LIME: Lunar Irradiance Model of ESA

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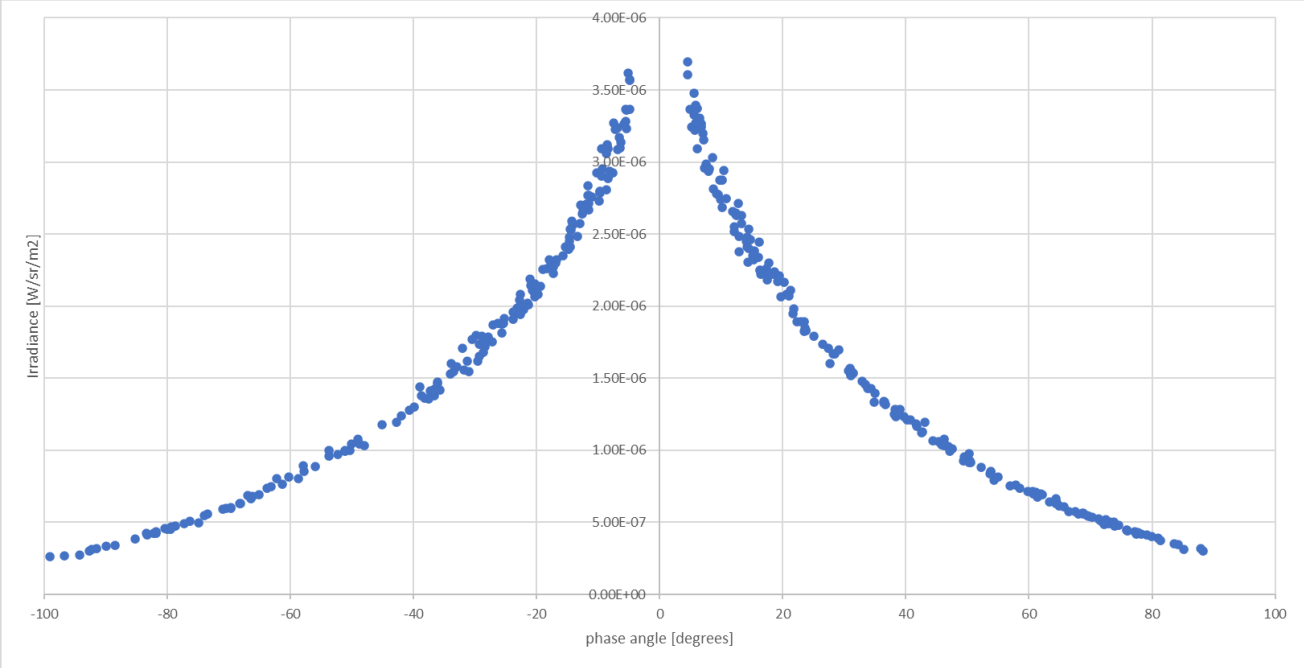
Overview

- Model overview
- Coefficient Regression
- Uncertainty analysis
- Spectral interpolation
- LIME Toolbox (Javier)
- Degree Of Linear Polarization

Model Overview



- 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 measurements corrected for observer/Moon/Sun distances based on more than 4 years of measurements for at 440 nm (about 440 lunar irradiance measurements)

Lunar Reflectance Model

LUNAR IRRADIANCE MODEL OF ESA

$$\ln(A_k) = \sum_{i=0}^{3} a_{ik} g^i + \sum_{i=1}^{3} b_{ik} \Phi^{2i-1} + c_{1k}\theta + c_{2k}\phi + c_{3k}\Phi\theta + c_{4k}\Phi\phi + d_{1k} e^{-\frac{gC}{p_1}} + d_{2k} e^{-\frac{gC}{p_2}} + d_{3k} \cos\left(\frac{gC - p_3}{p_4}\right)$$

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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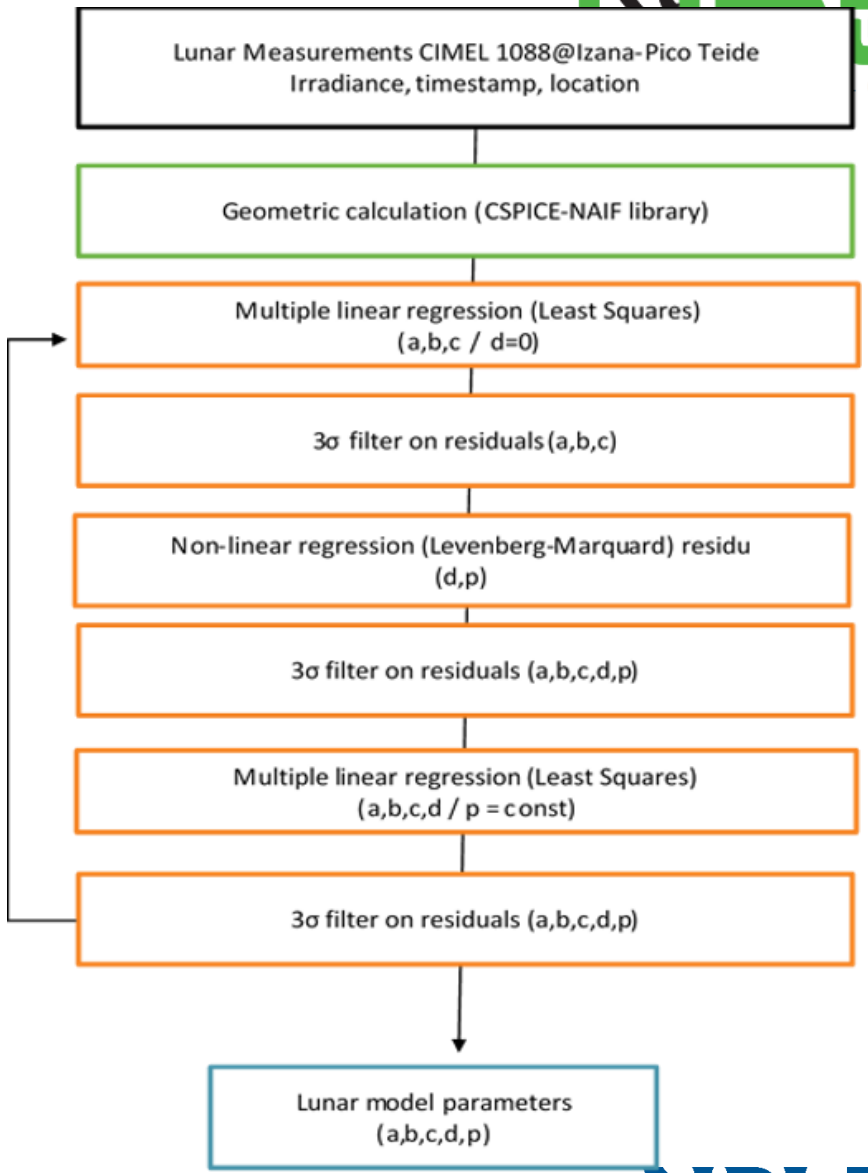
Coefficient Regression

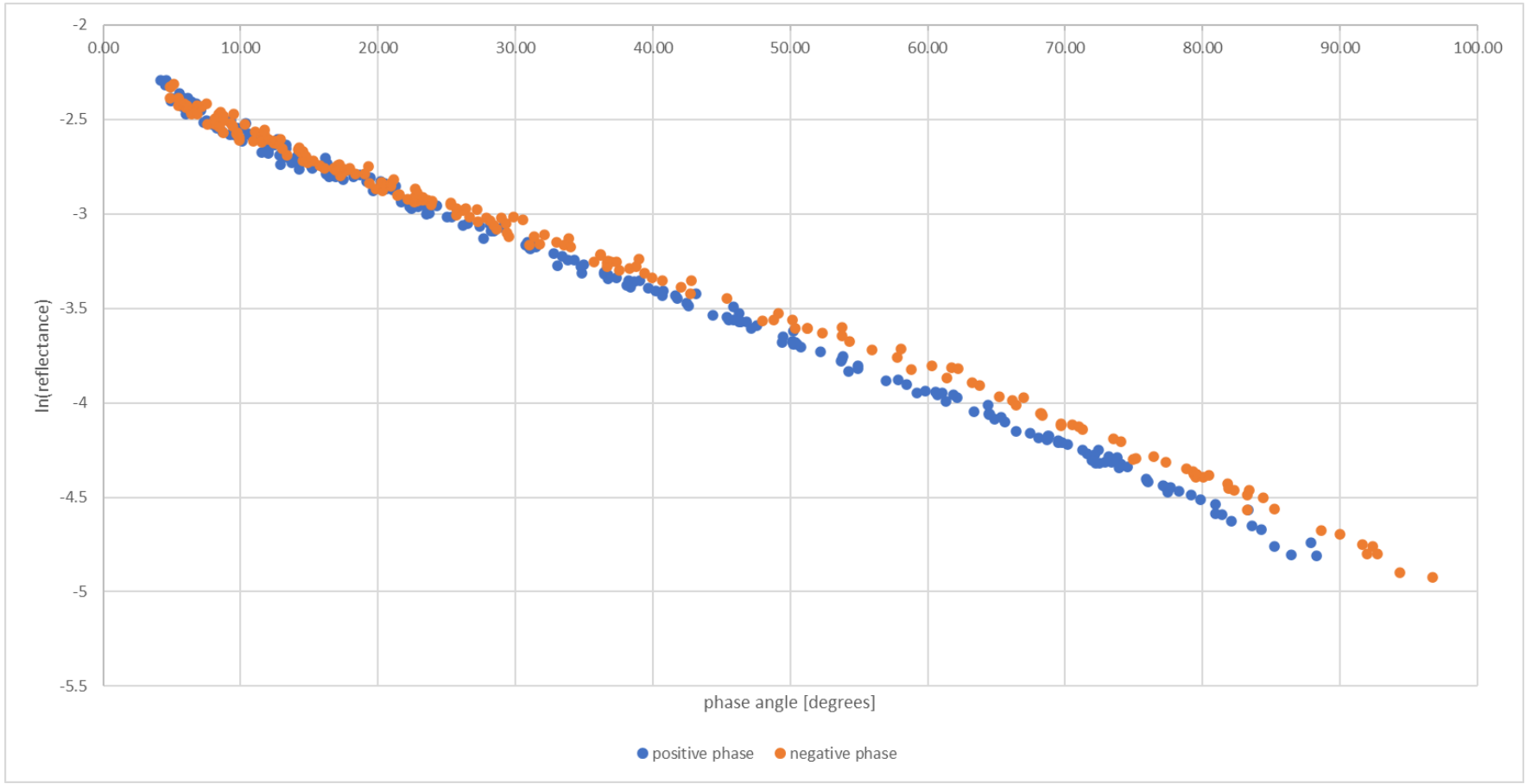
Regression sequence :

- Irradiance to reflectance conversion (applying TSIS-1)
- Fit the linear coefficients *a*, *b* and *c* (all *d* coefficients equal to zero)
- Remove outlier 3-sigma from the residuals :
  - Residual = (measurement irradiance – model as is)
- Perform non-linear regression for d-coefficients and p-coefficients
- Remove outlier 3-sigma from the residuals
- Perform fitting over all linear coefficients : a, b, c, d
  - non-linear p coefficients previous step
- Remove outliers based on residuals full model

