Assessing Bias in Lunar Irradiance Model Outputs Using Nighttime Aerosol Optical Depth Retrievals

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Lunar Calibration Basics

The lunar surface is an ultra-stable diffuse reflector of sunlight
- the Moon target is available for viewing by all Earth orbiting satellites
- no intervening atmosphere when viewed from orbit

The Moon's observed brightness is continuously changing
- phase angle dependence and non-Lambertian reflectance

Requires using a model for the calibration reference
- to generate the lunar brightness for any observation conditions
- the lunar surface reflectance is invariant to 10^{-8}/year
- stability means a lunar reflectance model can achieve sub-tenths percent uncertainty

The most common lunar calibration quantity is spatially integrated spectral irradiance
- avoids the need to spatially co-register Moon images with the reference (model)
- used in development of the original lunar calibration system: ROLO, ca. 2003
- other, more recently developed models: LIME (ESA), SLIM (H. Kieffer), Miller-Turner

There is a recognized need to improve the absolute accuracy of the lunar irradiance reference

- Current ROLO model has estimated 5−10% uncertainty
  - known low bias in irradiance outputs, wavelength dependent
- New measurements are needed to specify the absolute lunar irradiance scale

<u>Characteristics of new lunar irradiance measurements</u>

- high accuracy, with SI traceability
- spectrally resolved
- ample coverage of phase angles and lunar librations
- fiducial reference measurements (e.g. air-LUSI)

Capabilities enabled by high-accuracy lunar calibration

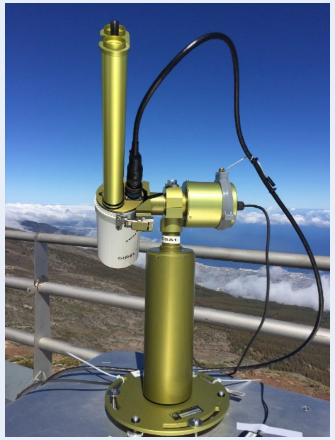
- transfer of pre-launch calibration to on-orbit operations
- additional opportunities for lunar views; reduced time for calibration convergence
- bridging a gap in an otherwise continuous observation record
- *application to satellite constellations*

Ground-based application — aerosol optical depth retrievals at night

Beer's Law for atmospheric extinction:

$$I_{\text{meas}} = I_0\, e^{-\tau\, m}$$

I_{meas} = measured solar/lunar irradiance
I_0 = exo-atmospheric solar/lunar irradiance
τ = atmospheric optical depth
m = airmass



Decomposed form for AOD retrievals:

$$\ln\left(\frac{I_{\text{meas}}}{I_0}\right) + \tau_{\text{ray}}\, m + \tau_{O_3}\, m_{O_3} = -m\, \tau_{\text{AOD}}$$

τ_{ray} = Rayleigh scattering optical depth
τ_{O_3} = ozone optical depth
m_{O_3} = ozone airmass
τ_{AOD} = aerosol optical depth

For nighttime retrievals, variations in I_0 with time (phase angle and distance) need to be accounted

- exactly the quantity generated by the ROLO lunar irradiance model.

Given acquisitions over a range of airmasses, Langley analysis can produce ground-based measurements of exo-atmospheric irradiance (solar or lunar).

