COMPARISON OF THE LUNAR SPECTRAL IRRADIANCE MODEL TO SEVERAL DATASETS

Delivery 8

ABSTRACT

This document describes the results of the comparison of the Lunar Model with several lunar datasets.

Adriaensen Stefan

VITO

31 March 2021

This document was produced as part of the ESA-funded project "Lunar spectral irradiance measurement and modelling for absolute calibration of EO optical sensors" under ESA contract number: 4000121576/17/NL/AF/hh

National Physical Laboratory

Universidad de Valladolid

1.1.1.1.1 Signatures and version history

1.1.1.1.2

	Name	Organisation	Date
Written by	Stefan Adriaensen	VITO	28-May-2019
Reviewed by (consortium)	Emma Woolliams	NPL	8-Dec-2019
Approved by (ESA)	Marc Bouvet	ESA	12-Dec-2019

1.1.1.1.3 Version history

Version	Date	Publicly available or private to consortium?
0.1	28/05/19	created
0.2	08/07/19	Added section on model smoothing
		Added new results for PV
0.3	29/08/2019	All sections, new results with latest model
0.4	06/09/2019	New sections on 1088 model, including PV and Pleiades context
0.5	10/09/2019	Update text, mainly on conclusions sections
0.6	04/11/2019	Updated all sections with newly revised results. Input measurement data delivered on 28/09/2019
0.7	22/11/2019	update on all sections, resolving reviews and textual anomalies
0.8	8/12/2019	Review by Emma Woolliams
0.9	12/12/2019	Approved by Marc Bouvet
1.0	18/12/2018	FINAL version
1.1	19/12/2019	update extension project 2019 • model coeffs (section 2.2) 1088 and 1088+933 model • update PROBA-V results • Added 2 sections, one on geometry and one on trending • Updated all PLEIADES results • Updated all GIRO • (conclusions on the results remain the same, numbers have changed very little)
1.2	03/12/2020	update extension project 2020 • model coeffs (section 2.2) 1088 and 1088+933 model • update PROBA-V results • update 2 sections, one on geometry and one on trending

		• Updated all PLEIADES results • Updated all GIRO • (conclusions on the results remain the same, numbers have changed very little) • Added appendix with results of the comparison with a lunar acquisition of S3A and B
1.3	31/03/2022	update extension project 2020 • model coeffs (section 2.2) 1088 and 1088+933 model • update PROBA-V results • Updated all PLEIADES results • Updated all GIRO • Updated S3 results • (conclusions on the results remain the same, numbers have changed very little)

1.1.1.1.4 Contents

comparison of the lunar spectral irradiance model to several datasets

1 Introduction

1.2 Purpose and Scope

This document describes comparison of the lunar irradiance model with other datasets and models.

1.3 Applicable and reference documents

1.3.1 Applicable Documents

The following applicable documents are those specification, standards, criteria, etc. used to define the requirements of this representative task order.

Number	Reference
[AD1]	ESA-TECEEP-SOW-002720. Lunar spectral irradiance measurement and modelling for absolute calibration of EO optical sensors.
[AD2]	LUNAR IRRADIANCE MODEL ALGORITHM AND THEORETICAL BASIS DOCUMENT (D7)

1.3.2 Reference Documents

Reference documents are those documents included for information purposes; they provide insight into the operation, characteristics, and interfaces, as well as relevant background information.

Number	Reference
[RD1]	H.H. Kieffer and T.C. Stone. The Spectral Irradiance of the Moon. 2005. The American Astronomical Society. DOI:10.1086/430185.
[RD2]	http://gsics.atmos.umd.edu/bin/view/Development/GiroV1Release
[RD3]	Lunar observations data set preparation + results with the Pleiades satellites – LEO, Lachérade et al., GSICS Workshop, Darmstadt
[RD4]	In-Orbit Radiometric Calibration and Stability Monitoring of the PROBA-V Instrument, Sterckx S. et al, Remote Sensing, 2016
[RD5]	PROBA-V Quarterly Calibration Report Q4 2019, http://proba-v.vgt.vito.be/en/quality/platform-status-information/quarterly-image-quality-reports, Sterckx et al

comparison of the lunar spectral irradiance model to several datasets

1.4 Glossary

1.4.1 Abbreviations

Abbreviation	Stands For	Notes
ESA	European Space Agency	Project customer
NPL	National Physical Laboratory	Project partner
DOLP	Degree of Linear Polarization	
EO	Earth Observation	
GIRO	GSICS Implementation of the ROLO model	
GLOD	GIRO Lunar Observation Database	
SWIR	Short-Wave InfraRed	
USGS	U. S. Geological Survey	
UVa	University of Valladolid	Project partner
VITO	Flemish Institute for Technological Research;*(Vlaamse Instelling voor Technologisch Onderzoek)*	Project partner
VNIR	Visual and Near InfraRed	

2 Introduction

As described in [AD2], there are currently two models derived from two different sets of data. The first model is derived from lunar measurements from one instrument: the CIMEL CE318-TP9 (annotated as 1088 instrument). The instrument is procured, fully calibrated, installed and operated within the context of the current project at the Meteorological institute of Izaña in Tenerife. This dataset is limited in time and therefore not sufficient to derive a fully-fledged model. To be able to make a comparison with EO sensors, it is decided that the 1088 measurement are combined with historical data from a second instrument (a CIMEL, previously recorded outside the scope of this project.