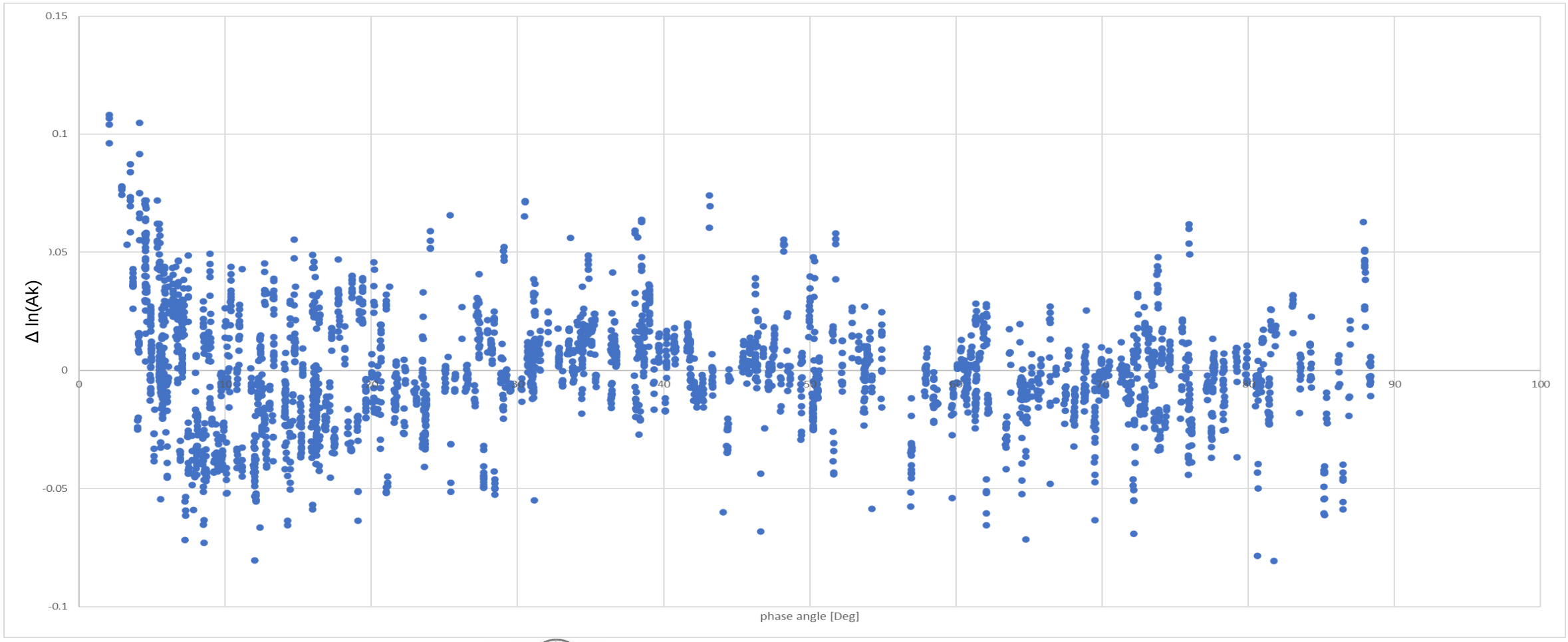
After the first iteration, a second full iteration is performed



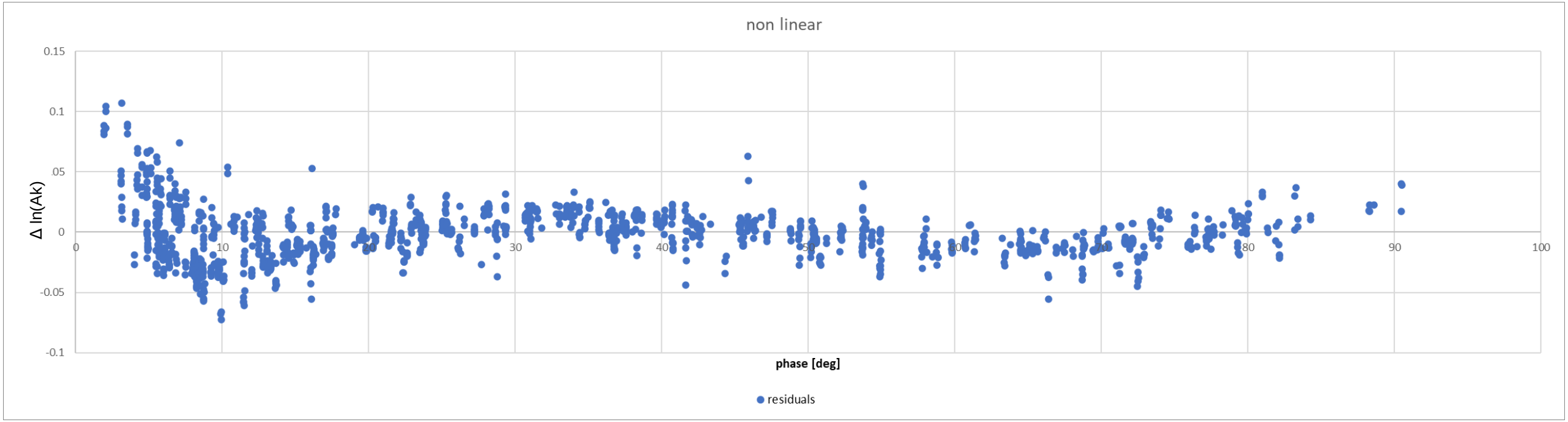
Coefficient Regression : measurement log reflectance



Coefficient Regression : residual to polynomial fit – phase angle

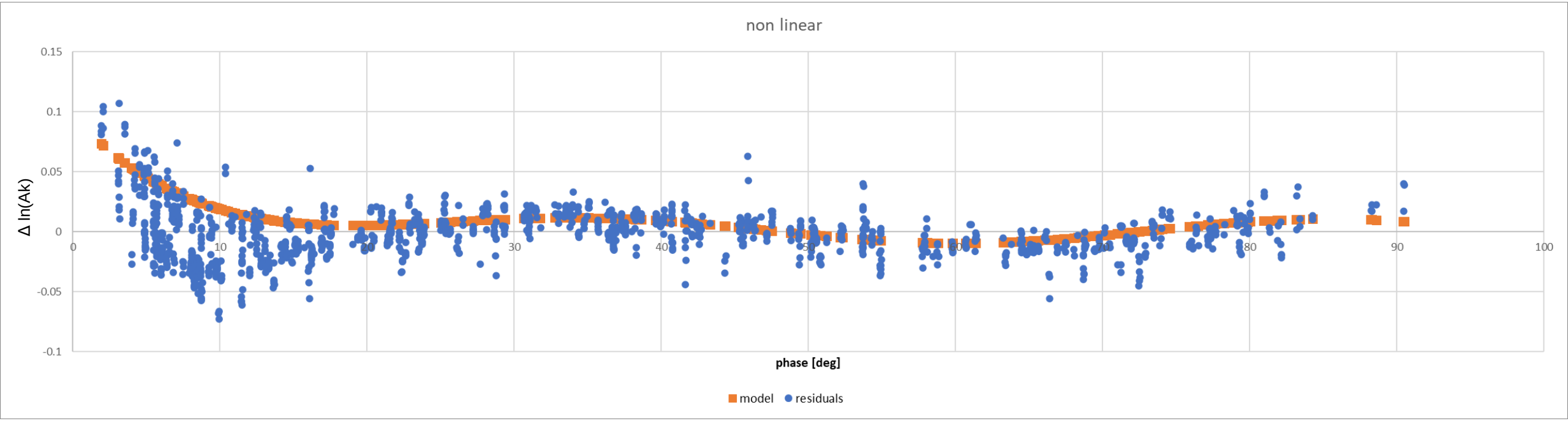


Coefficient Regression : residual to polynomial fit – phase angle

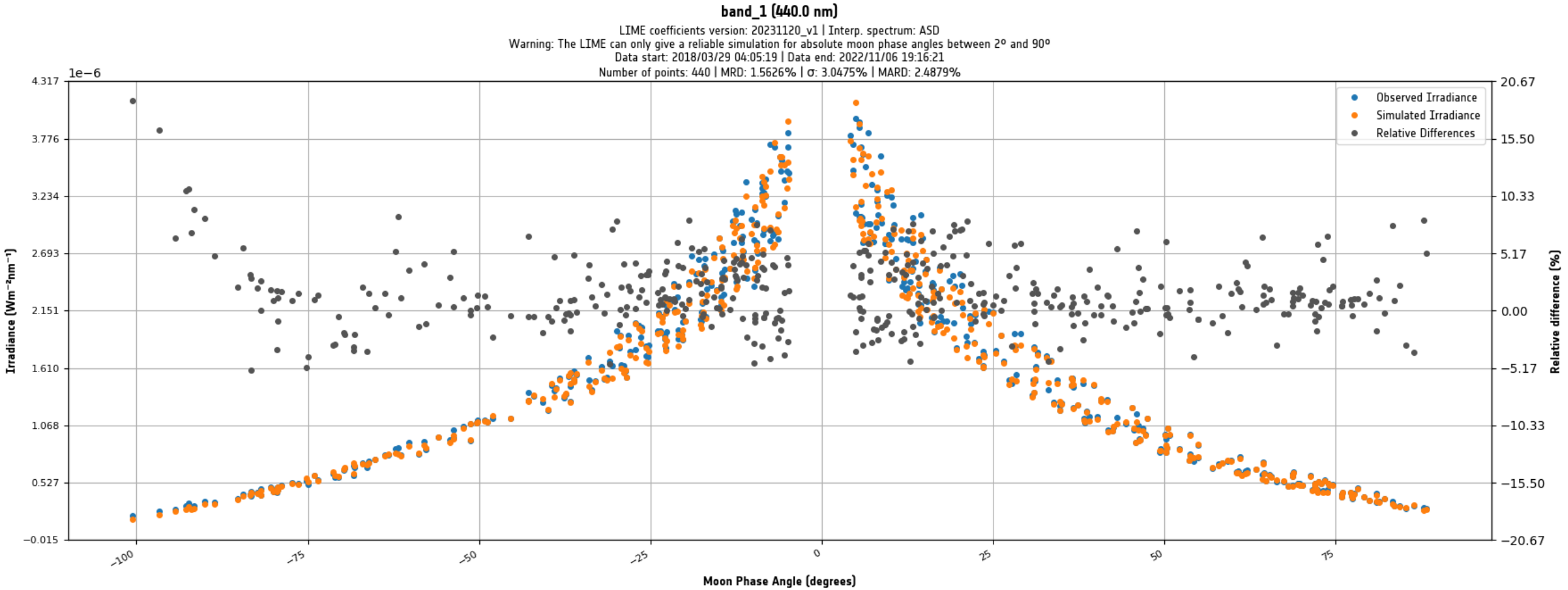


After removing the upper Langley uncertainty values (median values ~0.11%)