PMOD Precision Filter Radiometer description

- **Filter radiometer with 4 channels in a 2x2 grid**

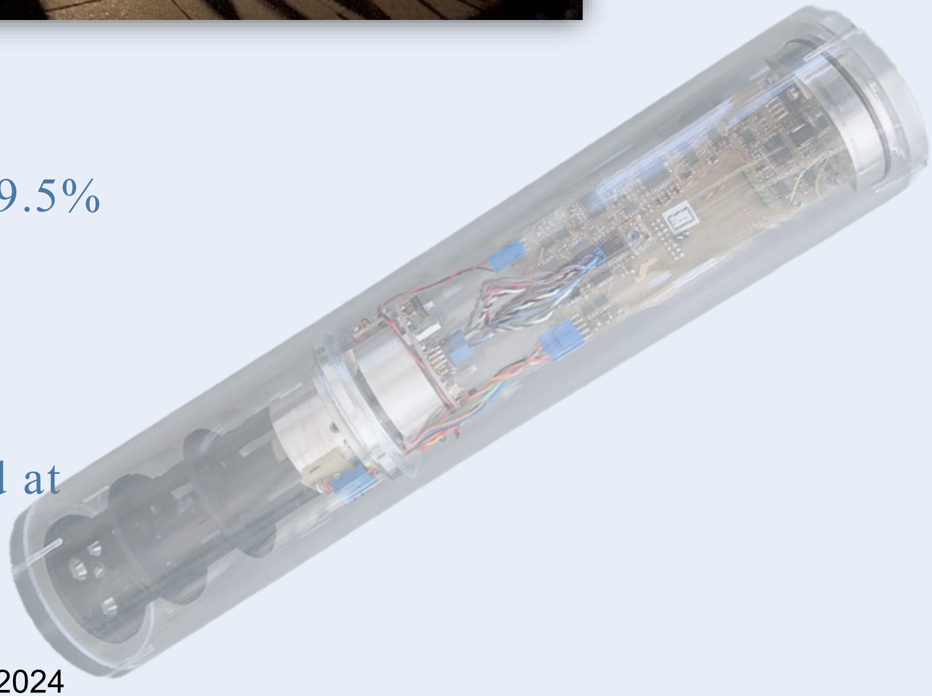
Interference filters :

Lunar version: 412 nm , 500 nm, 675 nm, 862 nm

FWHM: ~5 nm

Optimized for Direct Irradiance Measurements

- **Reference Plane: the precision aperture**
- **Temperature stabilized photodiodes**
- **Purged with nitrogen**
- **FOV: 1.2° plateau** , 0.7° slope angle, homogeneity in plateau > 99.5%
- The PFR signal (V) is provided by a 22-bit data acquisition system (SACRAM) specifically designed for the PFR.
- SACRAM Linearity checked against a reference source calibrated at Metas



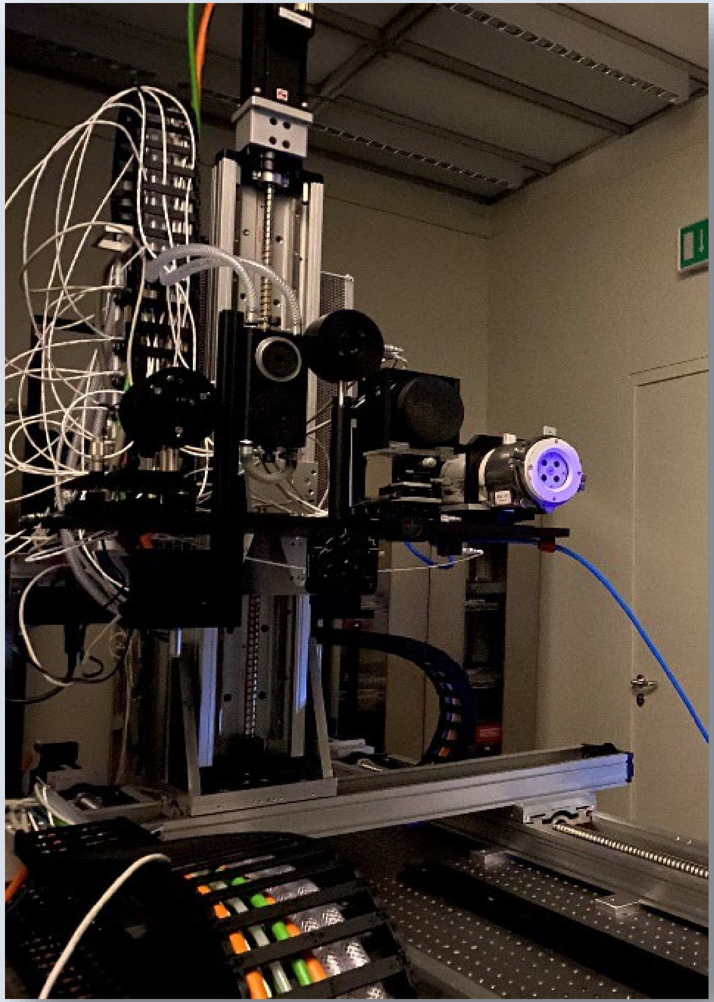
Lunar-PFR Characterisation

TUnable Lasers In Photometry (TULIP) setup at PTB

- ps-OPO system
- Fully automated system (230 nm to 2030 nm)
- Wavelength scale: Laser Spectrum analyser (LSA)
- Homogenized beam
- Reference detector: 3-element trap detector and equipped with a calibrated aperture, giving an uncertainty better than 0.1 %

