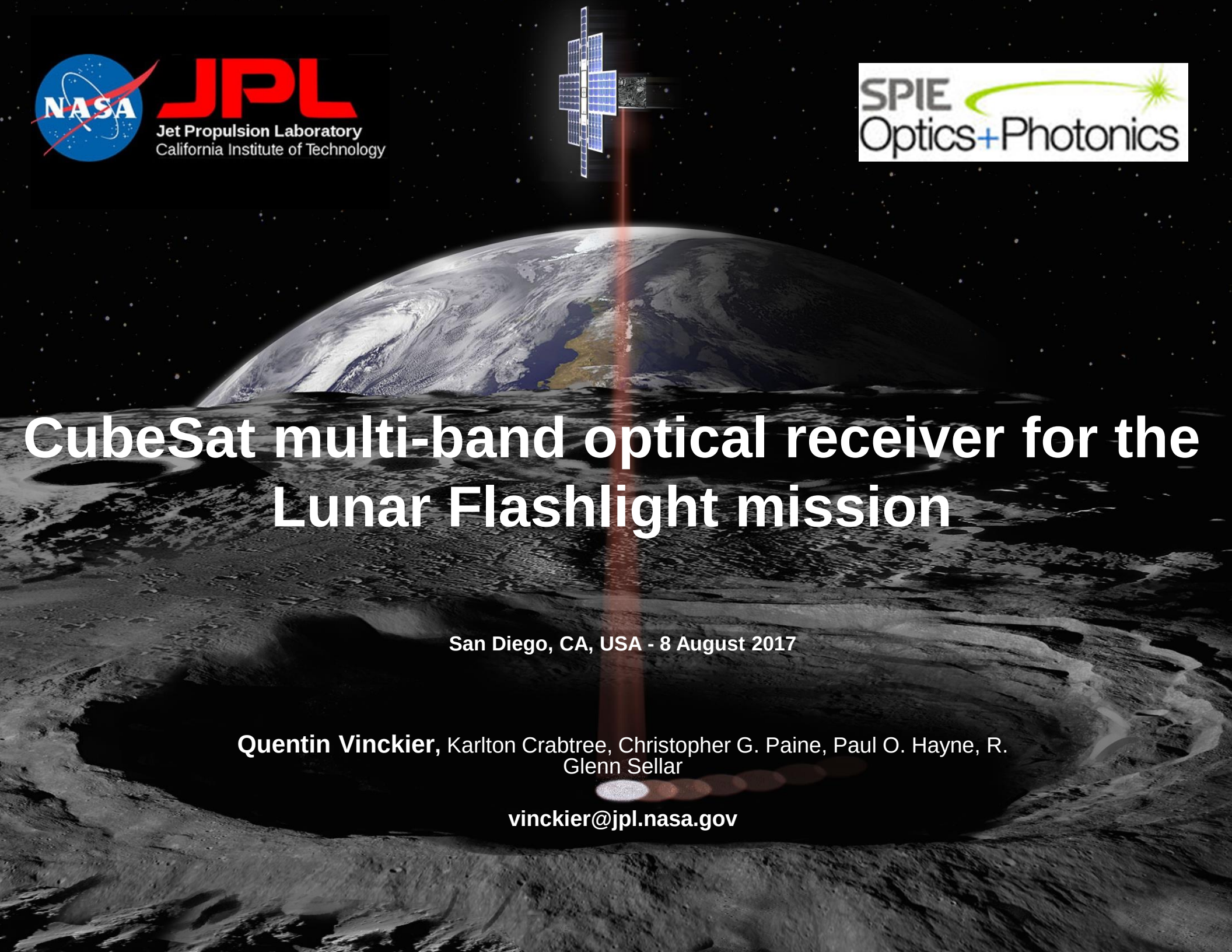

CubeSat multi-band optical receiver for the Lunar Flashlight mission

San Diego, CA, USA - 8 August 2017

Quentin Vinckier, Karlton Crabtree, Christopher G. Paine, Paul O. Hayne, R. Glenn Sellar

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Outline

1 Introduction

2 Instrument operation principle

3 Receiver optical design

4 Conclusions and perspectives

Introduction

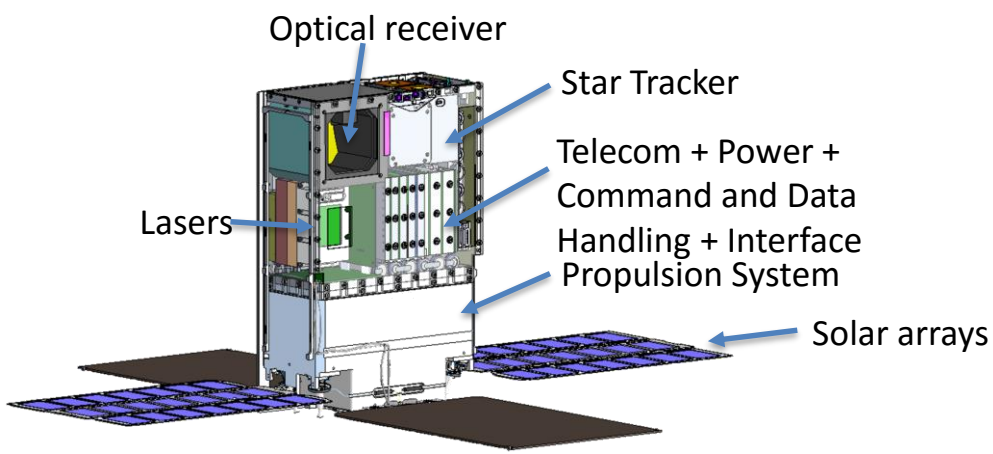
NASA Strategic Knowledge Gaps : concentration and distribution of lunar volatiles, in particular water ?

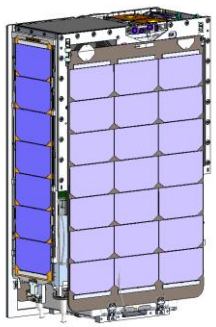
Background : strong indications of the presence of water ice in the Permanently Shadowed Regions (PSRs) of the lunar south pole [1-4].

Lunar Flashlight goals :

1. measure water ice concentrations on the lunar south pole above 0.5 weight %
2. map water ice distribution with a resolution of 1 km

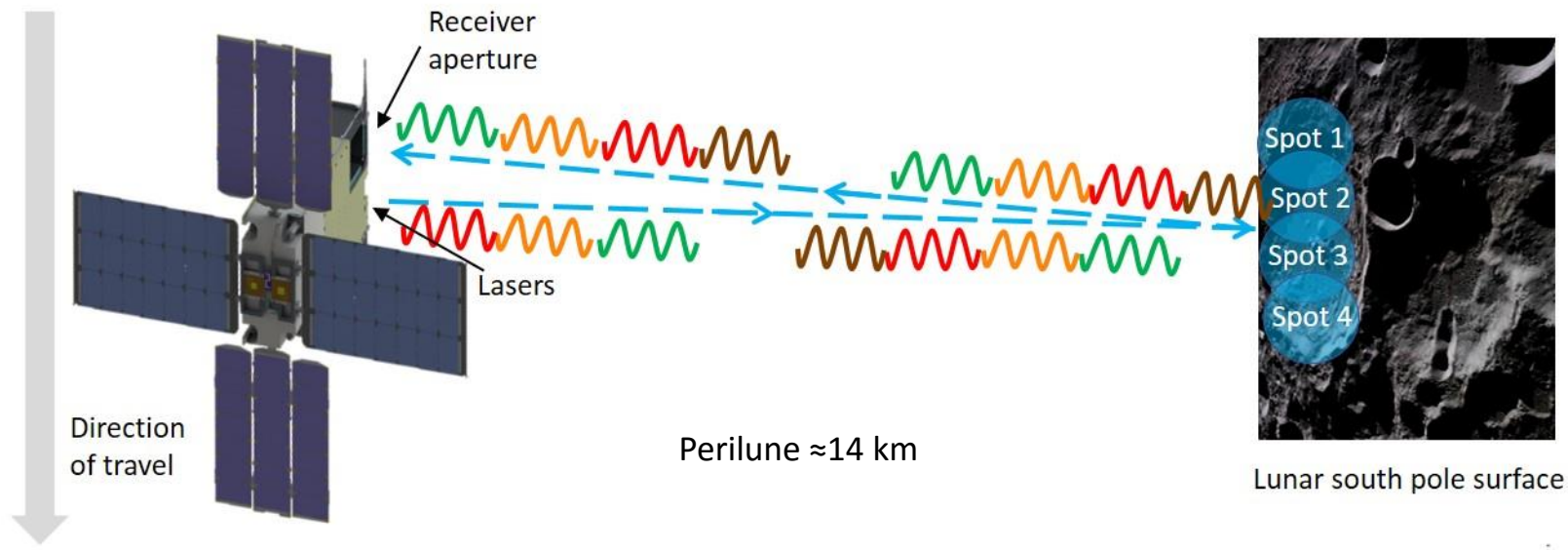
How : multi-band reflectometry from orbit.

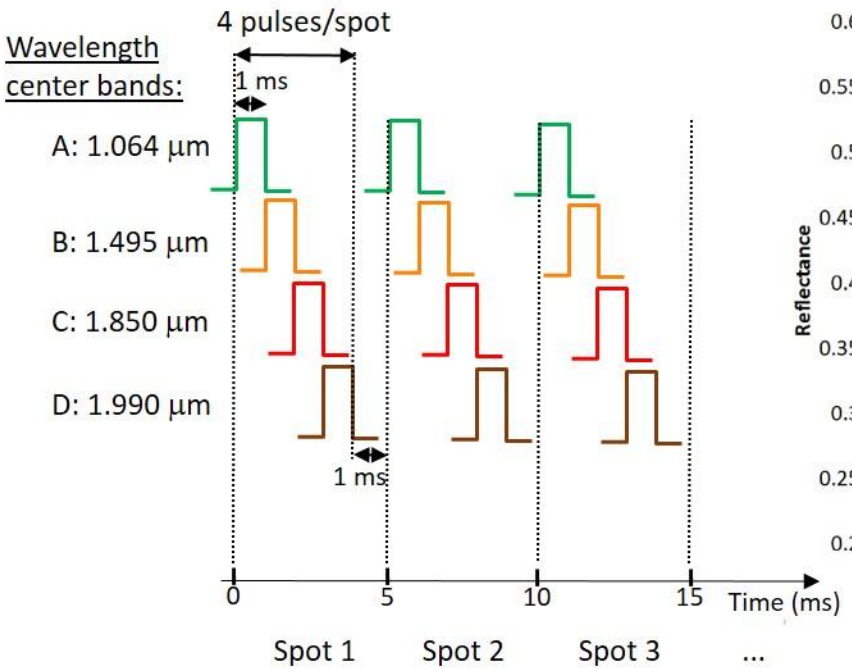


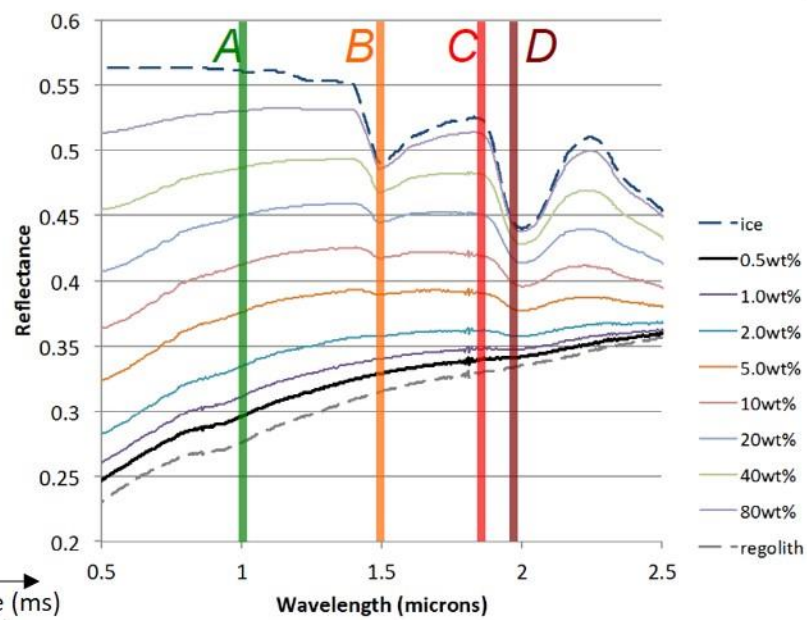


[1] Hayne, P. O. et al., "Evidence for exposed water ice in the Moon's south polar regions from Lunar Reconnaissance Orbiter ultraviolet albedo and temperature measurements," Icarus 255, 58-69 (2015).
[2] Thomson, B. J. et al., "An upper limit for ice in Shackleton crater as revealed by LRO Mini-RF orbital radar," Geophysical Research Letters 39(14) (2012).
[3] Schwadron, N. A. et al., "Signatures of volatiles in the lunar proton albedo," Icarus 273, 25-35 (2016).
[4] Fisher, E. A. et al., "Evidence for surface water ice in the lunar polar regions using reflectance measurements from the Lunar Orbiter Laser Altimeter and temperature measurements from the Diviner Lunar Radiometer Experiment," Icarus 292, 74-85 (2017).