The second instrument (CIMEL CE318T), annotated with identifier 933, has been operated in the period 2014 up to 2019, partially in parallel with the 1088 instrument. The current up-to-date database of the 933 instrument contains 3 years of data, from beginning of 2016 up to 2019. The last two years of data are recorded in parallel with the 1088 instrument. Combining both instruments, the total amount of measurements currently becomes 500+ per band.

The overall aim of this continuing activity is to obtain a model solely based on the 1088 instrument data. Therefore the 1088 instrument will be continued to be operated over the next years.

In this report, both the models [AD-2] are compared with the spectral imagers PROBA-V and PLEIADES-HR-1B (Pleiades). Lunar acquisitions from the PROBA-V platform are limited in lunar phase, but extended in time. Pleiades are rather limited in time, but more extended in lunar phase angles.

In addition, the model is compared to the GIRO model, which is the EUMETSAT reference implementation of the ROLO model as published in [RD1].

2.1 Models

As mentioned, the comparison will be applied to two lunar irradiance models both derived from the 1088 and 933 instrument measurements. This allows comparison of the performance of both derived lunar irradiance models in terms of absolute level and their ability to simulate the different geometric cases.

The two figures below are the simulated reflectances (in blue) for one model spectral band (440 nm) and on top (in orange) the measurements used the generate the reflectance model. It is clear that the second model (1088+933) is based on far more measurements, which have a better coverage over the total phase angle range. The measurements used for the 1088 model, clearly show gaps in phase angle coverage. Both plots are for the 440 nm instrument band.

It must be stated that for both models, the measurements are pre-filtered before being introduced into the regression procedures. The following tables contain the latest derived model parameters, which are applied during the following comparison exercise.

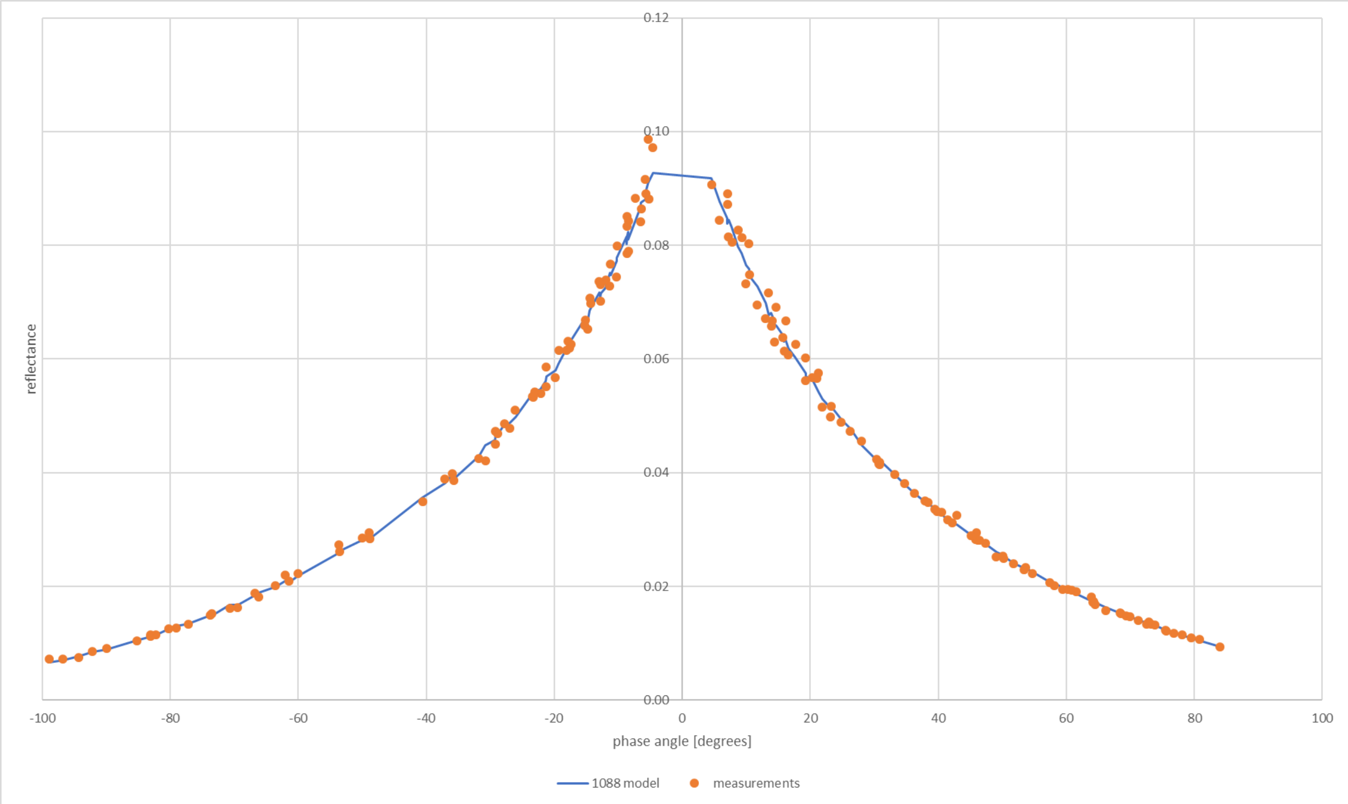

Figure 1: Simulated reflectance (blue) at 440 nm from 1088 model based on the plotted measurements from the 1088 instrument(orange)

