Traceability of Lunar Direct Irradiance Measured with a Precision Filter Radiometer

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19ENV04 MAPP
Metrology for aerosol optical properties

EMPIR EURAMET
The EMPIR initiative is co-funded by the European Union's Horizon 2020 research and innovation programme and the EMPIR Participating States

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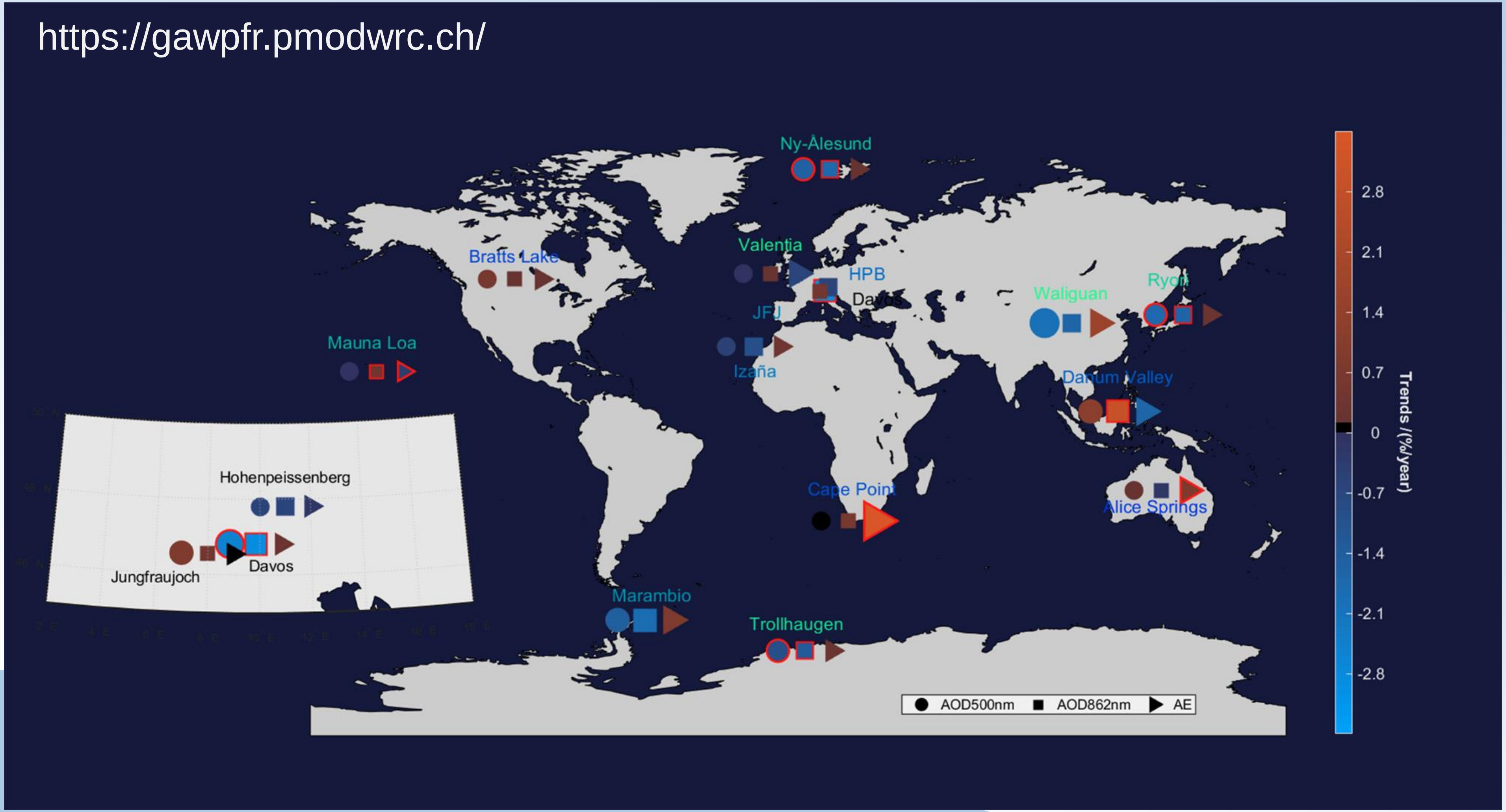
GAW-PFR network - AOD measurements

World aerosol **O**ptical depth **R**esearch and **C**alibration **C**enter (WORCC – PMOD/WRC)

- Maintain the WMO AOD Reference
- Monitor Aerosol Optical Depth (AOD) within the framework of Global Atmospheric Watch (GAW) of WMO in background stations



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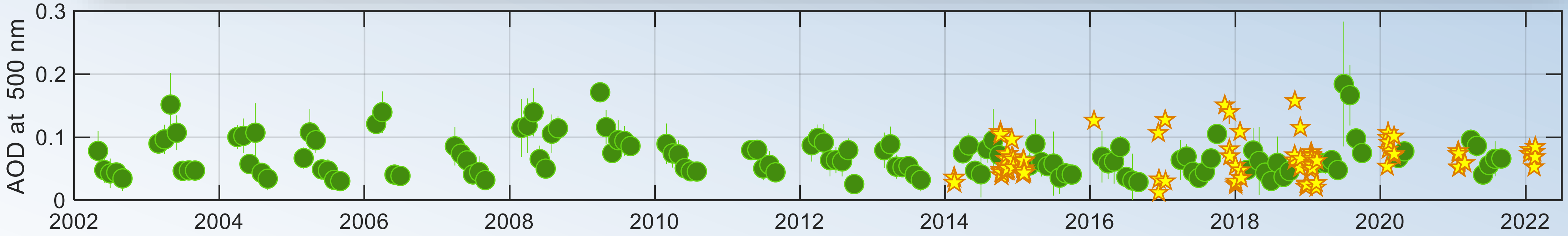
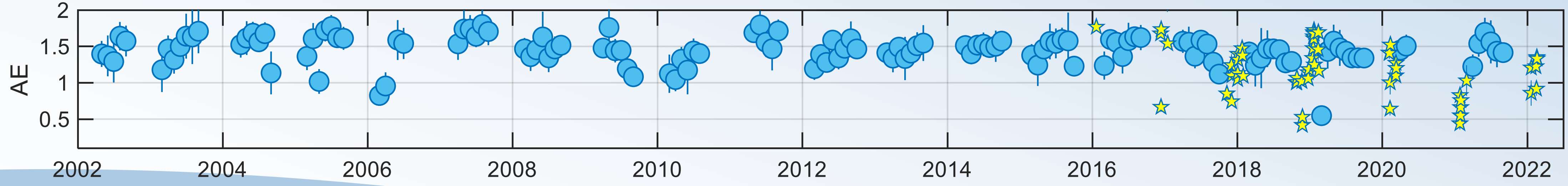
Motivation for nighttime AOD measurements

Arctic Haze - Ny-Ålesund





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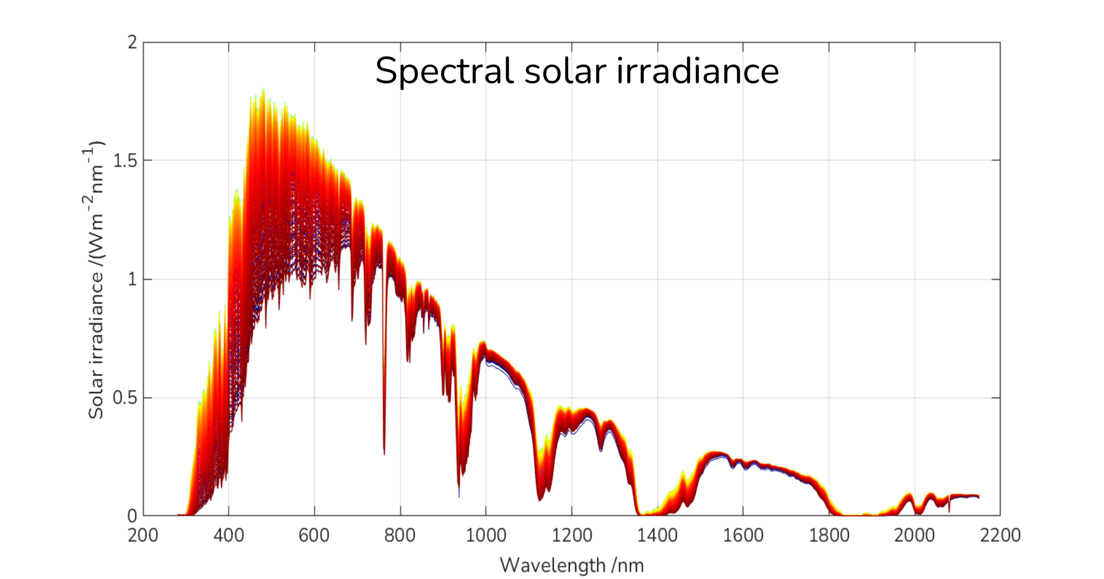
Top of Atmosphere Spectrum from surface direct solar/lunar irradiance measurements?