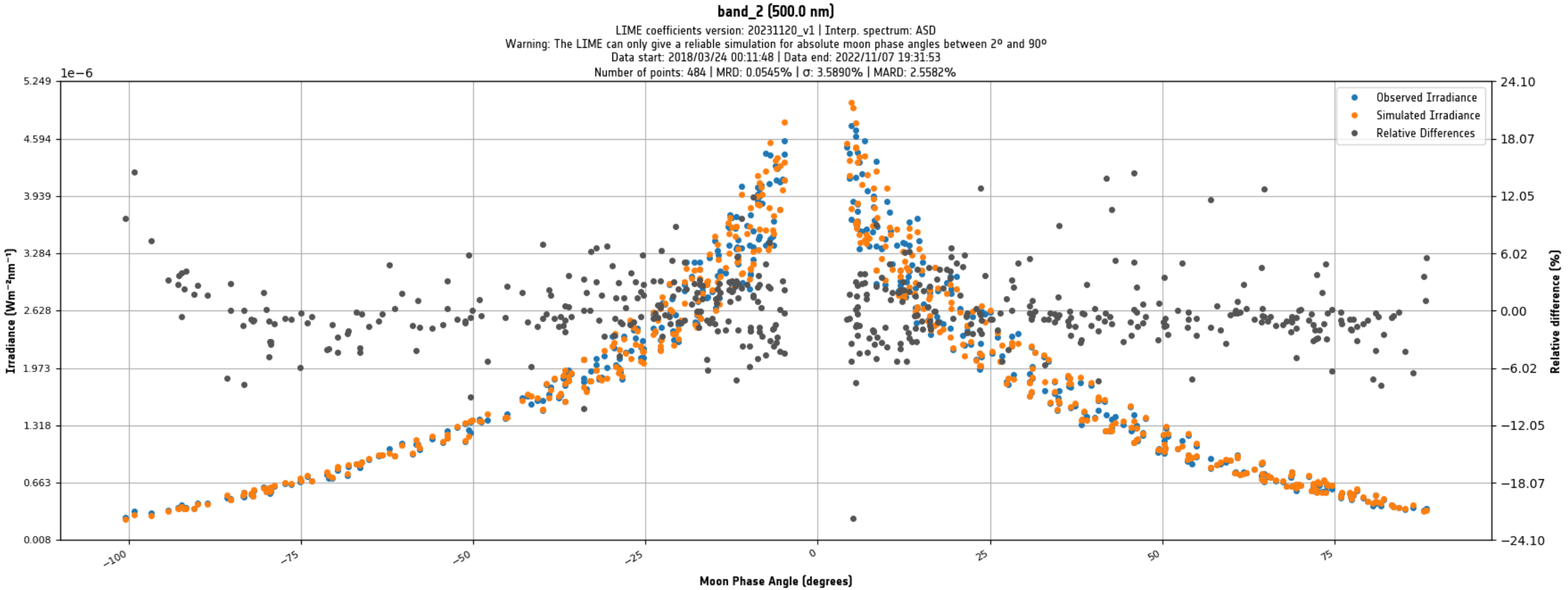
Coefficient Regression : residual to polynomial fit – phase angle



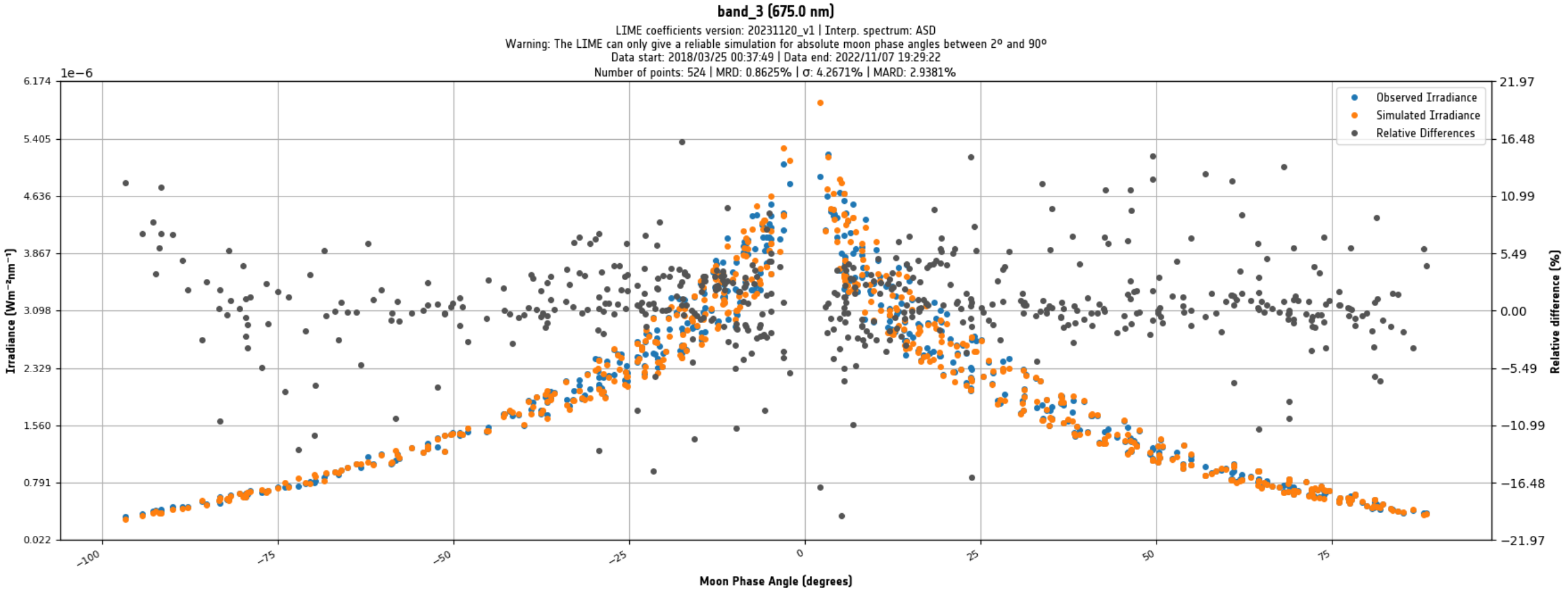
Final performance: relative difference in irradiance wrt all CIMEL measurements (reintroducing measurements filtered during model fitting)



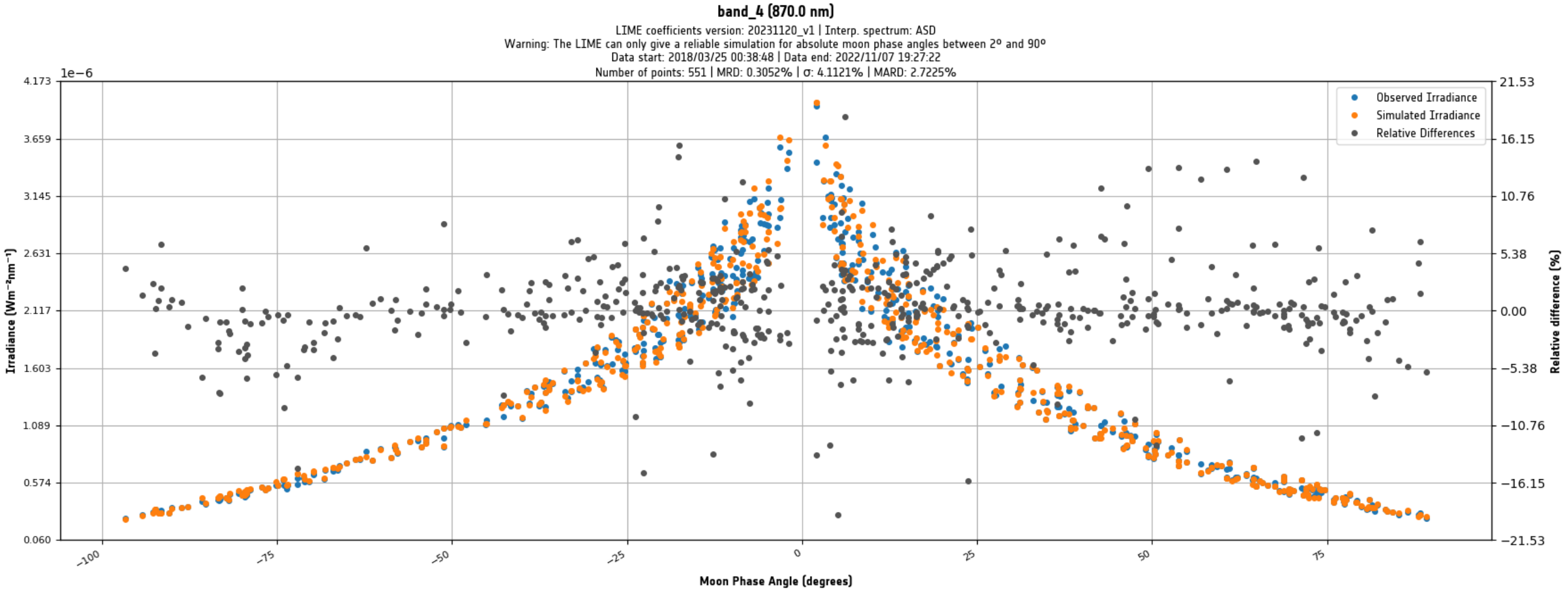
Final performance: relative difference in irradiance wrt all CIMEL measurements (reintroducing measurements filtered during model fitting)



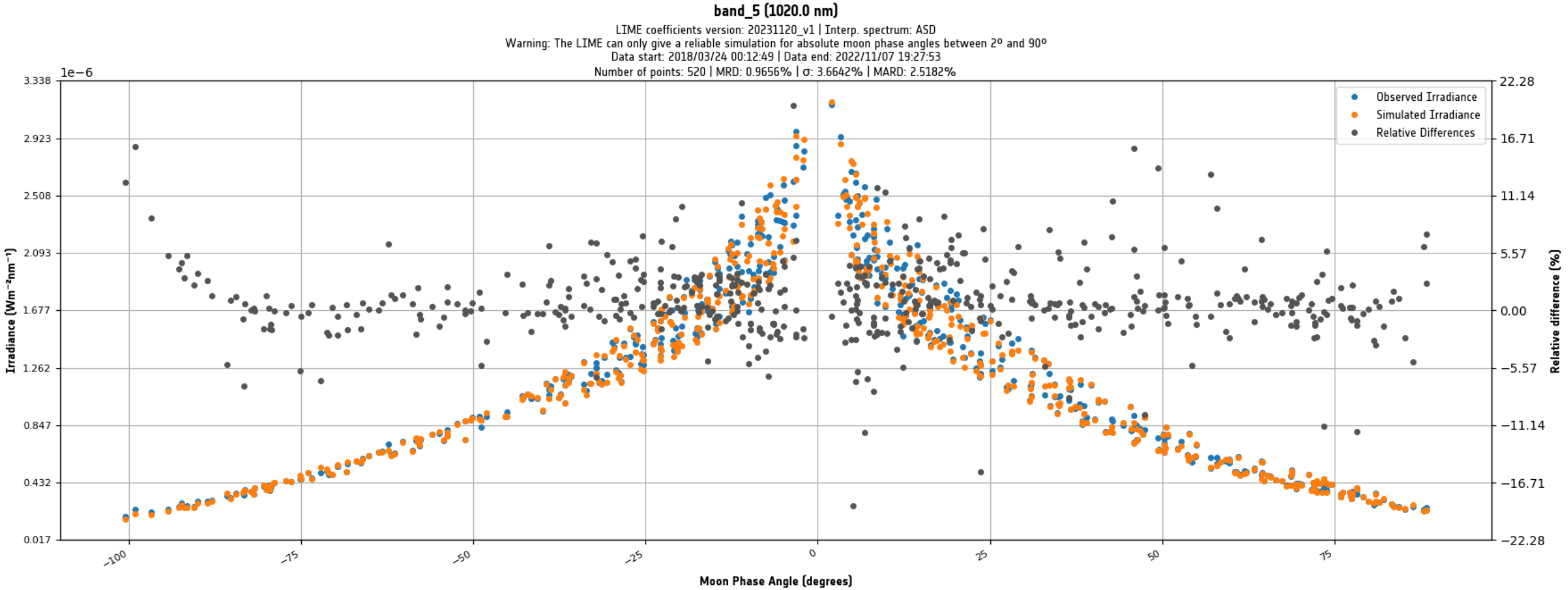
Final performance: relative difference in irradiance wrt all CIMEL measurements (reintroducing measurements filtered during model fitting)



