LIME: Lunar Irradiance Model of ESA

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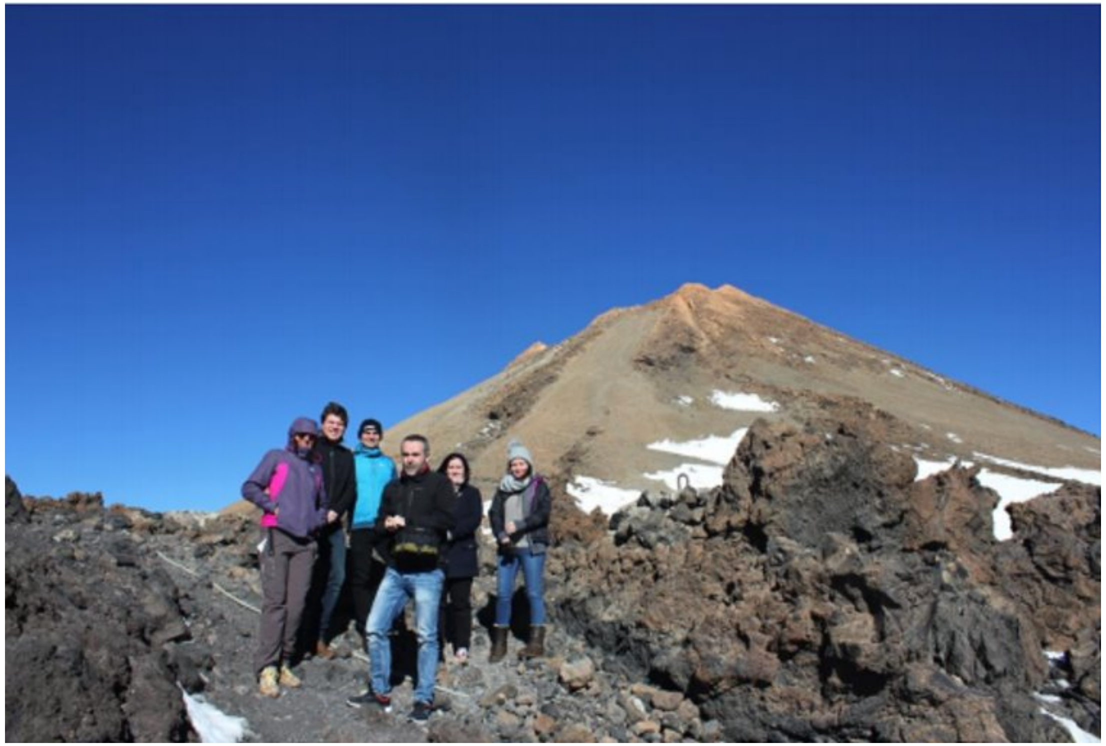
Overview

- The LIME model: overview and status
- Comparison of LIME output to lunar disk irradiance measurements
- A hyperspectral measurement campaign to better understand the moon reflectance spectrum
- LIME toolbox

The LIME model

LUNAR IRRADIANCE MODEL OF ESA

- LIME is based upon ROLO model
- Derived using SI-traceable ground-based measurements acquired with CIMEL 318-TP9 photometer from high altitude location at Teide Peak and Izaña Atmospheric Observatory in Tenerife
- Characterization and calibration at NPL and University of Valladolid
- Uncertainty computation based on Monte Carlo simulations accounting for calibration, modelling and measurement uncertainties



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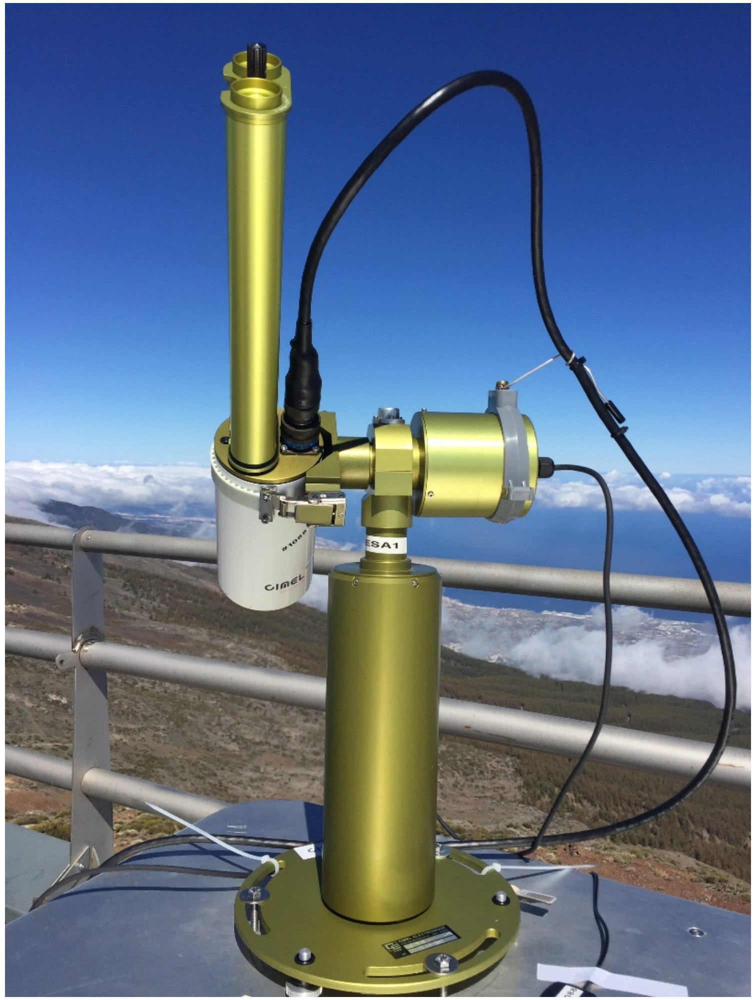
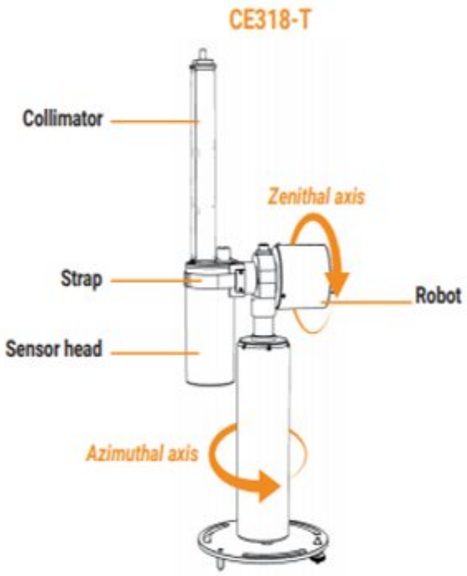
The LIME measurements





CIMEL 318-TP9

Specification	value
Irradiance precision	< 0.1%
Field of view	1.3°
Minimal scaterring angle from the sun	2°
Spectral range	340 to 1640 nm
Optical filter drift	< 1% / year
Automated mount	Azimuth and zenith motors
Sky angular scanning	Whole sky : Azimuth: 0 – 360° Zenith: 0 – 180°
Mechanical precision spot	0.003°
Solar tracking precision	0.01°
Power consumption	< 2W
Interferential filter bandwidth	< 30 nm
Total weight without support	25 kg
Power supply	Autonomous through solar panel
Mode	Sun, Sky, Lunar
memory	32 GB on SD card
Solar and moon scanning	4 quadrant sensor
Temperature	-30 to 70° C
humidity	0 to 100 %
RS232 (up to 100 m cable)	9600 baud/s
Numeric count dynamic	0 to 2 097 152

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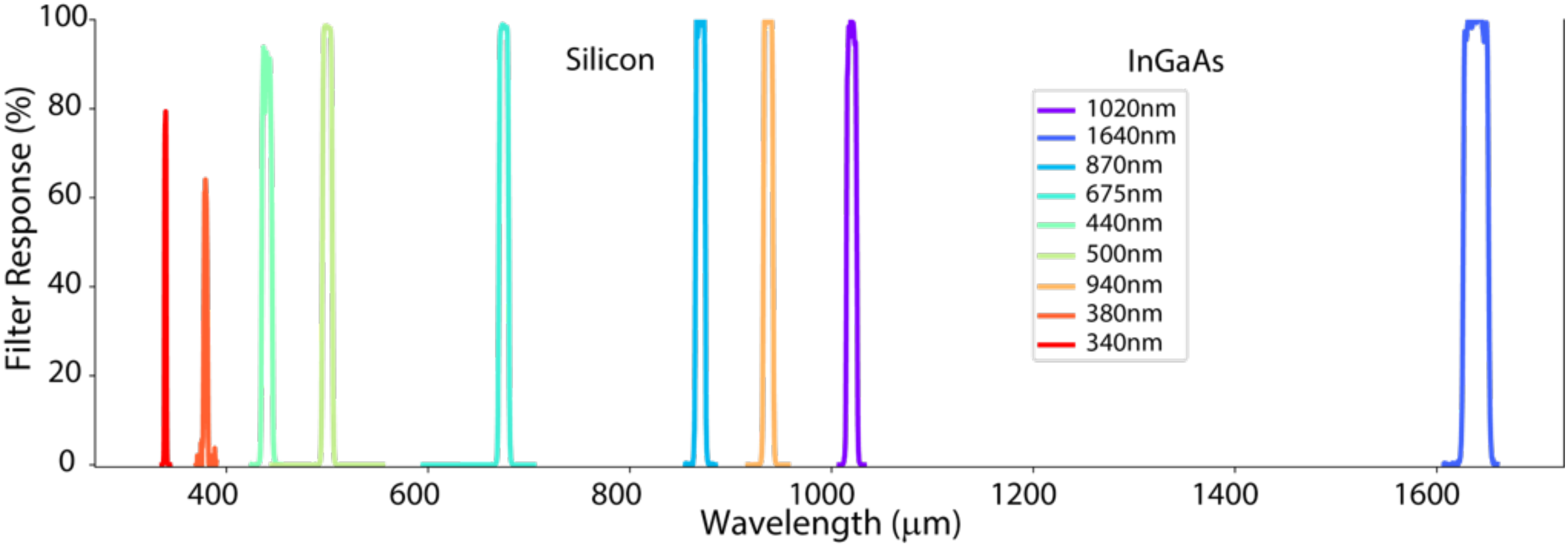
CE318-TP9 Filters