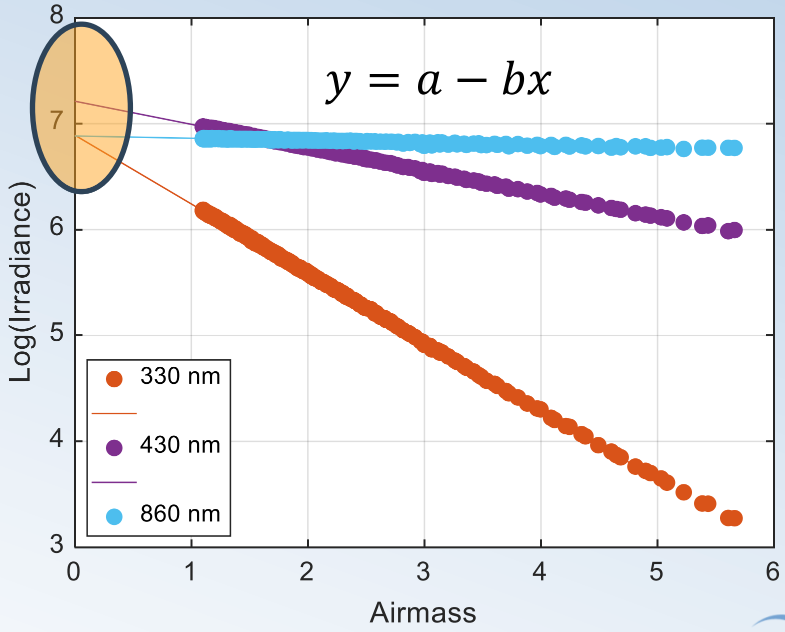


The Beer-Lambert Law $\boldsymbol{I(\lambda) = I_0(\lambda)e^{-\tau_\lambda m}}$

$$\log I(\lambda) = \log I_0(\lambda) - \tau_\lambda m$$

The optical depth constant during half-day (aerosols and trace gases)

The Langley-plot



The retrieved I_0(l) represent the solar spectrum at the top of the atmosphere and can be compared to space-based measurements from satellites (in certain spectral bands).

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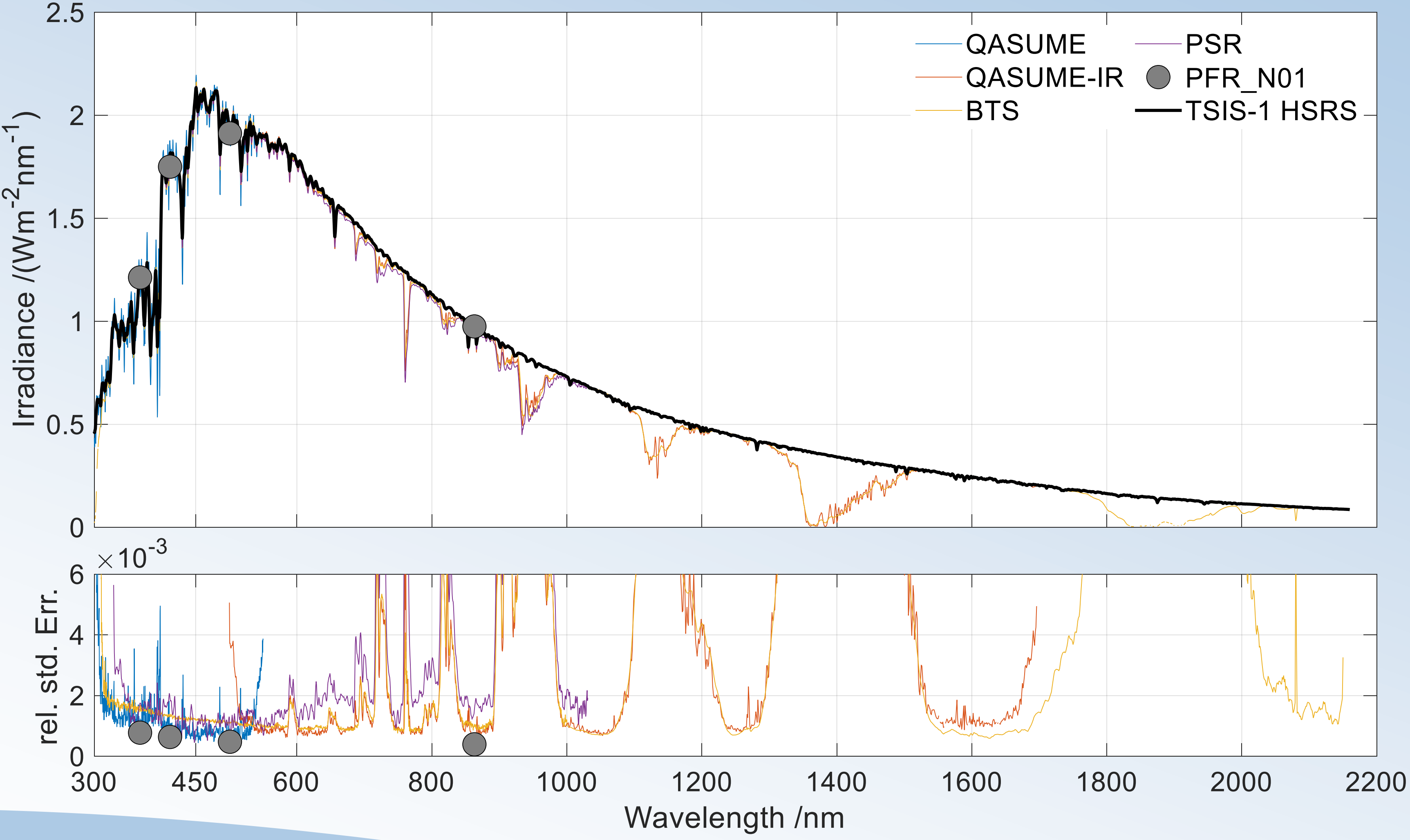
Top of Atmosphere solar spectra using Langley



PFR: Kouremeti et al., Metrologia, 2022
Spectroradiometers: Gröbner et al., AMT, 2023
QASUMEFTS ToA solar spectrum: Gröbner et al., AMT, 2017

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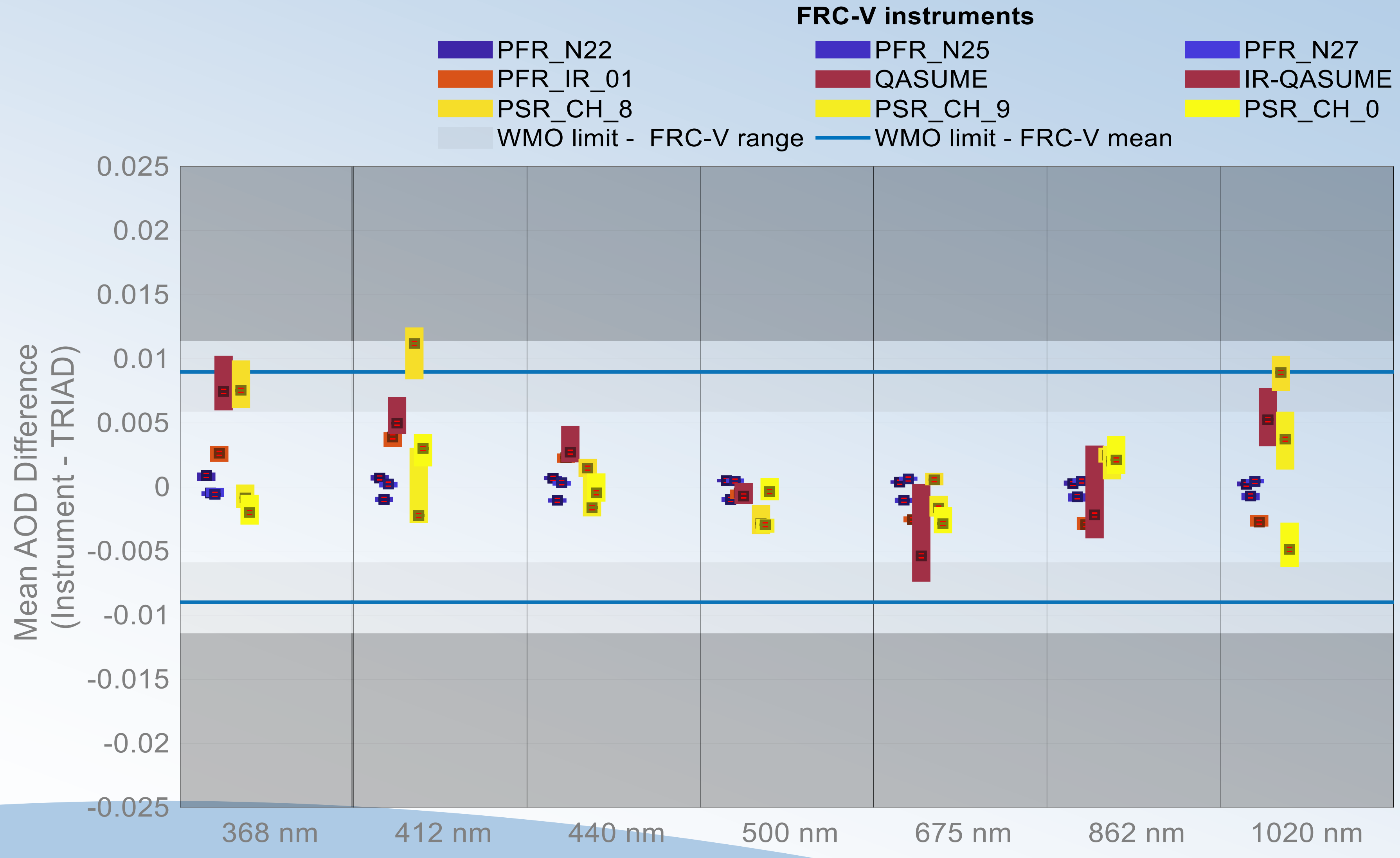
Comparison Campaign against the WMO AOD reference – FRC-V(Davos,2021)