Instrument operation principle



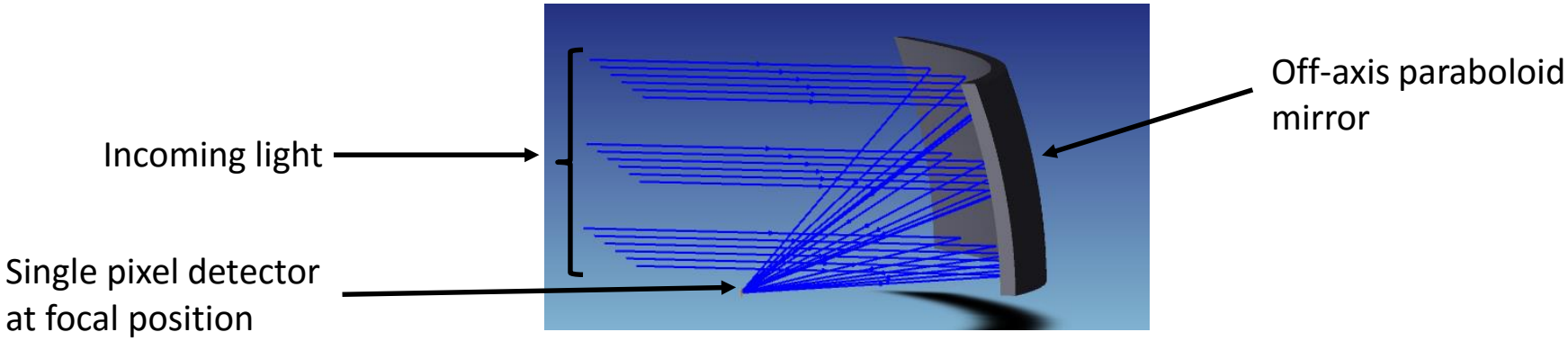




[5] Cohen, B. A. et al., "Payload Design for the Lunar Flashlight Mission," Proc. Lunar and Planetary Science Conference 48, 1709 (2017).

Receiver optical design

Receiver concept:



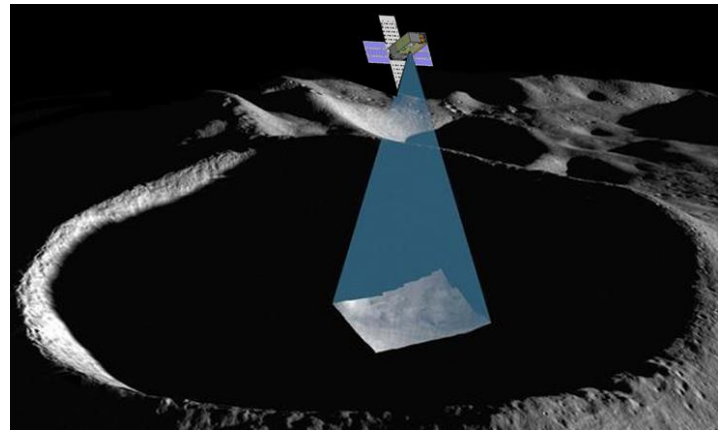
Design phases:

1. Selection of the mirror focal length and the detector active area
2. Stray light analysis to minimize the background

Receiver optical design

Mirror Focal Length (FL) and diameter (Ø) of the detector active area :

$$FOV = 2 \times arctan\left\{\frac{\emptyset}{2 \times FL}\right\}$$

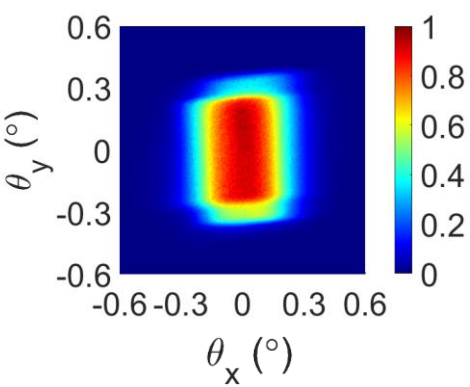


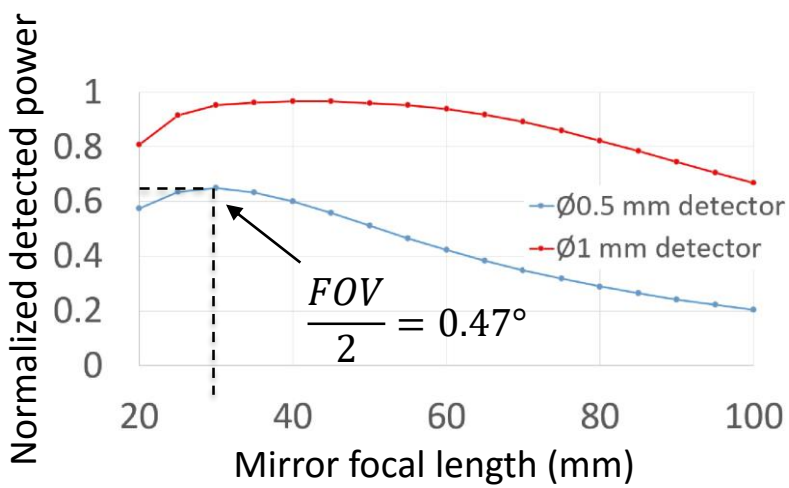
Driven factors:

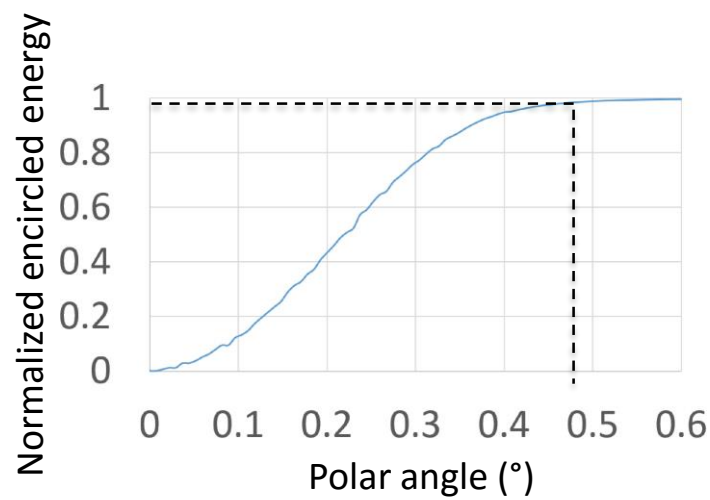
- Minimization of detected solar illumination of the Moon surface (background)
- Maximization of the lasers photons detection efficiency

$$\emptyset = 1\,mm \quad FL = 70\,mm \quad FOV = 0.82°$$

Beams divergence profile



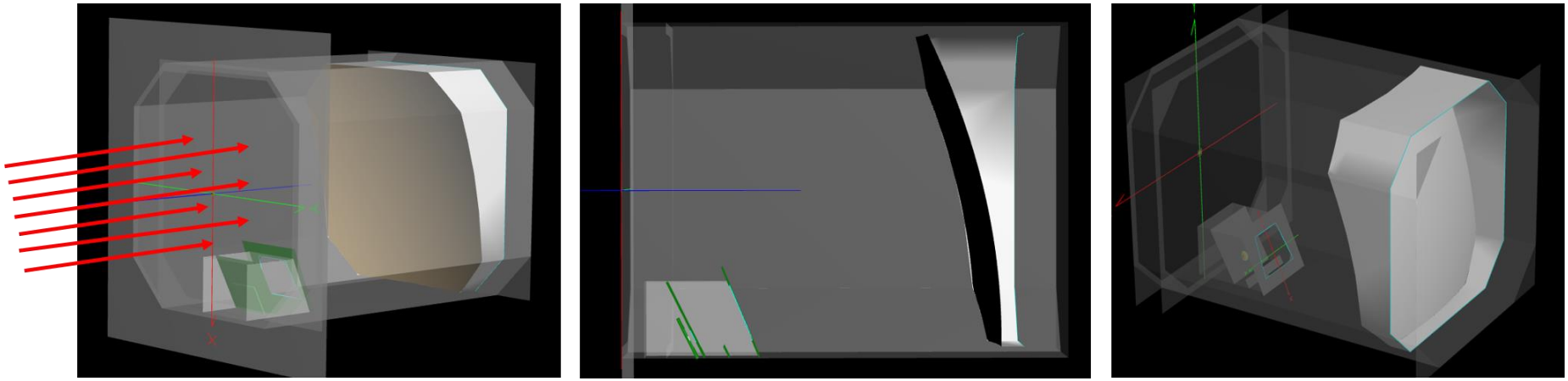


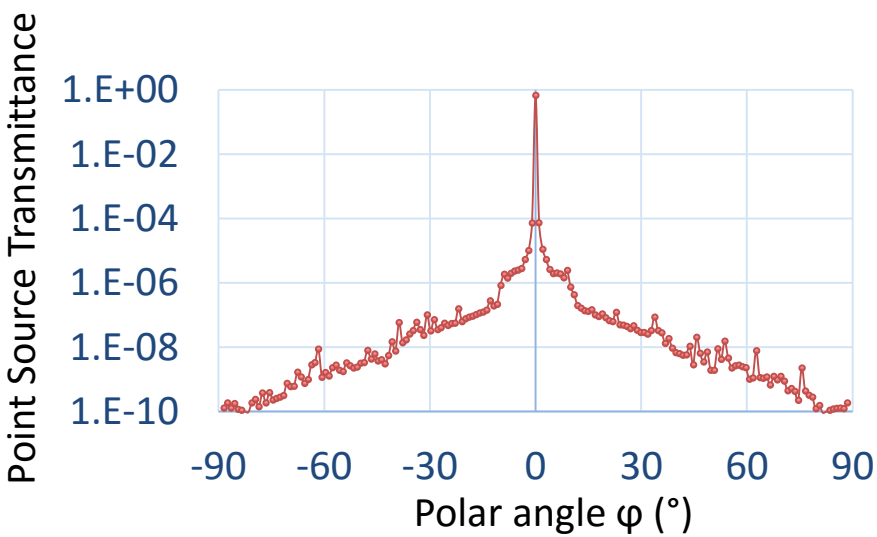


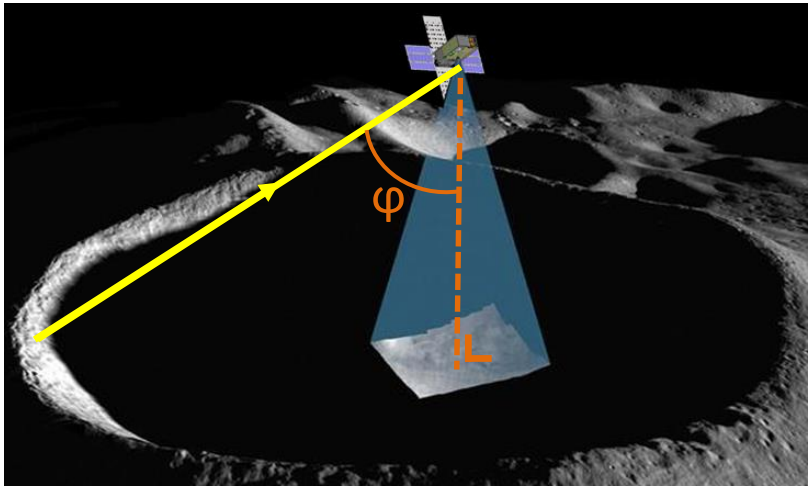
Receiver optical design

Stray light analysis:

- *Goal:* Minimization of detected solar illumination of the Moon surface outside the receiver FOV
- *Optical design:*