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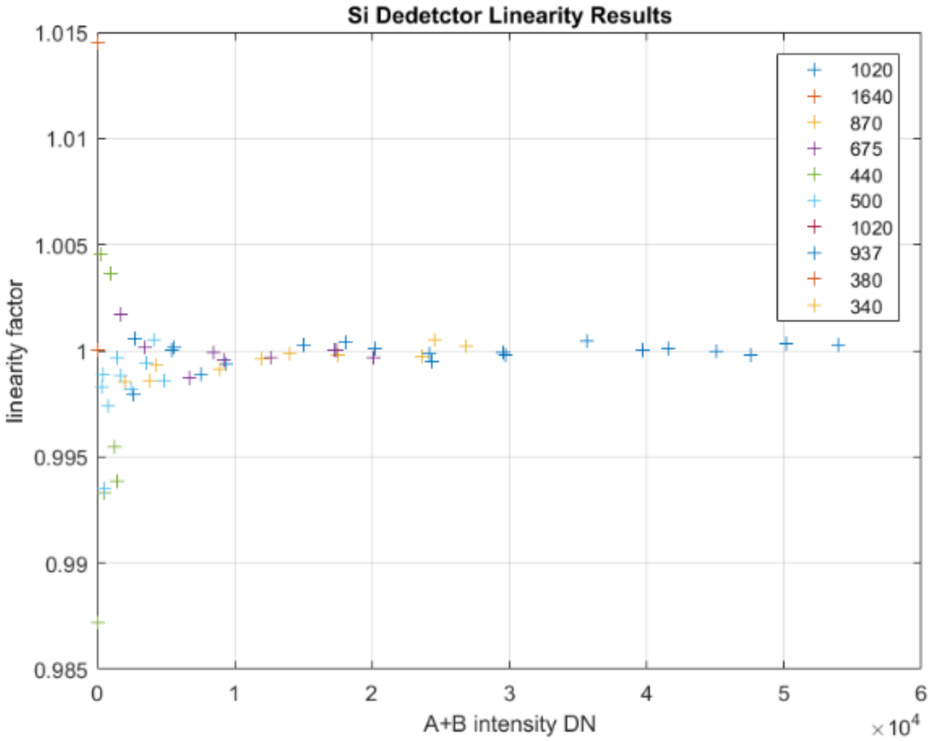
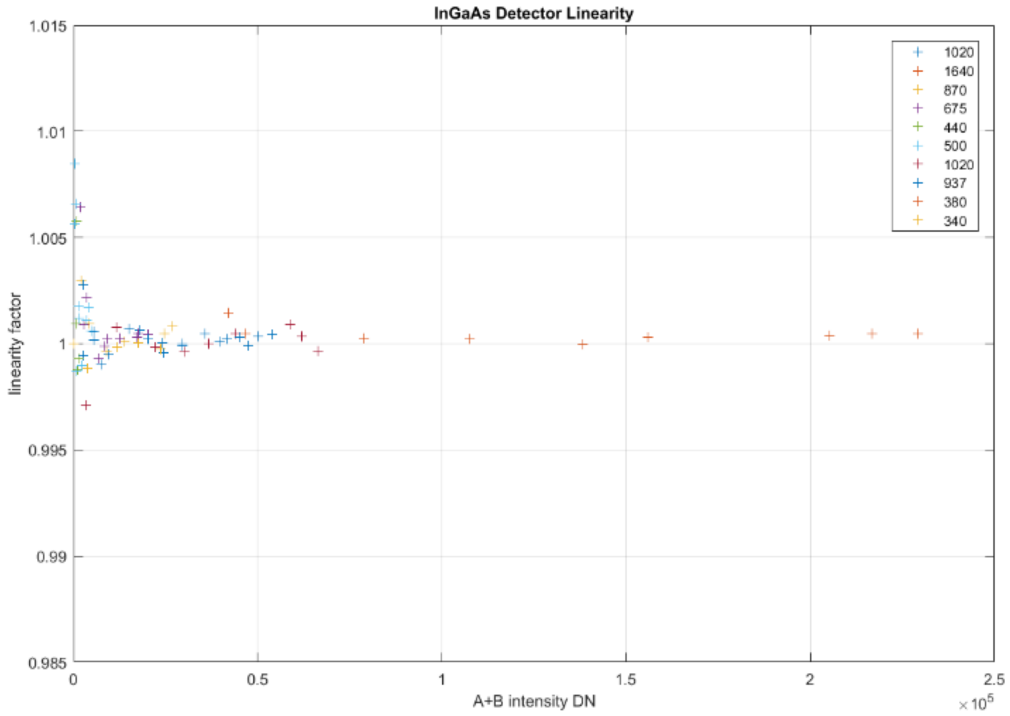
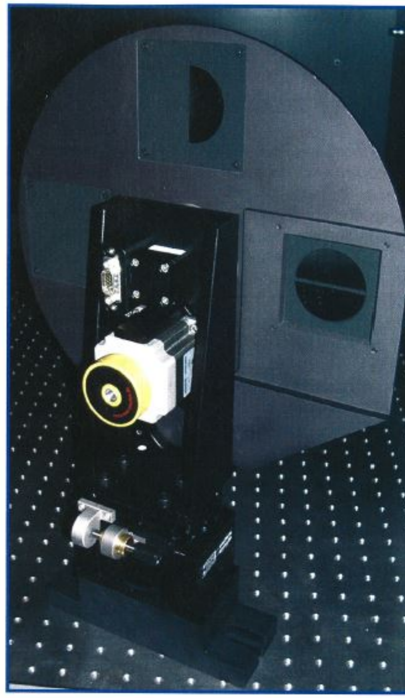
Linearity (NPL)







$$L(V_{\mathrm{A+B}}) = \frac{V_{\mathrm{A+B}}}{(V_{\mathrm{A}} + V_{\mathrm{B}})}$$

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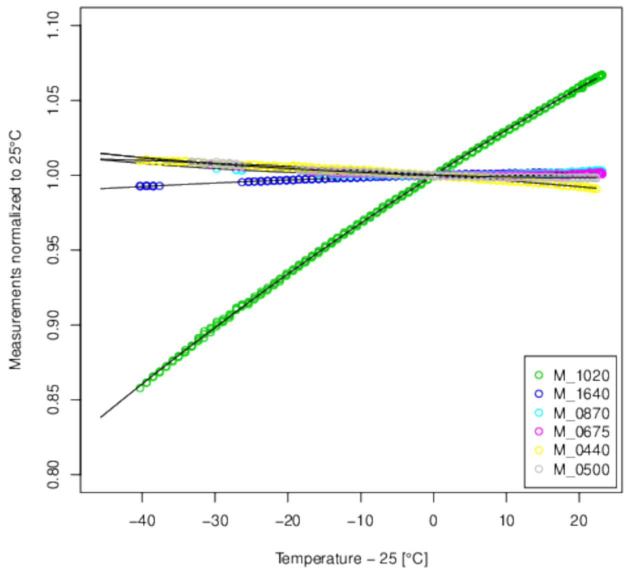
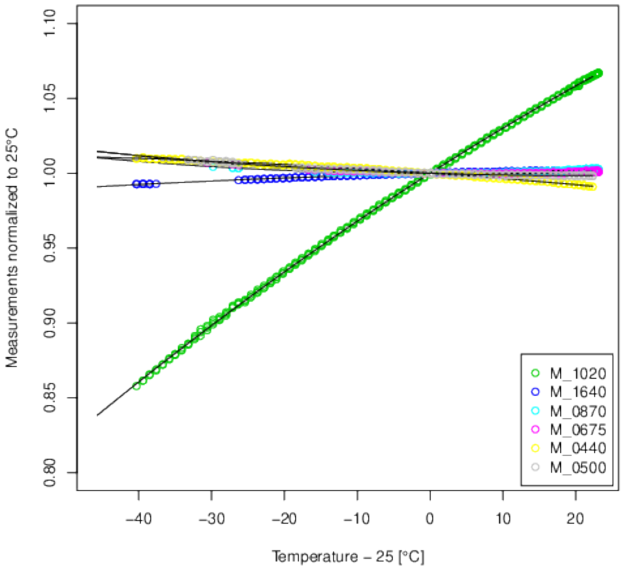
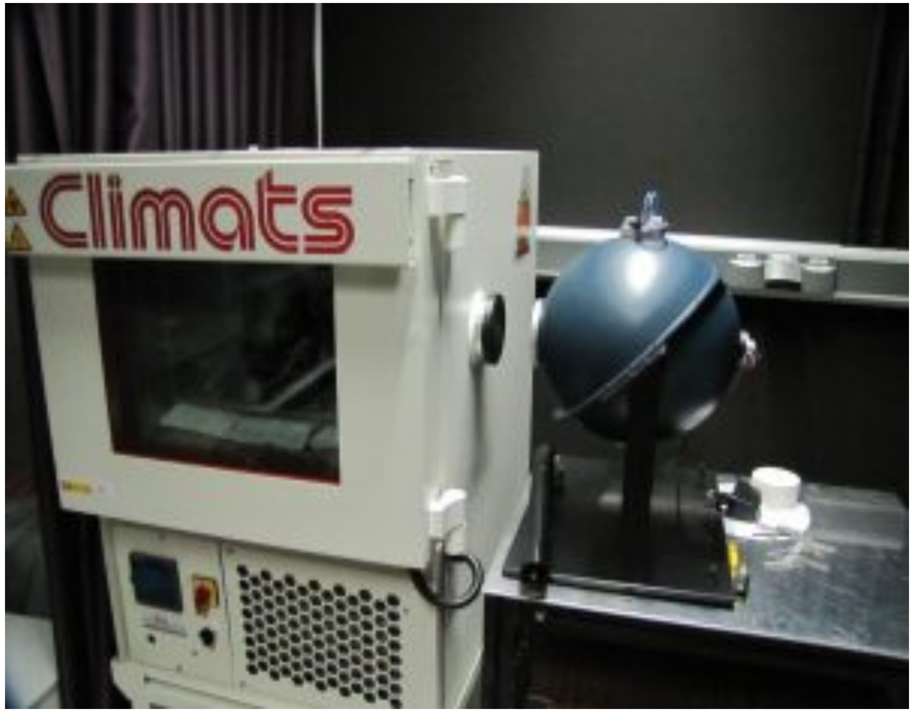
Temperature Sensitivity (UVa)

Pico Teide	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Percentile 98 [°C]	7.7	8.0	8.7	11.7	14.1	16.6	18.7	18.8	15.1	13.0	9.9	7.5
Percentile 2 [°C]	-9.5	-12.0	-8.1	-5.7	-2.7	1.8	5.0	5.0	1.9	-3.5	-5.9	-8.2







$$F_T = \left[1 + C_{1,i}(T - T_{\text{ref}}) + C_{2,i}(T - T_{\text{ref}})^2\right]$$

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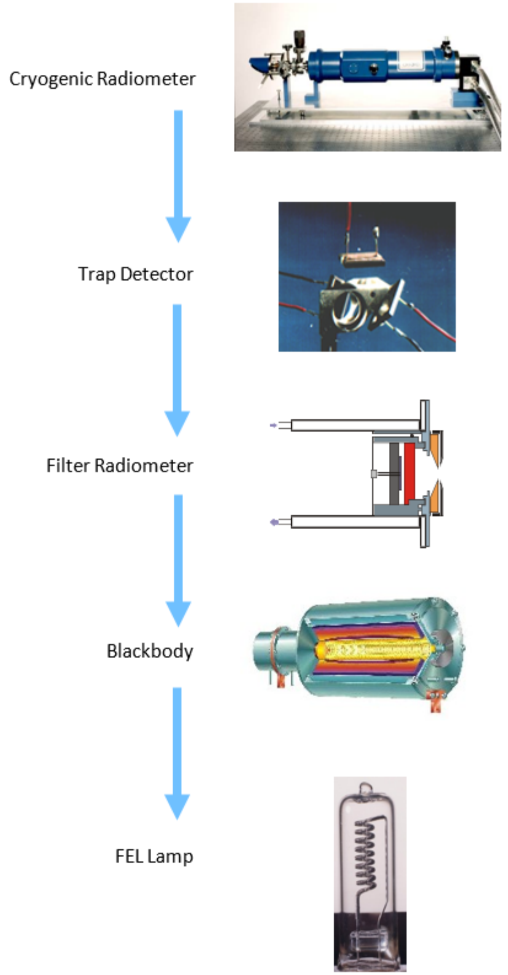
Irradiance Responsivity

LIME
LUNAR IRRADIANCE MODEL OF ESA

Spectral Channel	Calibration Coefficient (MOON gain)	Standard uncertainty
440 nm Si	5.759×10^{-10}	0.97%
500 nm Si	4.481×10^{-10}	0.96%
675 nm Si	3.205×10^{-10}	0.92%
870 nm Si	2.547×10^{-10}	0.91%
937 nm Si	2.431×10^{-10}	0.97%
1020 nm Si	2.735×10^{-10}	1.05%
1020 nm InGaAs	2.119×10^{-10}	1.01%
1640 nm InGaAs	4.893×10^{-11}	1.06%

$$C_{\bar{E},\mathrm{CIMEL}}(\lambda_i) = \frac{\left(\sum_j E_{\mathrm{lamp},x}(\lambda_j)\xi_i(\lambda_j)\delta\lambda\right)F_T}{G_{\mathrm{ratio}}\left[D_{\mathrm{CIMEL,lamp},x}(\lambda_i) - D_{\mathrm{CIMEL,dark}}(\lambda_i)\right]}$$



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CIMEL Stability by Solar Langley Calibration