Aerosol Optical Depth from SI-traceable direct solar spectral irradiance measurements

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Precision Filter Radiometers description

- Filter radiometer with 4 channels in a grid

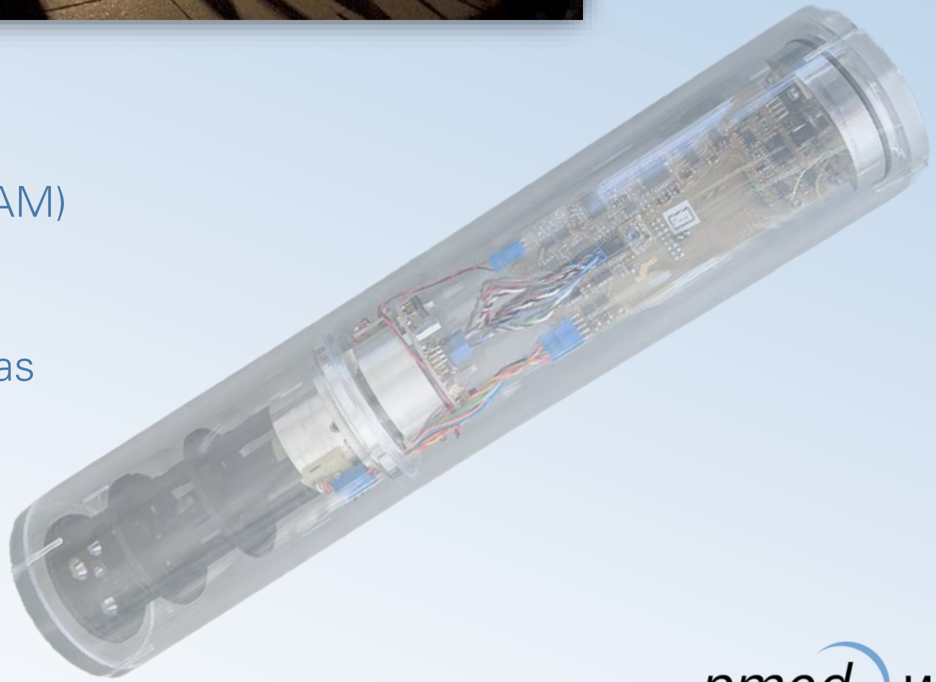
Interference filters :

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



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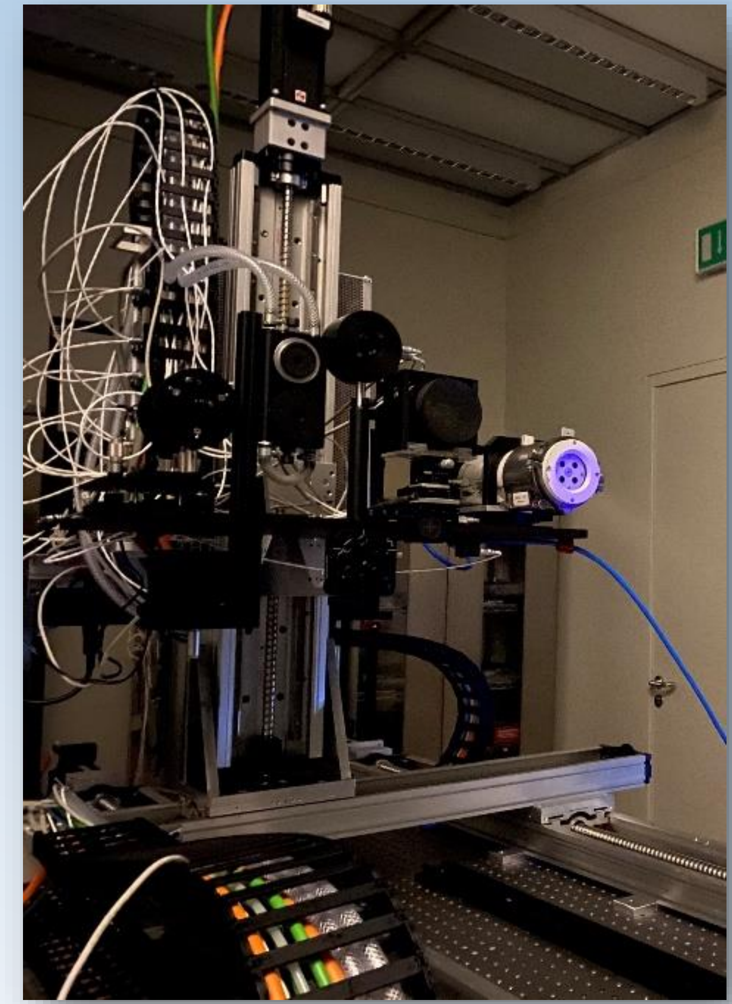
Lunar-PFR Characterisation

TUnable Lasers In Photometry (TULIP) setup

- 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

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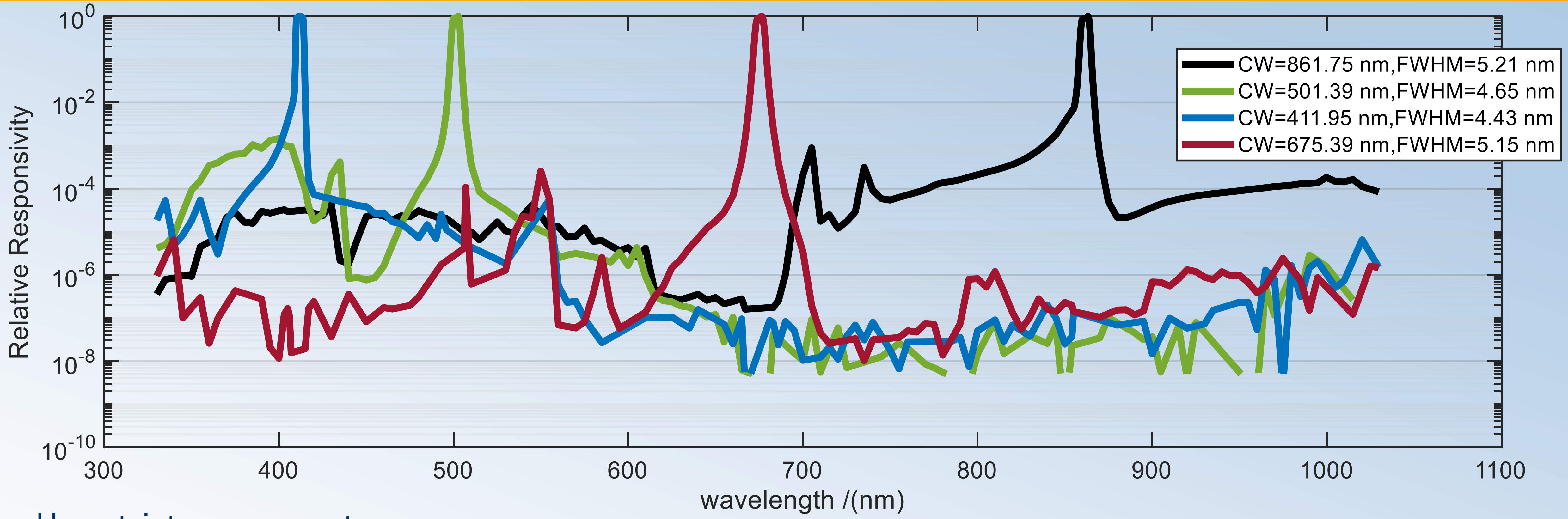
Lunar-PFR Characterisation



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

Combined uncertainty based on Montecarlo model

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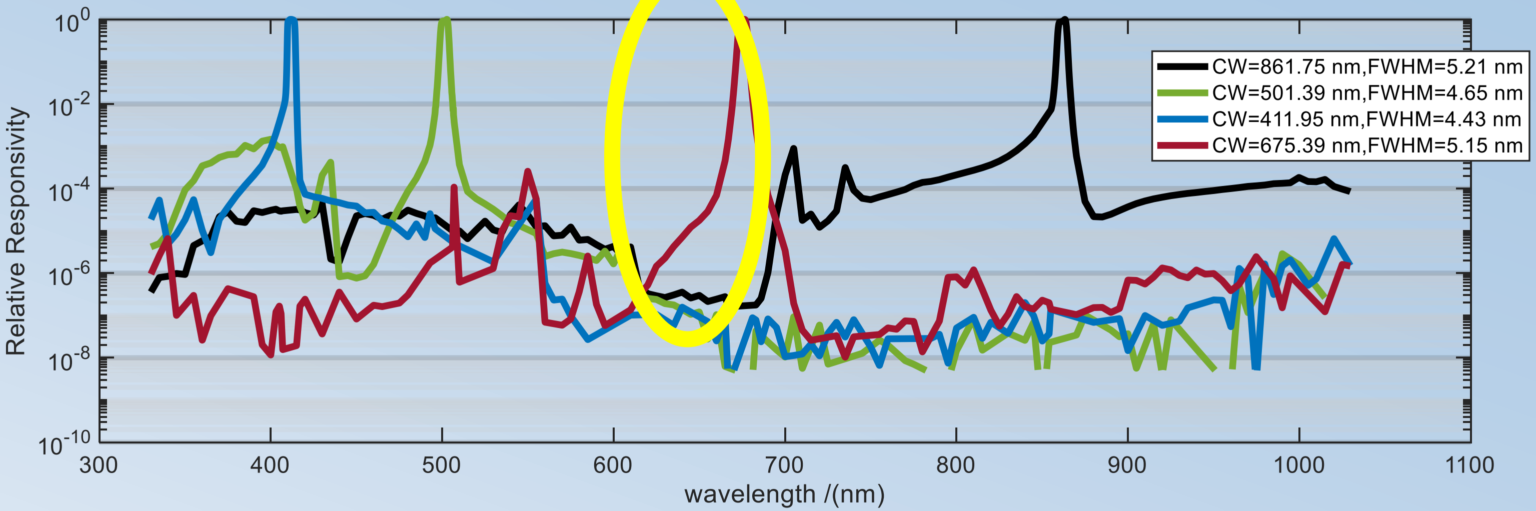
Lunar-PFR Characterisation