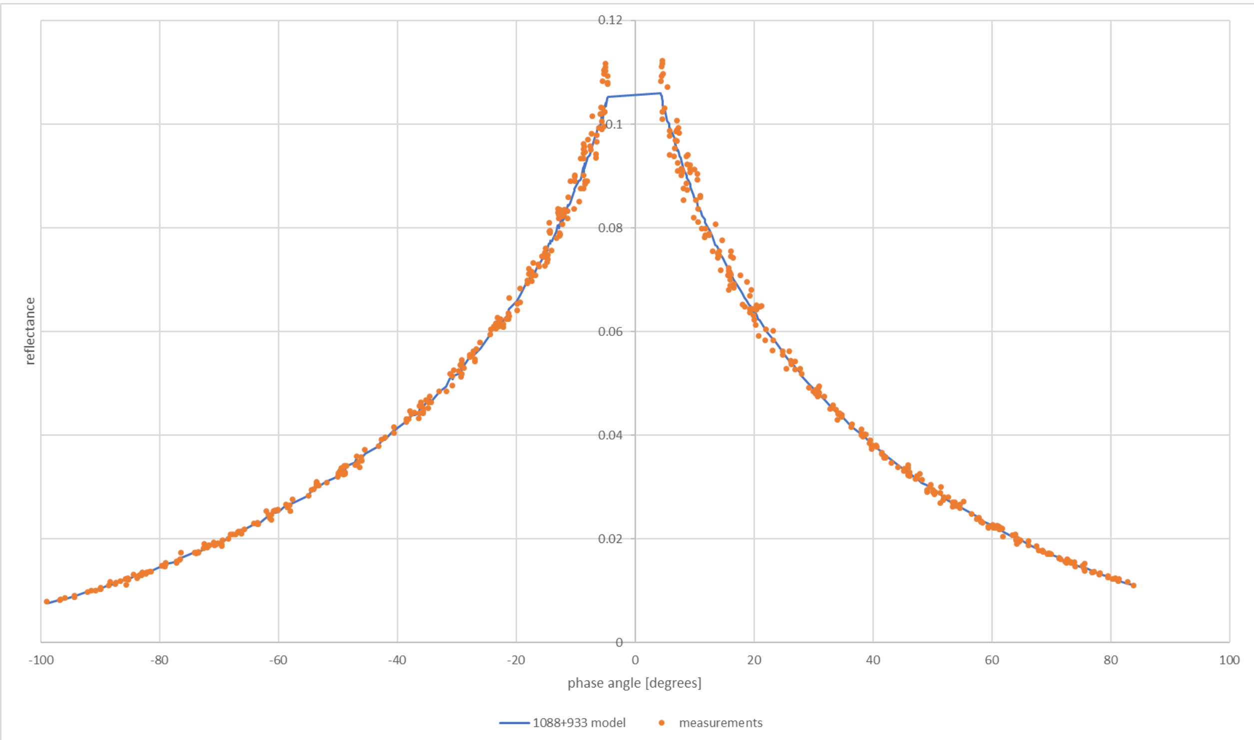

Figure 2 : Simulated reflectance (blue) at 440 nm from 1088+933 model based on plotted measurements from both 1088 and 933 measurements (orange)

2.2 Model coefficients

Table 1: Model coefficients derived from both 1088 and 933 instrument measurements

wl[nm]	**a0**	**a1**	**a2**	**a3**	**b1**	**b2**	**b3**
440	-2.65258	-0.96613	-0.16512	-0.05613	0.055342	0.002354	-0.0025
500	-2.48433	-0.99921	-0.11038	-0.07738	0.051227	0.009385	-0.00459
675	-2.28276	-0.79841	-0.23396	-0.04785	0.047962	0.01173	-0.00517
870	-2.18597	-0.67903	-0.31185	-0.02611	0.049425	0.015415	-0.00646
1020	-2.04979	-0.77511	-0.21366	-0.05543	0.052251	0.01795	-0.00704
1640	-1.72468	-0.63211	-0.28734	-0.03826	0.049243	0.010931	-0.00482
wl[nm]	**c1**	**c2**	**c3**	**c4**	**d1**	**d2**	**d3**
440	0.000544	-0.00082	0.001017	0.000492	0.829733	0.4292	-0.00098
500	0.000547	-0.00086	0.001113	0.000757	0.818083	0.382242	-0.00109
675	0.000594	-0.00084	0.001214	0.00067	0.426578	0.412195	-0.00114
870	0.000535	-8.43E-04	0.001424	0.00066	0.430293	0.417168	0.000264
1020	0.000501	-9.80E-04	0.001567	0.000596	0.502954	0.345195	0.000195
1640	0.000593	-8.35E-04	0.001237	0.000605	0.466135	0.292403	0.001622
	p1	**p2**	**p3**	**p4**			
all	1.454154	17.11146	13.32686	8.604854			

Table 2: Table 3: Model coefficients derived from the 1088 instrument measurements

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			

comparison of the lunar spectral irradiance model to several datasets

comparison of the lunar spectral irradiance model to several datasets

3 Measurement to model comparison procedure

In this section the procedure to compare the lunar model with different lunar measurements is described.