Characterization Measurements

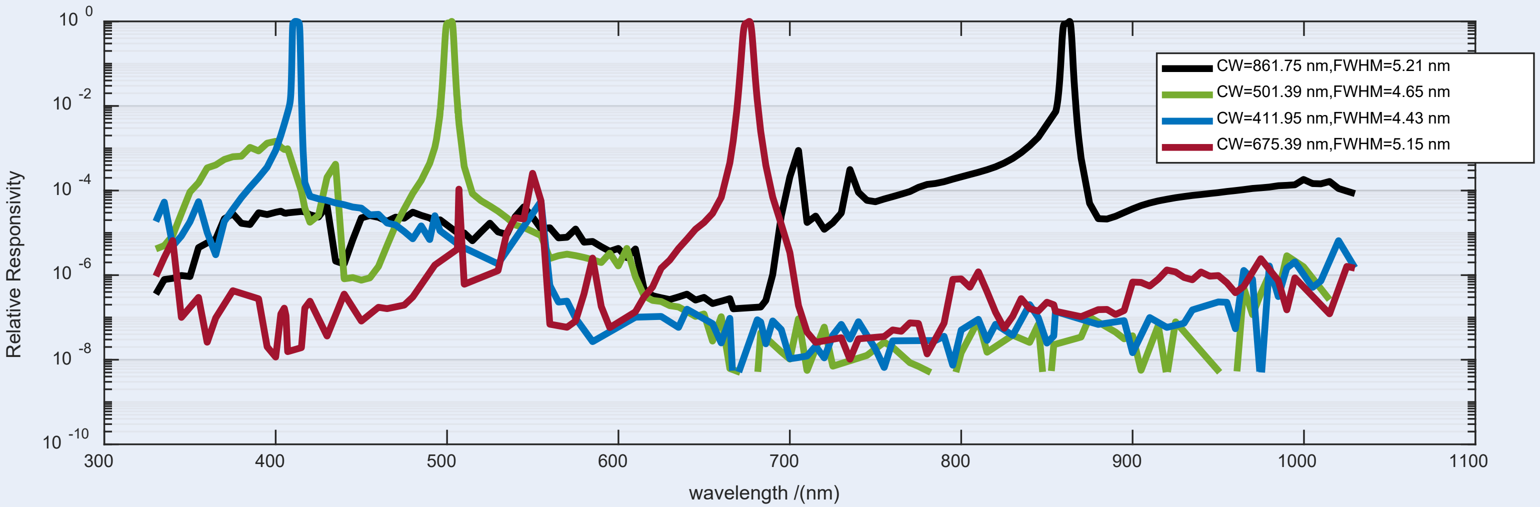
- Reference plane
- Spectral responsivity (s)
- PFR Gain



Lunar-PFR Characterisation

Spectral responsivity uncertainty < 0.3%

TULIP - 2021		
λ (nm)	*s* (μV.W^{-1}m^{2})	U_s (%,k=2)
861.75	12.96	0.26
501.39	9.78	0.25
411.95	10.88	0.27
675.39	6.80	0.18