Spectral responsivity uncertainty < 0.3%

TULIP - 2021		
λ (nm)	s (μV.W⁻¹m²)	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

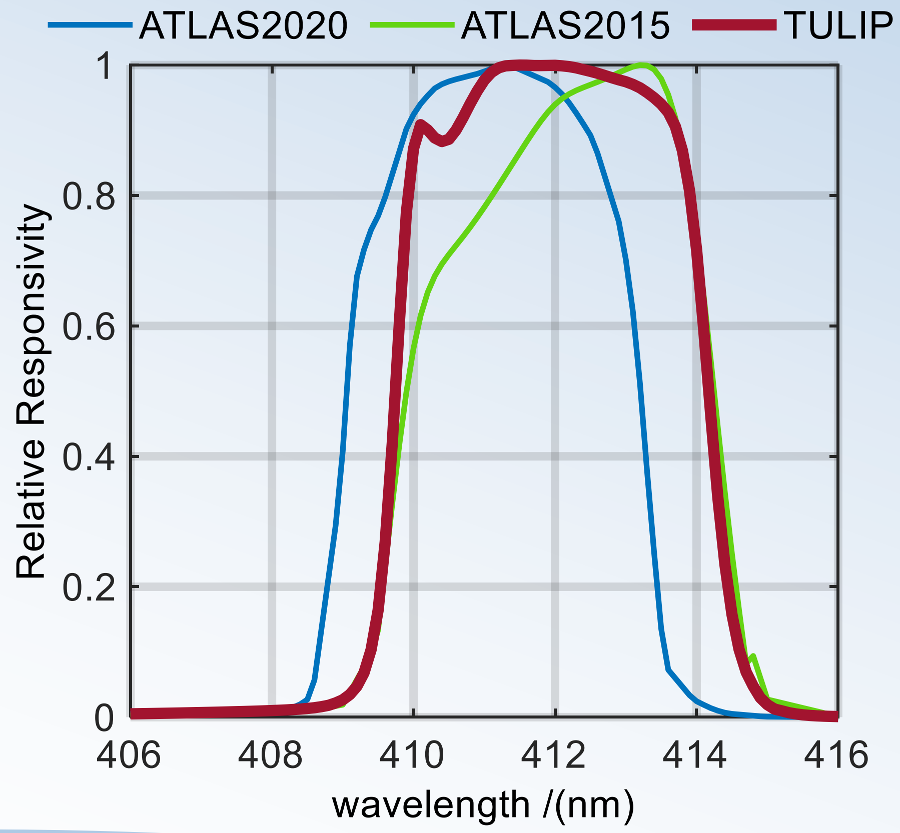


Gain uncertainty 0.3%

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

Lunar-PFR Characterisation : ATLAS (Pulsed) vs TULIP

- Non – linear response of the PFR to pulsed laser radiation
- The interference filters highly depend on the measuring geometry.



Relative responsivity of 412 nm channel retrieved from measurements at TULIP and ATLAS setups.
highest discrepancies

Spectral responsivity uncertainty reduced from 1.5% to 0.3%

TULIP - 2021			Differences to TULIP ATLAS-2020	
λ (nm)	*s* (W/m²)	U (%,k=2)	δλ (nm)	δ*s* (%)
861.75	12.96	0.26	**0.2**	**-1.4**
501.39	9.78	0.25	**1.1**	**0.8**
411.95	10.88	0.27	**0.8**	**5.1**
675.39	6.80	0.18	**0.1**	**-2.5**

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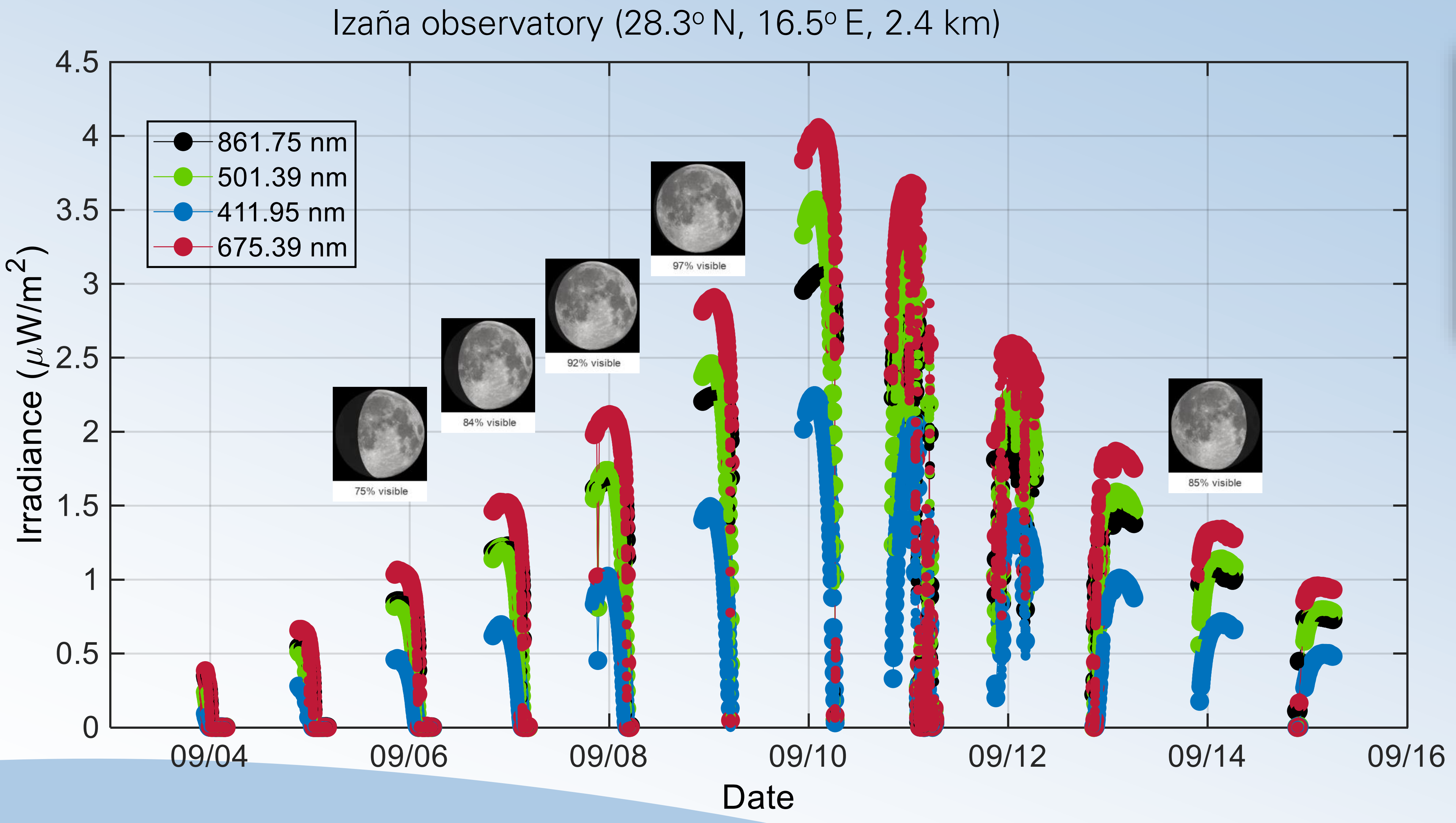
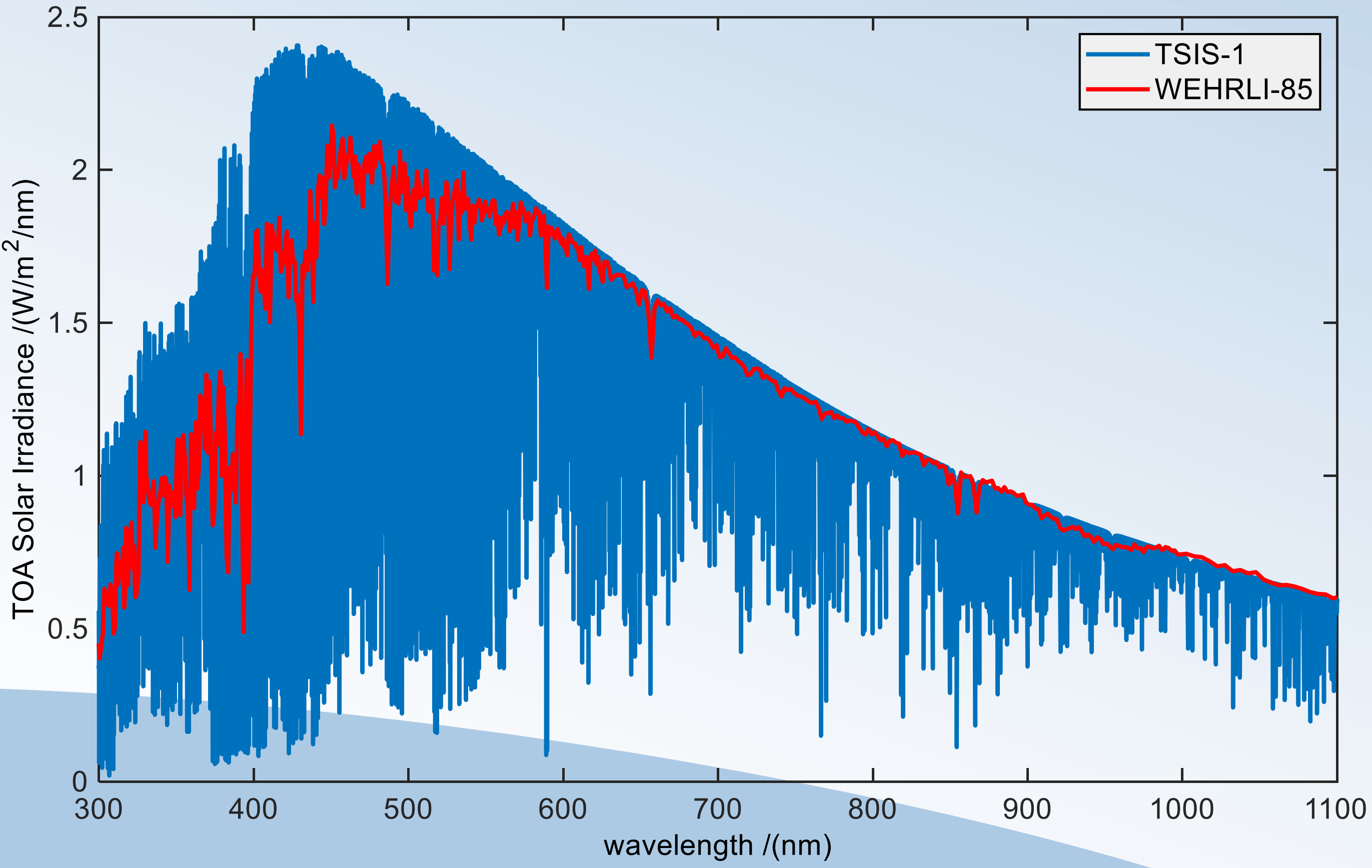
Top-Of-Atmosphere Lunar Irradiance