Any irradiance measurement of the moon disk can be compared with the model. The model provides as an output the lunar irradiance for a given viewing geometry and spectral response. The following limitations of the model have to be taken into account:

- Lunar Phase angle between 2 and 90 degrees
- Spectral range between 400 nm and 2500 nm

Simulations outside the phase angle range produce a result, but these are unsupported. When an instrument spectral response falls (partially) outside the spectral range, an error is raised.

3.1 Input to the model

The model requires a minimum set of input parameters to allow for the comparison with lunar acquisitions:

- Timestamp of the acquisition [Julian Day]
- Position of the instrument/platform (J2000 coordinates – x,y,z [km])

Extra input (for comparison):

- EO sensor Integrated Irradiance from lunar acquisition

The irradiance observed by the EO sensor acquisition is provided to the software for comparison purposes. Its value is outputted next to the tabulated model irradiance, this allows direct comparison between measured and modelled parameters. Using these parameters, the model calculates the geometric parameters per acquisition required for the comparison:

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

All geometric parameters are calculated using the NASA SPICE toolkit. The instrument spectral response curve is used to calculate the model irradiance.

Extra configuration needed for the model is required:

- Model Coefficients
- Spectral response curves
- Spectral band identifier (the model run are band specific)
- Reflectance Spectrum (i.e. Apollo reflectance)
- Solar Irradiance Spectrum (i.e. Wehrli 1985 spectrum)
- Spice kernels
- DOLP (Degree of Linear Polarization) model location

All these config parameters are stored into dedicated files (example config below):

comparison of the lunar spectral irradiance model to several datasets

```
[run_model]

input.location=blue.csv
model.location=montecarlo_model_base.csv
spectral.mix.location=lunar_model/data/apollo_mix_rolo.txt
irradiance.location=lunar_model/data/wehrli1985_rolo.txt
response.location=lunar_model/data/probav.txt
output.location=blue_output_1088_last.csv
band.id=0
convert.to.km=1.0
kernel.location=lunar_model/data/kernels/kernels.txt
dolp.location=lunar_model/data/measurements/dolp/output_dolp.csv
```

.

3.2 Algorithmic steps

The following figure is a flowchart of the procedure that is applied to the input to the model. Output of the procedure is the simulated lunar irradiance, which can be compared with the correlated measured irradiance.