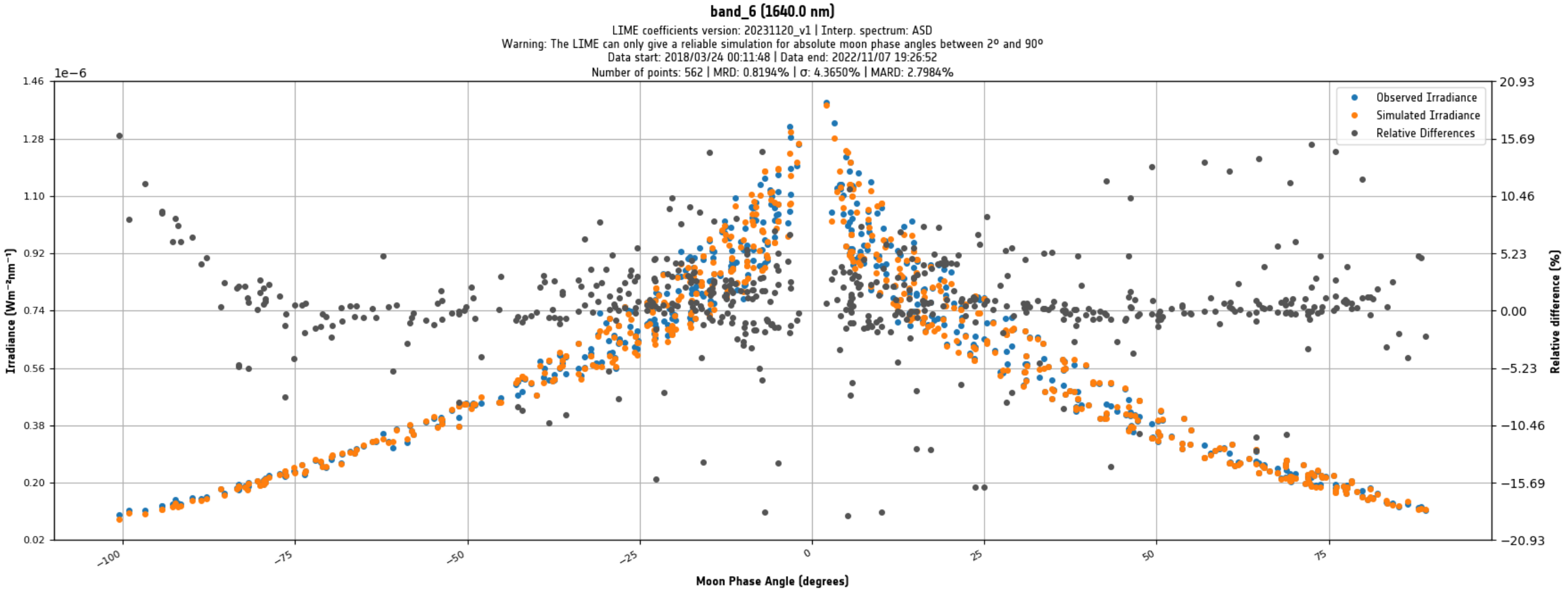
Final performance: relative difference in irradiance wrt all CIMEL measurements (reintroducing measurements filtered during model fitting)



Final performance: relative difference in irradiance wrt all CIMEL measurements (reintroducing measurements filtered during model fitting)



Final performance: relative difference in irradiance wrt all CIMEL measurements (reintroducing measurements filtered during model fitting)



Coefficient Regression : model parameters

LUNAR IRRADIANCE MODEL OF ESA

wl [nm]	a0	a1	a2	a3	b1	b2	b3
440	-2.2512	-2.18724	1.079583	-0.47752	0.048273	0.022578	-0.01016
500	-2.1239	-2.08042	0.958826	-0.4252	0.044062	0.018495	-0.00692
675	-1.8828	-1.99794	0.983553	-0.4559	0.04588	0.017006	-0.00741
870	-1.74906	-1.86916	0.856575	-0.4009	0.047385	0.01586	-0.00421
1020	-1.68441	-1.8366	0.871022	-0.41836	0.053858	0.017565	-0.0066
1640	-1.37617	-1.55937	0.70443	-0.38787	0.048349	0.010047	-0.00412
wl [nm]	c1	c2	c3	c4	d1	d2	d3
440	0.000994	-0.0004	0.001578	0.000952	1.49109	-0.00624	-0.00571
500	0.00043	-0.00103	0.001204	0.000463	1.637928	-0.01004	-0.00273
675	0.00074	-0.00123	0.001562	0.000982	0.699086	-0.0025	-0.00594
870	0.00049	-0.00098	0.001677	0.00069	0.503896	-0.00192	-0.00342
1020	0.000386	-0.00128	0.001503	0.000597	0.491352	-0.00314	-0.00255
1640	0.000315	-0.00091	0.001347	0.001181	0.373388	-0.00227	3.48E-06
	p1	p2	p3	p4			
all	1.393821	15.10385	12.07322	8.061068			

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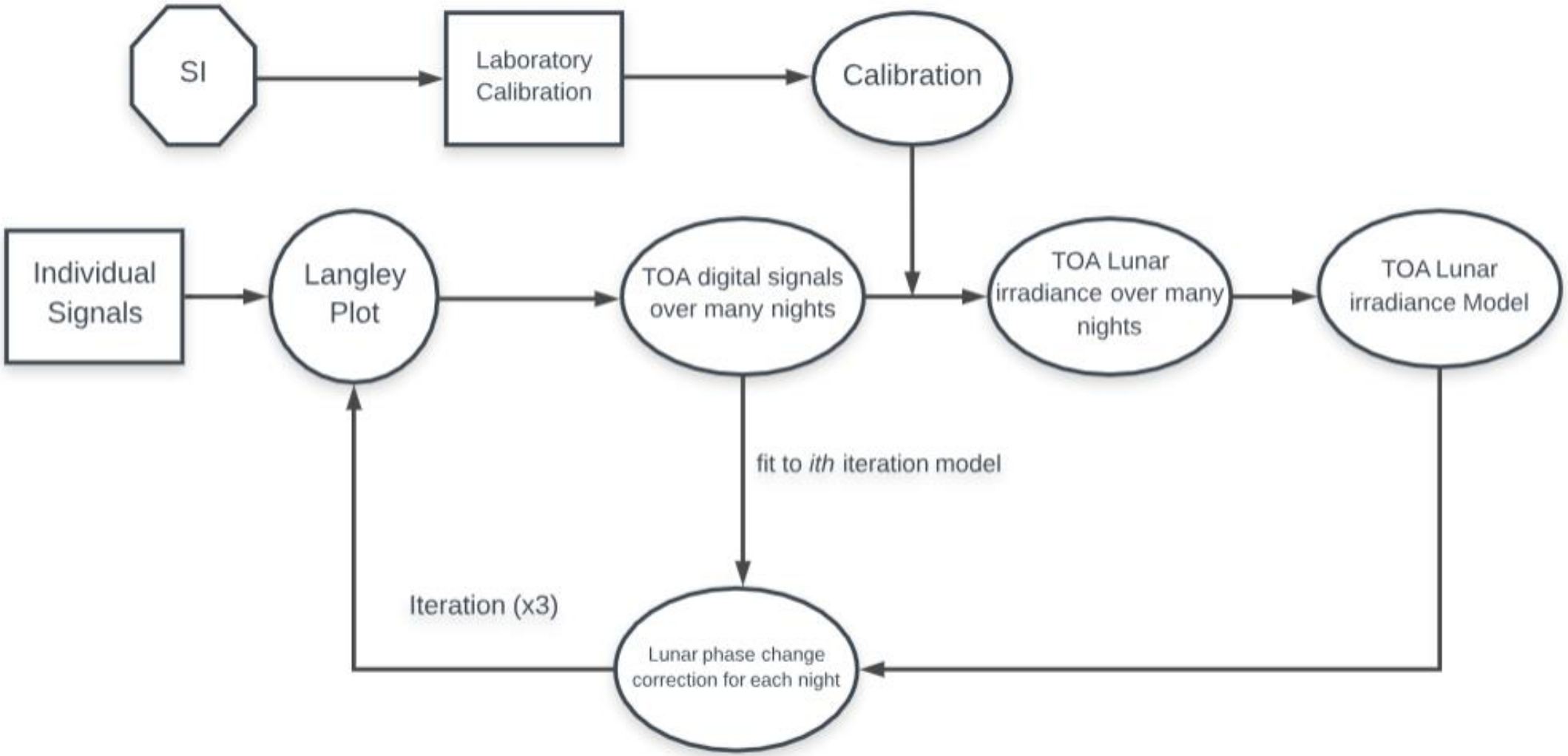
Uncertainty Analysis



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

- Monte Carlo approach is used to propagate uncertainties, taking into account error-correlations