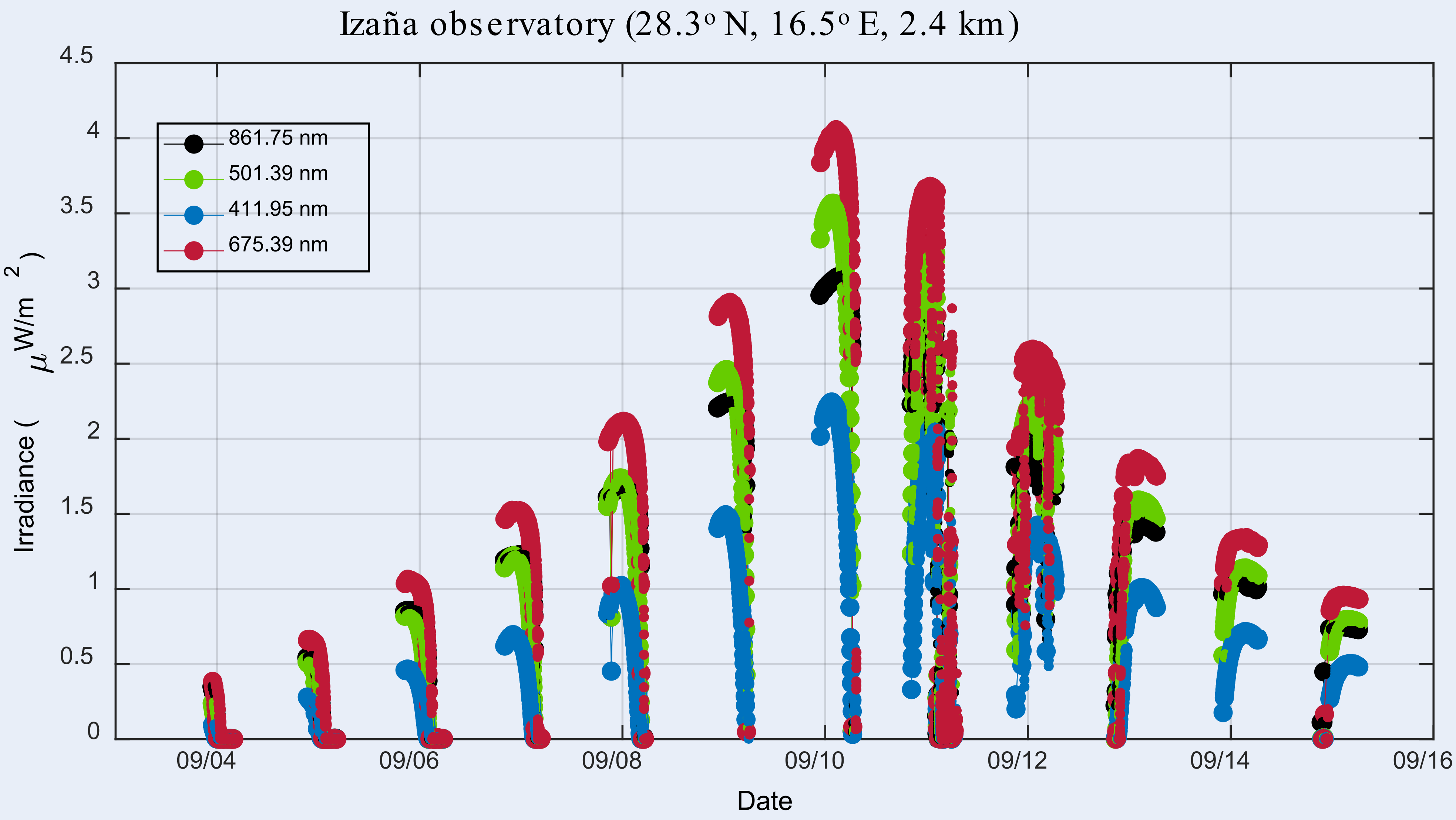
Uncertainty components

- spectral power responsivity of the trap detector: current measurements, aperture area, temporal stability and the homogeneity of the laser irradiance field
- Field of view of the PFR and of the trap detector,
- laser wavelength,
- positioning of the detectors,
- electronic noise of the PFR