WLN	Extraterrestrial Sun counts on 23/06/2018	Extraterrestrial Sun counts 25/06/2020	Difference(%)
1020	628596.4	631346	0.44
1640	1114638.9	1114576	-0.01
870	882649.8	885586	0.33
675	1111487.4	1114076	0.23
440	760622.6	761067	0.06
500	1026944.7	1029153	0.21
1020i	805945.7	808002	0.25
935	827605.4	814508	-1.60
380	129951	126758	-2.49
340	43550.4	43042	-1.17

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Lunar disc irradiance measurements

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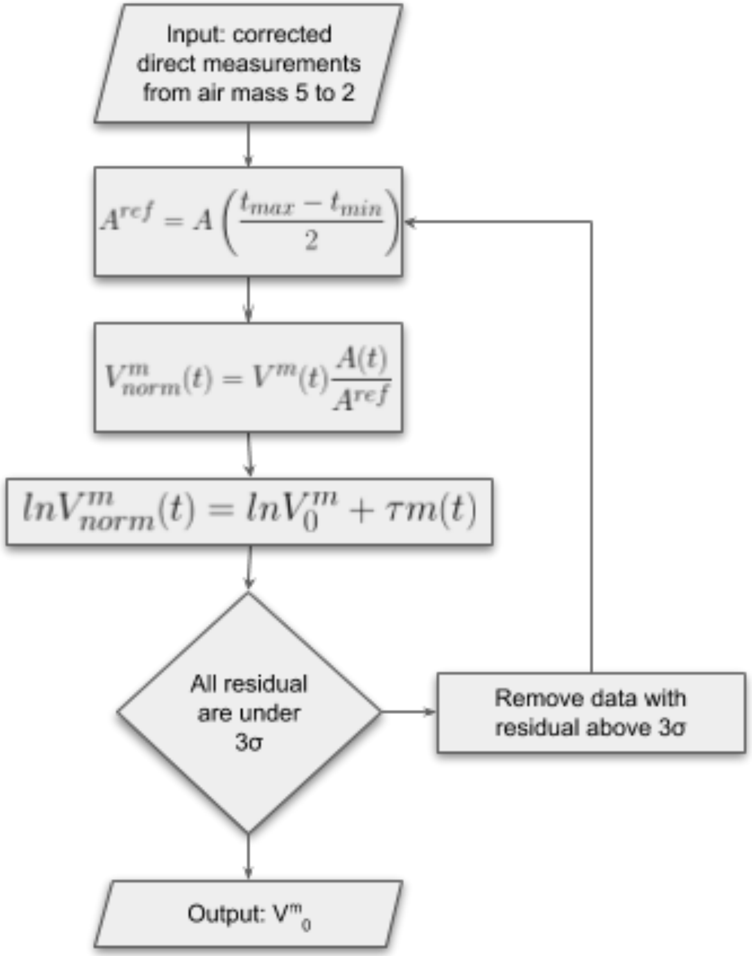

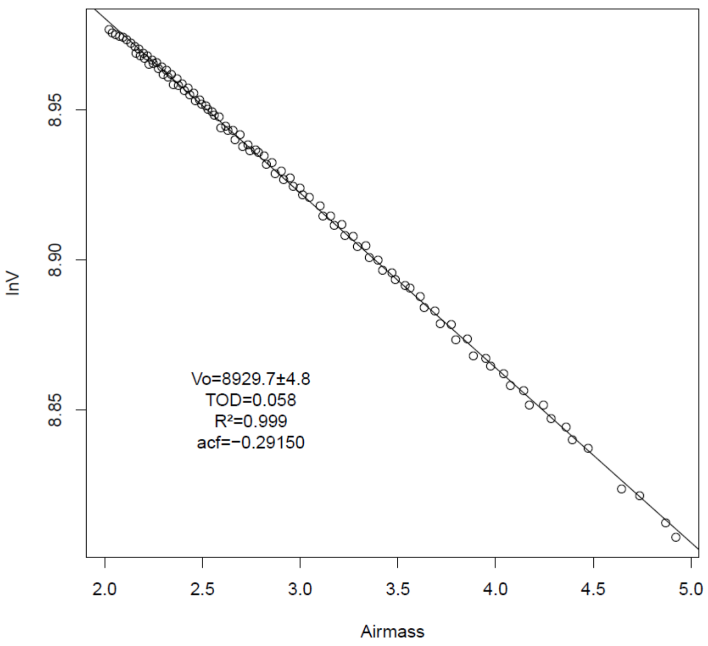

$$ln(V^{s}(\lambda, t)) = ln(V_0^{s}(\lambda)) - m(\theta)\tau_{\lambda}$$

$$V'(\lambda, t) = V(\lambda, t)\frac{A(t_{ref}, \lambda)}{A(t, \lambda)}$$

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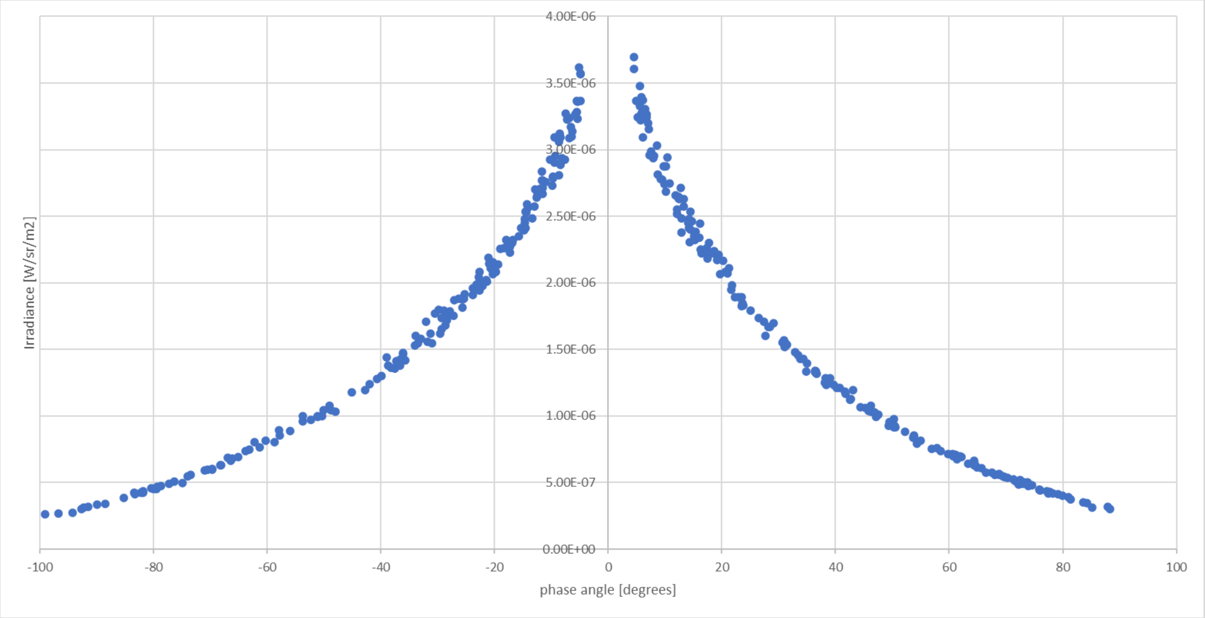
Model Regression Overview



Lunar irradiance measurements at 440 nm based on more than 3+ years of measurements (about 400 lunar irradiance measurements)

- Based upon the work done by Kieffer and Stone [Kieffer and Stone,2005]
- Minor adaptations to the model formulation discussed with T. Stone

Lunar Irradiance Model

LUNAR IRRADIANCE MODEL OF ESA

$$\ln(A_k) = \sum_{i=0}^{3} a_{ik} g^i + \sum_{i=1}^{3} b_{ik} \Phi^{2i-1} + c_1\theta + c_2\phi + c_3\Phi\theta + c_4\Phi\phi + d_{1k} e^{-\frac{g}{p_1}} + d_{2k} e^{-\frac{g}{p_2}} + d_{3k} \cos\left(\frac{g - p_3}{p_4}\right)$$

k = model spectral band
A = lunar reflectance
g = absolute phase angle [radians]
θ = selenographic latitude of observer [degrees]
ϕ = selenographic longitude of observer [degrees]
Φ = selenographic longitude of the Sun [radians]

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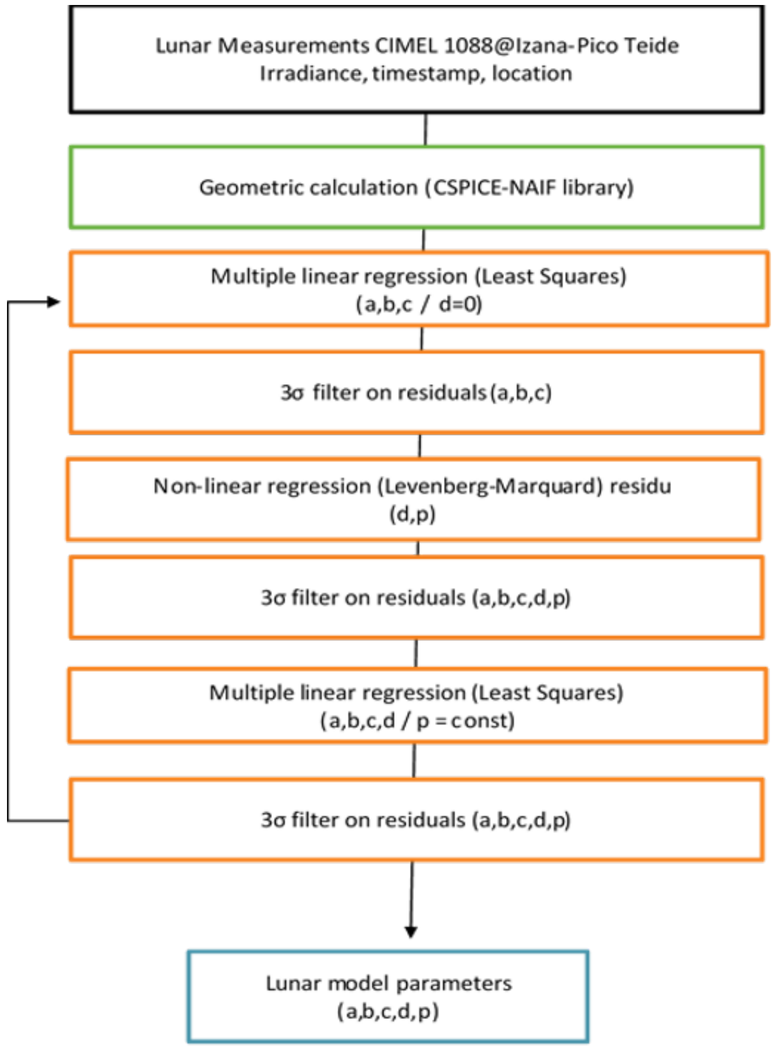
Coefficient Regression



wl[nm]	a0	a1	a2	a3	b1	b2	b3
440	-2.26317	-1.95341	0.691585	-0.30189	0.052456	0.008714	-0.00415
500	-2.15048	-1.82816	0.59675	-0.27933	0.050078	0.010695	-0.00382
675	-1.91452	-1.72298	0.562315	-0.2762	0.047094	0.012212	-0.00484
870	-1.81647	-1.5906	0.465803	-0.24815	0.046823	0.018782	-0.007
1020	-1.75279	-1.50502	0.401689	-0.22989	0.052412	0.021768	-0.00864
1640	-1.47438	-1.21778	0.189073	-0.16837	0.047555	0.011999	-0.00487
wl[nm]	c1	c2	c3	c4	d1	d2	d3
440	0.001217	-0.00036	0.00161	0.000732	-0.09294	2.000626	-0.00571
500	0.001117	-0.00041	0.00178	0.000945	12.96653	-12.422	-0.00273
675	0.001113	-0.00043	0.00171	0.000936	9.886489	-9.75239	-0.00594
870	0.001153	-3.74E-04	0.001882	0.000895	10.47813	-10.3637	-0.00342
1020	0.001044	-4.50E-04	0.001817	0.000837	11.93628	-11.8154	-0.00255
1640	0.000945	-4.90E-04	0.001732	0.001093	14.32673	-14.4102	3.48E-06
	p1	p2	p3	p4			
all	1.35446	1.314674	9.324089	9.596769			