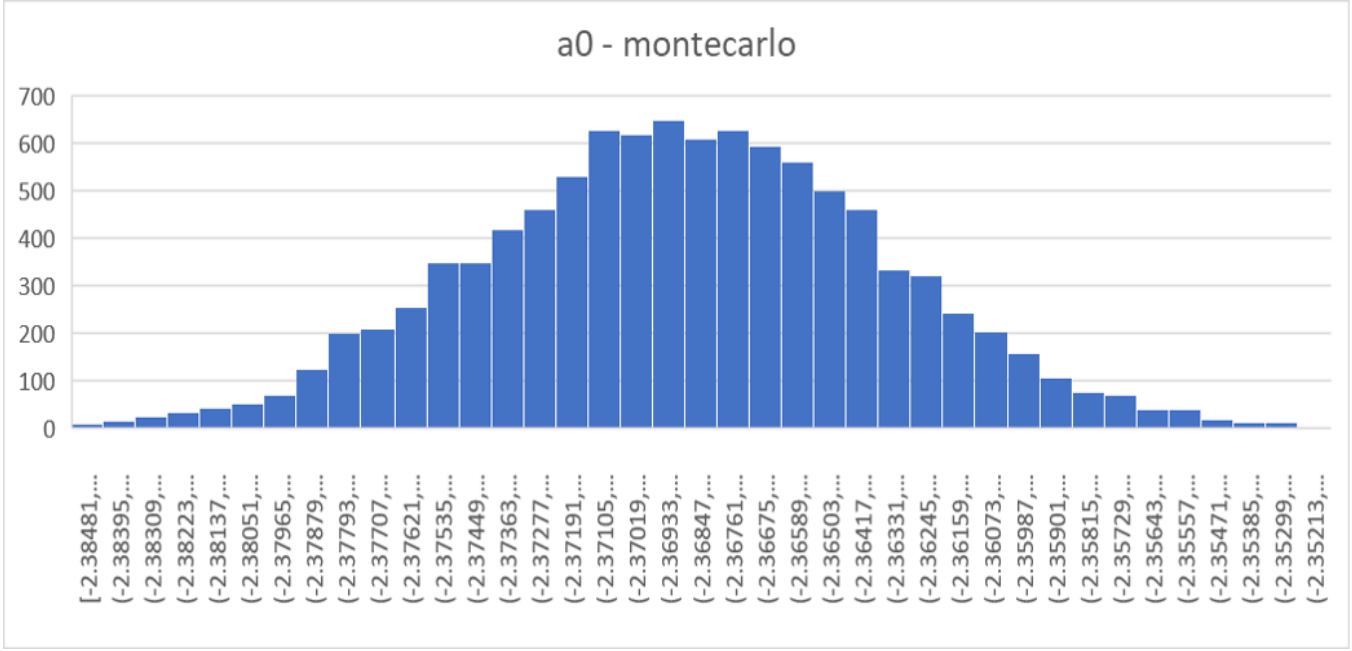
- CoMet-toolkit is used for uncertainty propagation using 1000 MC iterations

- Includes random measurement uncertainties, systematic instrument uncertainties, regression uncertainties & interpolation uncertainties

LUNAR IRRADIANCE MODEL OF ESA

CoMet

www.comet-toolkit.org



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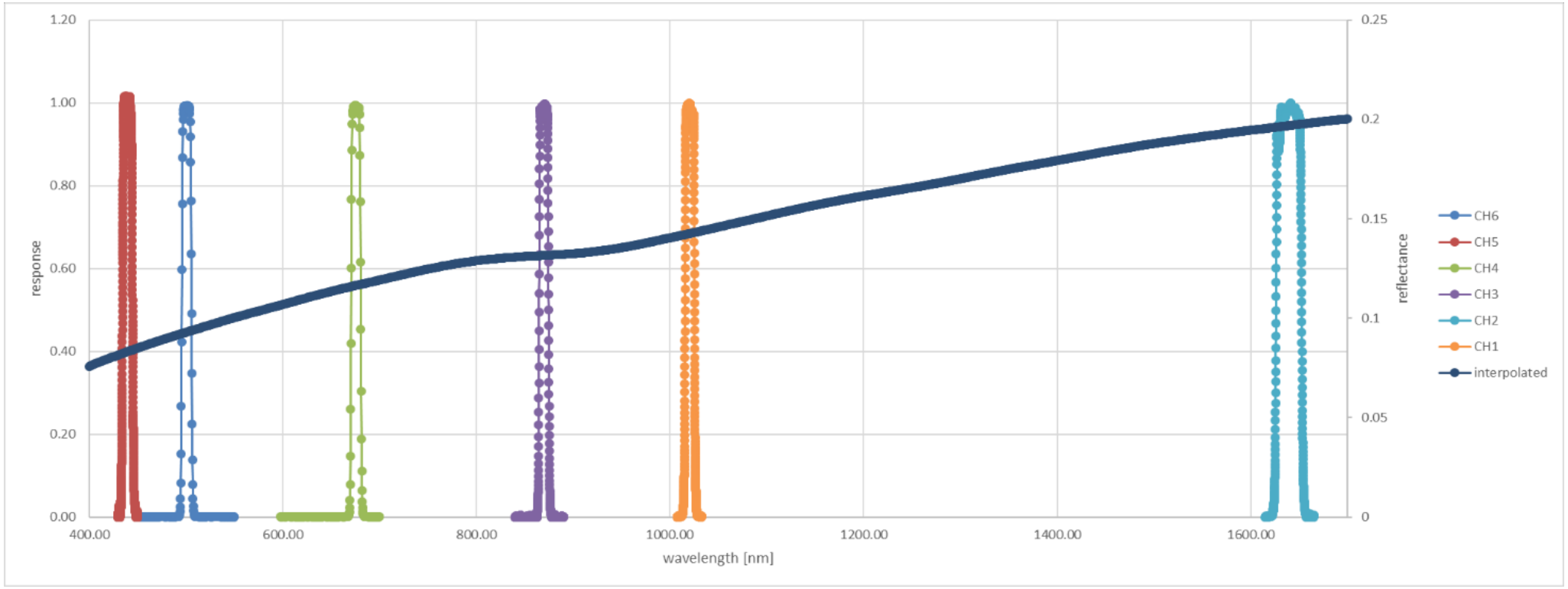
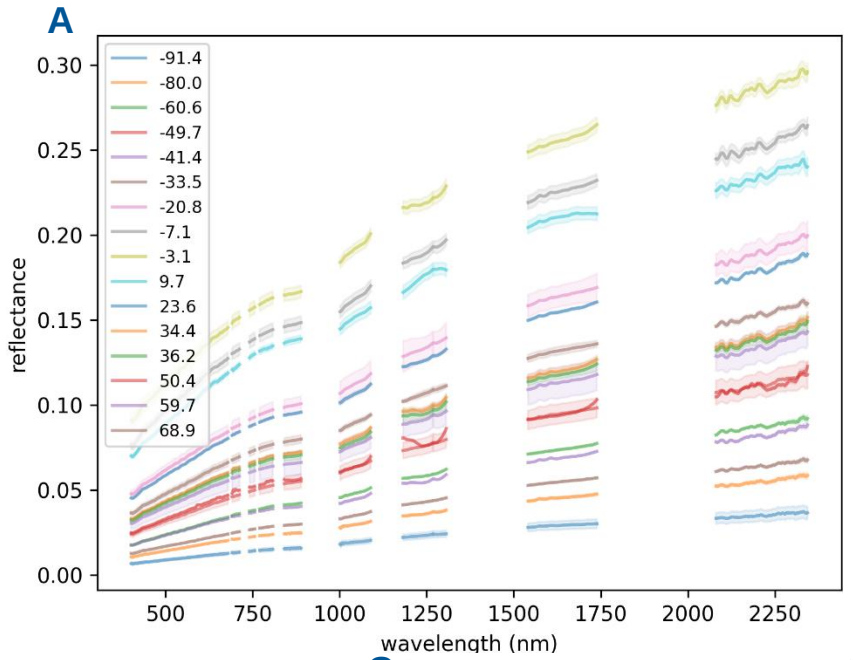
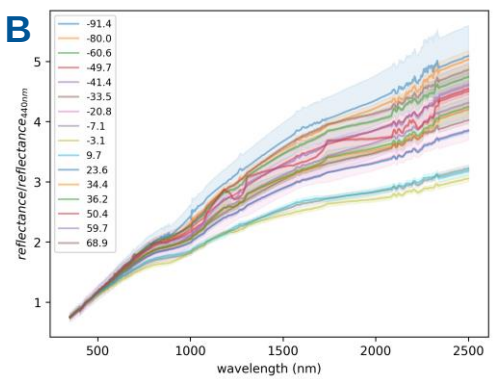
Spectral interpolation

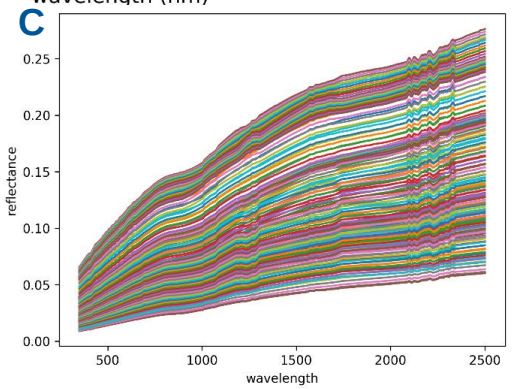


LIME spectral interpolation dataset

- ASD measurements were taken over 3-month campaign
- Measurements in absorption features are too noisy and are omitted (replaced using spectral interpolation)
- Data divided in bins of 10° spanning -95° to 95° (Fig A)
- Dependence of spectral shape with phase angle (Fig B)
- linearly interpolated with phase angle to phase angle required within the LIME-TBX (Fig C)

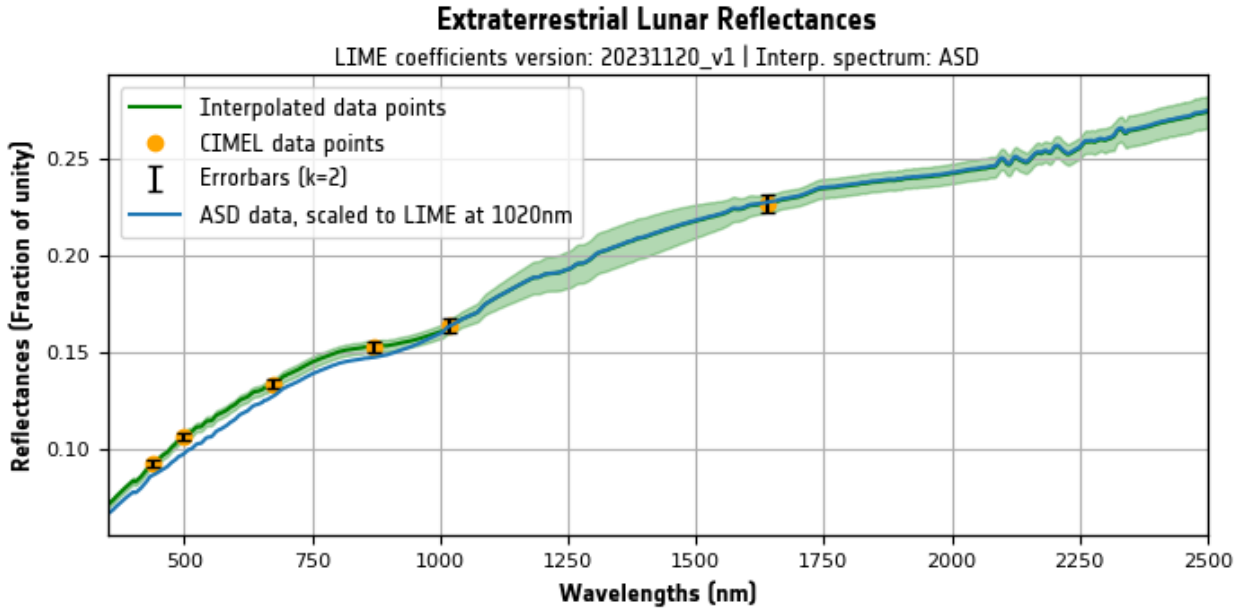






Spectral interpolation method

- ASD measurements (rescaled to CIMEL measurements – see plot) are used by default in LIME TBX (Apollo spectrum can be optionally used)
- Reference dataset is rescaled to go through the LIME model reflectances at CIMEL wavelengths (taking into account SRF)
- Scaling factors are spectrally interpolated
- CoMet toolkit used (including uncertainties)



www.comet-toolkit.org

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.
- Available to the community.
- Expected end 2023.