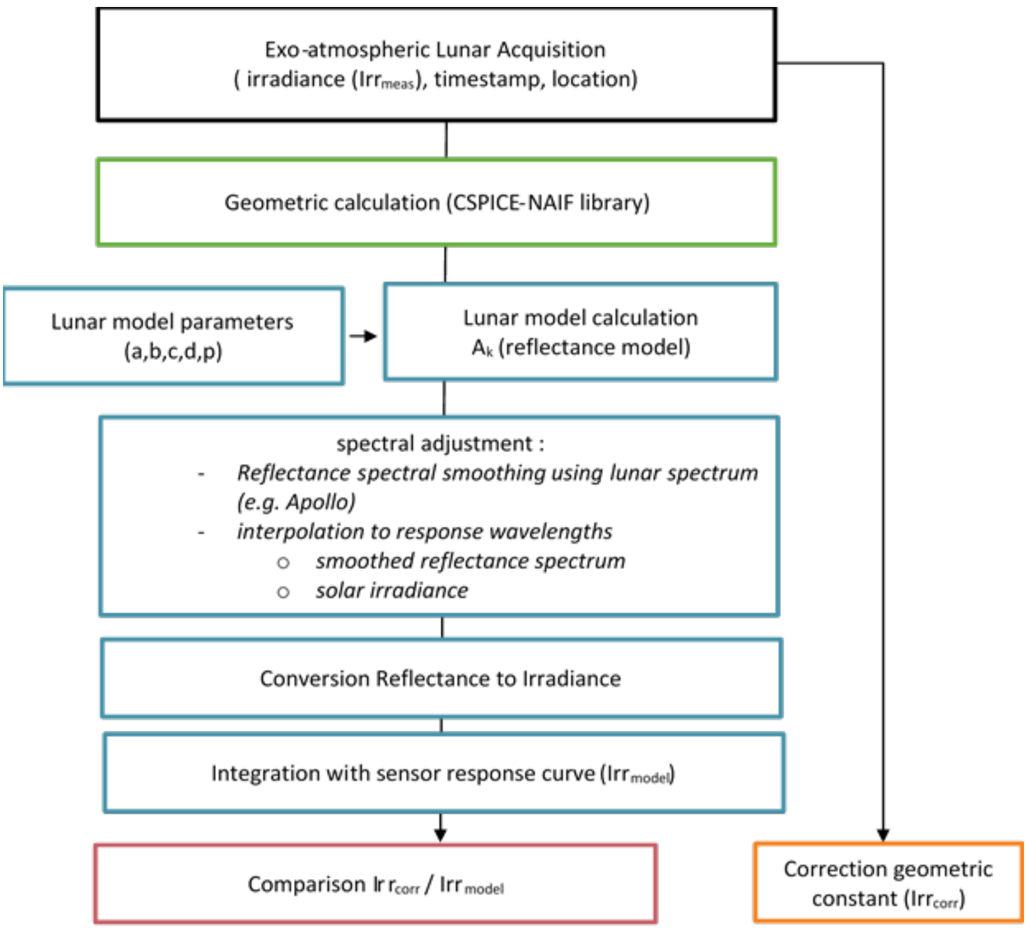

Figure 3: Measurement and Model comparison procedure

comparison of the lunar spectral irradiance model to several datasets

The different steps that are applied to obtain the simulated sensor irradiance are:

- Calculate geometry (NAIF spice)
- Calculate model reflectance for all model wavelengths
- Spectral adjustment
    - Smoothing of lunar reflectance spectrum to model reflectance
    - Spectral interpolation reflectance to sensor spectral response curve
    - Interpolation of the solar irradiance to sensor spectral response curve
- Conversion reflectance spectrum to irradiance spectrum
- Integration with sensor response curve
- Correction for the distance factor of the input irradiance value

Finally, the obtained modelled or simulated reflectance can be compared against the correlated sensor lunar measurement. The smoothing, interpolation and integration procedures are explained in detail in [AD-2].

3.3 Apply distance factor

For a direct comparison of the measured irradiance with the model irradiance output, the distance factor needs to be taken into account.

$$E'_{k\_\text{meas}} = \frac{E_{k\_\text{meas}}}{f_d}$$

And

$$f_\text{d} = \left(\frac{D_{\text{S-M}}}{[1\ \text{AU}]}\right)^2 \times \left(\frac{D_{\text{V-M}}}{[384400\ \text{km}]}\right)^2$$

Where $D_{\text{S-M}}$ is the distance between Sun and Moon in AU, $D_{\text{V-M}}$ the distance between viewer and moon in km. E'_{k_meas} is measured irradiance (E_{k_meas}) after correction for distances.

3.4 Measurement and model comparison

In general, the Lunar Model is compared to sensor irradiance recordings of the Moon. By defining the radiometric ratio between the instrument and the lunar model, the instrument performance is evaluated.

$$C_k = \frac{E'_{k\_\text{meas}}}{E_{k\_\text{model}}} - 1$$

The ratio between instrument and model irradiance, expressed in percentage, is a measure of the quality of the absolute calibration of the instrument.

In this study, the lunar model output is compared to:

- PROBA-V instrument measurements
- Pleiades 1B instrument measurements

comparison of the lunar spectral irradiance model to several datasets

- The GIRO model measurements

3.5 Calculating the uncertainty associated with the comparison to a satellite sensor

The hyperspectral lunar model is convolved with the (normalised to unit area) spectral response function of the satellite sensor and the modelled integral is compared with the sensor measurement. This is ideally done to compare the uncertainties of the two 'observations'. We can do this in terms of absolute uncertainties:

$$\Delta_{\text{model}} = \frac{\left(\overline{E}_{\text{sensor}} - \overline{E}_{\text{model}}\right)}{k\sqrt{u^2\left(\overline{E}_{\text{sensor}}\right) + u^2\left(\overline{E}_{\text{model}}\right) + u^2\left(\overline{E}_{\text{matchup}}\right)}}$$

Or in terms of relative uncertainties

$$\Delta_{\text{model,rel}} = \frac{\left(\frac{\overline{E}_{\text{sensor}}}{\overline{E}_{\text{model}}} - 1\right)}{k\sqrt{u_{\text{rel}}^2\left(\overline{E}_{\text{sensor}}\right) + u_{\text{rel}}^2\left(\overline{E}_{\text{model}}\right) + u_{\text{rel}}^2\left(\overline{E}_{\text{matchup}}\right)}}$$

The uncertainty associated with the sensor measurement is taken as the nominal uncertainty. The uncertainty associated with the match up, is the uncertainty due to any mismatch between the model and the sensor. This uncertainty is likely to be small when the required inputs (timestamp and platform and sensor position) are well defined and have very small uncertainties themselves.

The uncertainty associated with the model is obtained by performing the spectral convolution for each of the 1000 hyperspectral models that we have through the MCUA and determining the standard deviation of those convolved quantities.

k is the coverage factor. If the distribution is Gaussian, then $k = 2$ provides a confidence interval of 95 %. We would therefore expect Δ_{model} to be less than one 95 % of the time.

For the moment, the sensor and matchup uncertainties are unknowns and therefore the current baseline only compares the sensor and model results. However, it is an interesting exercise to look in the future developments of the model.