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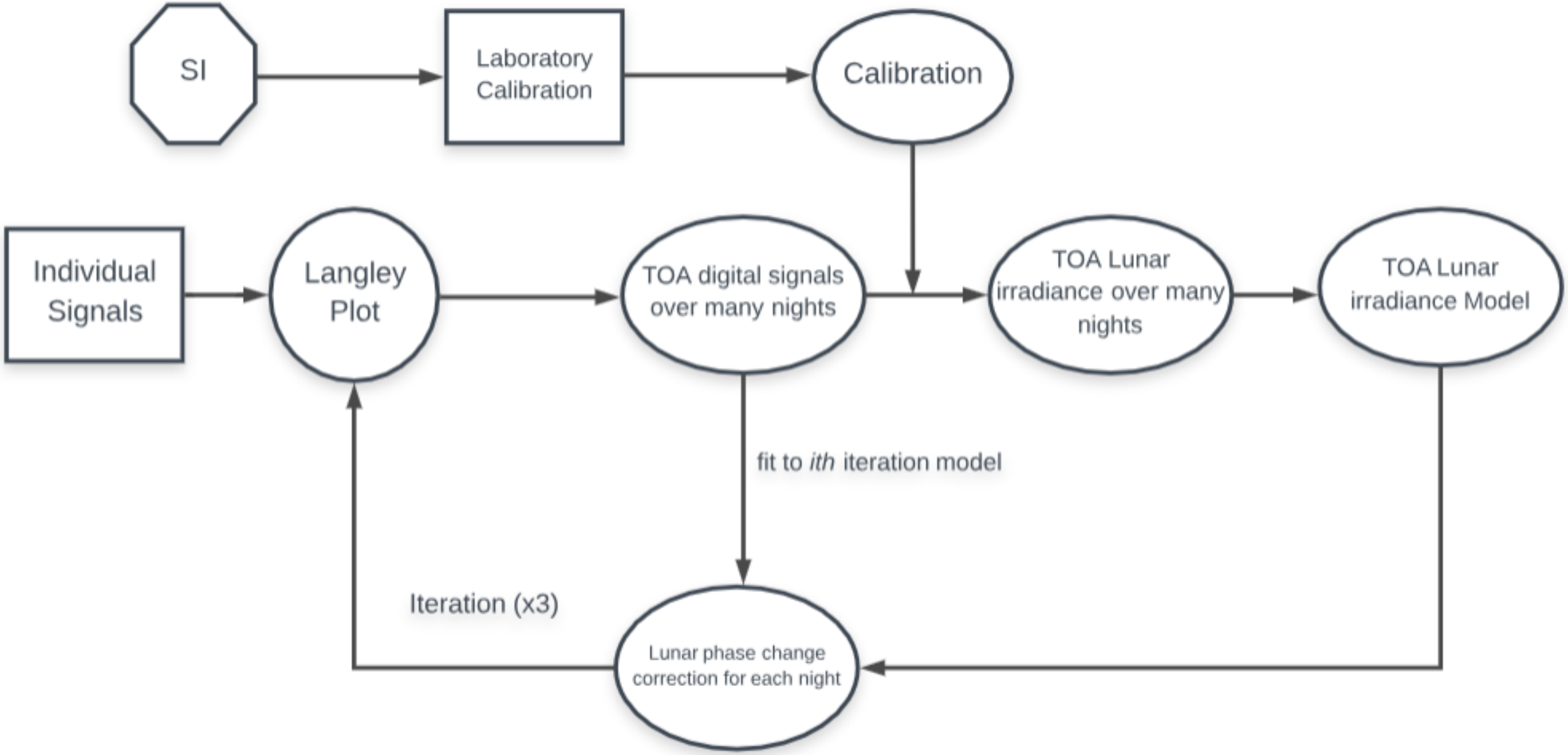
Uncertainty Analysis



Error Correlation Structures

Errors can be correlated between:

- Individual points on the Langley (within one night)
- Individual nights
- Spectral bands

	Langley points	Nights	Spectral
Calibration	C	C	PC
Instrument Noise	I	I	I
Temperature	C	I	C
Aerosol variability	PC	I	C

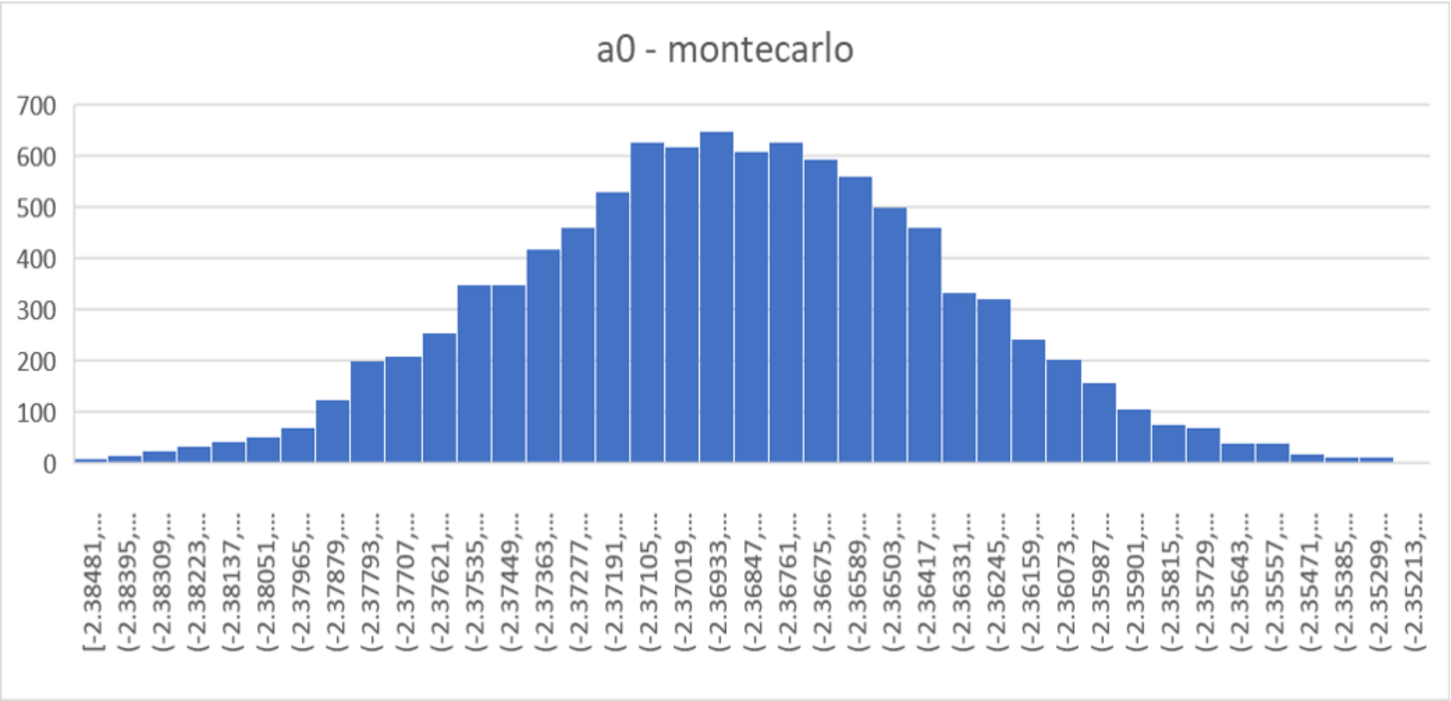
C = correlated; I = independent; PC = Partially correlated