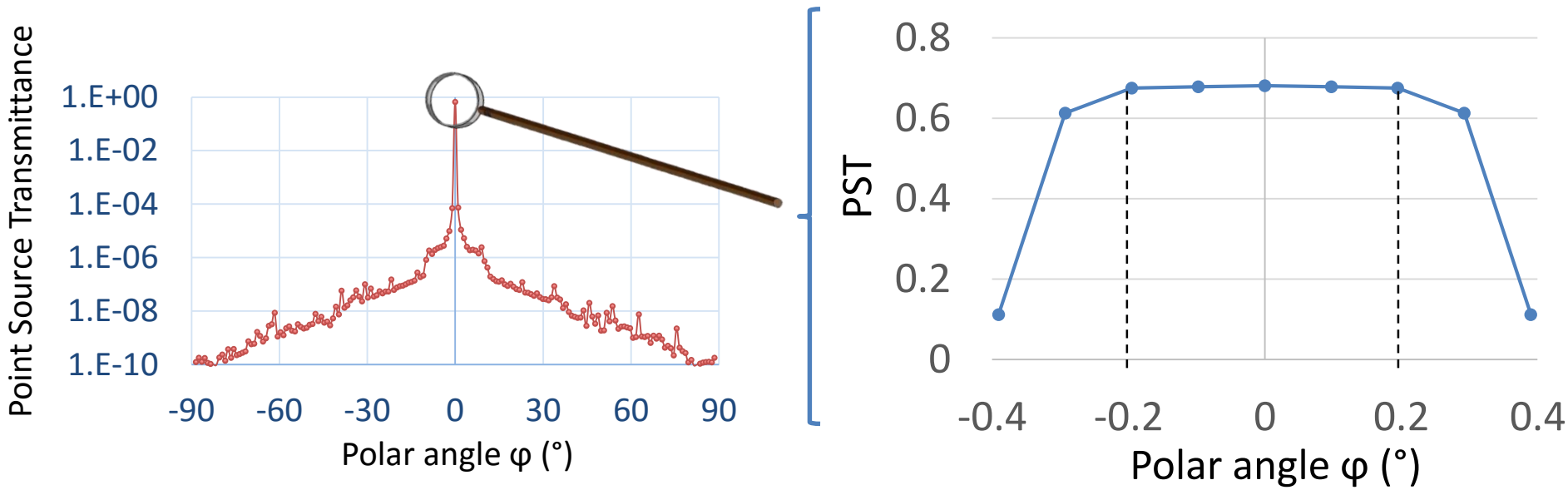




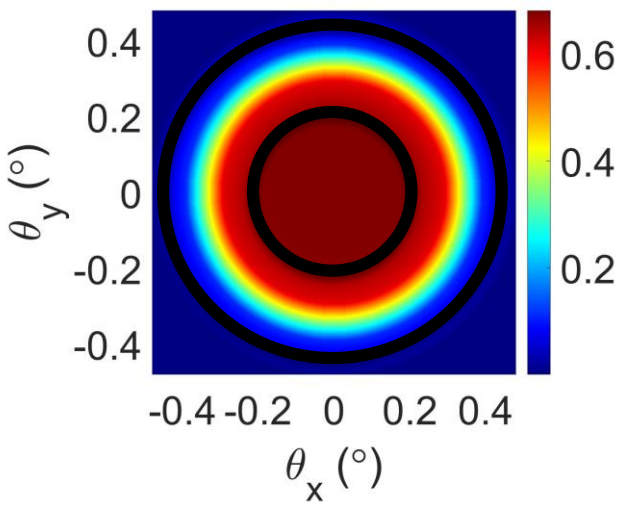


Receiver optical design

Rotationally average Point-Source-Transmittance function:



Receiver 2D PST

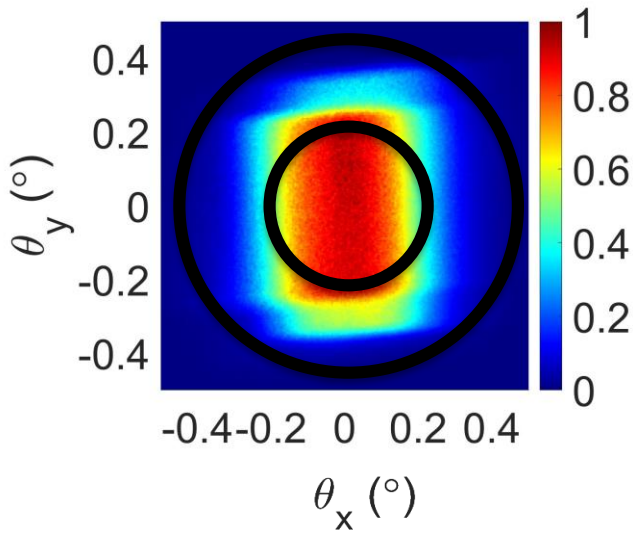


$\emptyset = 1\ mm$

$FL = 70\ mm$

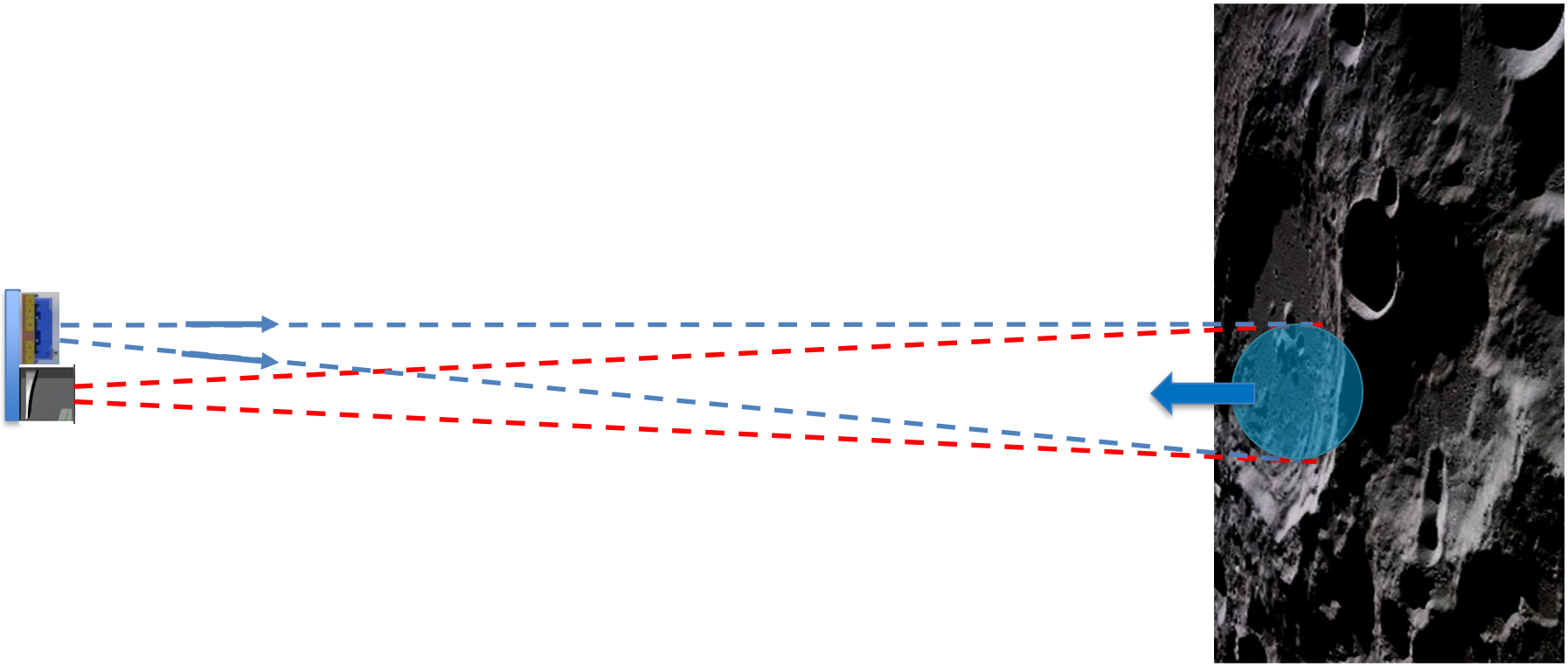
$FOV \approx 0.8°$

Laser beams divergence profile



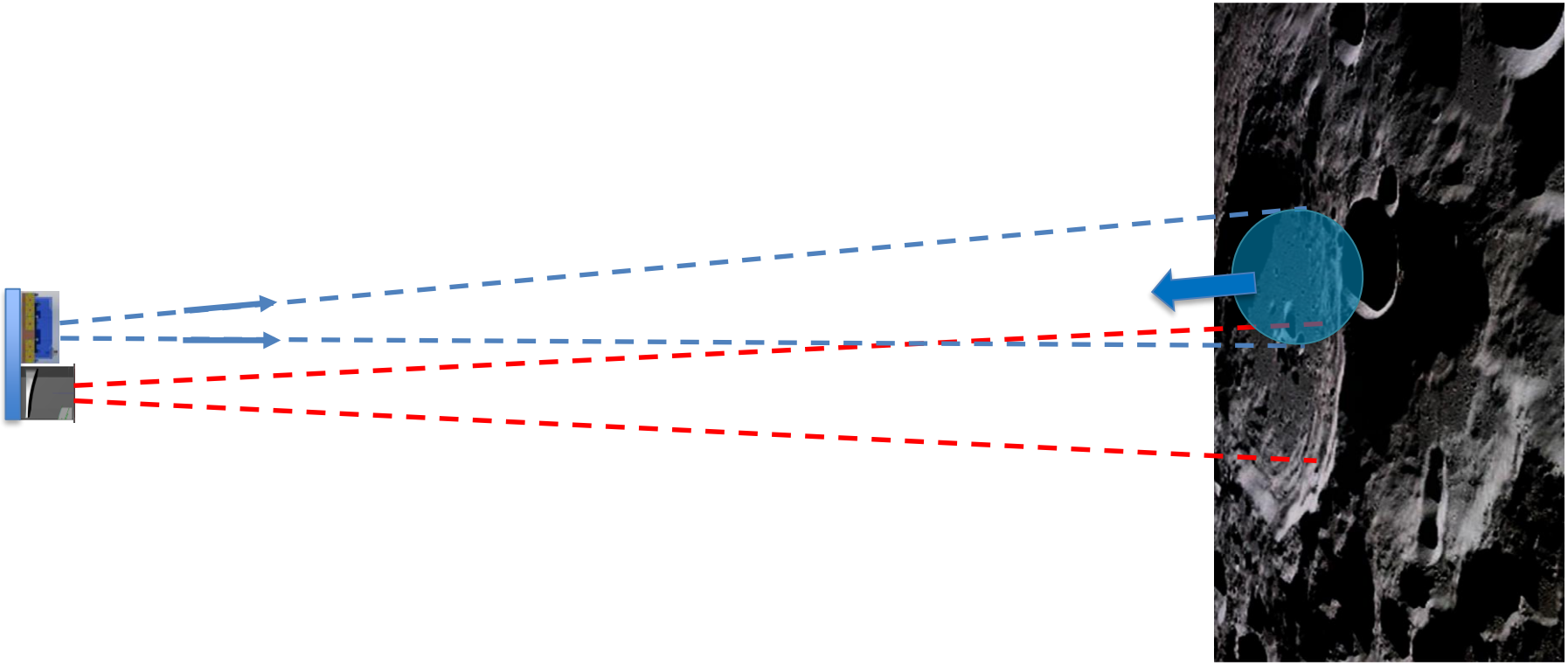
Receiver optical design

Lasers-to-receiver pointing instability :



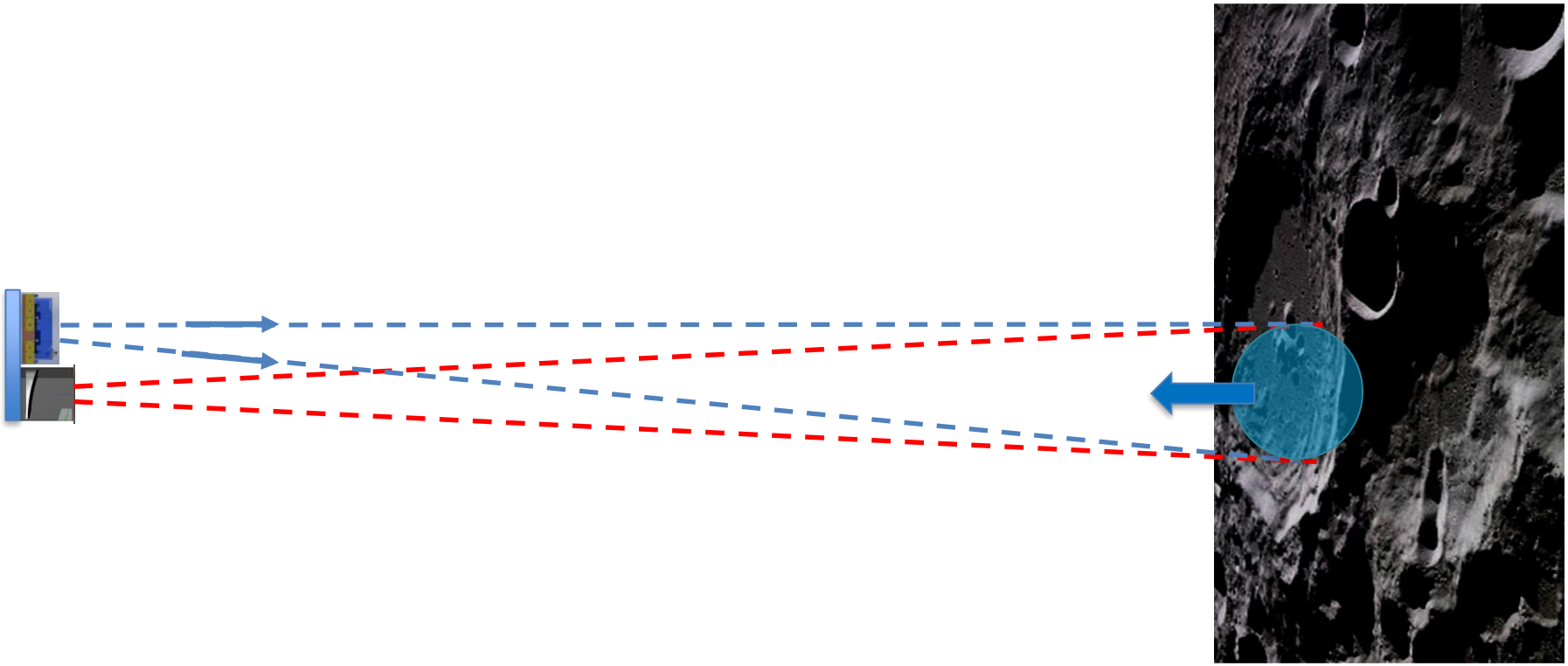
Receiver optical design

Lasers-to-receiver pointing instability :



