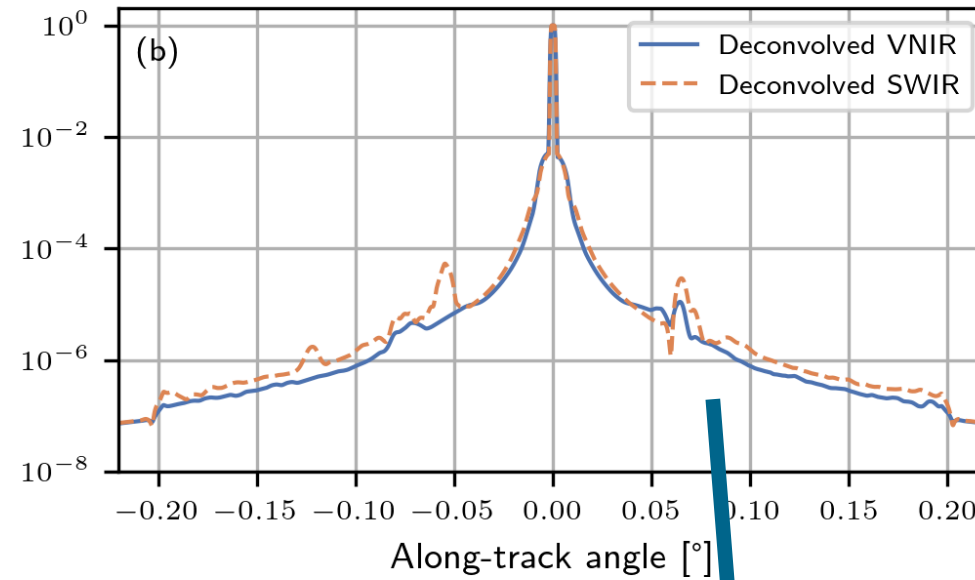
- Light source: SLTS without bandpass filter (broadband)
- 10 x 2 EnMAP IFOV (across- x along-track) target
- Scanning range $\sim 1.2^\circ$ along-track

Results:

- Along-track response independent of across-track position
- Deconvolution: get stray light relative to frame signal
- Along-track stray light 0.12% (VNIR) and 0.20% SWIR
- Not corrected in operational L1-processor



Correction Method



$$y_{ib,j} = y_{meas,j} - S y_{sl,j}$$

Scaling factor S :

- Accounting for OGSE stray light
- Was intended to be found during commissioning phase

$$y_{sl,j} = \sum_{i=-\frac{n}{2}}^{\frac{n}{2}-1} z_{sl,i} y_{ib,i+j}$$

Assumption:
 $y_{ib} \approx y_{meas}$

$$y_{sl,j} \approx \sum_{i=-\frac{n}{2}}^{\frac{n}{2}-1} z_{sl,i} y_{meas,i+j}$$

Conclusion



- EnMAP has relatively low stray light levels
- For SL measurements detectors must be very well understood:
Saturation, blooming, non-linearity (esp. low signal), pedestal offsets, etc.
→ Detector requirements for SL measurement usually exceed operational requirements
- Hard to separate OSGE SL from instrument SL
- Masked pixels can help to estimate OGSE SL
- More details in
A. Baumgartner et al. (2024). **Stray Light Calibration and Correction of EnMAP's Imaging Spectrometers.** Manuscript submitted for publication