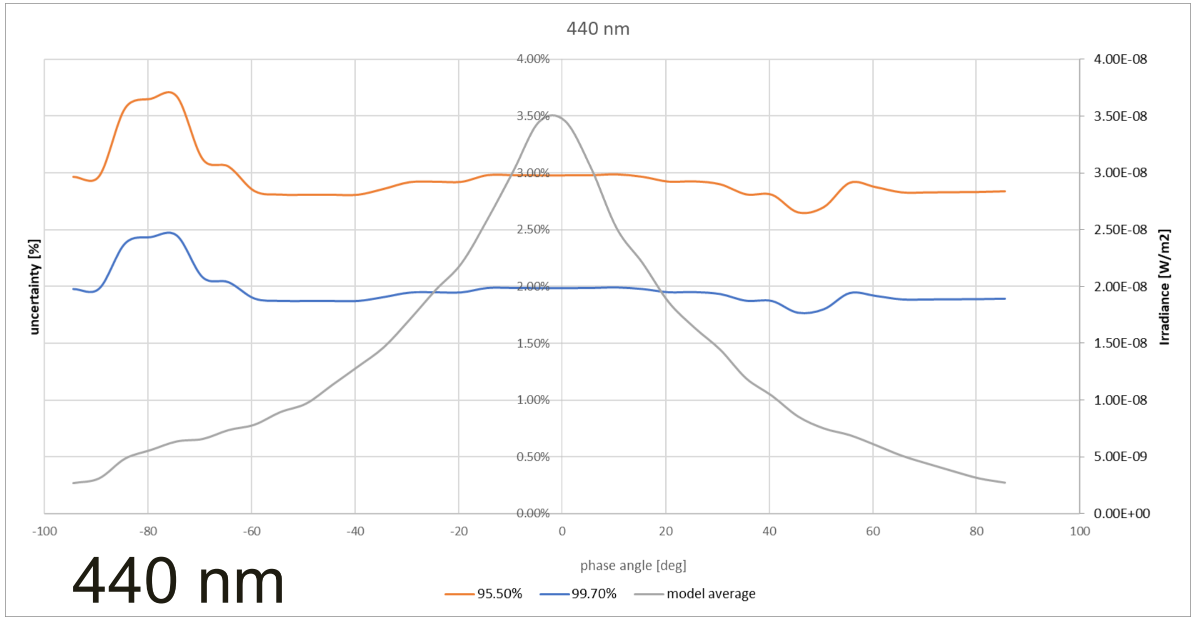
Uncertainty Analysis

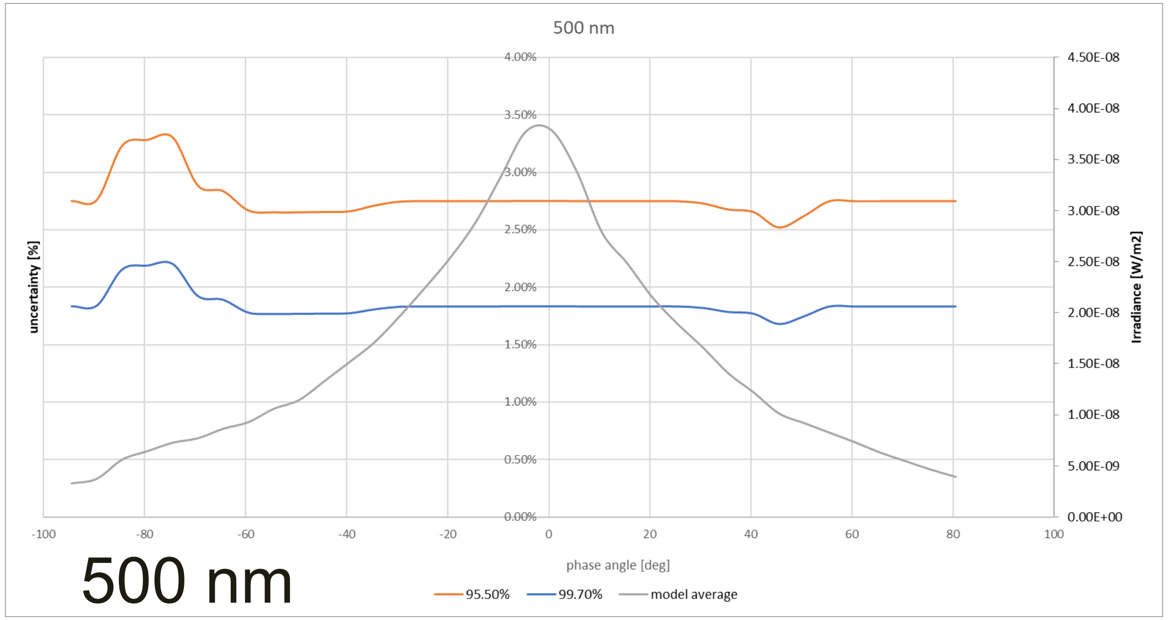
LUNAR IRRADIANCE MODEL OF ESA

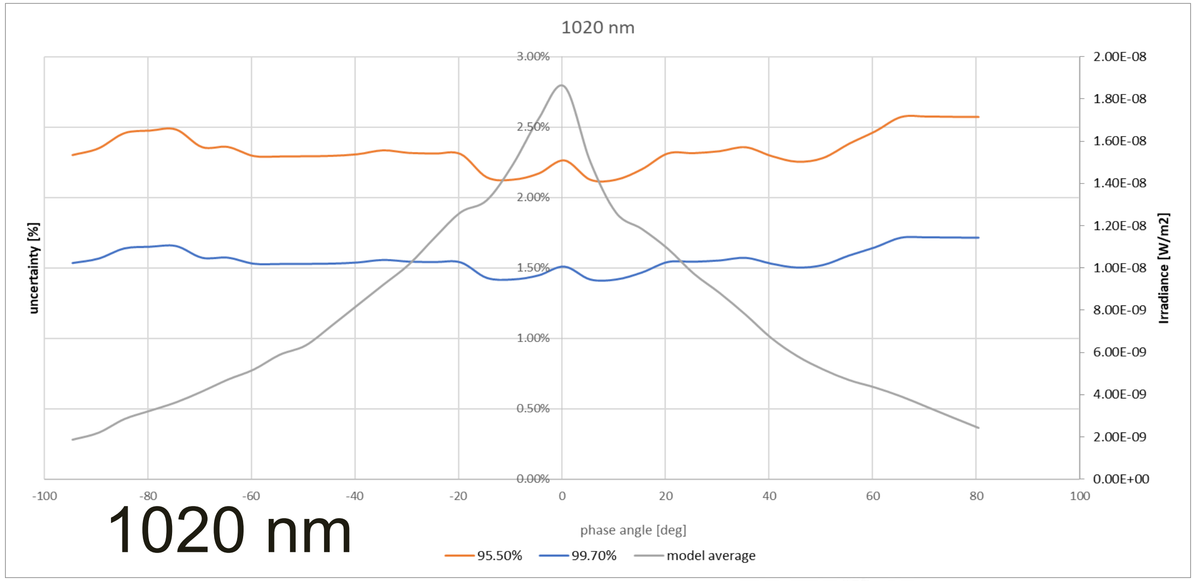
- Perform Monte Carlo analysis to define total uncertainty
- Including the uncertainty related to the model regressions
- 1000 models by modifying the input
- Introduced perturbation based upon the instrument and measurement uncertainty

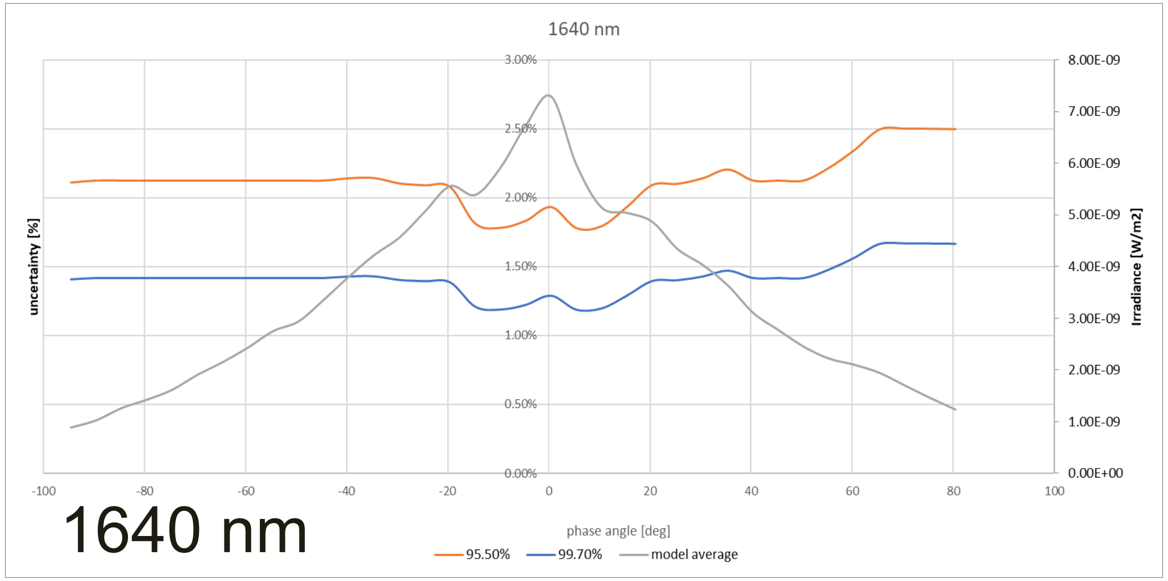
$$E_{i,\lambda} = E_{i,\lambda}^{\text{True}} \times (1 + R_{i,\lambda})(1 + S_\lambda)(1 + C)$$











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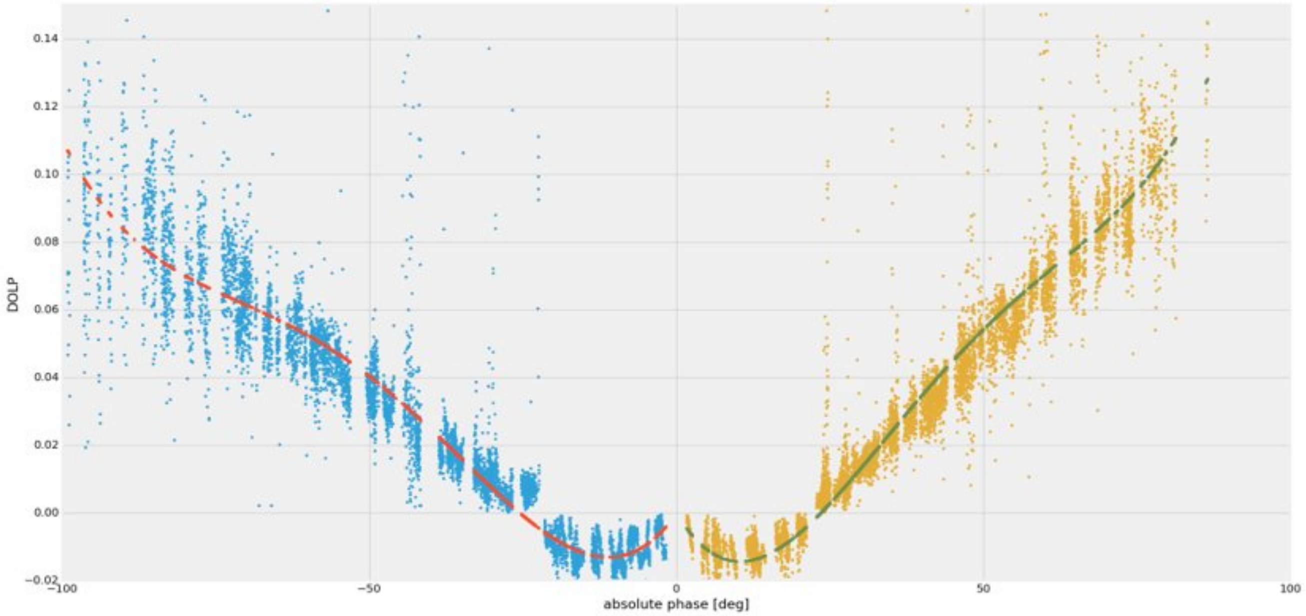
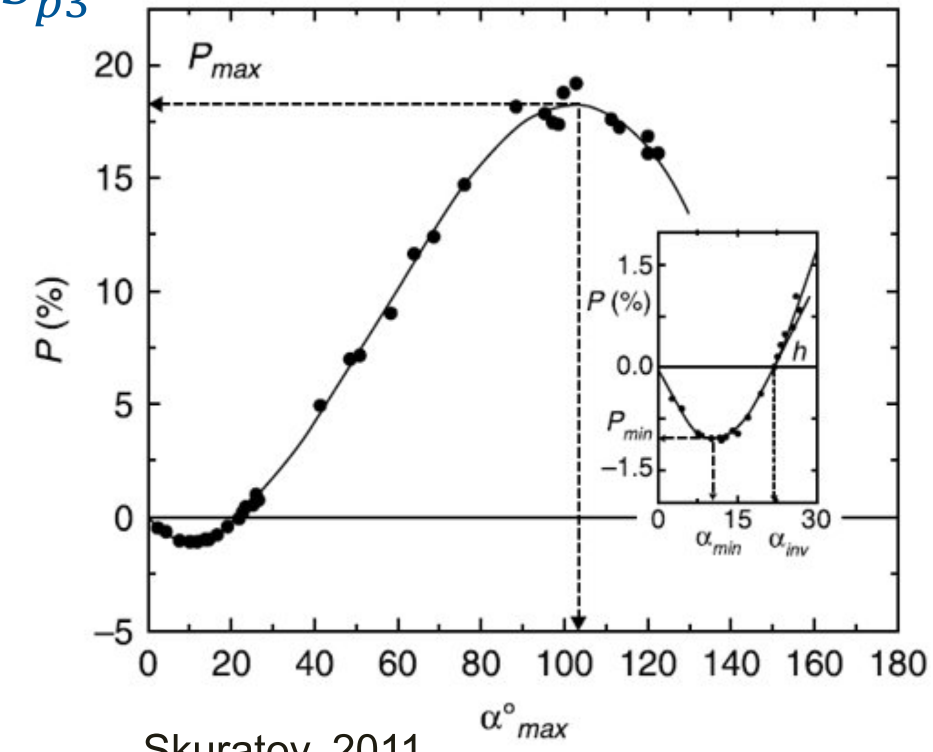
Degree of Linear Polarisation measurements

$$DoLP = \frac{2\eta\sqrt{S_{p1}^2 + R_{12}^2 S_{p2}^2 + R_{13}^2 S_{p3}^2 - R_{12}S_{p1}S_{p2} - R_{13}S_{p1}S_{p3} - R_{12}R_{13}S_{p2}S_{p3}}}{S_{p1} + R_{12}S_{p2} + R_{13}S_{p3}}$$