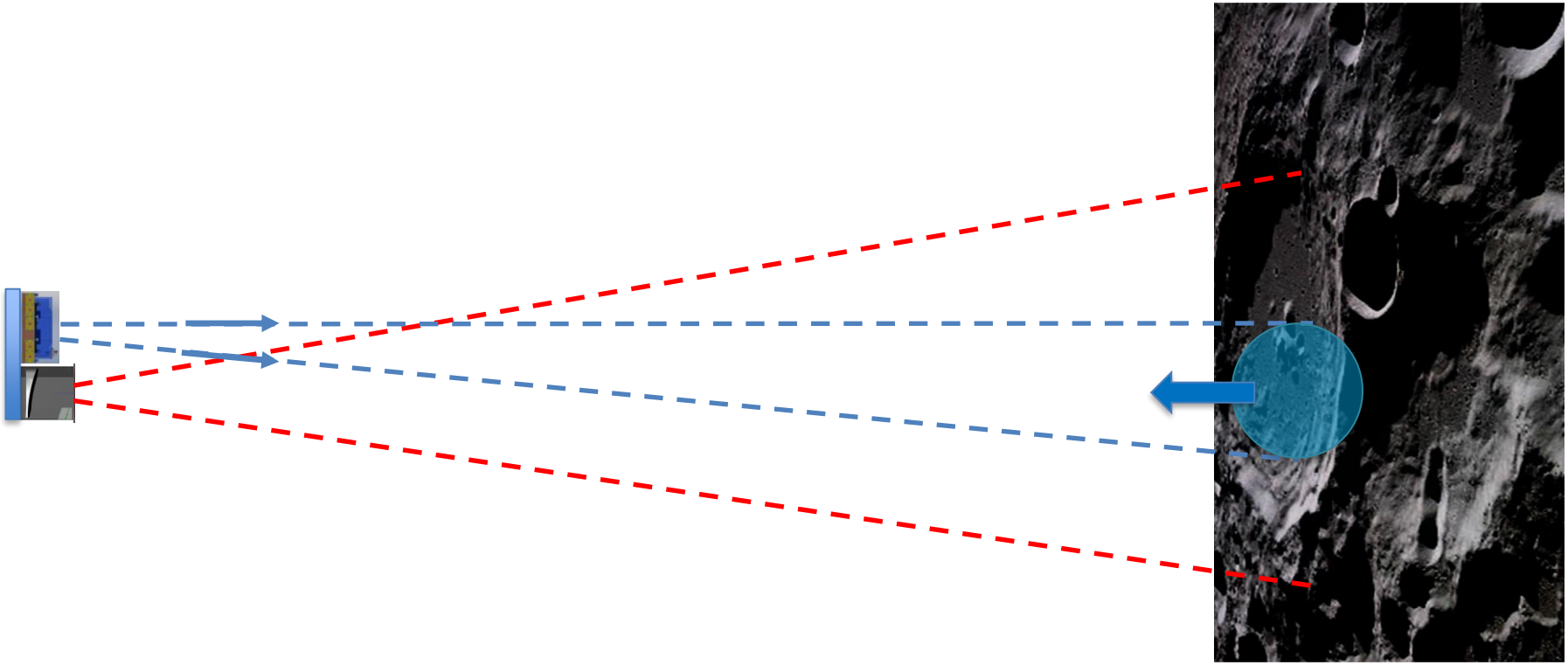
Receiver optical design

Lasers-to-receiver pointing instability :



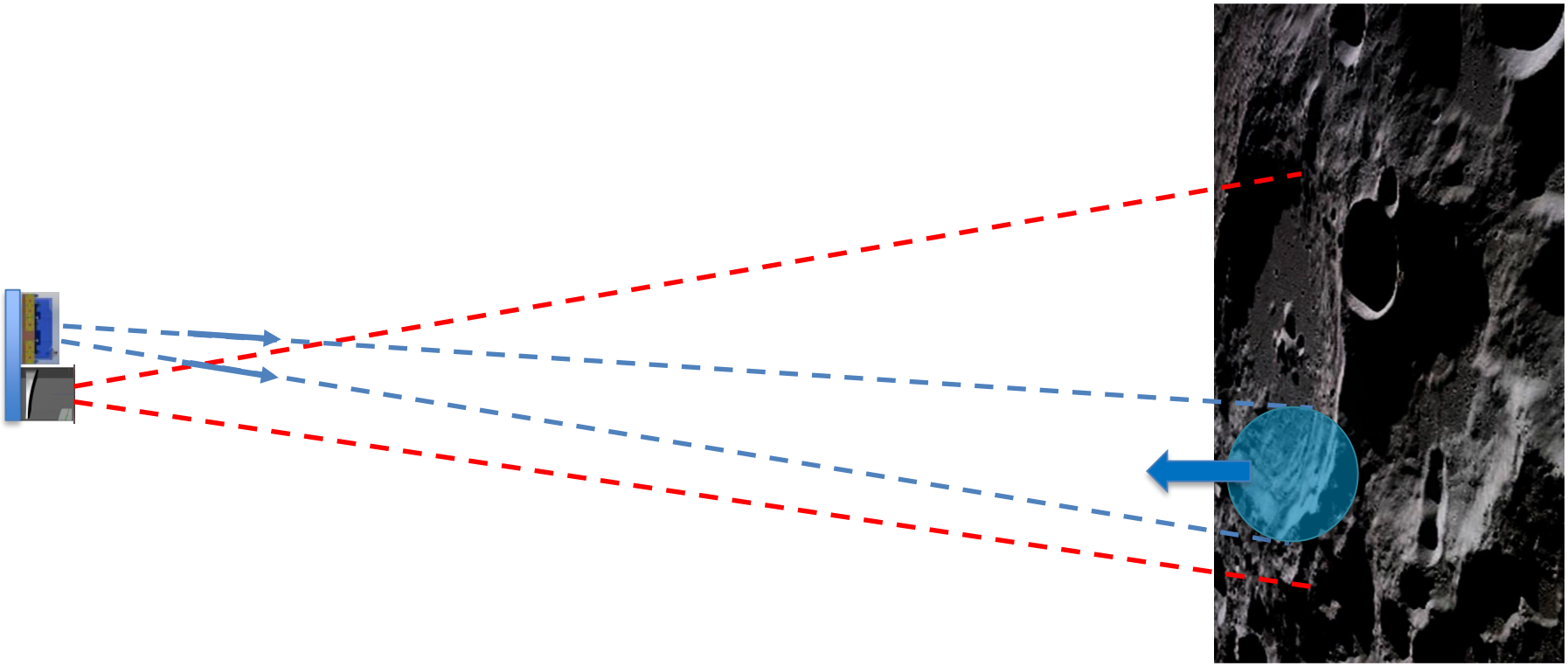
Receiver optical design

Lasers-to-receiver pointing instability :



Receiver optical design

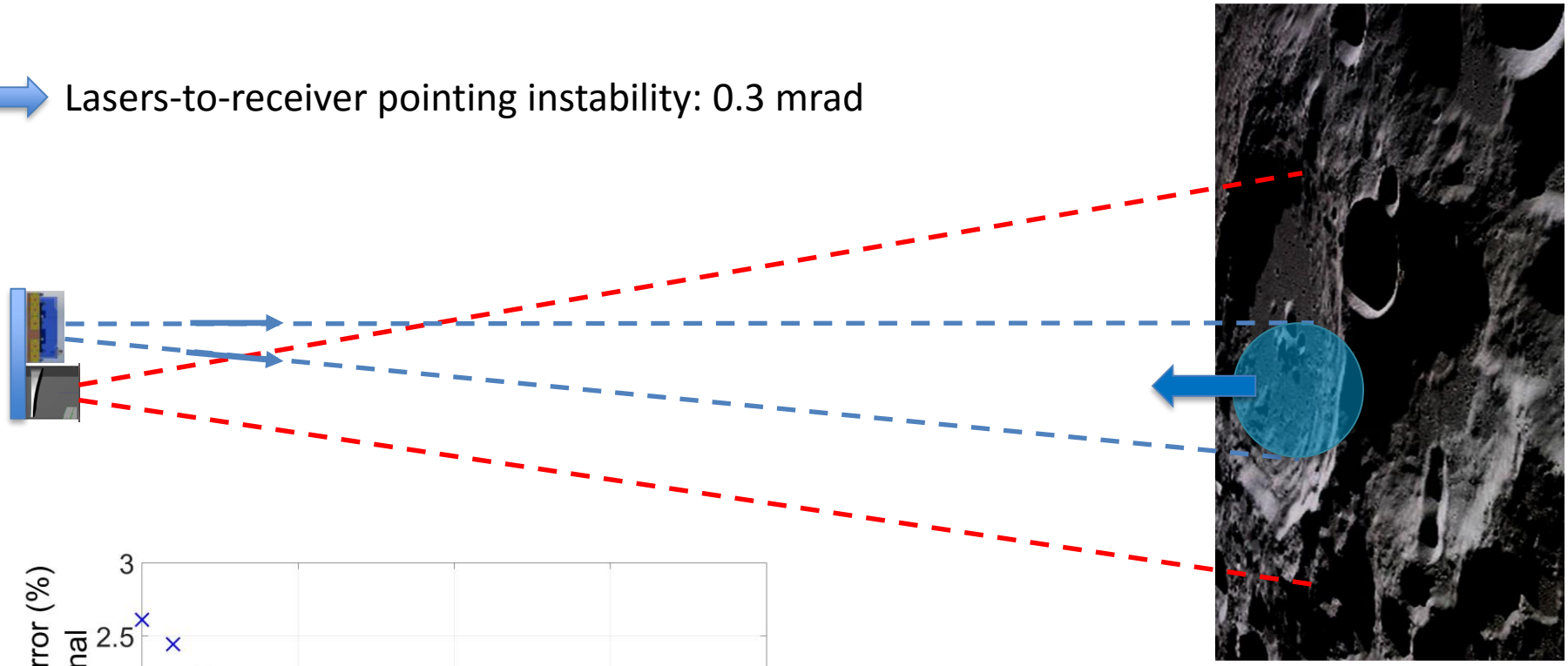
Lasers-to-receiver pointing instability :

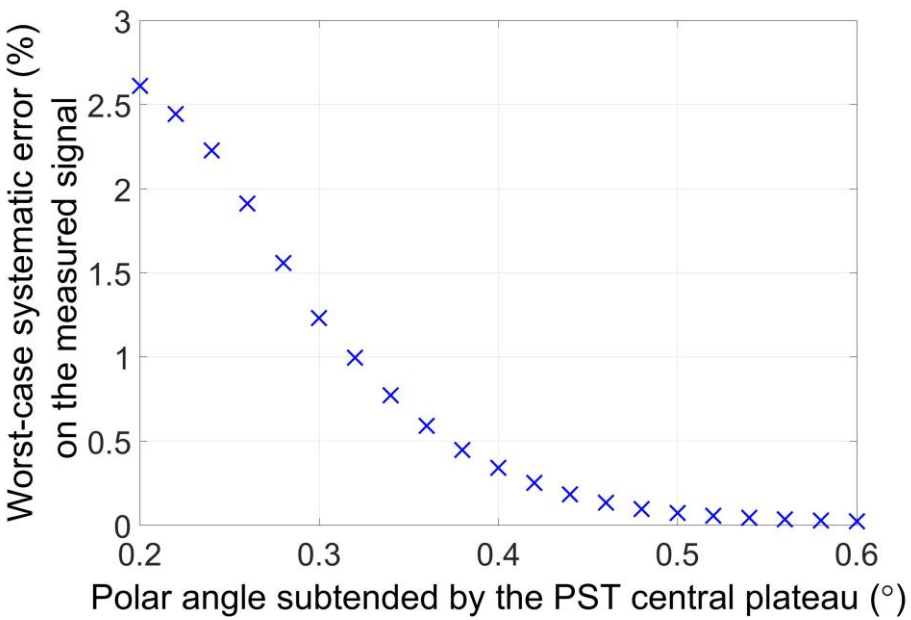


Receiver optical design

Lasers-to-receiver pointing instability :

Lasers-to-receiver pointing instability: 0.3 mrad





Conclusions and perspectives

- Design of a NIR optical receiver based on an aluminum paraboloid mirror focusing incoming light onto a single detector.
- Main challenge: design optimization (detector diameter, focal length, vanes/baffles) to minimize the overall uncertainty on the measurements.
- Next steps: receiver optical design update, opto-mechanical design, manufacture, calibration & characterization, integration to the CubeSat.
- This will be one of the first instruments onboard a CubeSat performing science measurements beyond low Earth orbit and the first planetary mission to use multi-band reflectometry from orbit.