Gain uncertainty 0.3%

Gain	TULIP 2021 *U*=0.3%
Laboratory: 0	1.0
1	934.6
2	4451.4
Lunar: 3	25164.0

Lunar Photometry Campaign — September 2022

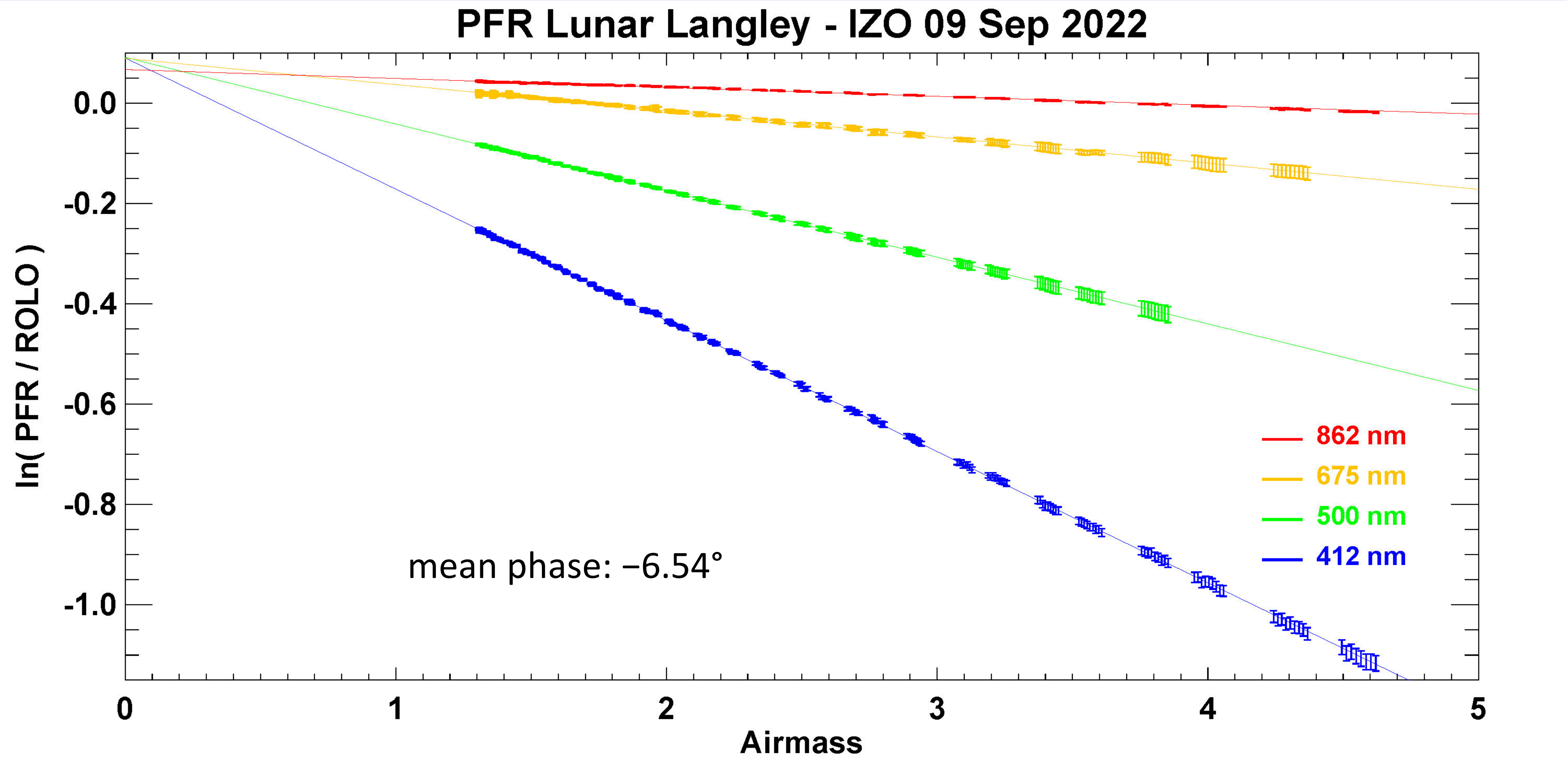


USGS pmod wrc PTB

Lunar Langley analysis

$$\ln\left(\frac{I_{\mathrm{PFR}} \pm \epsilon}{I_{\mathrm{ROLO}}}\right) = -\tau_{\mathrm{atm}}\, m + c$$

Izaña Observatory (IZO): 28.3° N 16.5° W 2401 m.a.s.l.