Top-Of-Atmosphere Lunar Irradiance Models

- **RIMO** (Barreto et al. , 2018) available online - spectral resolution 1 nm
- **ROLO** - provided by Tom Stone
  Accounting for the Relative spectral responsivity of Lunar PFR
  i. ROLO – TSIS-1 adjustment
  ii. ROLO* - (August 2023, under development)



	Difference WEHRLI & TSIS-1 (%)
862 nm	**1.52**
675 nm	**-0.24**
500 nm	**-2.17**
412 nm	**-2.24**

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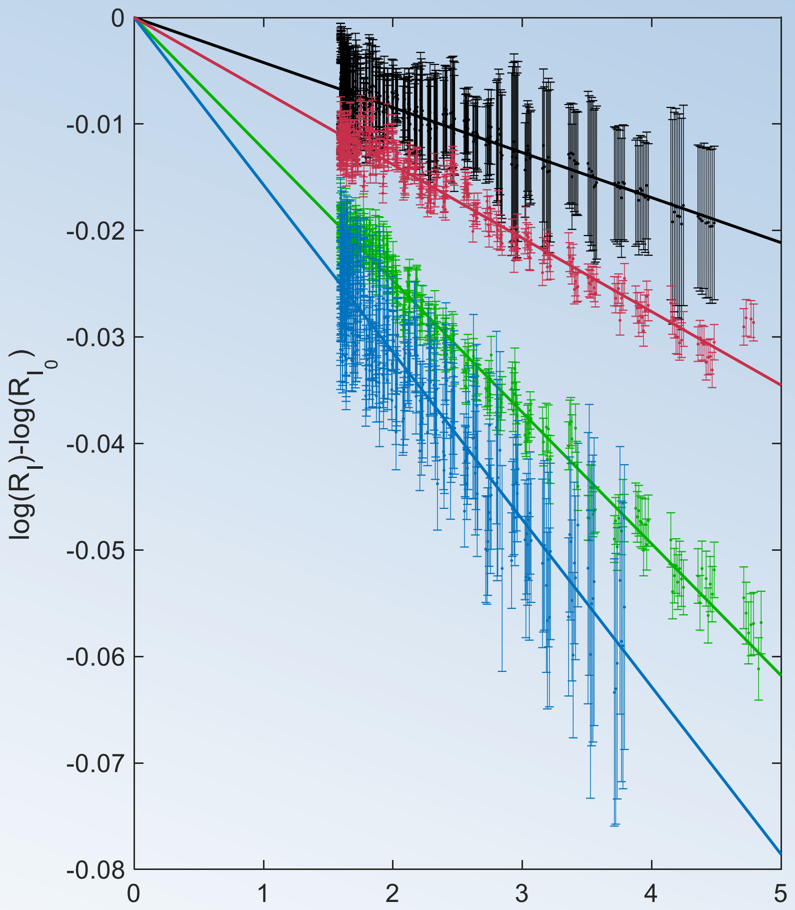
Top-Of-Atmosphere Lunar Irradiance

Component	Description	Type	Value
I_λ			
Signal Noise Atmospheric	Standard deviation of the 10 sequential measurements	A	
Dark Noise	Standard deviation of the day	A	
τ_{ray} - Pressure	Uncertainty of pressure measurement	B	3mbar
τ_{O3} Total column of ozone	Daily value of ozone measurement (OMI)	B	2%
τ_{O3} Ozone airmass	Height of ozone layer	B	3km
Airmass			
Equation	Comparison of ROLO and Lunar tracking algorithms	B	<0
Time	Measurement integration time 1s, all channels	B	0

$$\ln\left(\frac{I_{PFR}(\lambda,t)}{I_{Lunar\ Irradiance}(\lambda,t)}\right) + \tau_{ray} m + \tau_{O_3} m_{O_3} = -m\tau_{aod}$$



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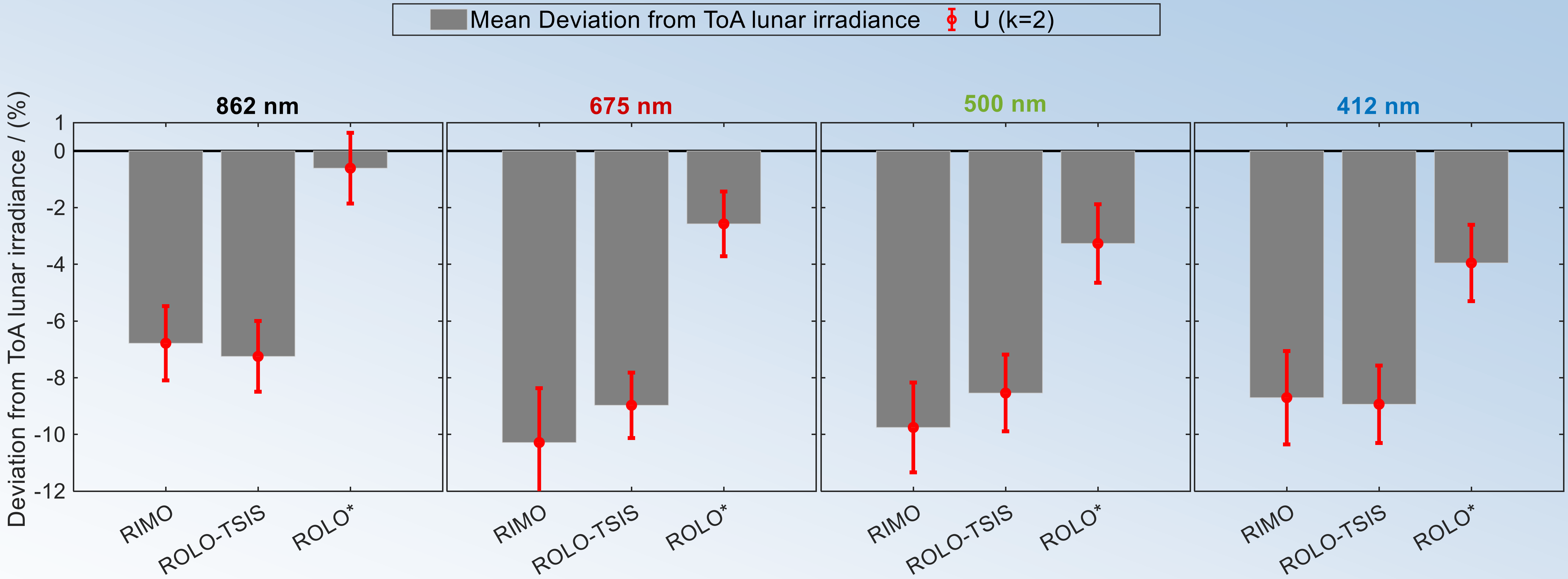