Thank you for your attention!

Appendices

Stray light – Model limitations

- **This includes only 2 levels of scatter (any ray which attempts to scatter a 3rd time is stopped)**
  - This is not a major limitation, since the energy remaining in such a ray will be quite small
- **The number of rays incident on the system is approximately 2 rays per sq mm**
  - Since all relevant structures are at least 2.5mm in the smallest dimension, this should be adequate
- **BSDFs are always approximate, even well characterized surfaces like Z306 can vary by nearly a factor of two between various measurements**

Receiver temperature ranges

Assembly	AFT (Allowable Flight Temperature)		FA (Flight Acceptance)		PF (Protoflight)	
	Op Cold/Hot (°C)	Non-Op Cold/Hot (°C)	Op Cold/Hot (°C)	Non-Op Cold/Hot (°C)	Op Cold/Hot (°C)	Non-Op Cold/Hot (°C)
Receiver Optics	-50(TBR)/-13	-50(TBR)/+50	-55(TBR)/-8	-55(TBR)/+55	-65(TBR)/+7	-65(TBR)/+70
Detector	-150/-61	-150/+60	-155/-56	-155/+65	-165/-41	-165/+80

PST theory

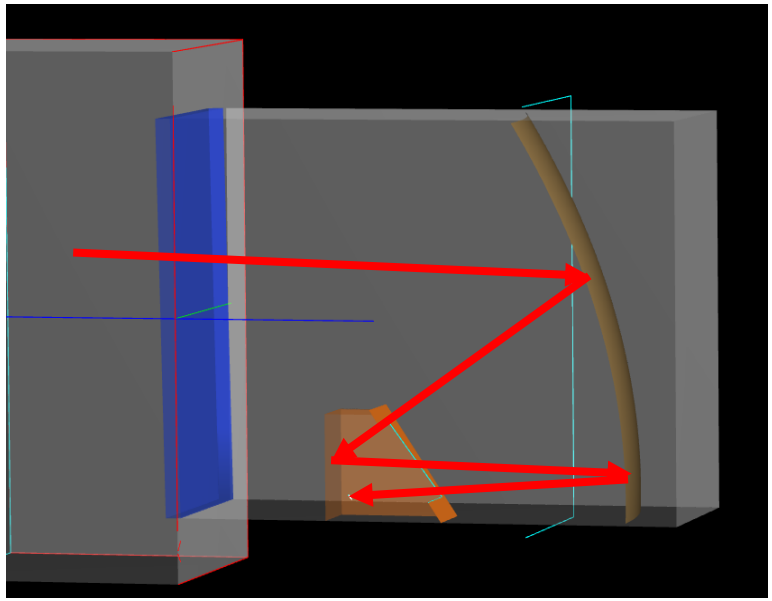
- **The PST is the ratio of the average detector irradiance to the incident irradiance, computed as a function of angle:**

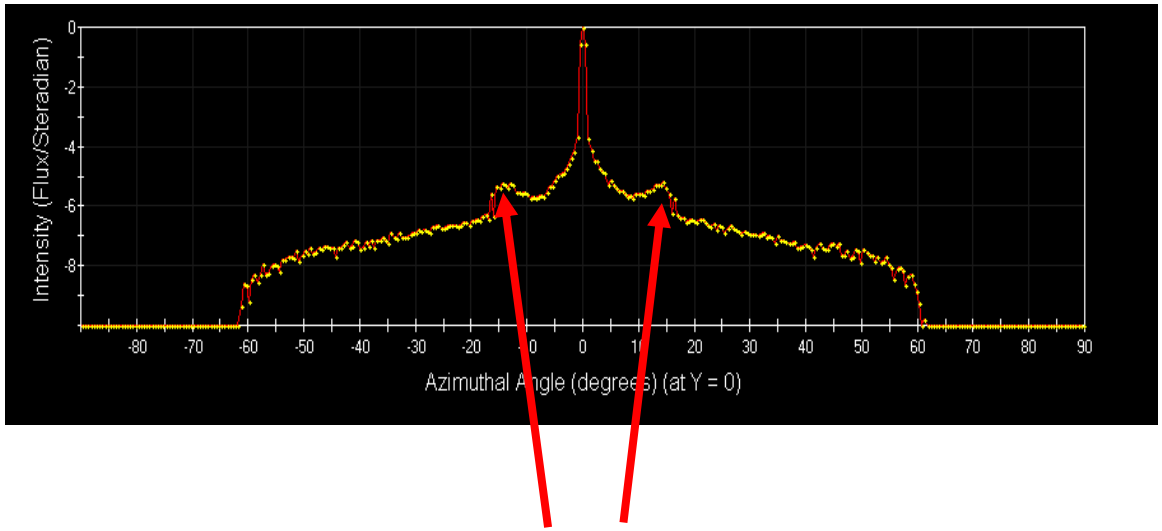
$$PST(\theta,\phi) = \frac{E_{det}(\theta,\phi)}{E_{inc}(\theta,\phi)} = \frac{E_{det}(\theta,\phi)}{P_{inc,norm} \cdot \cos(\theta) / A_{entrance}}$$

- **The source irradiance at normal incidence is typically set to unity.**
- **This PST can be used as a transfer function: the total amount of light (stray or otherwise) reaching the focal plane is**

$$P_{det}(\theta,\phi) = E_{inc}(\theta,\phi) \cdot PST(\theta,\phi) \cdot A_{det}$$

PST humps





This feature is due to scatter from the inside of the orange housing

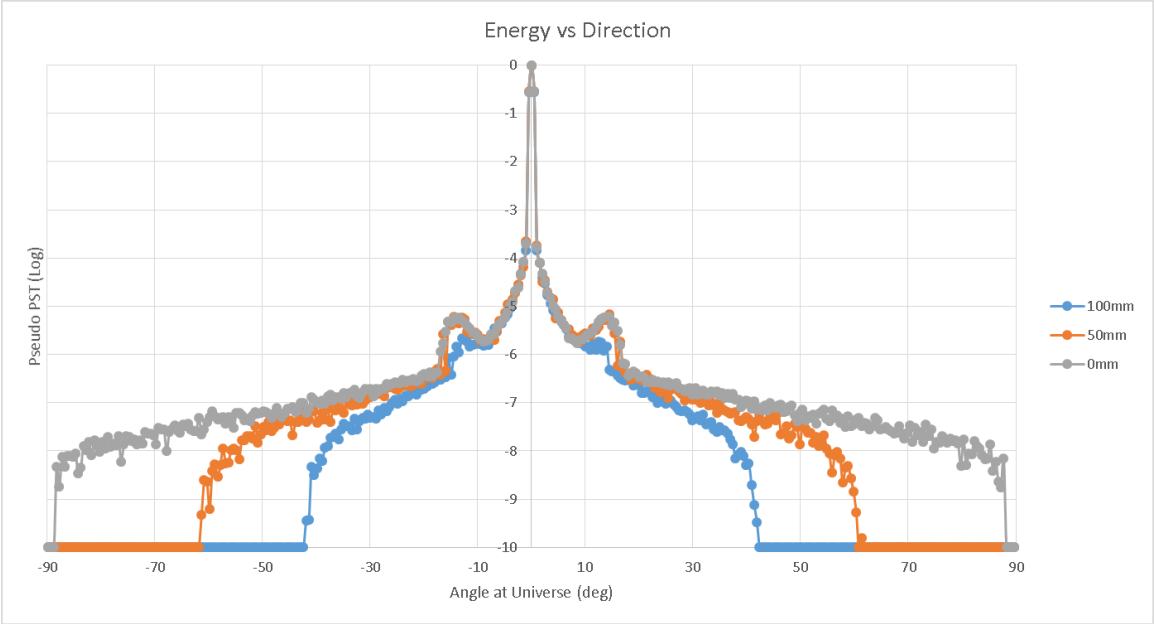
Path:

mirror -> housing -> mirror -> detector

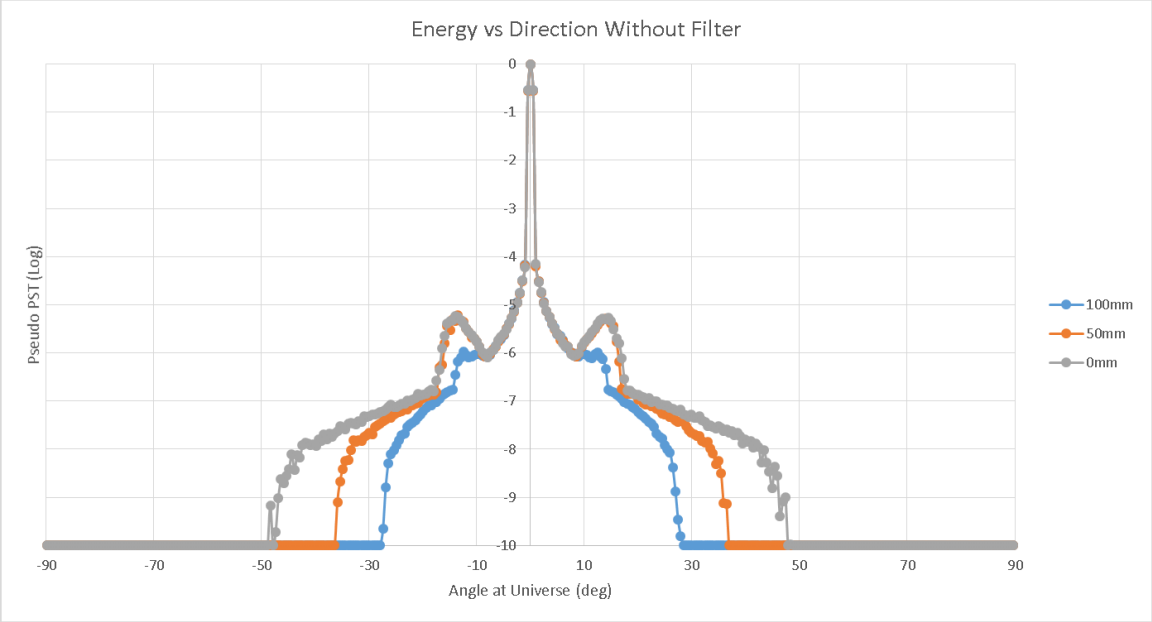
A 100mm baffle would partially blocks this path.