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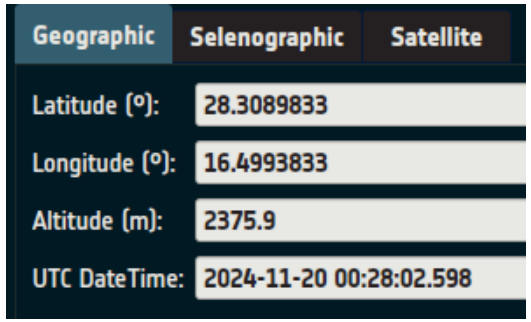
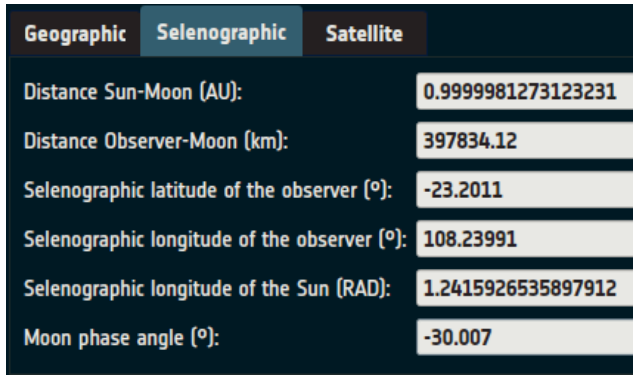
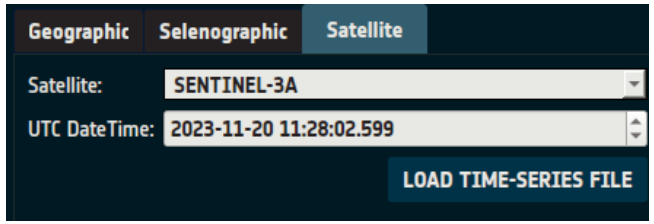
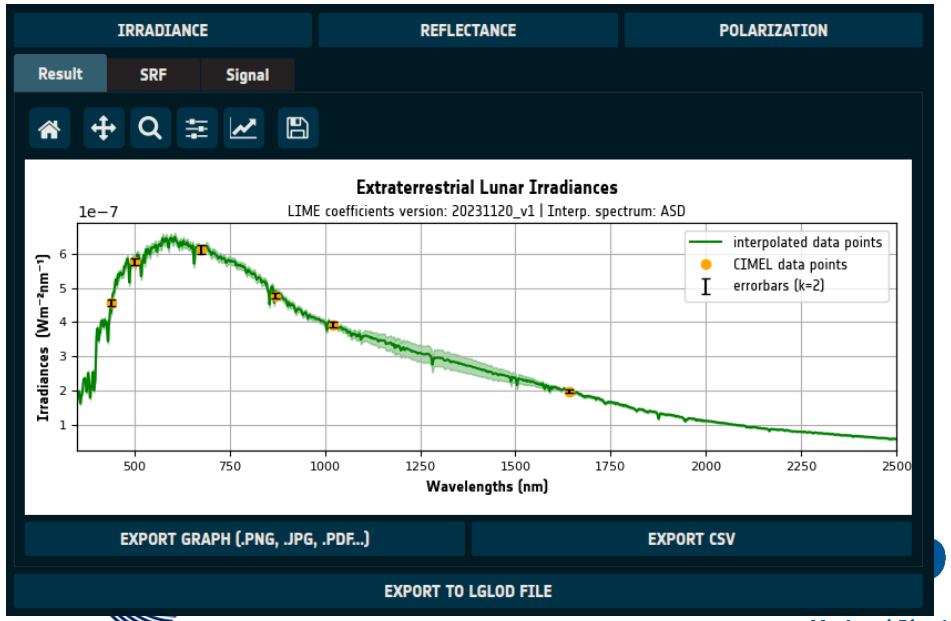
TBX Main Functionalities - Simulation

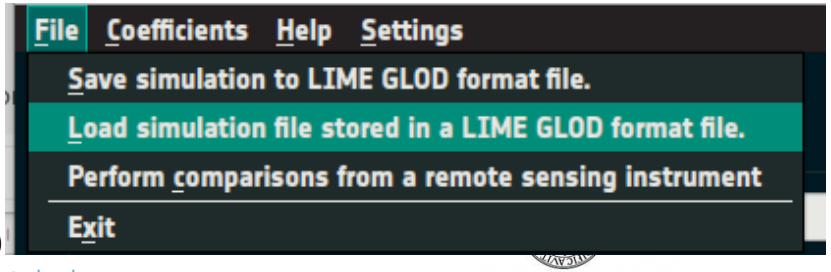
- Irradiance, Reflectance & Polarization
- Input:
  - Geographic coordinates & datetime/s
  - Selenographic coordinates
  - Satellite name & datetime/s
  - Optional: SRF file in GLOD format
- Output:
  - CSV
  - Graph (jpg, png, pdf...)
  - netCDF (LGLOD format, reloadable)





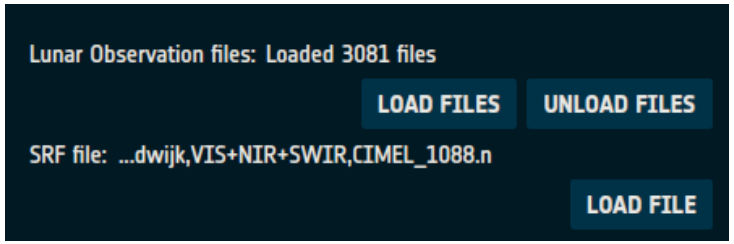




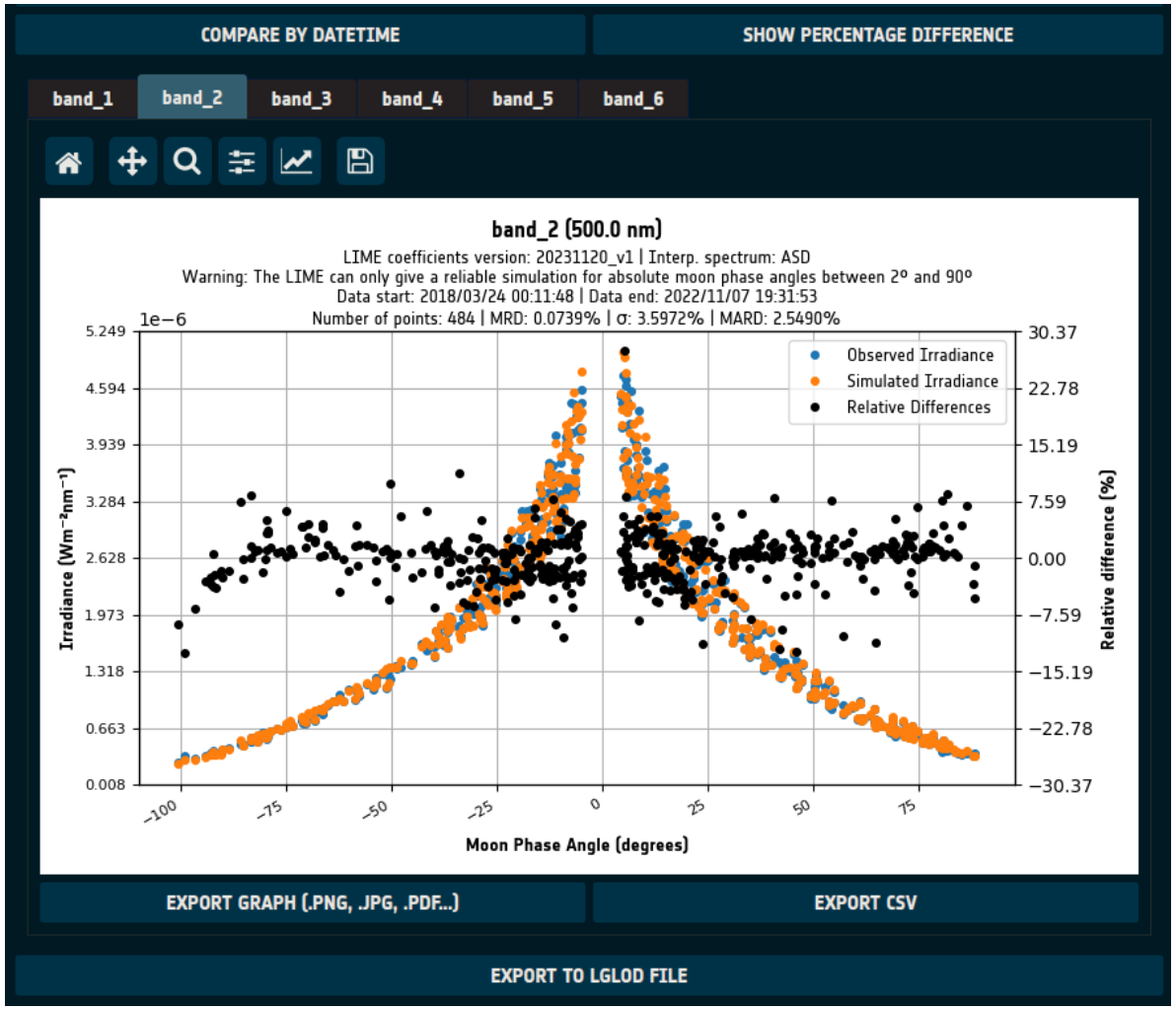


TBX Main Functionalities - Comparison

- Irradiance
  - Compare by MPA or by datetime
- Input: Observation files in GLOD format
  - & SRF file in GLOD format

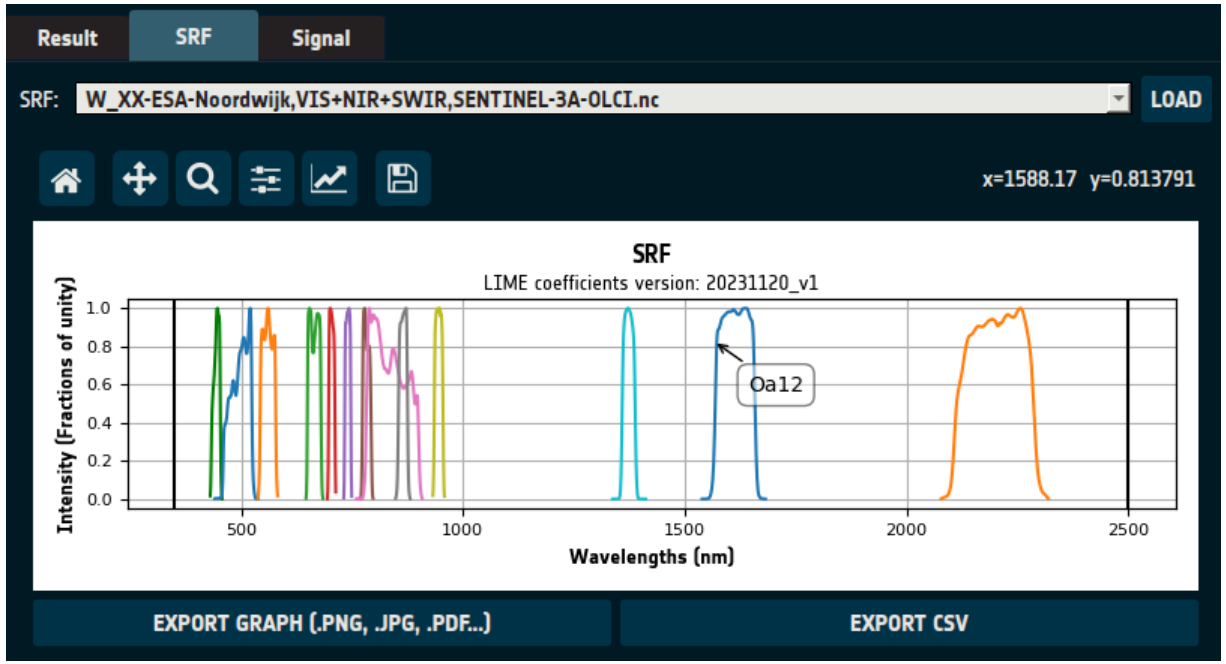


- Output:
  - CSV
  - Graph (jpg, png, pdf...)
  - netCDF (LGLOD format, reloadable)