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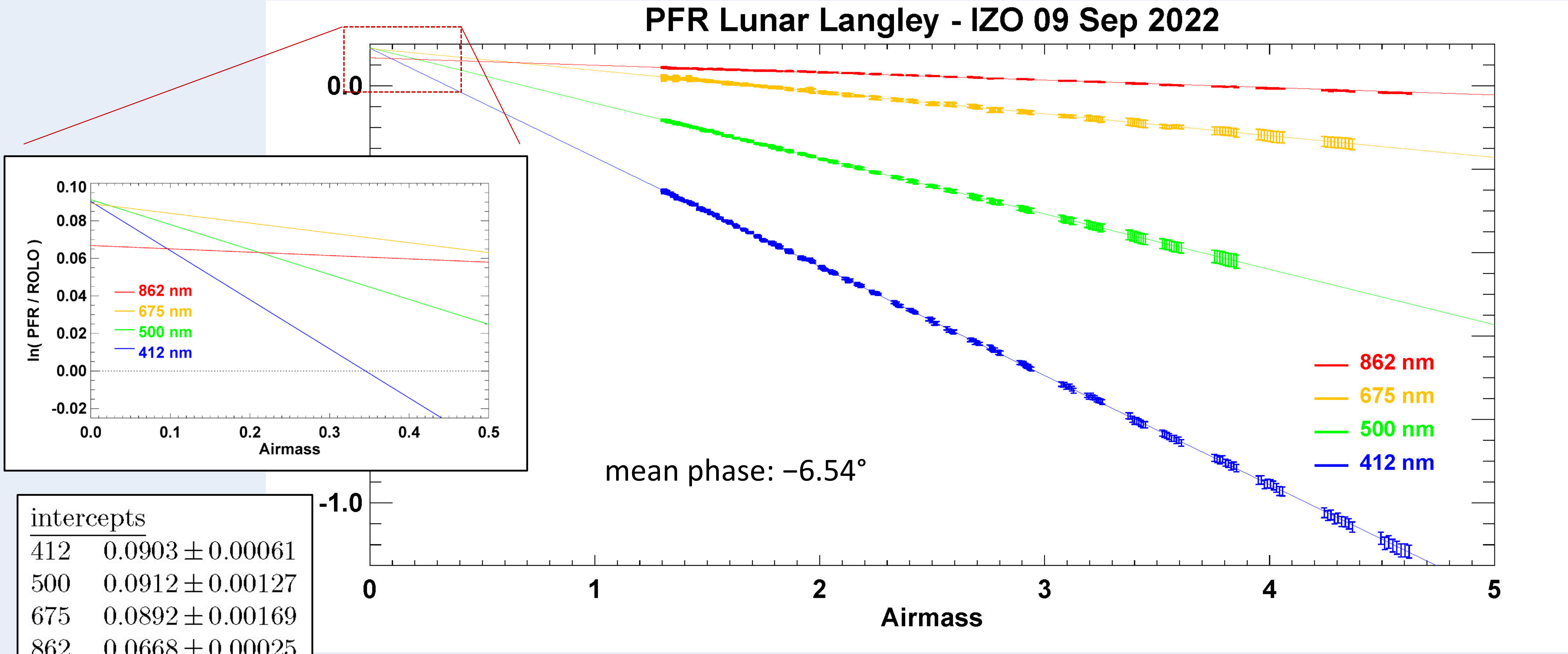


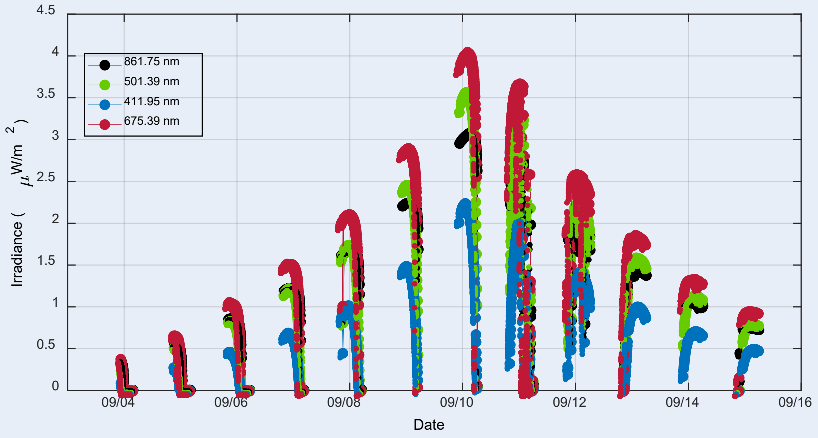
intercepts	
412	0.0903 ± 0.00061
500	0.0912 ± 0.00127
675	0.0892 ± 0.00169
862	0.0668 ± 0.00025