Effect of extended baffles and filter on PST

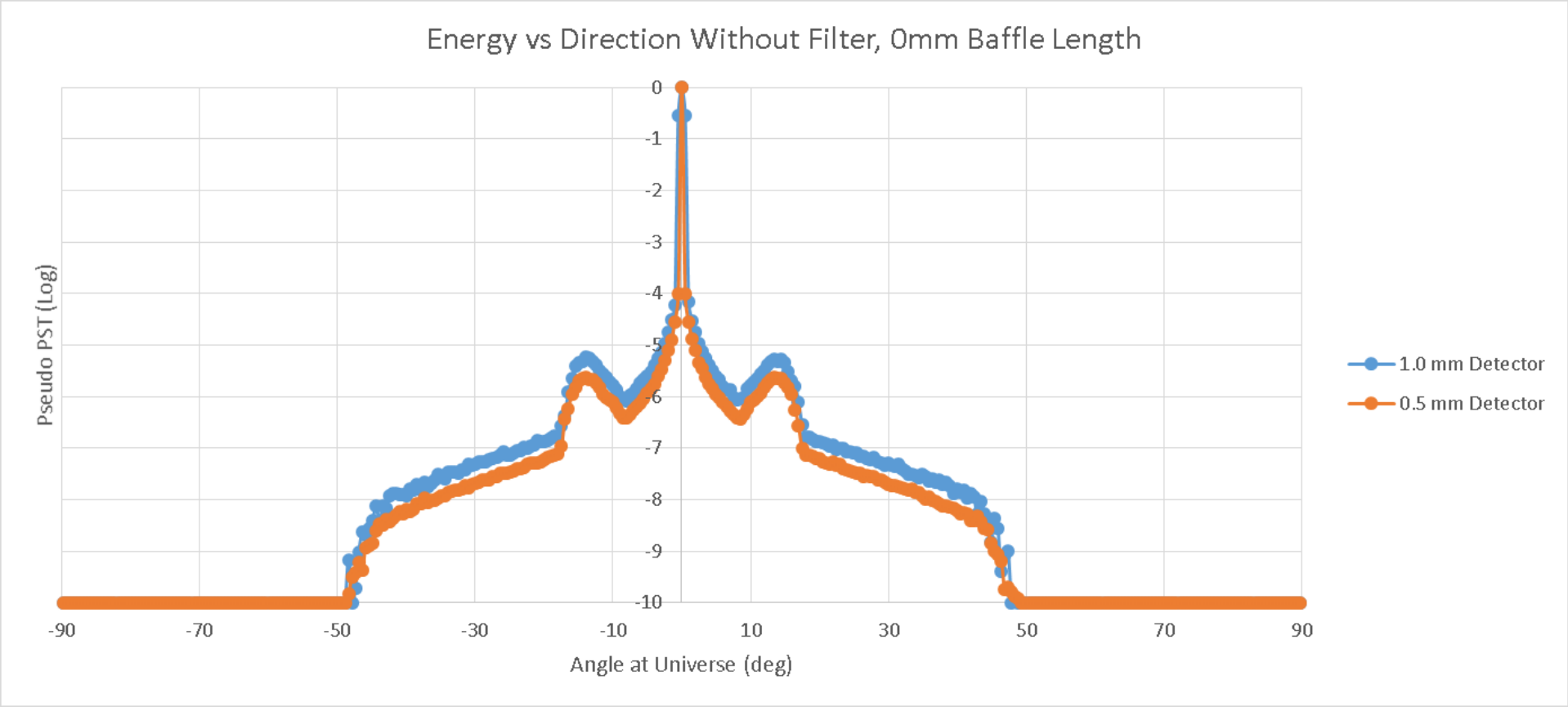
With Filter



Without Filter

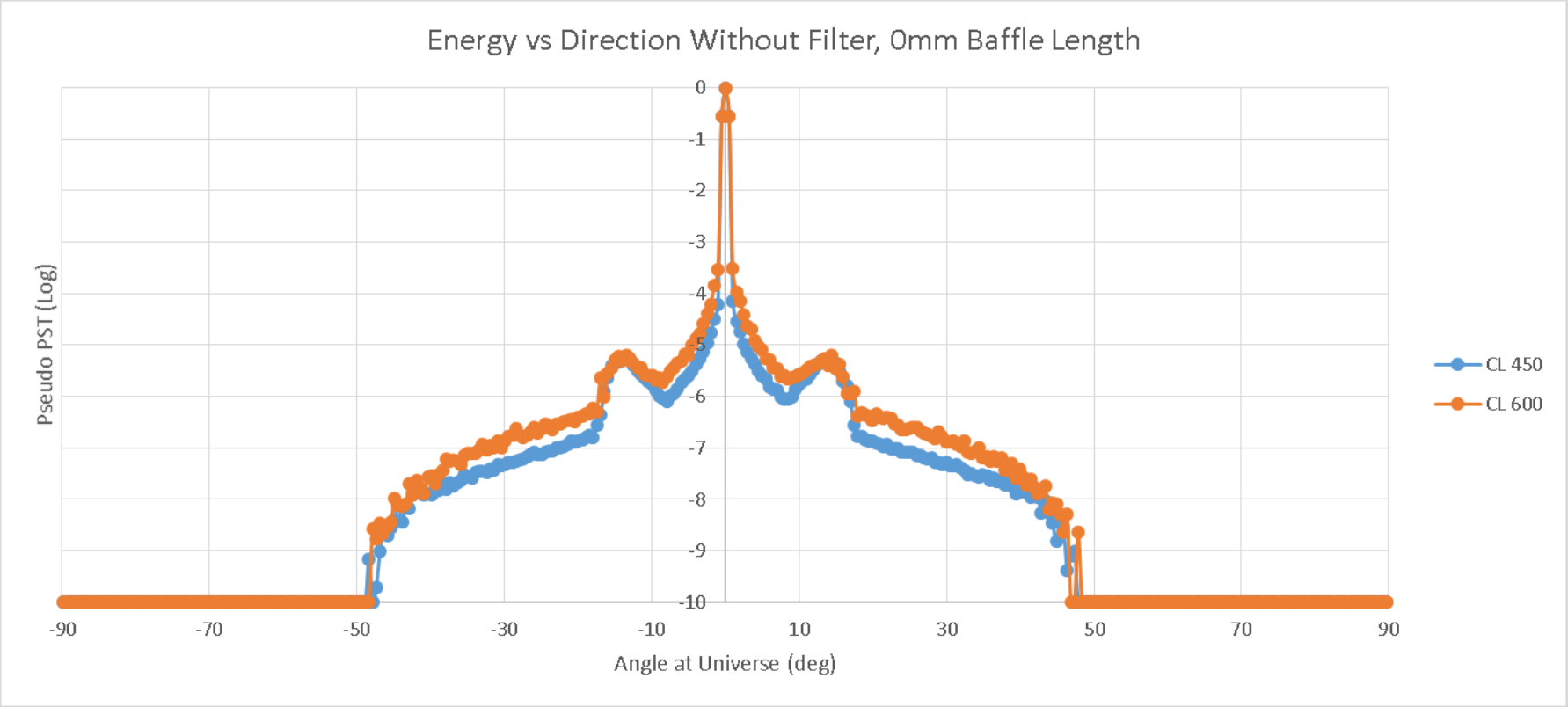


Effect of detector size on PST

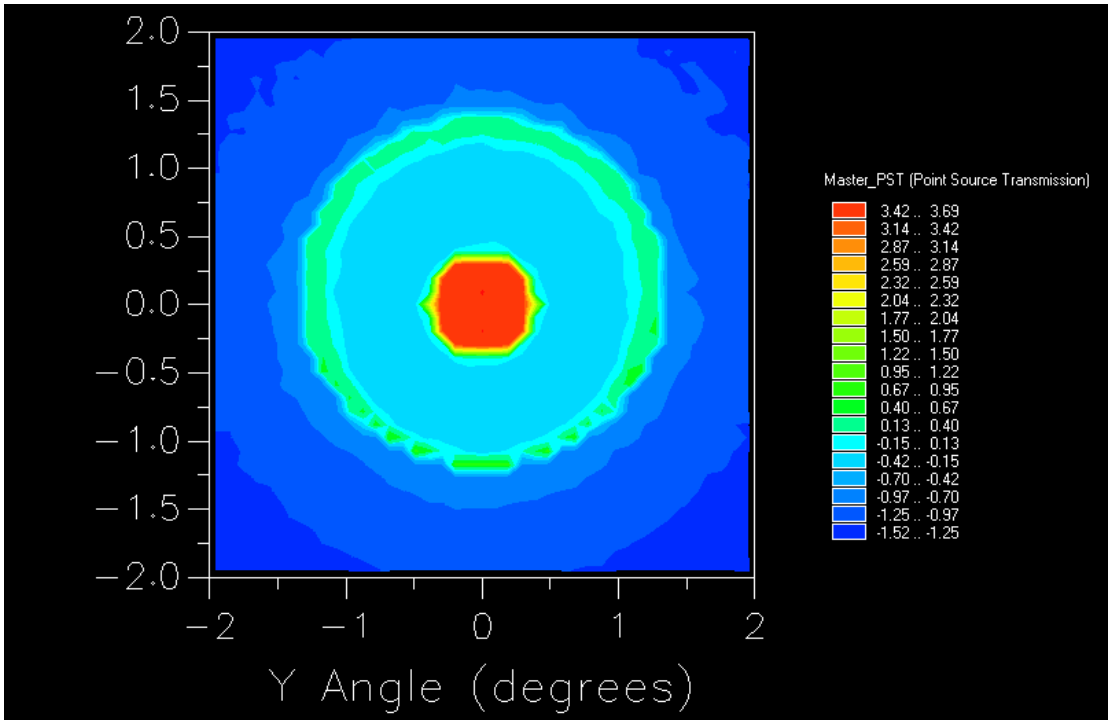


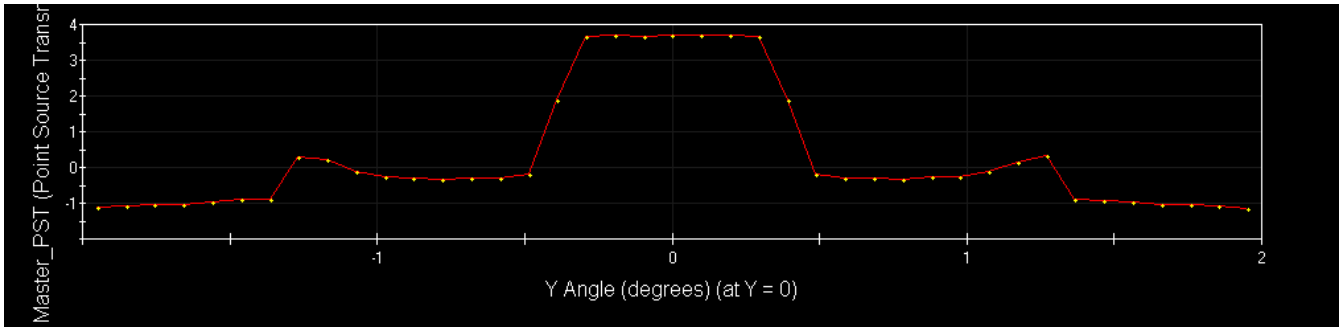
Contamination effect on the PST

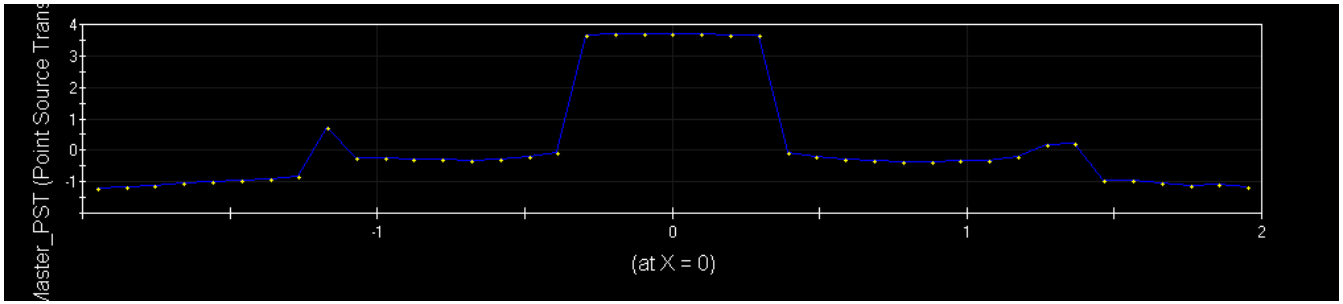
- **Percent Area Coverage (PAC) = percent of surface which is obscured by particulates**
- **CL 450 = 0.164 PAC**
- **CL 600 = 0.696 PAC**