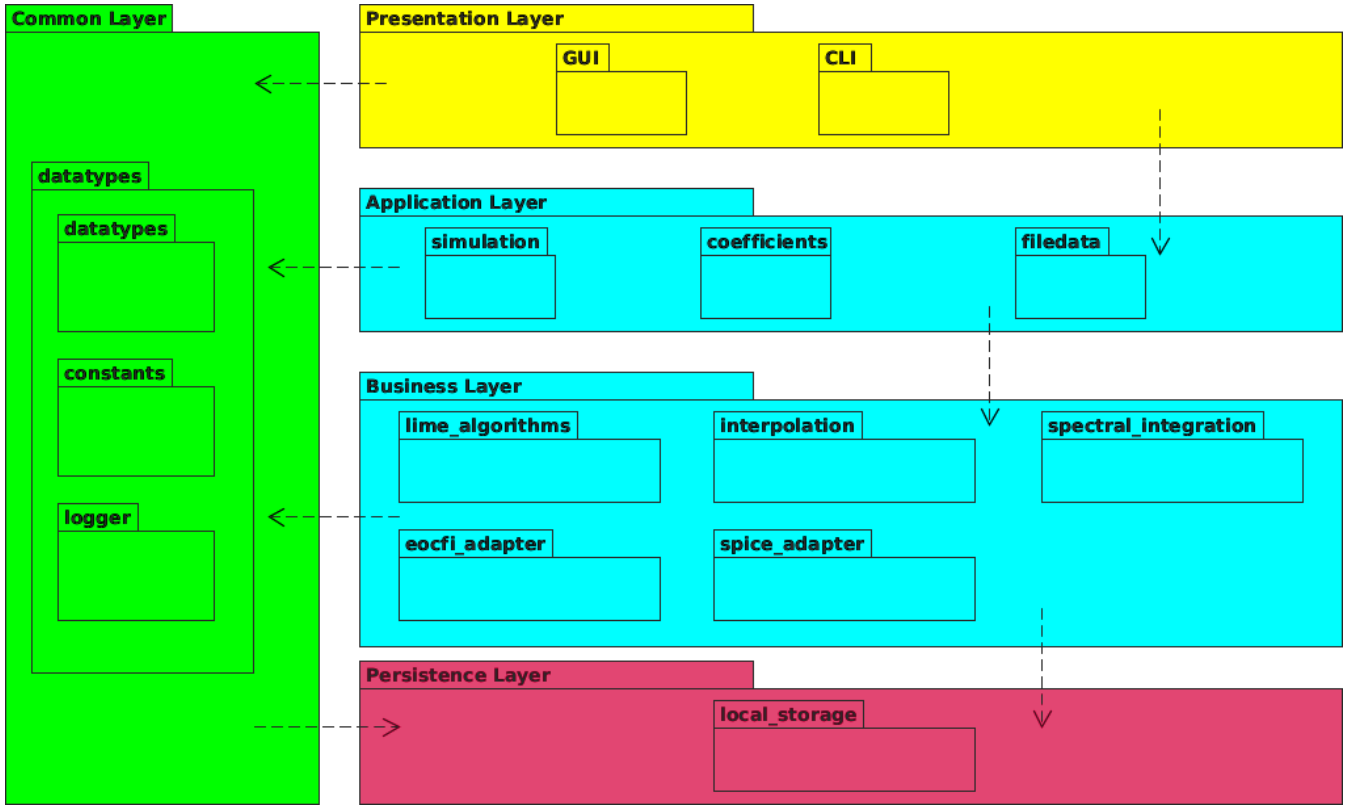
TBX Main Functionalities - Other

- Reading SRFs
  - NetCDF file in GLOD format
- Downloading & switching between coefficient versions
- Command line interface
  - Same features as GUI

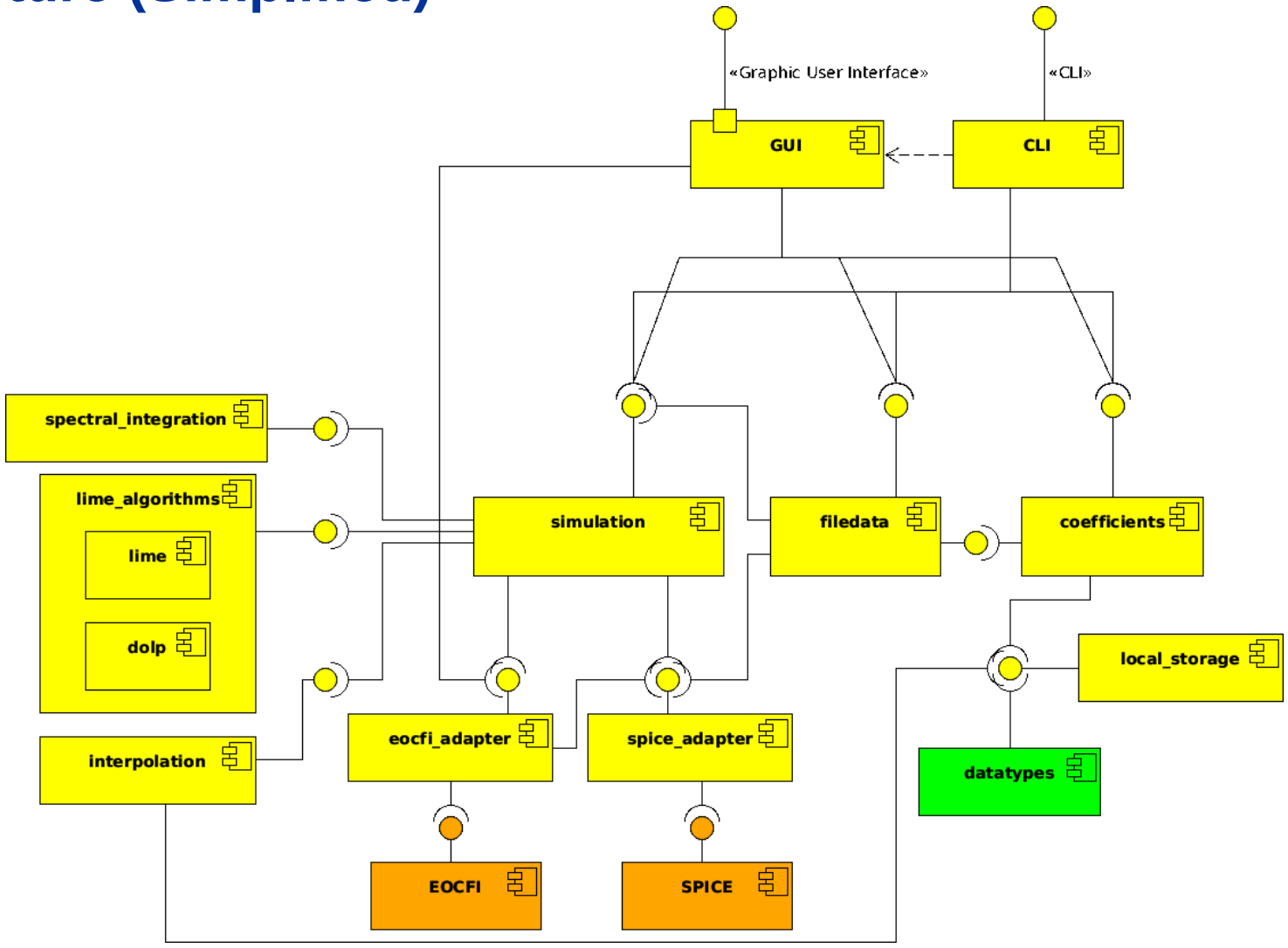


TBX Architecture (Simplified)

- **Multitier architecture**
- **Modules:**
- **GUI**: graphical user interface
- **CLI**: command-line interface
- **simulation**: Manages comparisons and simulations.
- **filedata**: Reading and storing data in multiple formats like .csv or .nc. It also checks that the GLOD format is correctly followed.
- **coefficients**: Accessing system's coefficients and downloading new ones.
- **lime_algorithms**: Performing LIME algorithms to calculate irradiance, reflectance or the degree of lunar polarization.
- **interpolation**: Interpolating using the different available options and spectra.
- **spectral_integration**: Performing spectral integrations over spectral response functions and more data.
- **eocfi_adapter**: Module that adapts an interface for the EOCFI library.
- **spice_adapter**: Module that adapts an interface for the SPICE library using spiceypy and spicedmoon.
- **local_storage**: Access to system's local storage to write the log files or to load the coefficients and the system options.
- **datatypes**: Datatypes and other definitions and features that are useful for most modules.