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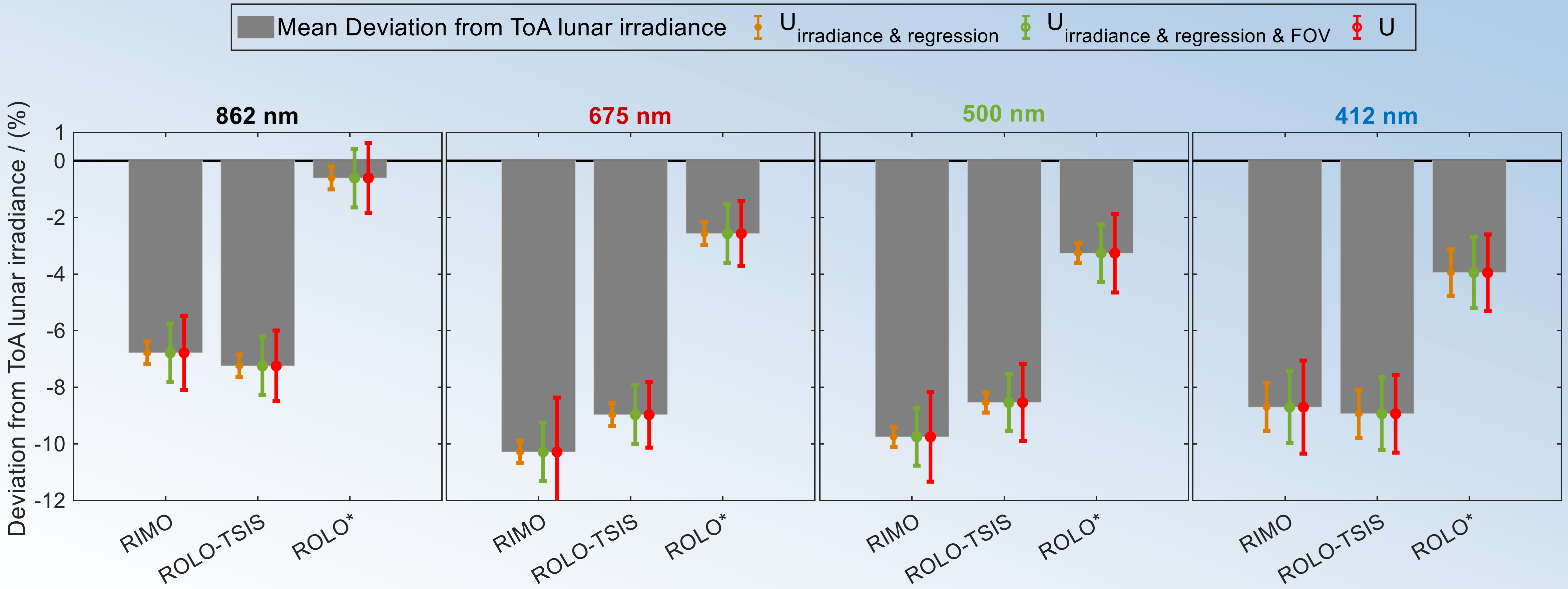

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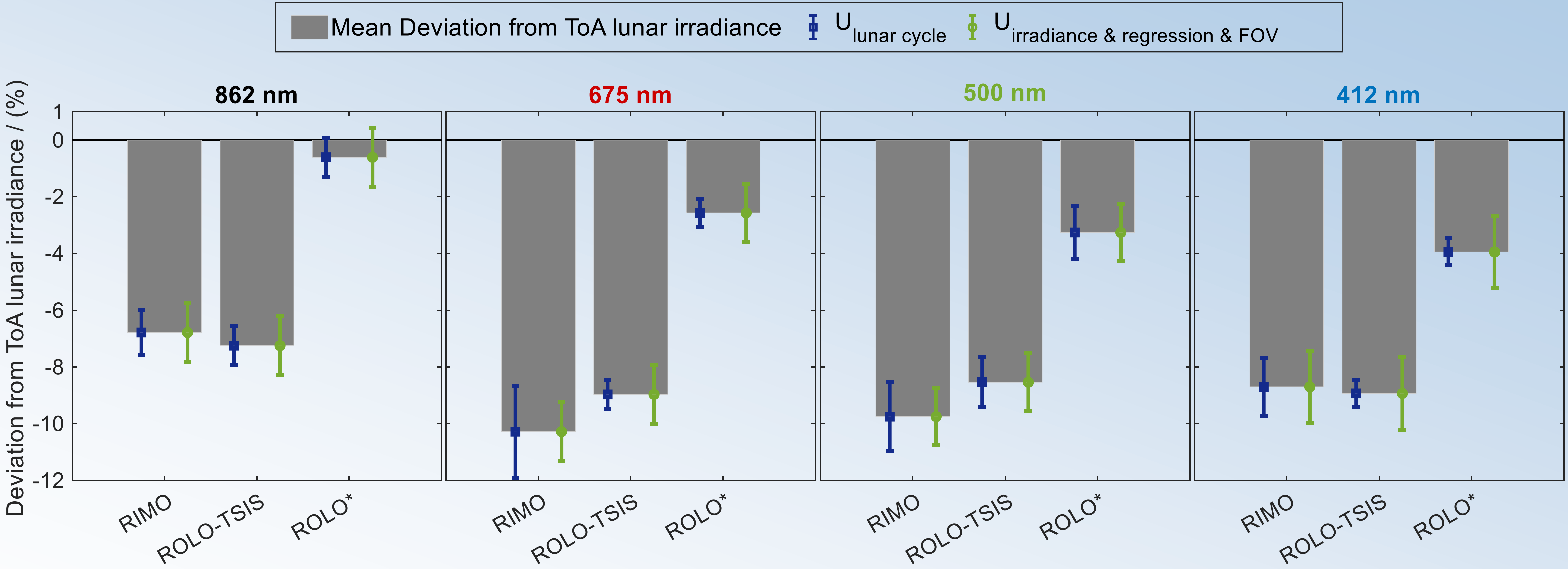

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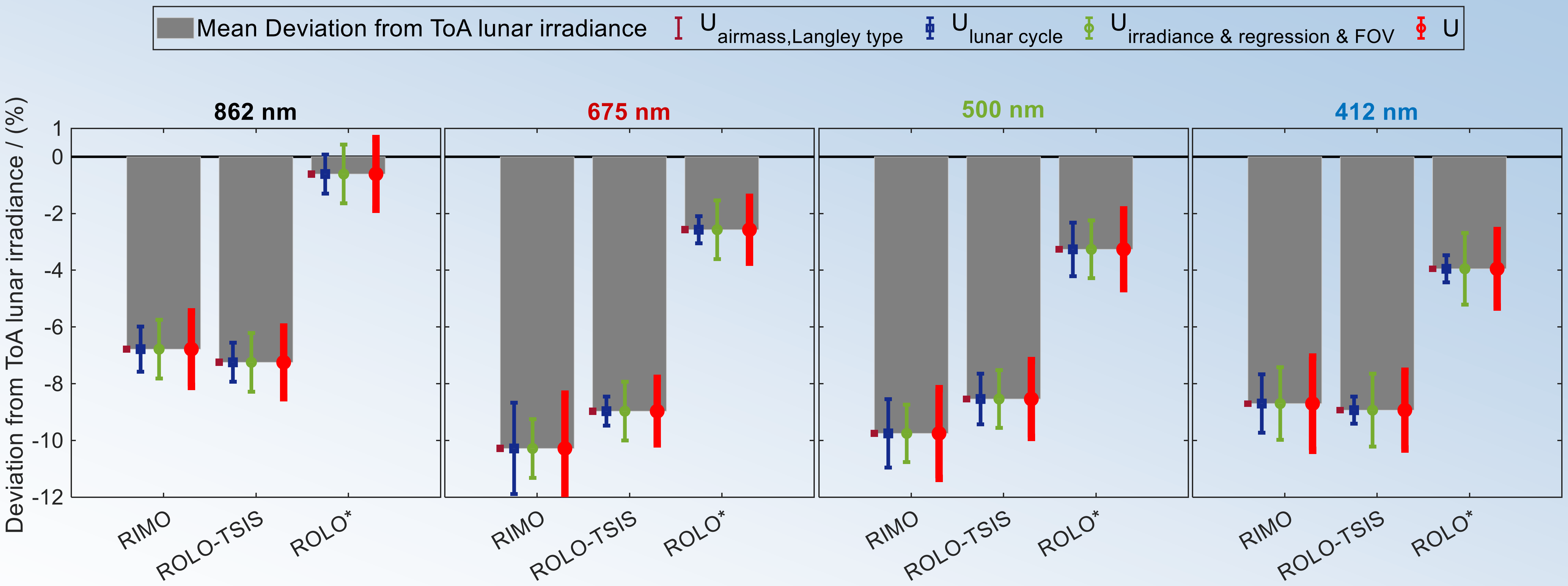

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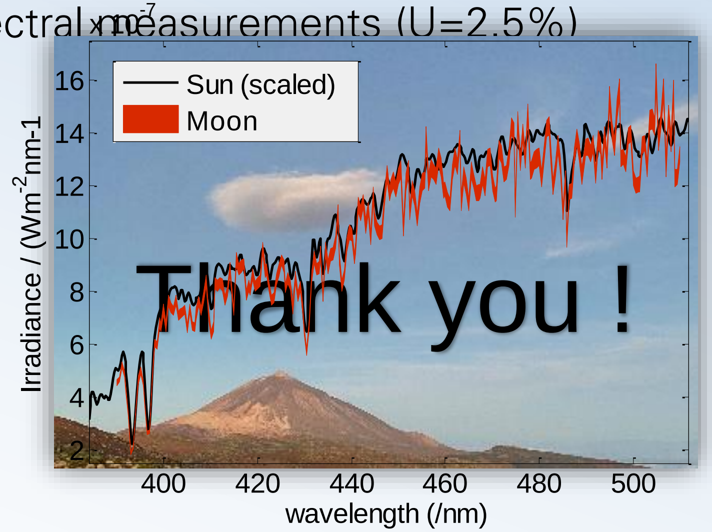
OUTLOOK

- Lunar PFR was characterized at PTB and provides lunar irradiance with an expanded relative uncertainty U< 0.5%
- The newest ROLO version gives excellent agreement within 0.5 % for the 862 nm and 2-4% for the rest. The deviations increase with decreasing spectral irradiance levels.
- The lunar irradiance phase variation from ROLO/RIMO is predicted with an uncertainty of less 1% (k=2) for a lunar phase variation ± 50°.