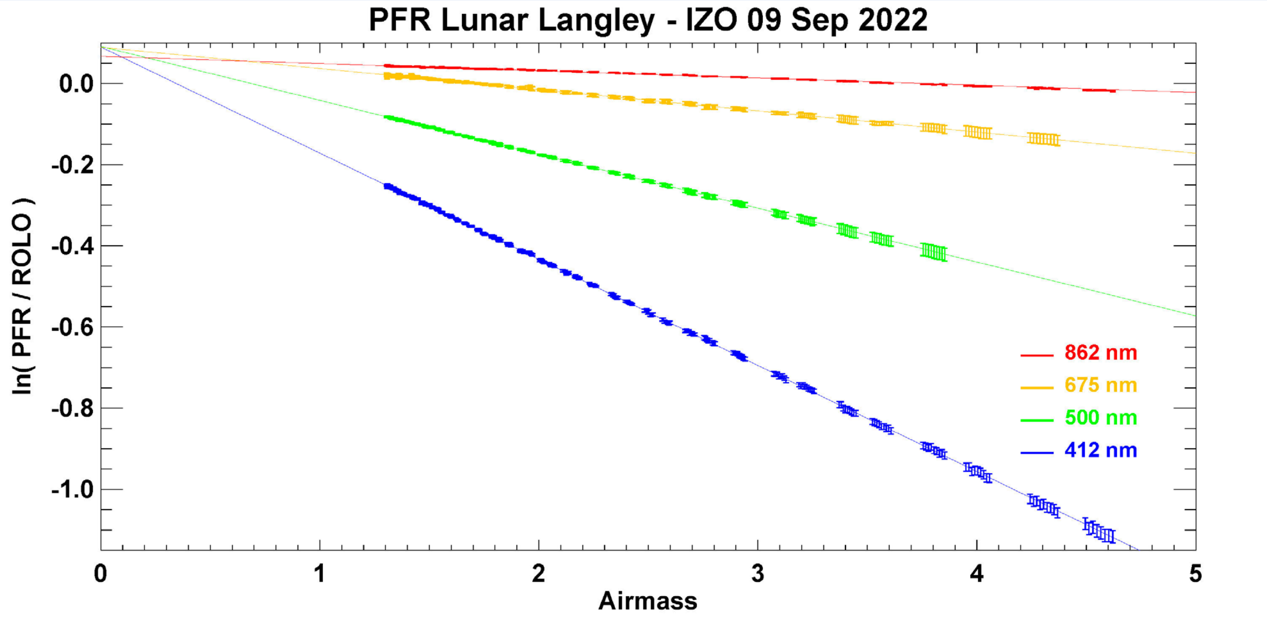
Remarks on the aerosol photometry application

Nighttime AOD retrievals are derived at each measured point.

- retrievals are very sensitive to bias in the lunar model results
- AOD processing requires corrections to the model outputs, equivalent to forcing the Langley intercepts to 0.0
- corrections are validated by continuity with daytime AODs

The photometry application highlights the need to improve the accuracy of lunar irradiance models.