Curve fitted DOLP measurements for 500 nm band



Skuratov, 2011

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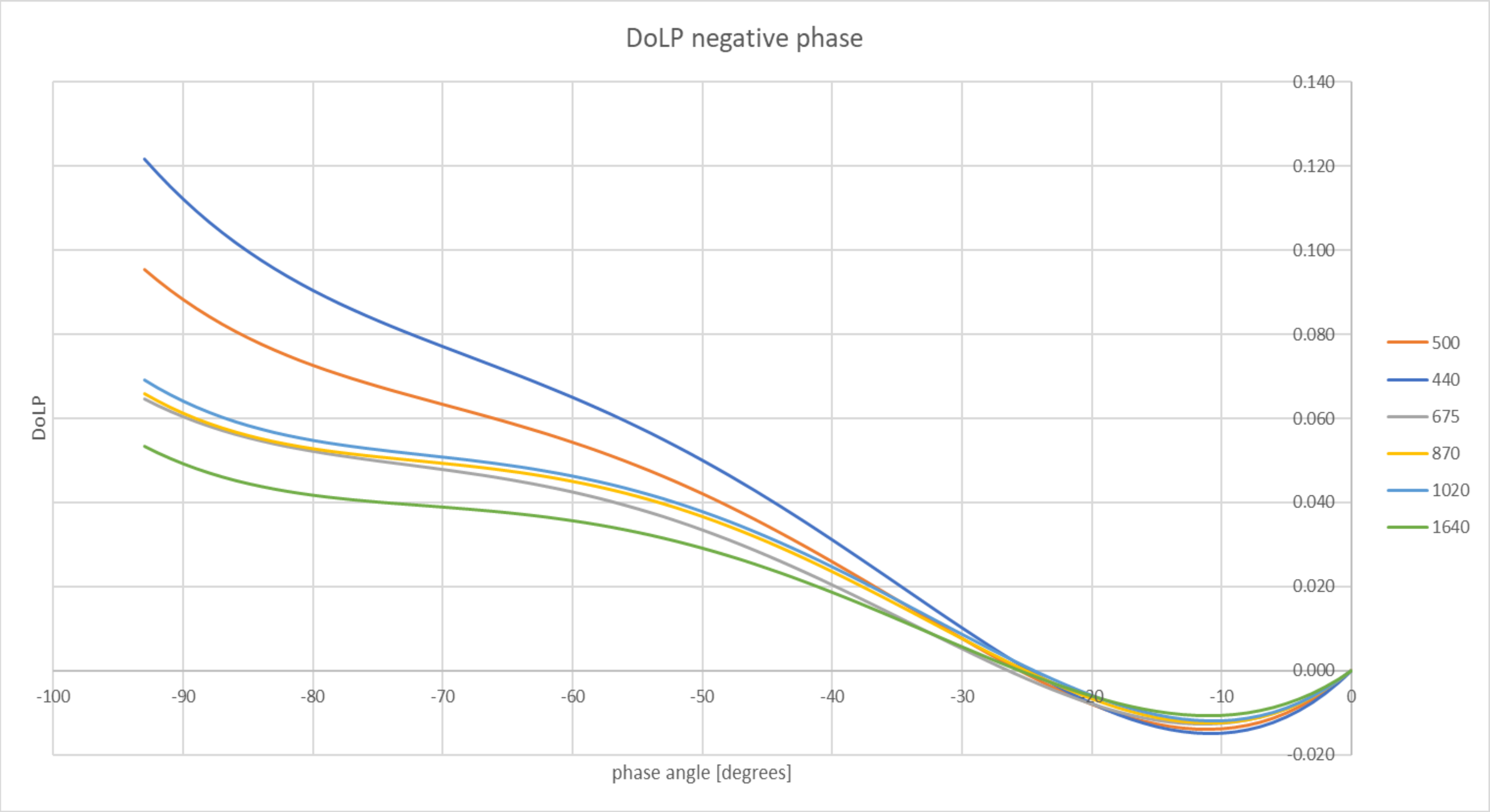
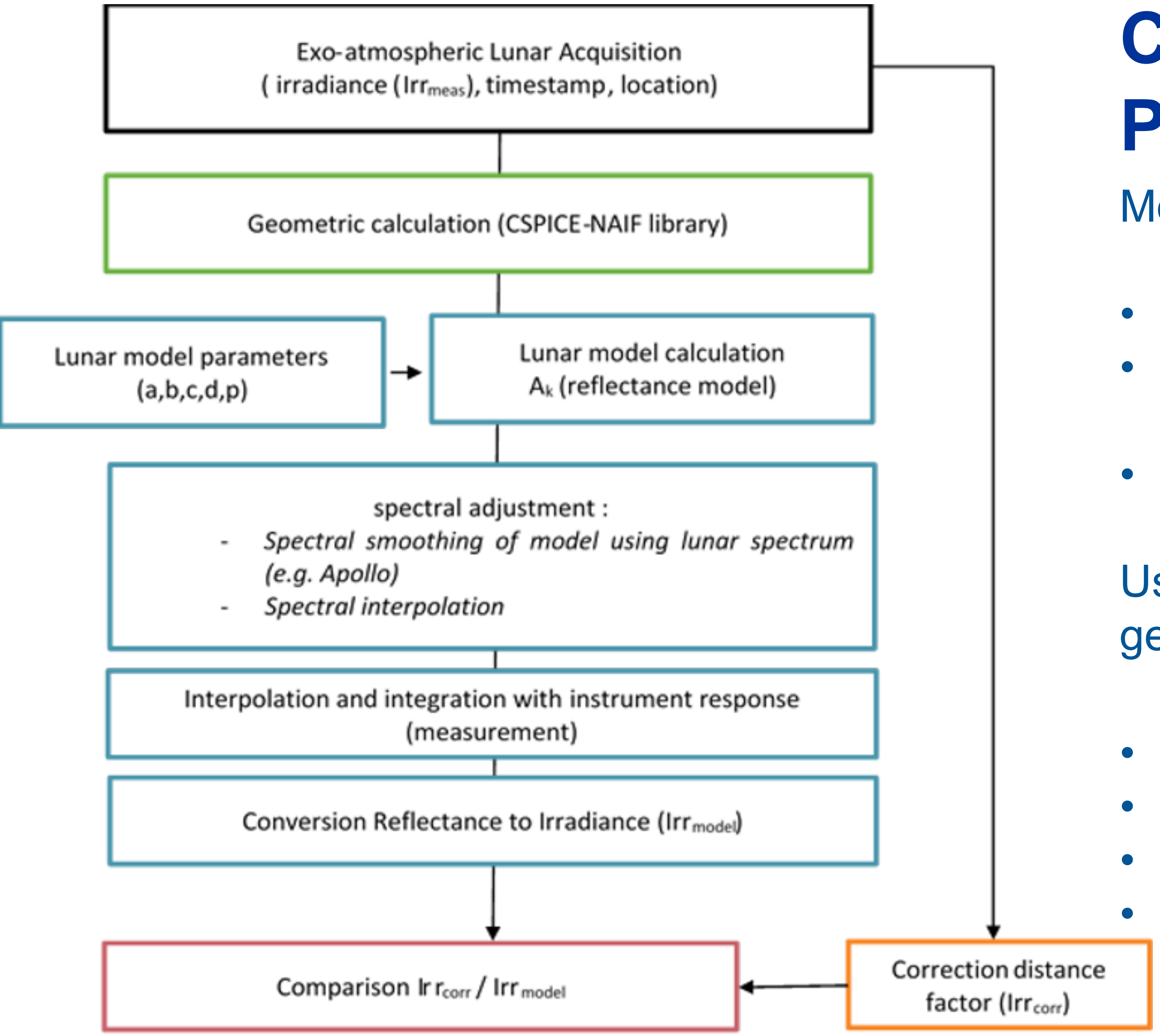
Degree of Linear Polarisation model



Modelled DoLP for all wavelengths (negative phase angle)



Comparison Procedure

LUNAR IRRADIANCE MODEL OF ESA

Model Input

- Timestamp of the acquisition
- Position of the instrument/platform (J2000 coordinates)
- Irradiance

Using these parameters, the model calculates the geometry parameters required for the comparison:

- Phase angle
- Solar selenographic longitude
- Observer selenographic latitude and longitude
- Distances between Sun, Moon and observer.

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Spectral Model using the ROLO approach: Apollo/Breccia spectrum

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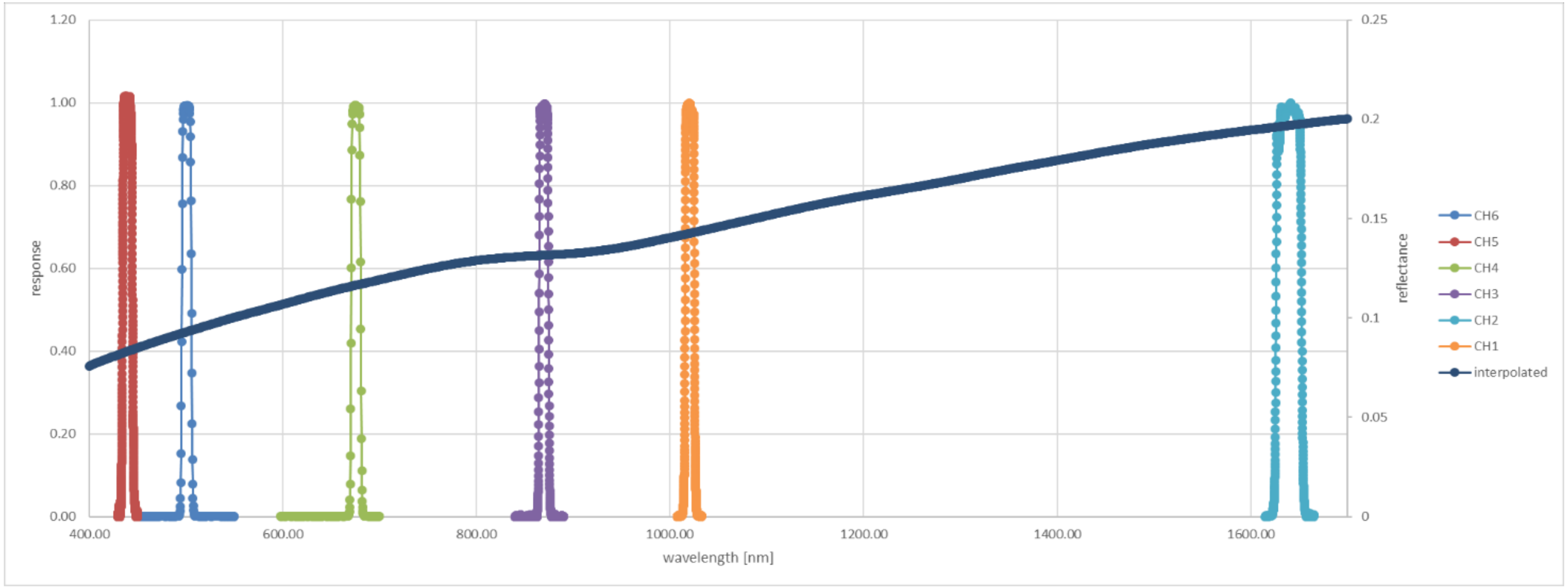

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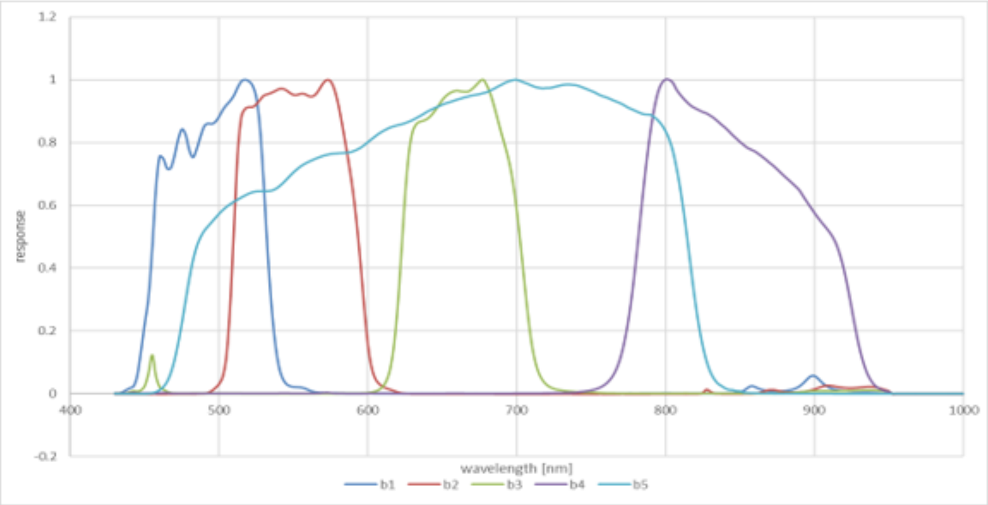
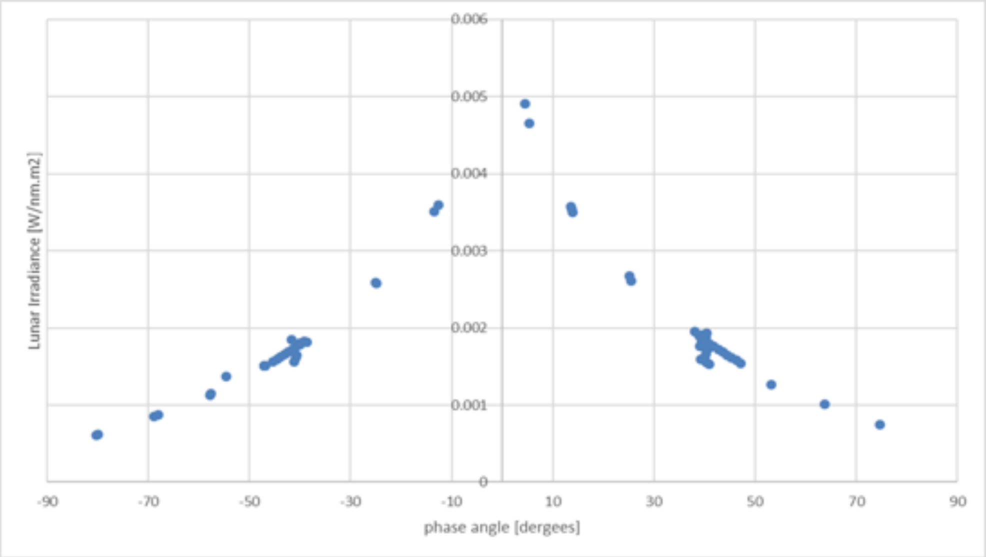
Pleiades-1B