4 PROBA-V

4.1 Instrument

The PROBA-V instrument is a multi-spectral imager with four broad spectral bands : BLUE, RED NIR and SWIR : 450, 645, 834 and 1665 nm central wavelength (Figure 4).

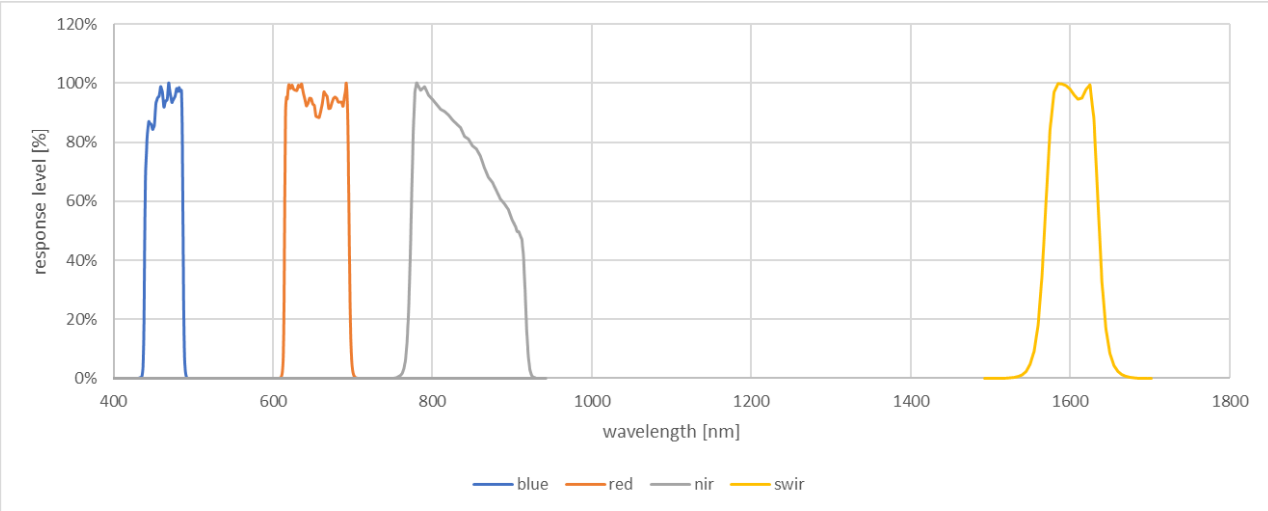

Figure 4 : PROBA-V spectral response curves

The spatial GSD for the central camera is 100 m. The combinations of three cameras allows for daily global coverage at 1 km resolution. The main applications for PROBA-V observations are for vegetation and crop monitoring and yield prediction.

4.2 PROBA-V Lunar acquisitions

PROBA-V lunar images are acquired twice every month, approx. 7 degrees before and after full Moon. Since the beginning of the launch, the Moon has been recorded. Currently about 138 lunar acquisitions are recorded with since 23/6/2013.

PROBA-V has three cameras (LEFT, CENTER and RIGHT) to ensure a ground sampling swath of approx. 2000 km. Each camera has three line-sensing VNIR bands and one line-sensing SWIR band. To reach the same on-ground swath, three SWIR sensors are butted next to each other.

The moon is recorded with the CENTER camera only, the SWIR channel only with the center SWIR strip (SWIR2).

comparison of the lunar spectral irradiance model to several datasets

Figure 5 : PROBA-V BLUE lunar acquisition

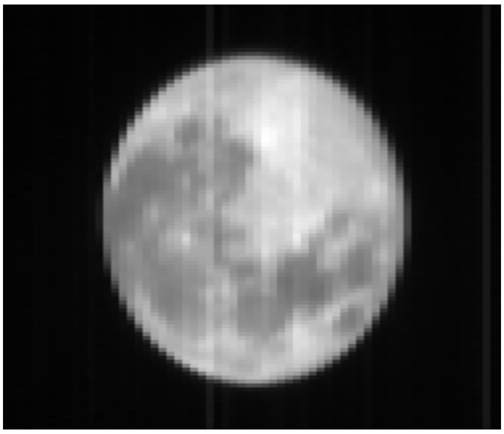

Figure 6: PROBA-V SWIR lunar acquisition

Example VNIR (BLUE) and SWIR acquisition is shown both Figure 5 and Figure 6.

VITO has implemented its own version of the ROLO model. The results of this model will also be inserted as an extra reference. In operational calibration modus, the model has not been used as an absolute calibration reference but rather to monitor spectral channel relative drift.

4.3 Processing steps

The PROBA-V lunar data is processed through the Data Ingestion Facility (DIF) up to level 1A (L1A). This is the basic level, after decompressing and reorganizing the downlinked data packets into HDF5 logic files. All platform and instrument data are combined into one file, image data is in raw sensor DNs.

In the operational scenario, the data is picked up by the Instrument Quality Center (IQC) and processed further through a dedicated workflow.