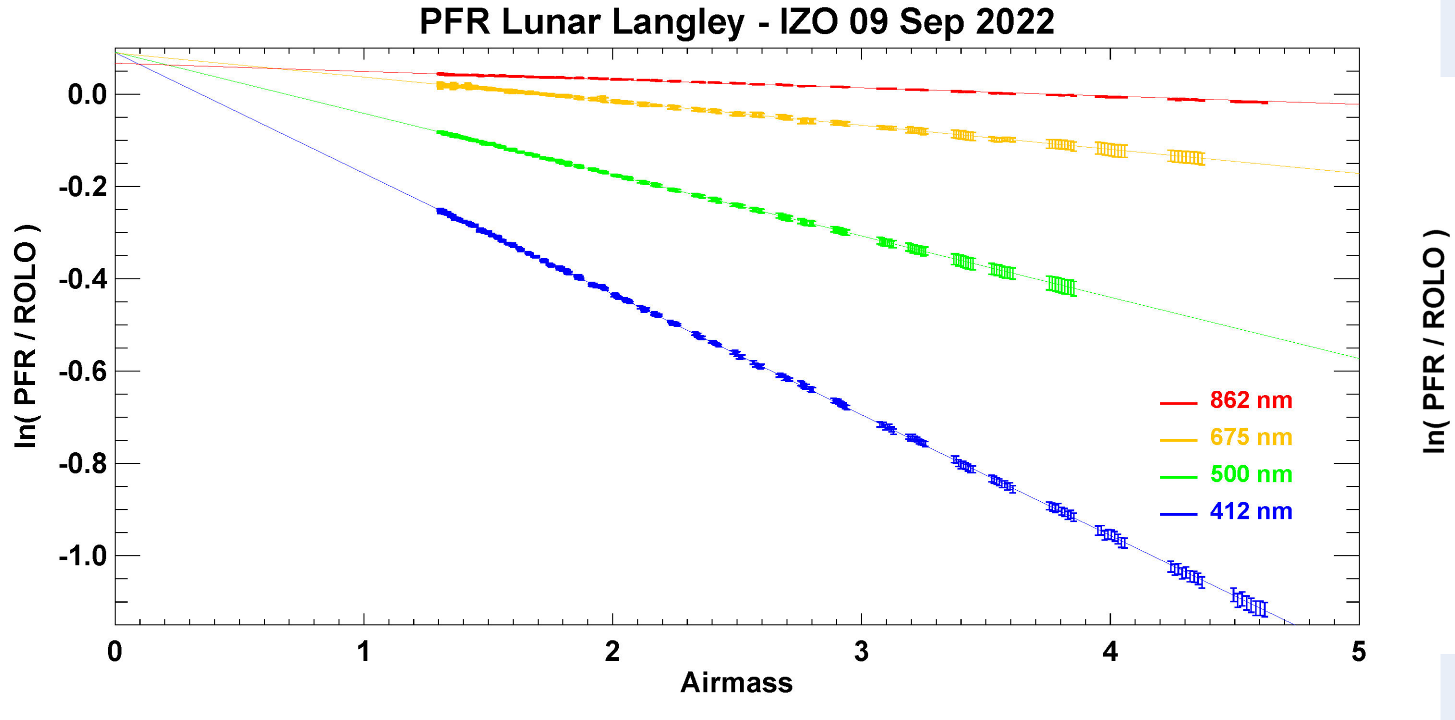
Remarks on the Langley analysis

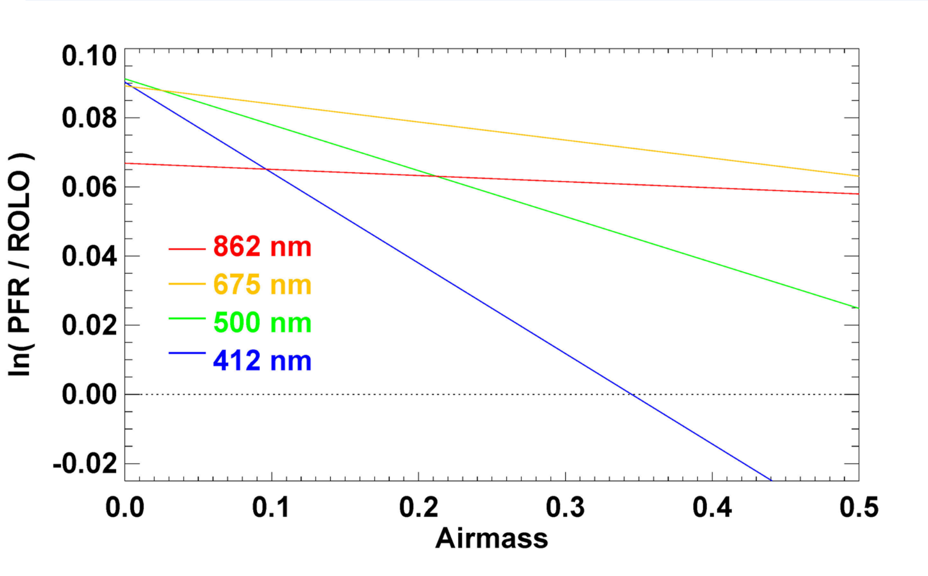
Linear regressions show remarkably good fits

- validates the measurement uncertainties and the relative accuracy of ROLO model outputs
- indicative of high-quality observing conditions at the Izaña site

Other Langley plots show consistent intercepts over the phase range of the Sept 2022 campaign

- the intercepts give an estimate of bias in the ROLO model





Summary and Conclusions

Improving the accuracy of the lunar calibration reference is a recognized need

- using the Moon as a common calibration target has important implications for inter-calibration, particularly for satellite constellations

New lunar measurements are necessary to specify the absolute irradiance scale

- to overcome the limitations of existing datasets currently used as the basis for modeling

Ground-based lunar irradiance measurements have been acquired by the calibrated, stabilized Precision Filter Radiometer (PFR) of PMOD

- operated for measuring aerosol optical depth at night in 4 bands
  - this application is highly sensitive to bias in lunar model outputs

Langley analyses have provided an evaluation of ROLO model bias

- successful regressions validate the PFR calibration and the relative accuracy of ROLO outputs

Future work:

Lunar measurements with the PMOD QASUME (Quality Assurance of Spectral Ultraviolet Measurements in Europe) instrument

- Spectrally resolved lunar irradiance acquisitions and Langley analysis

Thank You!