LUNAR IRRADIANCE MODEL OF ESA

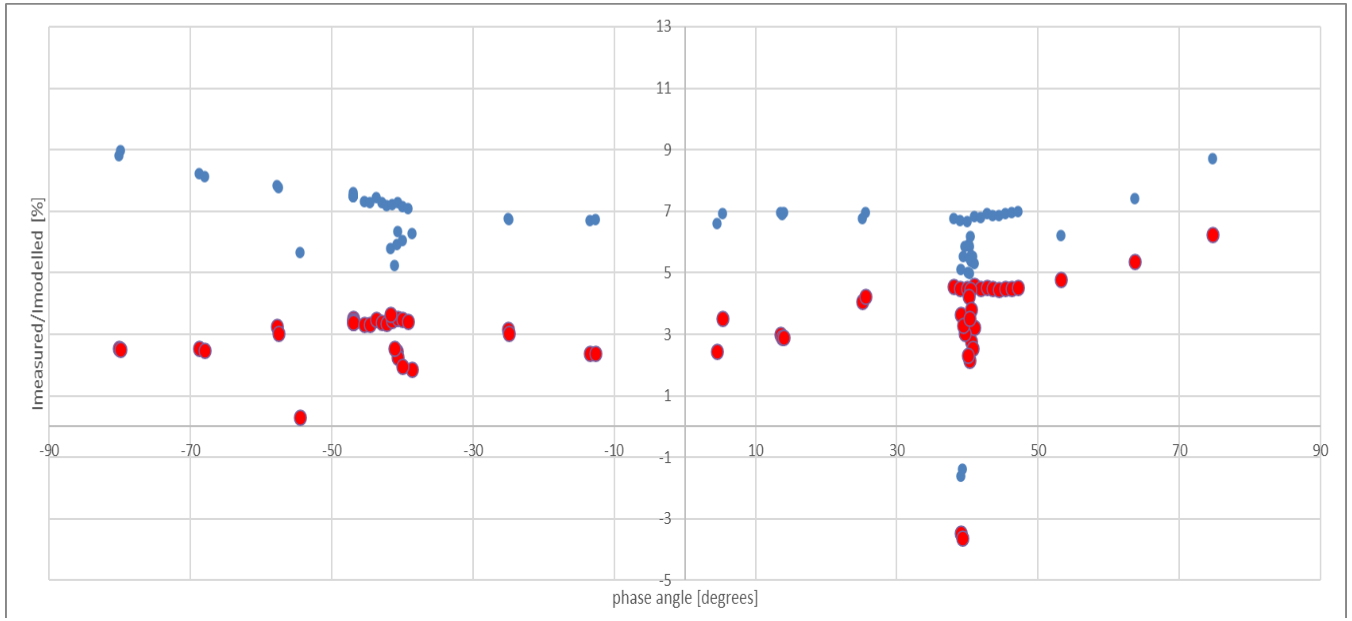




Date	B0	B1	B2	B3	PAN
01/12/2012	1.117	1.085	1.075	1.015	1.034
01/09/2013	1.112	1.079	1.071	1.013	1.034
01/12/2013	1.110	1.078	1.070	1.012	1.034
01/03/2014	1.108	1.076	1.069	1.011	1.034
01/06/2014	1.106	1.074	1.067	1.011	1.034
01/09/2014	1.104	1.072	1.066	1.010	1.034
01/12/2014	1.103	1.070	1.065	1.009	1.034
01/03/2015	1.100	1.068	1.064	1.008	1.034
01/06/2015	1.099	1.066	1.062	1.008	1.034
01/09/2015	1.097	1.064	1.062	1.007	1.034
01/12/2015	1.095	1.061	1.062	1.006	1.034
01/03/2016	1.093	1.061	1.062	1.006	1.034
01/06/2016	1.090	1.056	1.054	1.003	1.032
01/09/2016	1.089	1.055	1.053	1.003	1.031
01/01/2017	1.087	1.053	1.050	1.001	1.029
01/03/2017	1.085	1.051	1.048	1.000	1.028

PHR1B calibration table

Pleiades-1B vs LIME



PHR1B band 1 vs. USGS ROLO (blue) and LIME (red)

Pleiades-1B vs. LIME

%	BLUE	GREEN	RED	NIR	PAN
AVG	3.204	4.678	4.353	6.599	5.867
STDEV	1.497	1.243	1.062	1.232	9.599

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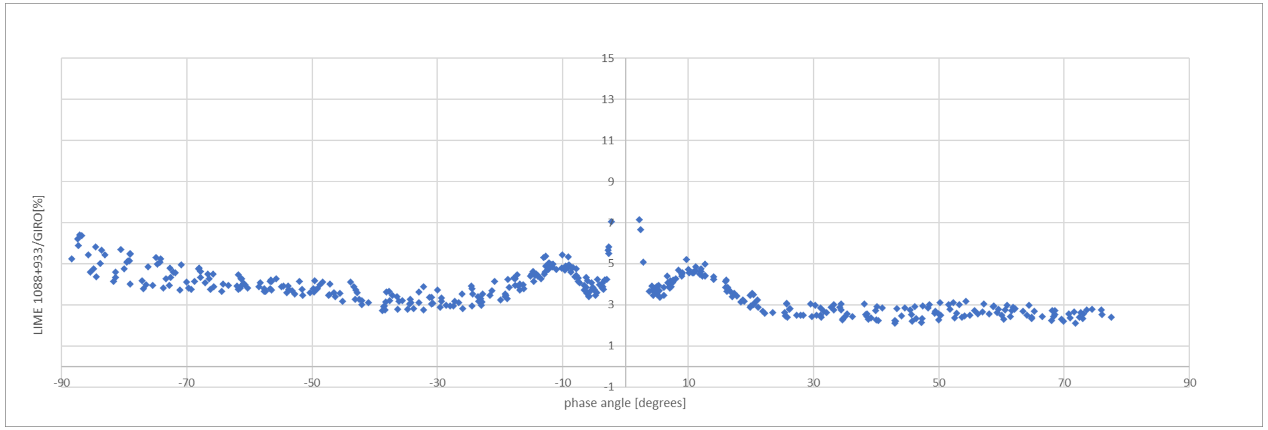
Comparisons with GIRO