PST of current optical design







Manufacture tolerances

3D decenter of Detector: 0.5 mm

3D decenter of mirror: 2.0 mm

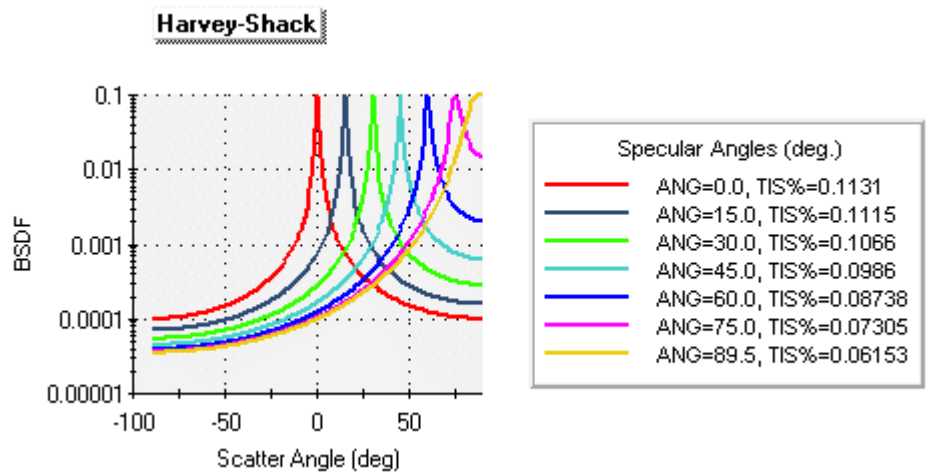
Mirror focal length 1.0 mm

Mirror tip/tilt: 0.05 rad

Detector tip/tilt: 0.05 rad

Scatter model

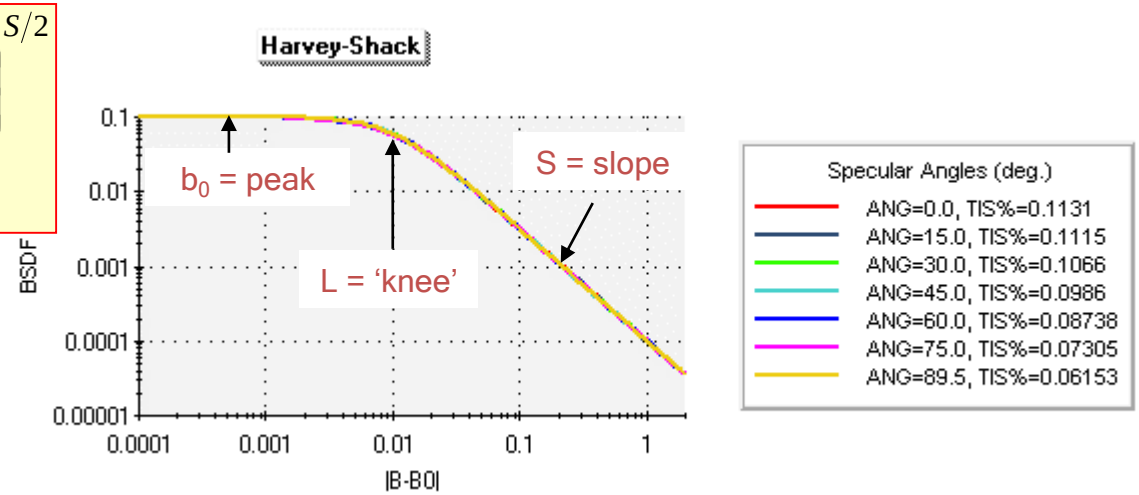
- **Empirically derived from measurement**
- **No intrinsic wavelength dependence**
- **Lorentzian around specular ray**
- ***Linear-shift invariant*: BSDF depends on the difference (β-β_0) between the specular and scattered rays**



Harvey-Shack

$$BSDF(\beta,\beta_0) = b_0\left(1+\left(\frac{\beta-\beta_0}{L}\right)^2\right)^{S/2}$$