Future Work

- RE-calibrate PFR and perform co-located measurements with MLO-LUSI
- Development of PFR with additional wavelengths (450 nm, 778 nm, 1024 nm)
- Verification of results through QASUME spectral measurements (U=2.5%)



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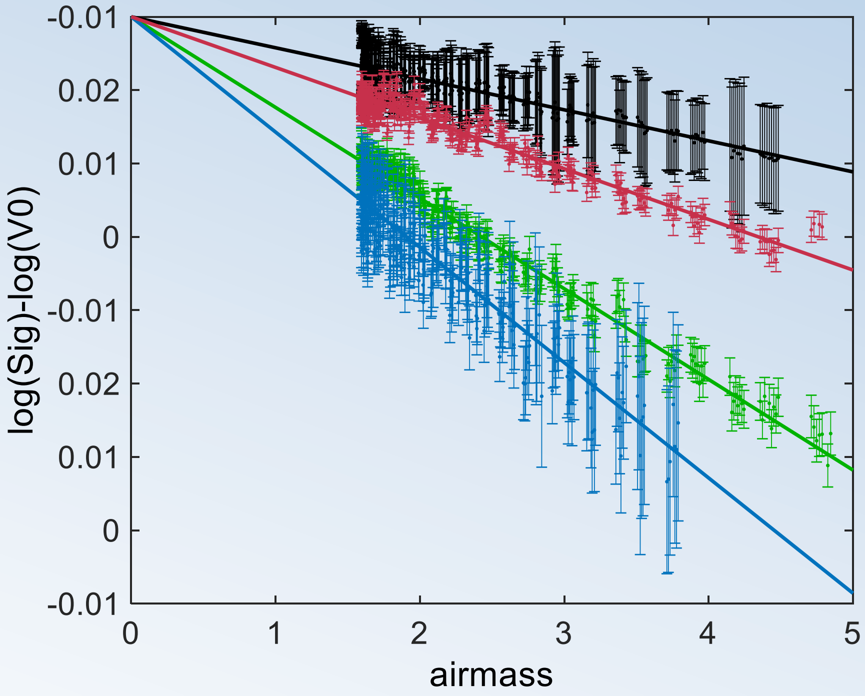
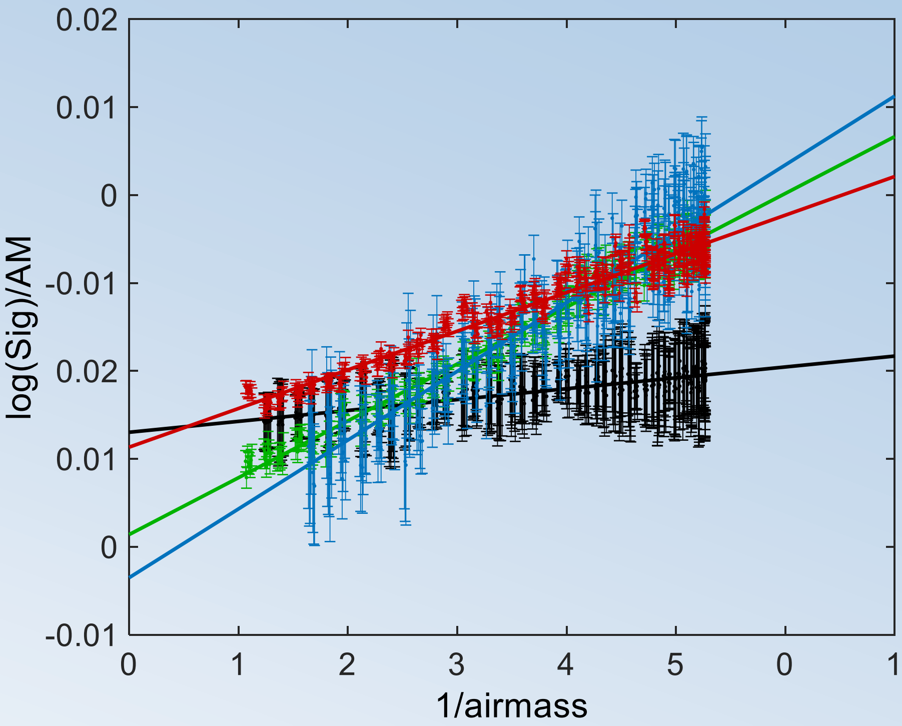
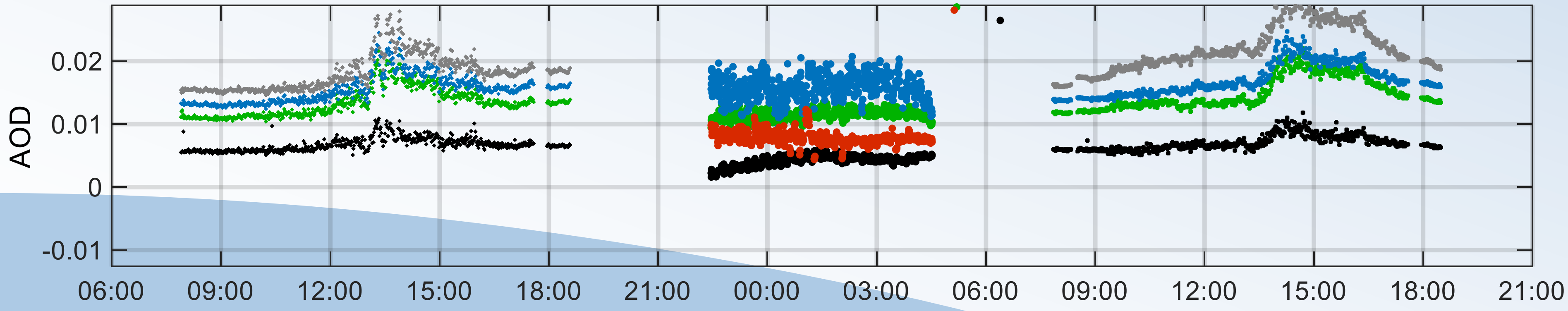
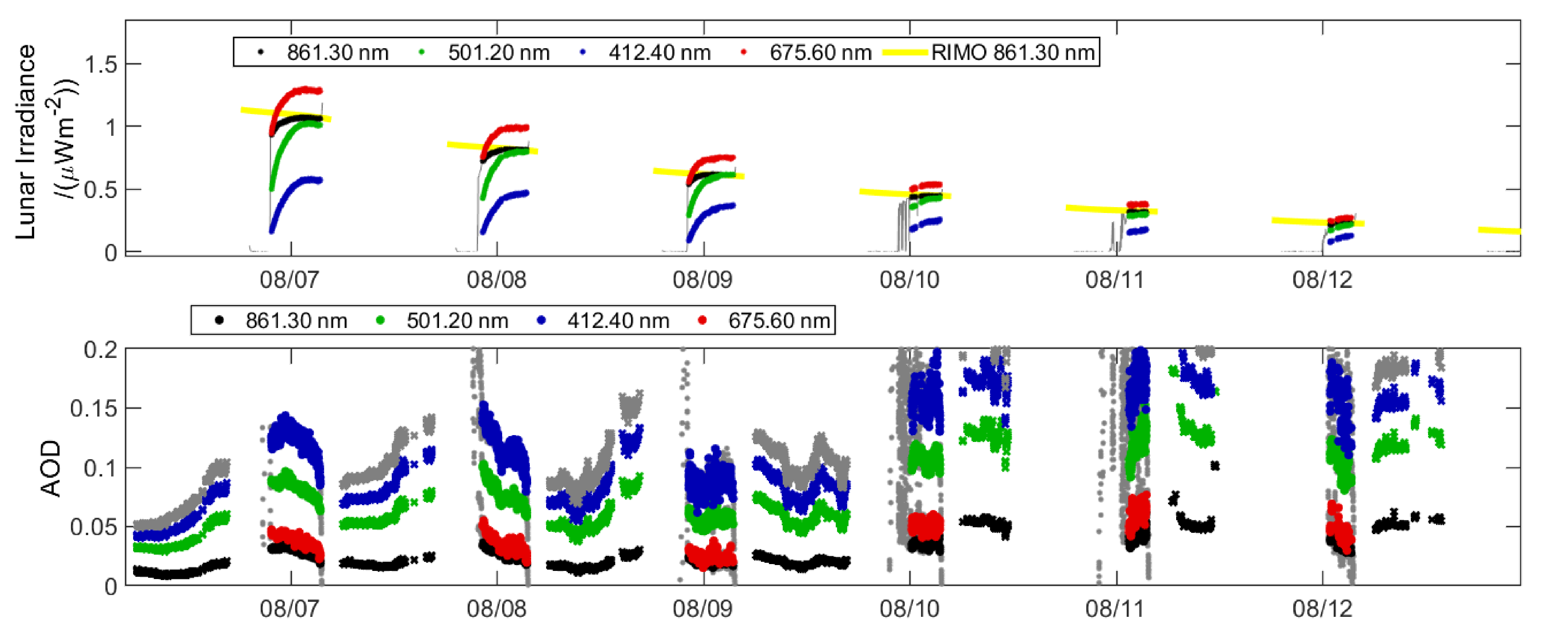