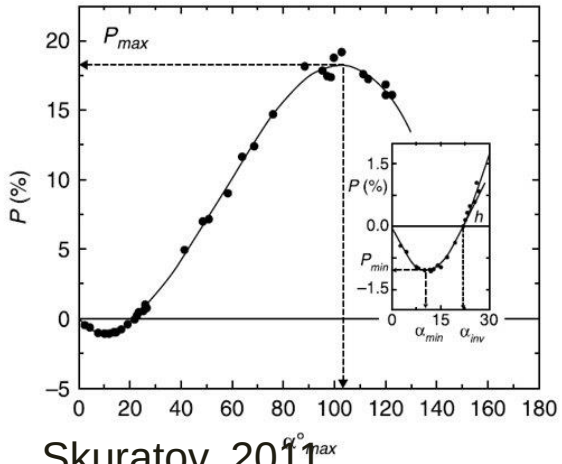
TBX Architecture (Simplified)



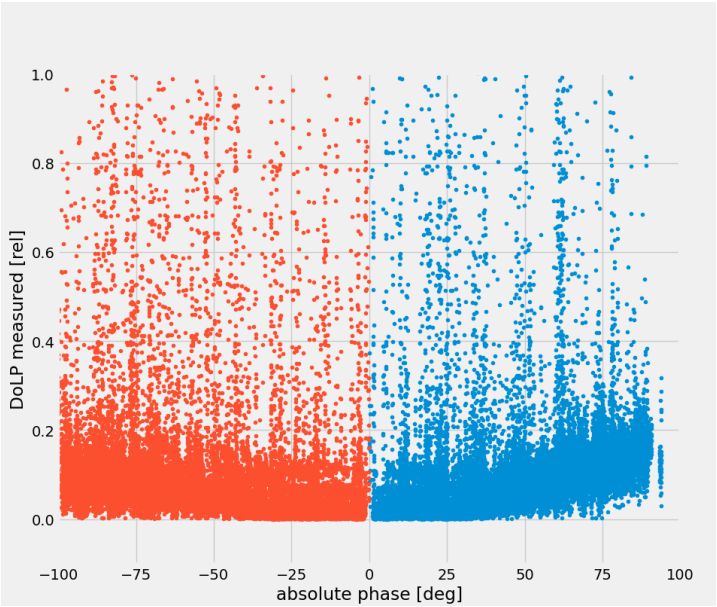
Simplified composite structure diagram

Degree of Linear Polarisation measurements

- Cimel measures DoLP
- Large scatter in ‘raw’ DoLP data
- Filtering based on :
  - Limitation max value
  - Binning per 1 degrees over full phase
  - Median values per bin
- Fit these values to Chebyshev polynomal
- Pos and Neg phase separately
- 4th order polynomial

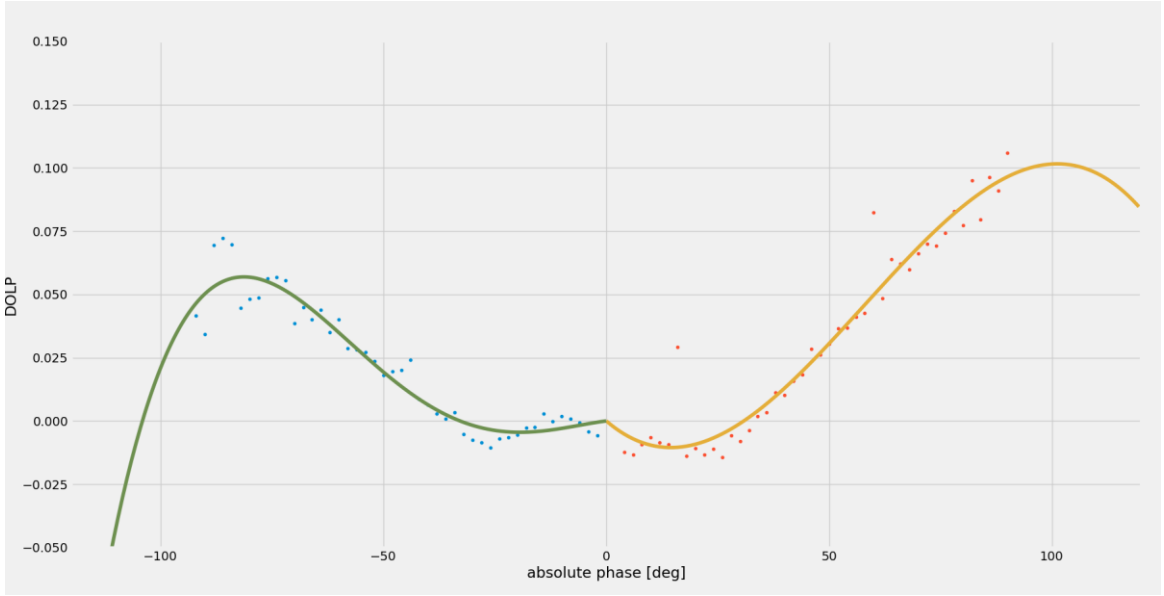


Skuratov, 2011

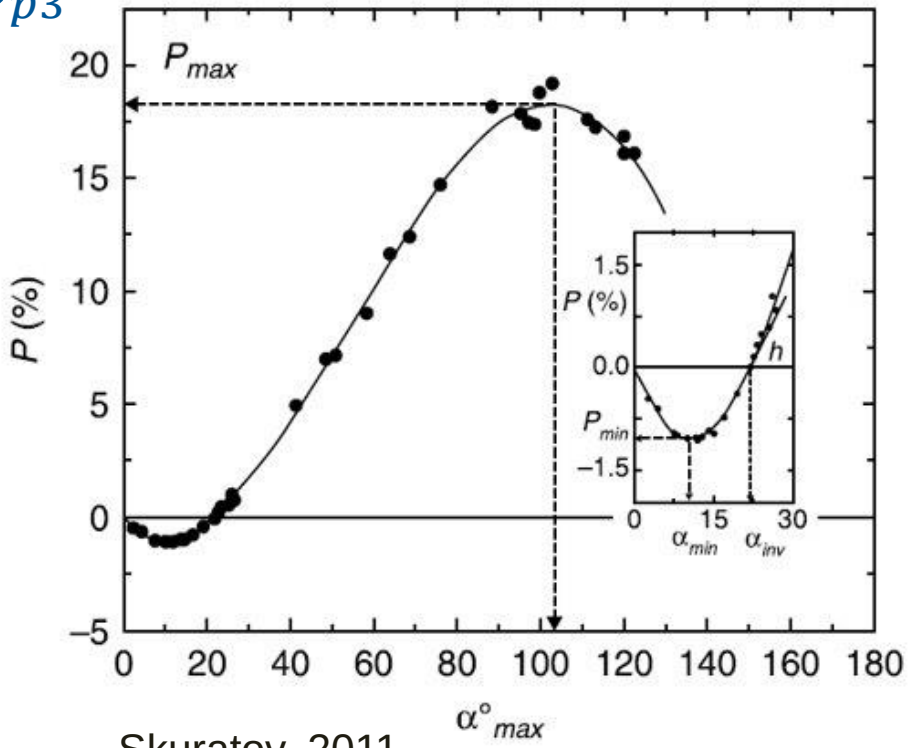


Degree of Linear Polarisation measurements

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



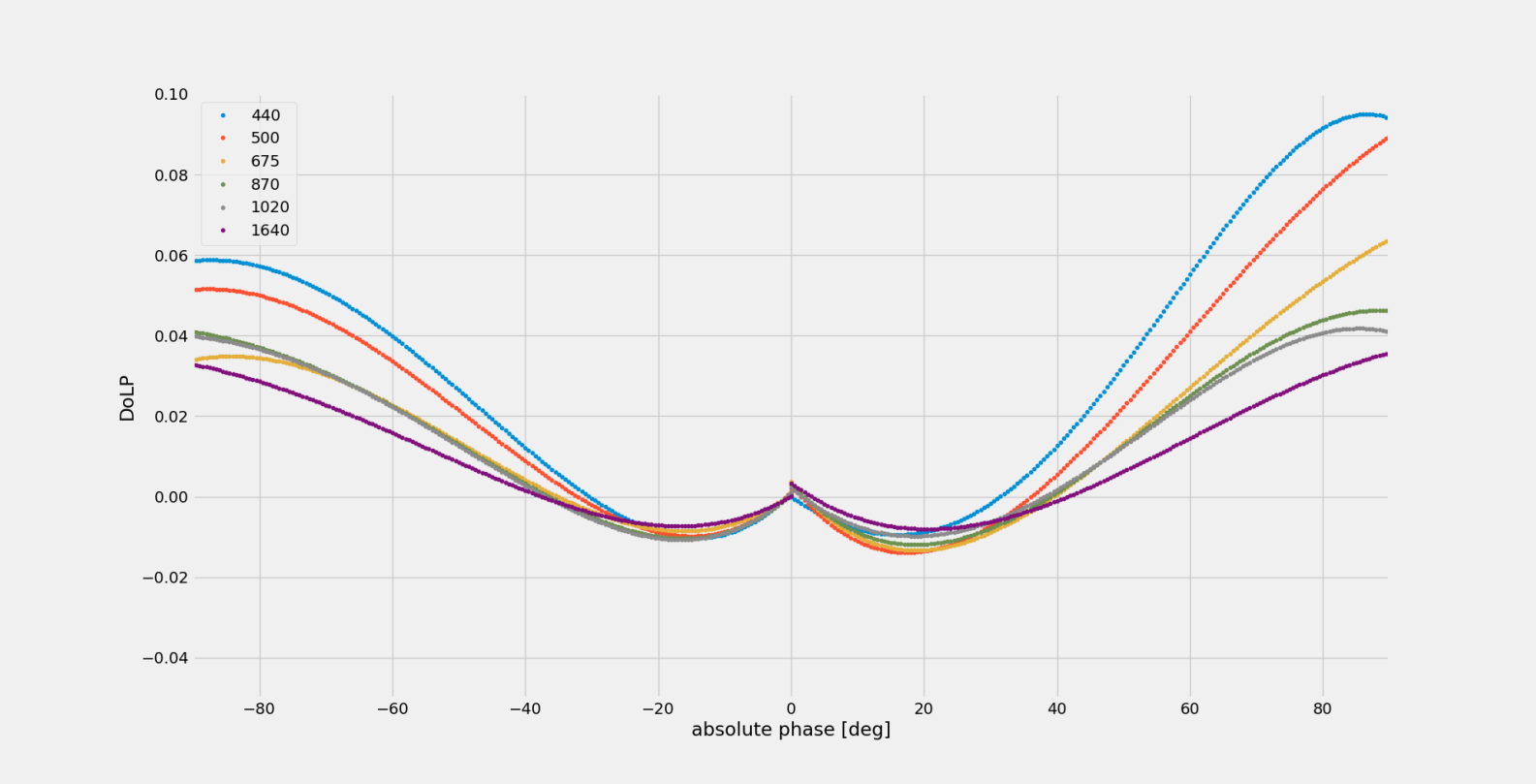
DOLP model at 500 nm *band against the DOLP measurements median values in each phase angle bin*



Skuratov, 2011

Degree of Linear Polarisation model

Modelled DoLP for all wavelengths



Degree of Linear Polarisation model

Modelled DoLP for all wavelengths

Table 1: Positive phase polynomial coefficients for DoLP model

a0	a1	a2	a3	a4
-0.00008640723	-0.00111900096	0.00002847413	0.00000037519	-0.00000000472
0.00290942646	-0.00206629645	0.00007140880	-0.00000047996	0.00000000067
0.00363515121	-0.00197646179	0.00006672987	-0.00000053349	0.00000000132
0.00307562466	-0.00172534256	0.00005595457	-0.00000035512	0.00000000006
0.00210103813	-0.00134150486	0.00004072434	-0.00000014668	-0.00000000097
0.00336742202	-0.00121256379	0.00003680994	-0.00000024534	0.00000000034

Table 2: Negative phase polynomial coefficients for DoLP model

a0	a1	a2	a3	a4
0.00116880128	0.00175041288	0.00007640722	0.00000071619	0.00000000180
0.00122120817	0.00159721462	0.00006581420	0.00000057929	0.00000000127
0.00072688434	0.00124056050	0.00004690610	0.00000036086	0.00000000043
0.00049053445	0.00147854795	0.00005858886	0.00000056618	0.00000000170
0.00105925760	0.00156370149	0.00006055805	0.00000057709	0.00000000167
0.00013907420	0.00096564587	0.00003598224	0.00000030507	0.00000000077

Conclusion

- LIME model now based on 5+ years of continuous lunar measurements
- Yearly updates ongoing with new measurements
- Ongoing efforts to continue to improve the model
- LIME toolbox should be available soon to the cal/val community

Thank you!

http://calvalportal.ceos.org/lime

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