$$specular\ \ peak = b_0$$



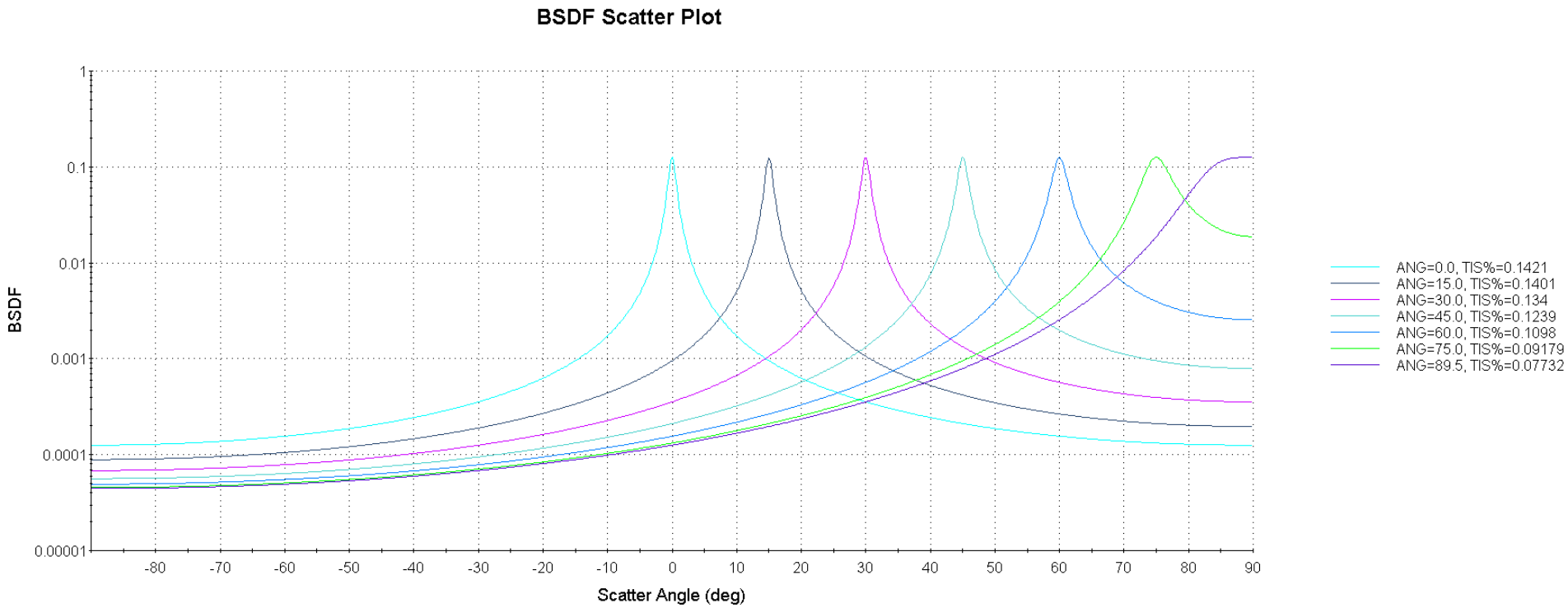
ABg

$$BSDF(\beta,\beta_0) = \frac{A}{B+\left(\beta-\beta_0\right)^g}$$

$$specular\ \ peak = A/B$$

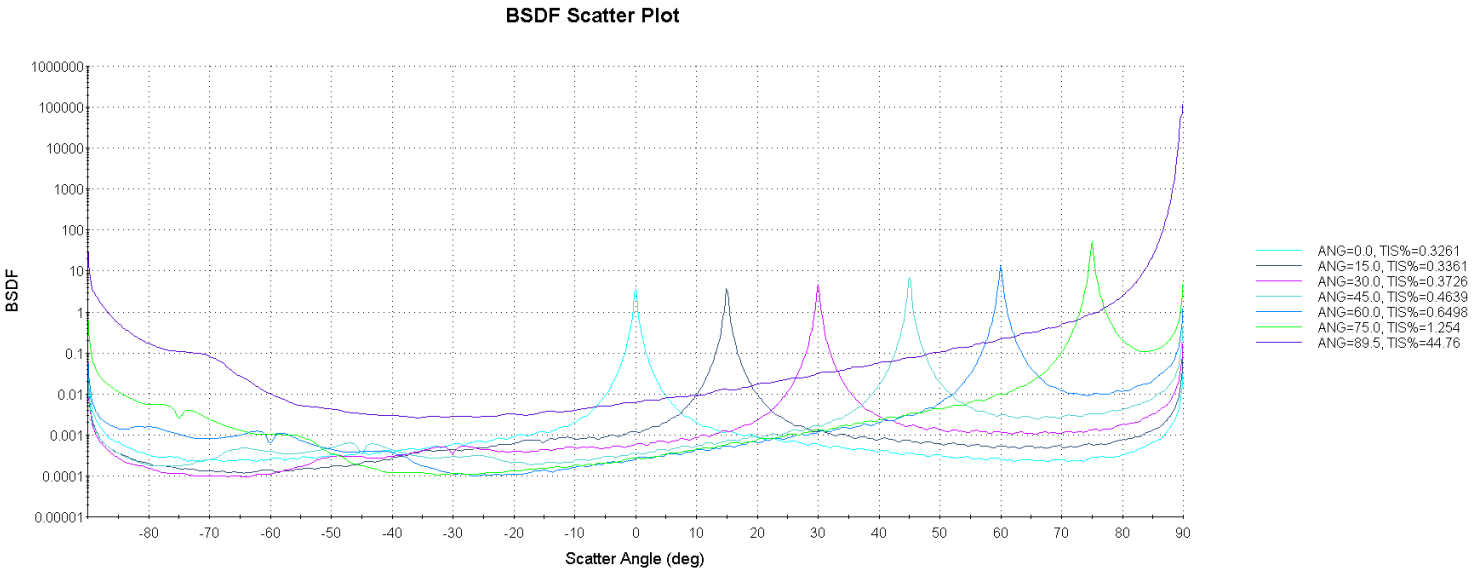
Scatter model

Mirror 30Å Surface Roughness

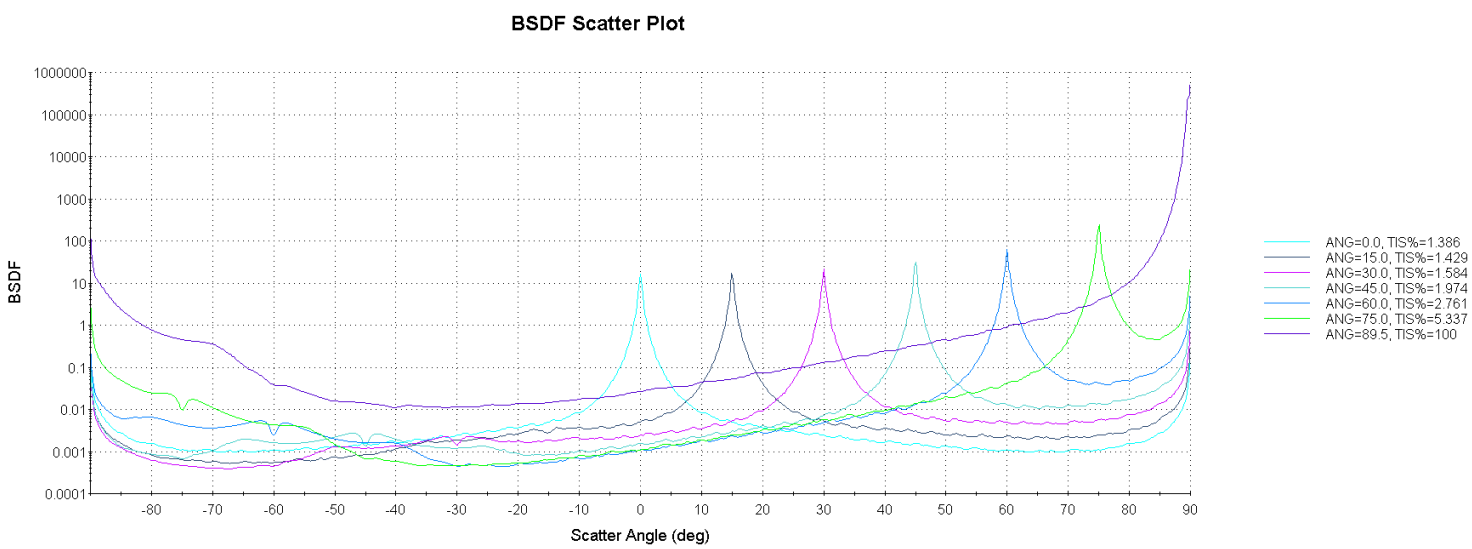


Scatter model

Mirror Particulates CL450

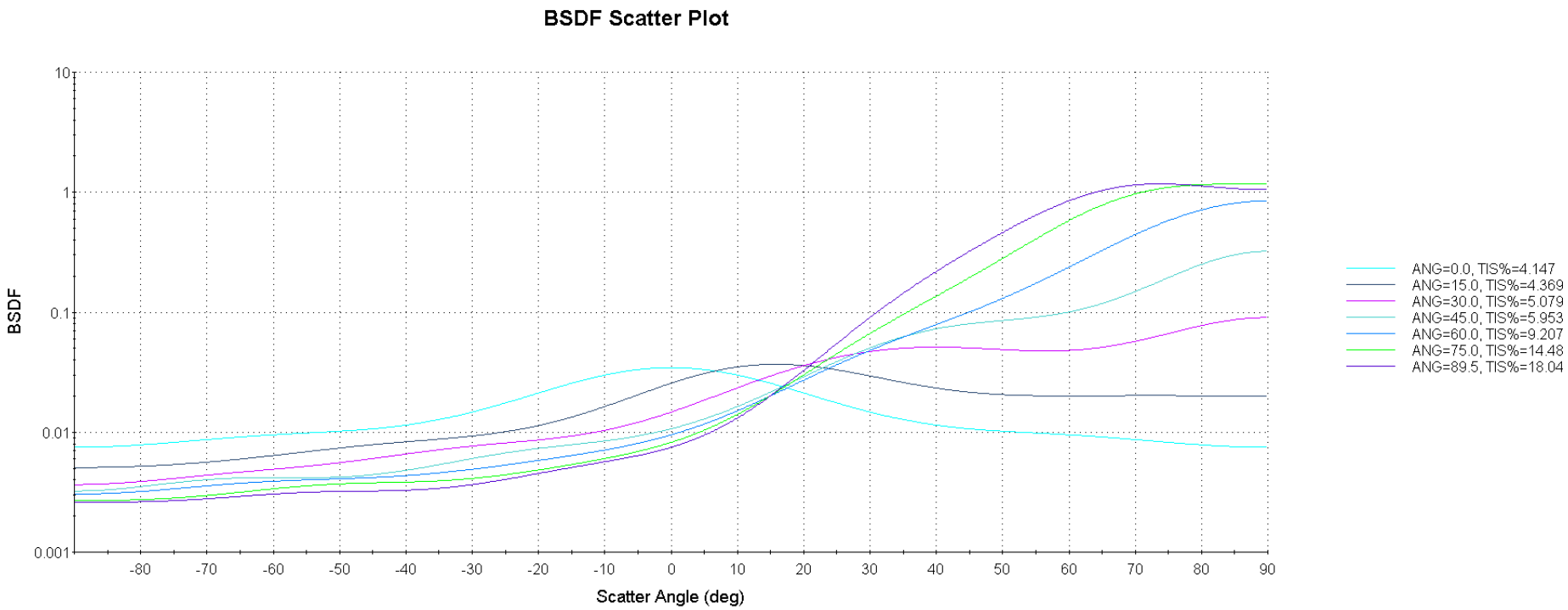


Mirror Particulates CL600

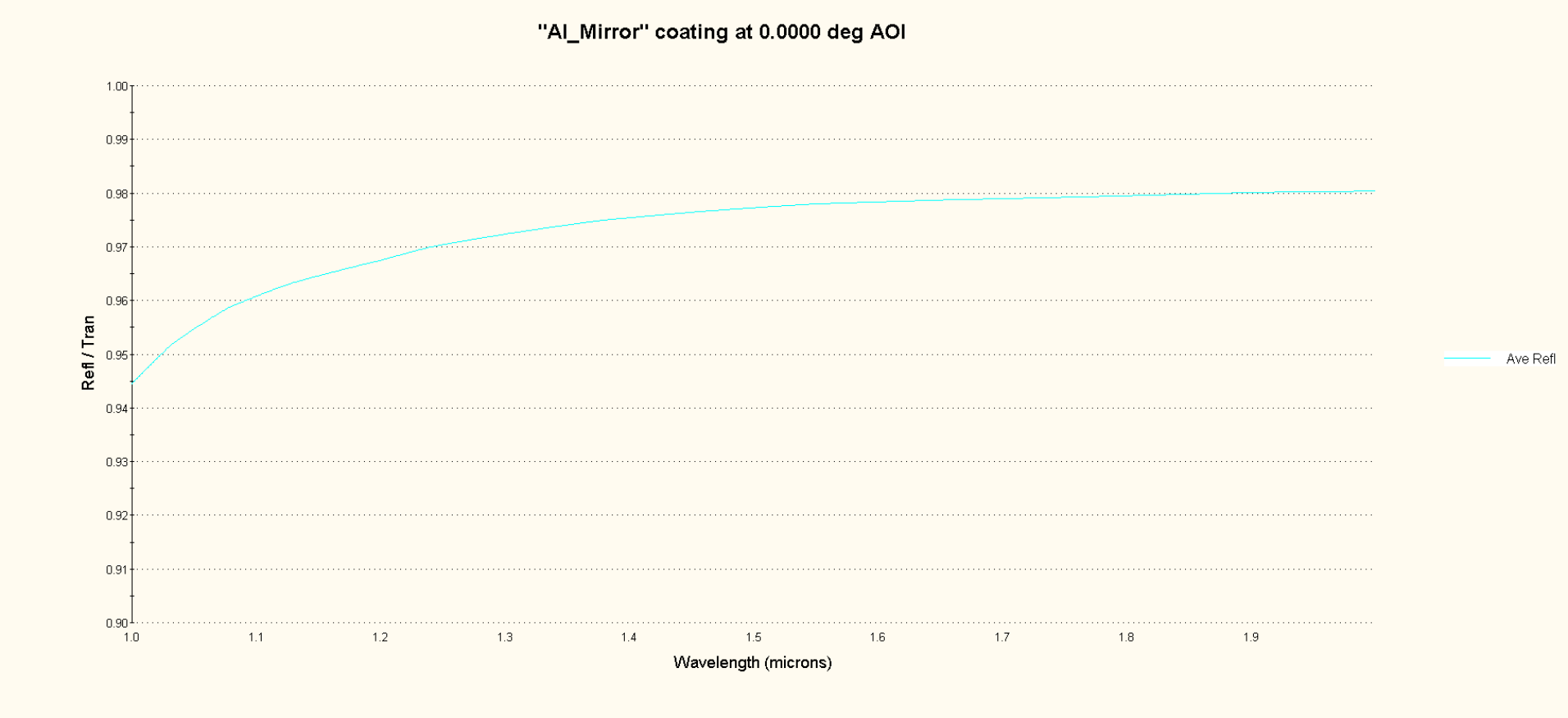


Scatter model

Z306 Diffuse Black Paint



Bare Al Coating (Mirror) - Reflectivity

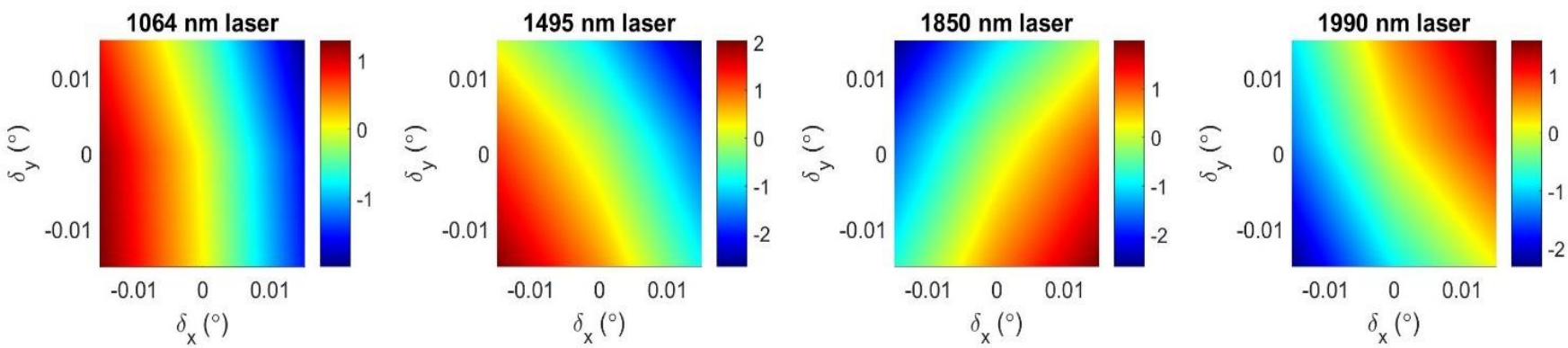


Systematic errors due to pointing instabilities

$$P_{detected,\lambda} = P_{emitted,\lambda} \times R_\lambda \times \int \mathrm{PST}_\lambda(\theta_x - \delta_x, \theta_y - \delta_y)\mathrm{LDP}_\lambda(\theta_x, \theta_y)\mathrm{d}\theta_x d\theta_y$$

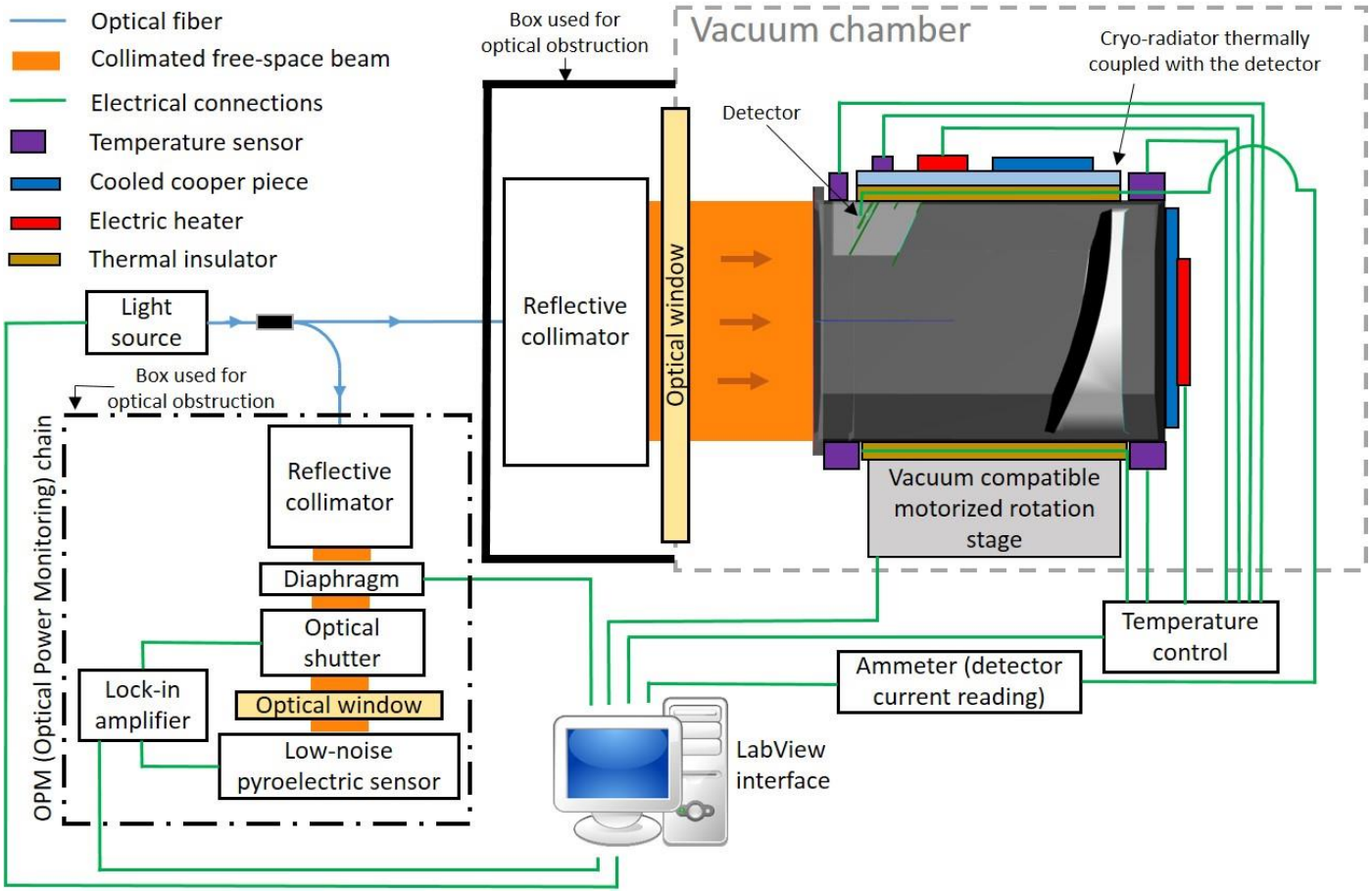
$$SE(\%) = \frac{\int \mathrm{PST}_\lambda(\theta_x, \theta_y)\mathrm{LDP}_\lambda(\theta_x, \theta_y)\mathrm{d}\theta_x d\theta_y - \int \mathrm{PST}_\lambda(\theta_x - \delta_x, \theta_y - \delta_y)\mathrm{LDP}_\lambda(\theta_x, \theta_y)\mathrm{d}\theta_x d\theta_y}{\int \mathrm{PST}_\lambda(\theta_x, \theta_y)\mathrm{LDP}_\lambda(\theta_x, \theta_y)\mathrm{d}\theta_x d\theta_y} \times 100$$

$$\Delta = max\left[\left|\frac{\int \mathrm{PST}_\lambda(\theta_x, \theta_y)\mathrm{LDP}_\lambda(\theta_x, \theta_y)\mathrm{d}\theta_x d\theta_y - \int \mathrm{PST}_\lambda(\theta_x - \delta_x, \theta_y - \delta_y)\mathrm{LDP}_\lambda(\theta_x, \theta_y)\mathrm{d}\theta_x d\theta_y}{\int \mathrm{PST}_\lambda(\theta_x, \theta_y)\mathrm{LDP}_\lambda(\theta_x, \theta_y)\mathrm{d}\theta_x d\theta_y} \times 100\right|\right]_{\forall \sqrt{\delta_x^2+\delta_y^2} \leq AS}$$



Characterization and Calibration

- PST VS incidence angles, detector temperature and receiver structure temperature
- Receiver responsivity VS wavelength, detector temperature and receiver structure temperature
- Detector bias current VS detector temperature and receiver structure temperature



Characterization/calibration conditions :

- Optical input power the range: [0.5, 50] nW
- Operating temperature range of the detector: [-165,-41] °C
- Operating temperature range of the receiver structure: [-65,7] °C
- Vacuum of 10-5 Torr