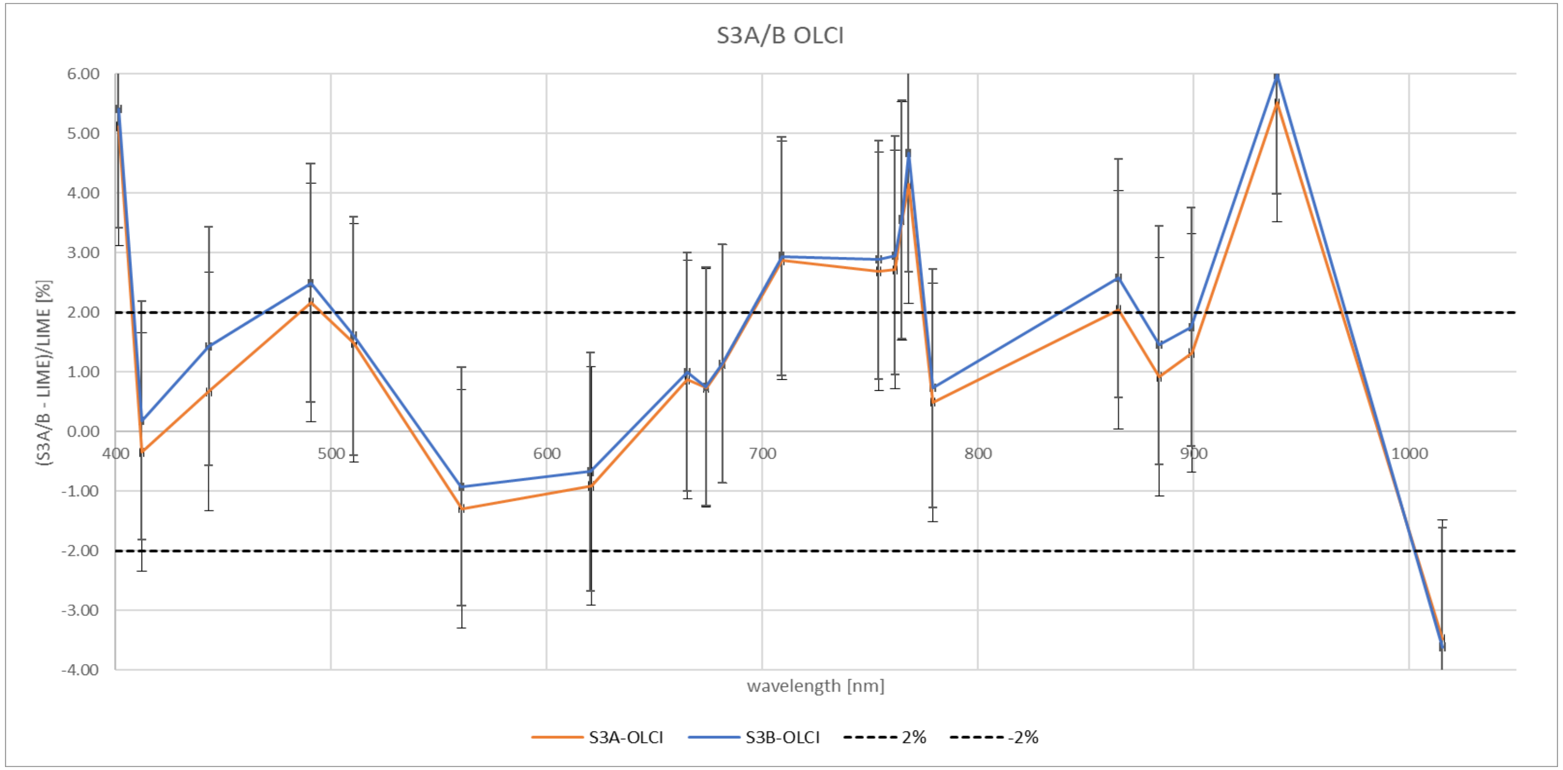


LIME vs. GIRO at 650nm

%	461	650	840	1604
AVERAGE	4.759	3.652	3.396	3.155
STDEV	1.512	0.917	0.836	1.201

- Simulation for one year of data
- Configured with Proba-V spectral response

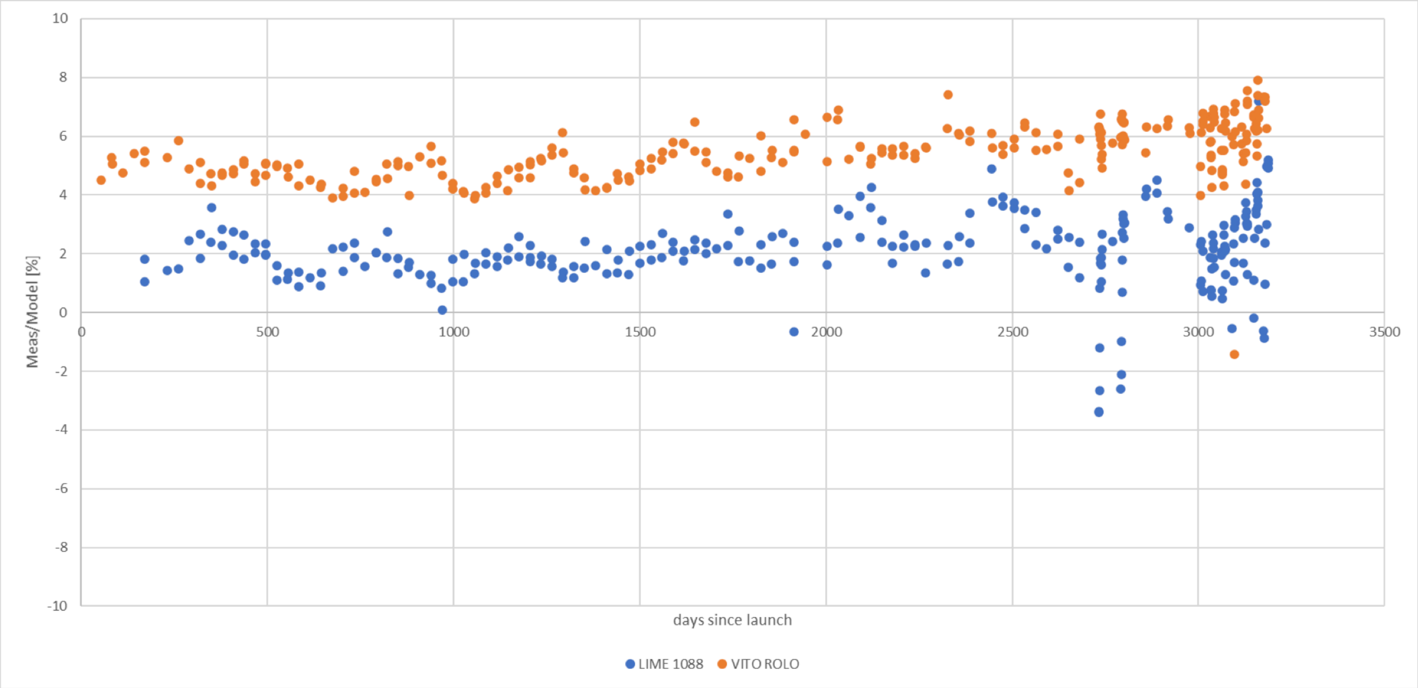
Comparison against S3A/B OLCI



Sensor	Timestamp
S3B	2018-07-27T05:22:43
S3A	2020-07-04T16:13:05

See also *Neneman, M.; Wagner, S.; Bourg, L.; Blanot, L.; Bouvet, M.; Adriaensen, S.; Nieke, J. Use of Moon Observations for Characterization of Sentinel-3B Ocean and Land Color Instrument. Remote Sens.* ***2020****, 12, 2543.*

Comparison against Proba-V



Full mission Proba-V NIR channel vs. LIME

BAND	BLUE	RED	NIR	SWIR
%	450nm	645nm	834nm	1665nm
AVG	-1.685	0.044	2.098	26.607
STDEV	1.935	1.988	1.297	0.854

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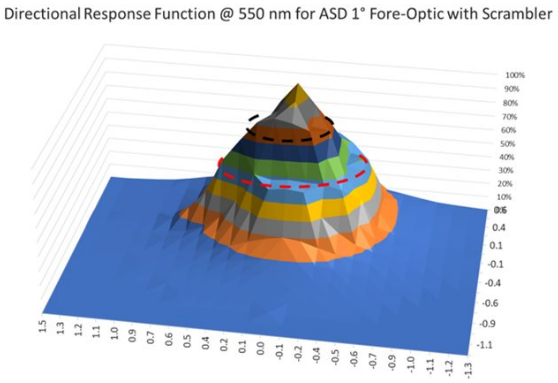
Hyperspectral measurements – improving the spectral interpolation of CIMEL measurements

LIME
LUNAR IRRADIANCE MODEL OF ESA



Hyperspectral instrument based on:
- ASD FieldSpec4
- Foreoptics (with scrambler) with 1 deg FOV
- Neutral density filter of Sun measurements

Characterised / calibrated at NPL

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Hyperspectral measurements – improving the spectral interpolation of CIMEL measurements

LUNAR IRRADIANCE MODEL OF ESA

- Automated daily acquistions covering 3 lunar cycles in spring 2022 (to be continued after summer)

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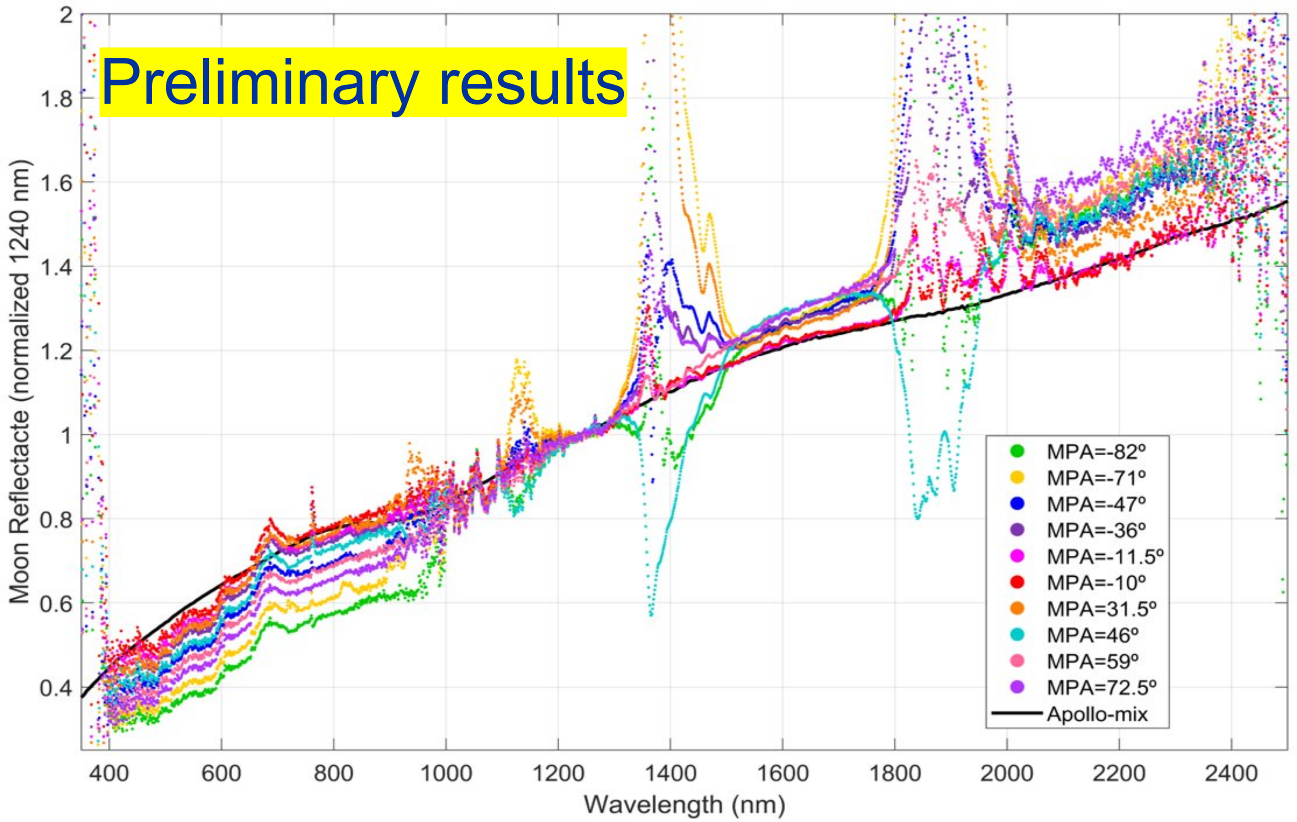
Hyperspectral measurements – improving the spectral interpolation of CIMEL measurements

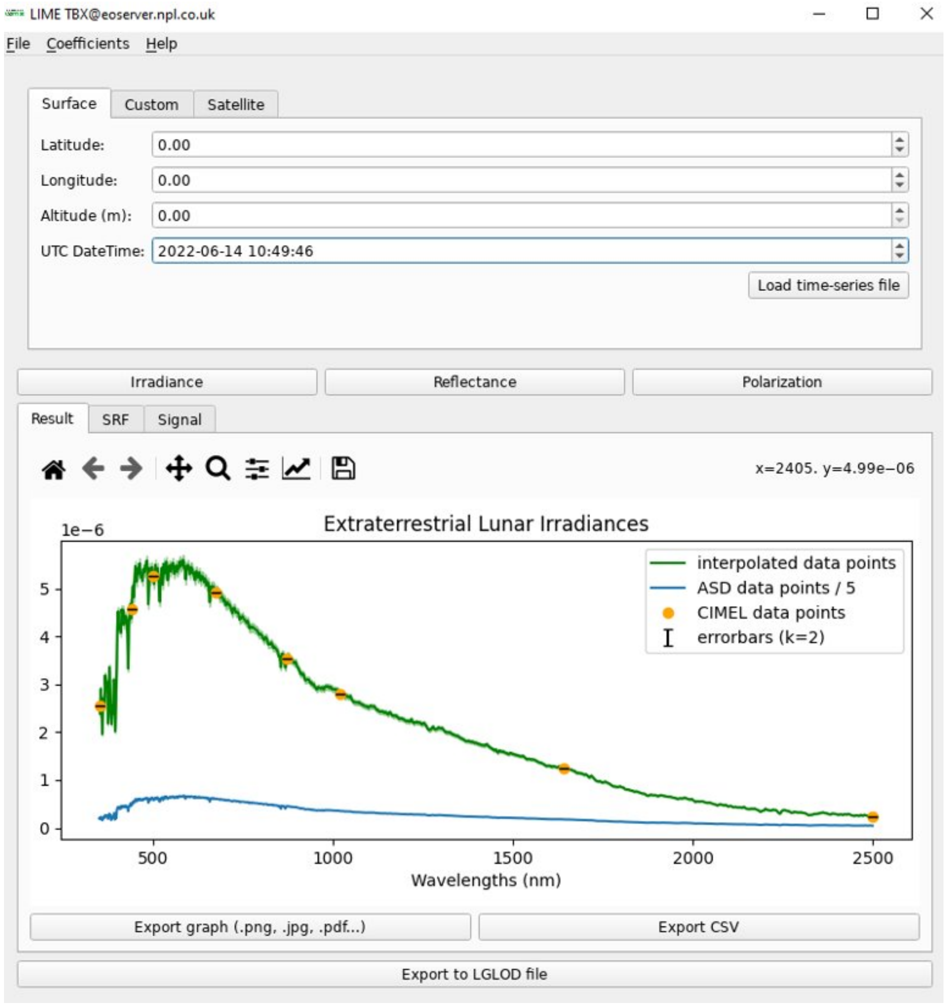
Reflectance spectra for various phase angles



LIME Toolbox development (ongoing)

LUNAR IRRADIANCE MODEL OF ESA

- Ongoing development allowing to simulate lunar irradiance based on LIME for any sensor position/spectral bands.
- Expected end 2023.
- Available to the community.



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Conclusion

- LIME model now based on 3+ years of continuous lunar measurements
- Yearly updates available on cal/val portal
- Ongoing efforts to continue to improve the model (new hyperspectral measurements, comparisons to sensors, e.g., air-LUSI)
- LIME toolbox should be available soon to the cal/val community

Thank you!

http://calvalportal.ceos.org/lime

LUNAR IRRADIANCE MODEL OF ESA

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