To prepare the L1A PROBA-V data for comparison with the lunar model, 5 major processing steps are required (the same for all strips):

comparison of the lunar spectral irradiance model to several datasets

- Find all moon-pixels in the image - masking
- Locate the center row of the moon and get the exact timestamp and satellite position (J2000-coords) for this central row
- Convert moon-pixels into radiance (apply instrument calibration parameters)
- Integrate all moon-pixels
- Calculate the solid angle of a pixel and find oversampling factor

The oversampling factor is a measure for the number of times the moon has been imaged. With a push-broom sensor like PROBA-V, the moon is recorded during a pitch maneuver of the satellite. During the maneuver, the moon is scanned. The rotational speed of the platform and the sensor line sampling period defines the oversampling factor of the lunar acquisition.

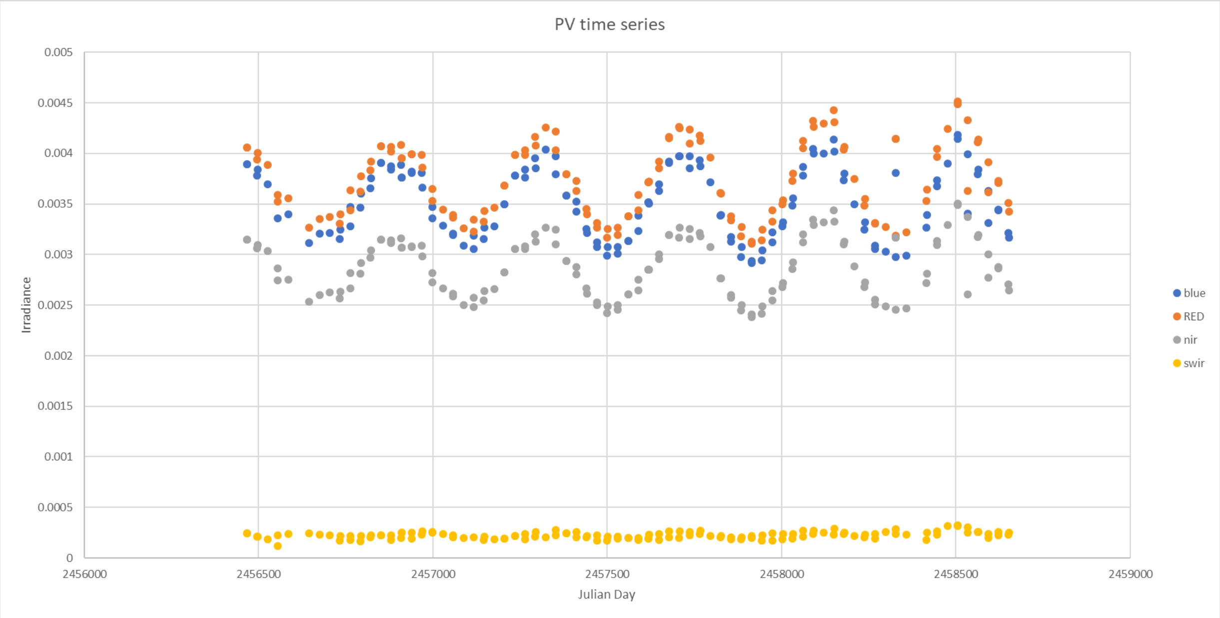

*Figure 7: PROBA-V measured lunar irradiances in [*W/(m² nm)*]*

4.4 SWIR data

During the process of the model development and comparison exercises, it became clear that for the PROBA-V SWIR data an extra iteration is required to get decent values out of the processing. The basis for the processing is masking, which appears to be rather difficult for the noisier SWIR channel. As an example, Figure 8 shows the failure of the masking in the image processing. The masking is the basis for all further processing and therefore the SWIR results, certainly the absolute level of the lunar irradiances should be assumed immature.

comparison of the lunar spectral irradiance model to several datasets

Figure 8: failed SWIR masking

4.5 Result for PROBA-V with 1088+933 model

The graphs below show the difference between PROBA-V and the lunar model plotted against days since launch. Blue plot is the new lunar model and the orange plot is the original VITO own implemented version of the ROLO. This implementation is validated against the GIRO as displayed in APPENDIX A.