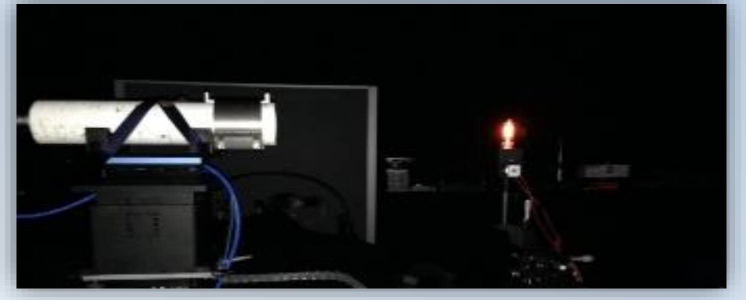


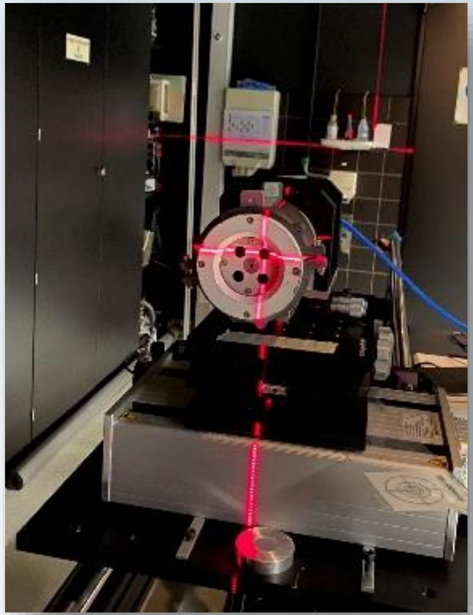
Top-Of-Atmosphere Lunar Irradiance

Successful Langley Example:



PFR-L Characterisation - Comparison of Calibration Methods





Irradiance Standard vs Monochromatic Irradiance

An irradiance calibration was performed at PTB after the TULIP calibration using 200 W lamps. The 2 calibration methods gave equivalent results, well within their uncertainties.

channel	862 nm	500 nm	412 nm	675 nm
1000 mm	-0.30%	-0.40%	-0.90%	0.30%
1500 mm	-0.10%	0.20%	0.30%	0.20%

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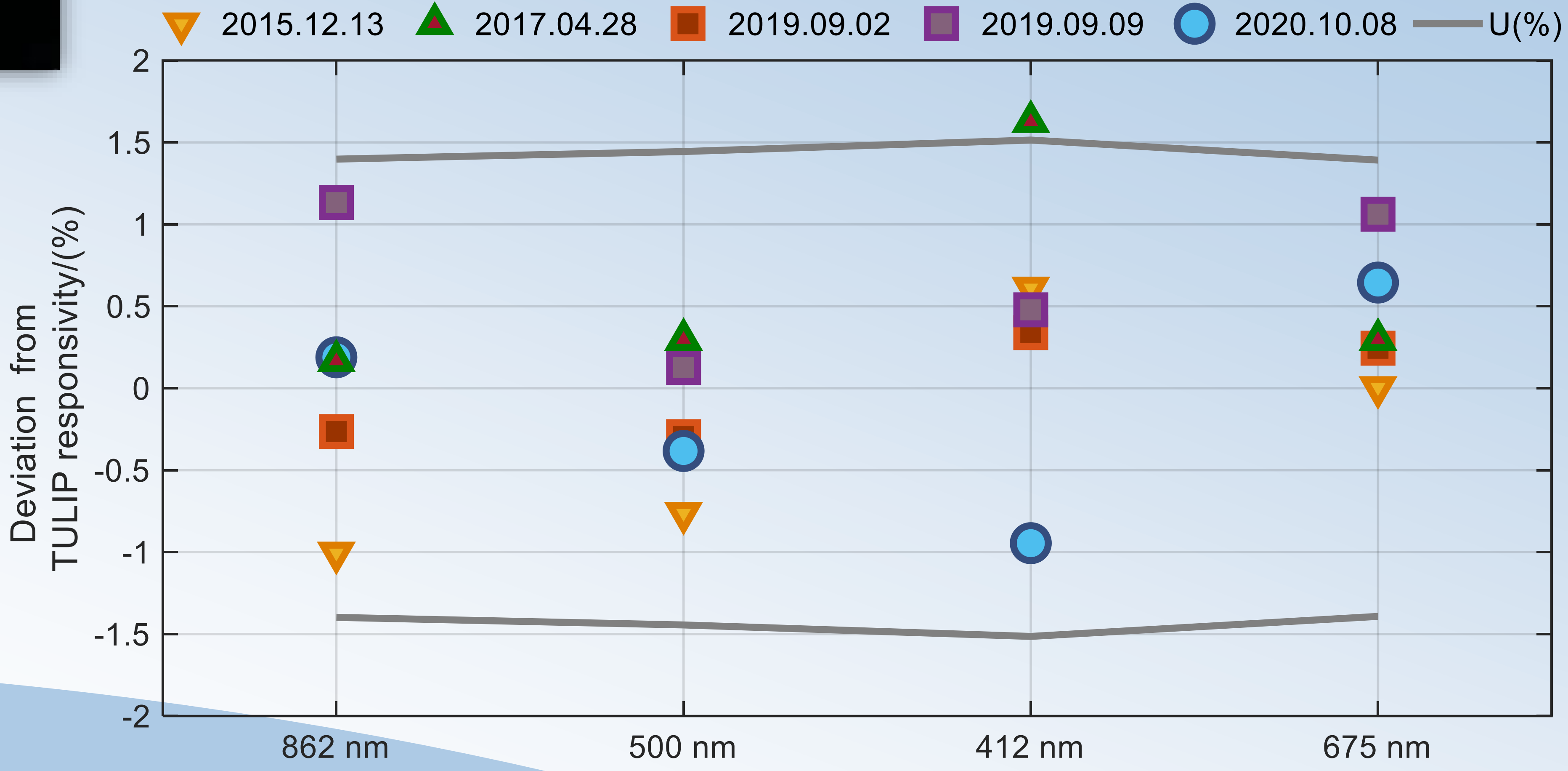
PFR-L Characterisation - Stability 2015-2021

Direct Irradiance Calibration Setup

- Reference irradiance source (1000W FEL-type lamp) calibrated at PTB.
- Motorized XYZ linear translators
- Motorized Rotation stages for azimuth and zenith angles.

Comparison of lamp calibrations performed since 2015 to TULIP calibration.

The gray lines: uncertainty of the lamp calibration.



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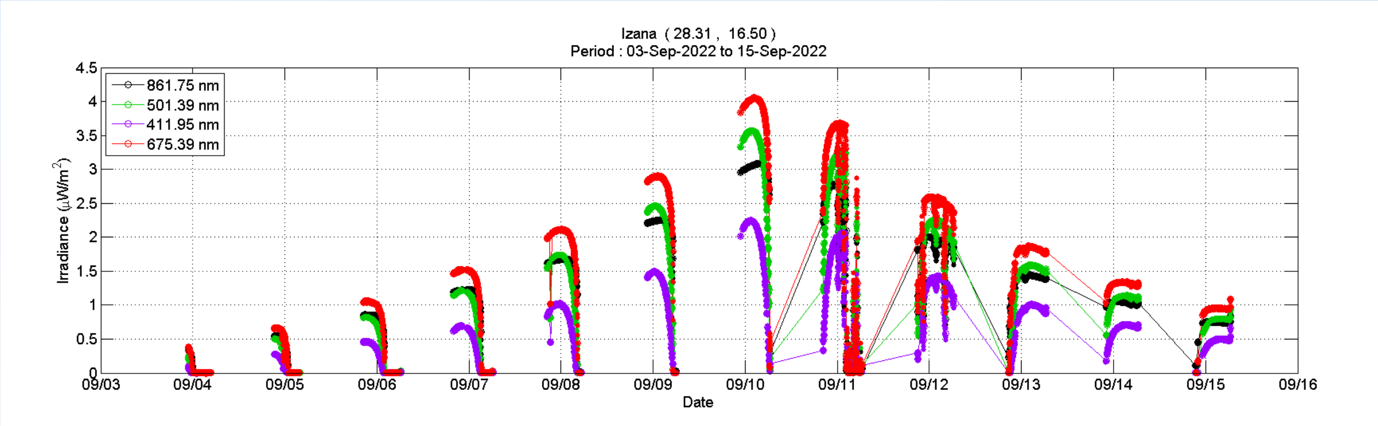
Top-Of-Atmosphere Lunar Irradiance



	Difference LunarPFR-RIMO TOA Lunar Irradiance (%)				Combined calibration and regression uncertainty (%, k=2)				
	862 nm	500 nm	412 nm	675 nm	862 nm	500 nm	412 nm	675 nm	Lunar Phase
Individual Langley retrievals	7.47	9.47	7.80	10.27	0.33	0.35	0.50	0.29	-47
	7.09	9.16	7.69	10.03	0.33	0.35	0.51	0.28	-33
	6.46	9.79	7.92	9.91	0.33	0.33	0.37	0.27	-19
	6.64	9.97	7.79	10.25	0.33	0.32	0.35	0.27	-6
	6.16	9.22	8.00	10.07	0.35	0.34	0.37	0.29	58
Mean TOA difference (%)	**6.76**	**9.52**	**7.84**	**10.10**	**0.40**	**0.40**	**0.47**	**0.36**	
standard deviation (%)	**0.52**	**0.36**	**0.12**	**0.15**					
Combined expanded uncertainty of TOA Lunar irradiance of PFR (k=2, %)	**1.60**	**1.41**	**1.27**	**1.25**					

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