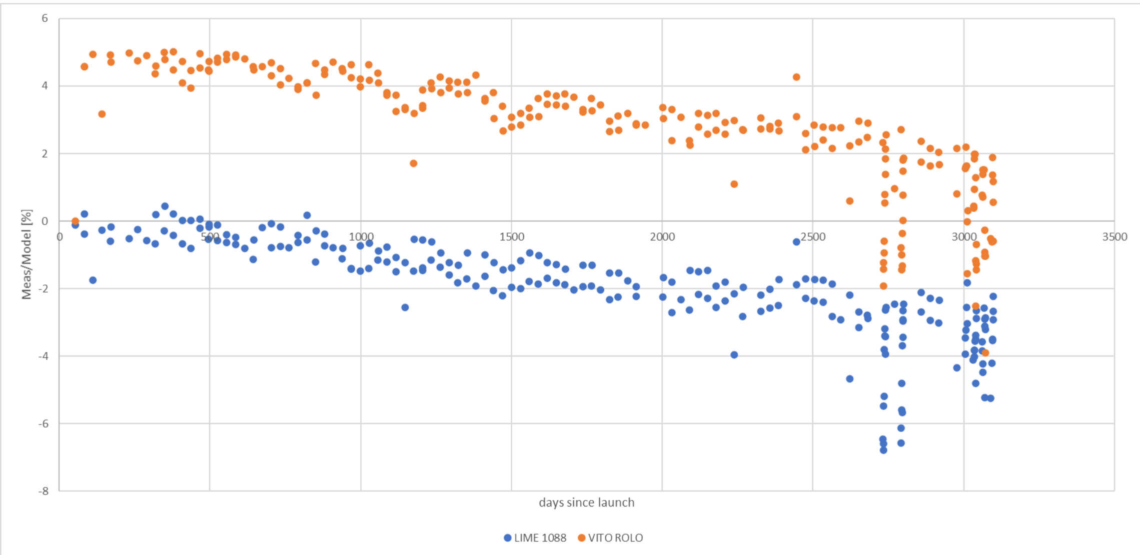

Figure 9: PROBA-V BLUE irradiance compared to the 1088+933 lunar model irradiance

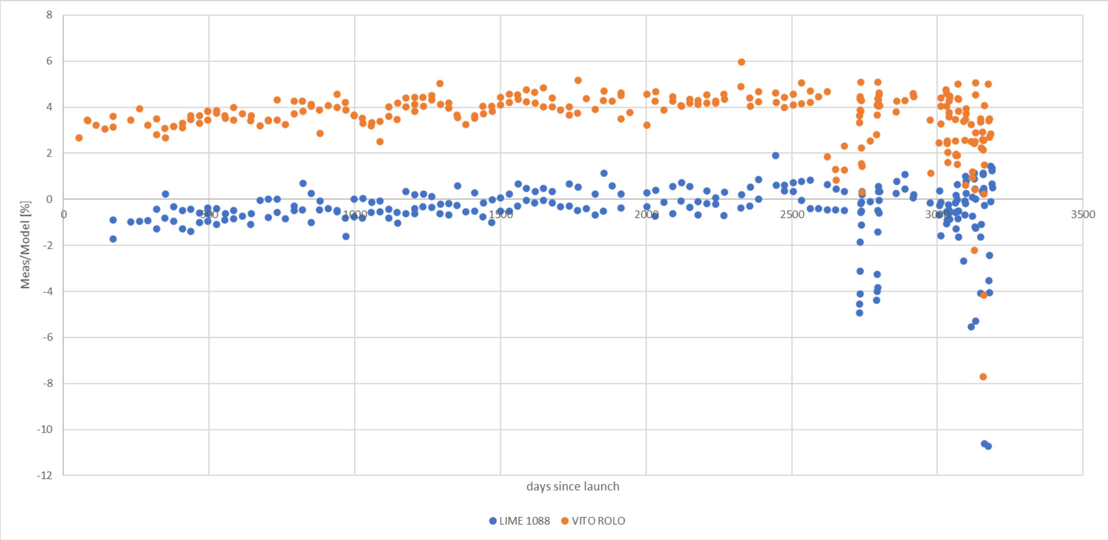

Figure 10 : PROBA-V RED irradiance compared to the 1088+933 lunar model

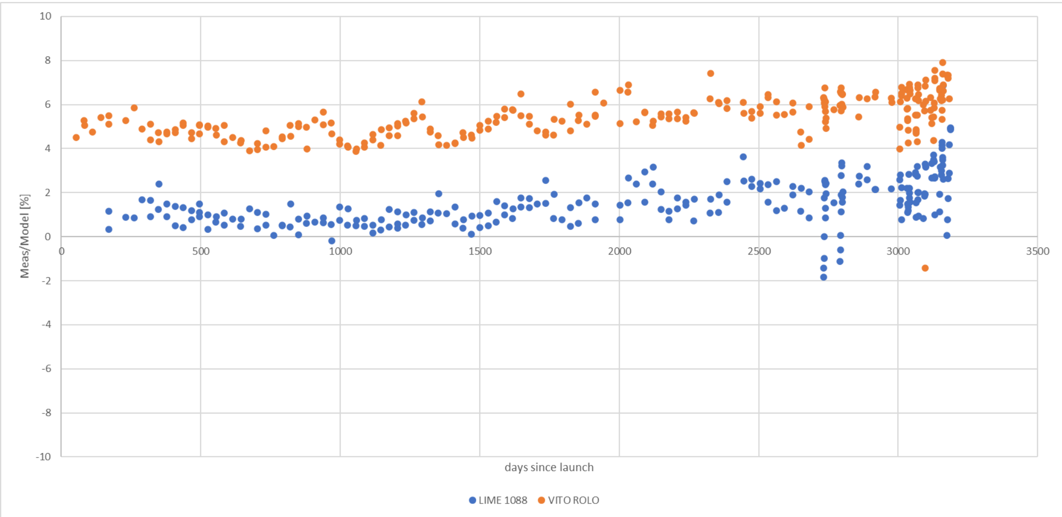

Figure 11 : PROBA-V NIR irradiance compared to the 1088+933 lunar model

comparison of the lunar spectral irradiance model to several datasets

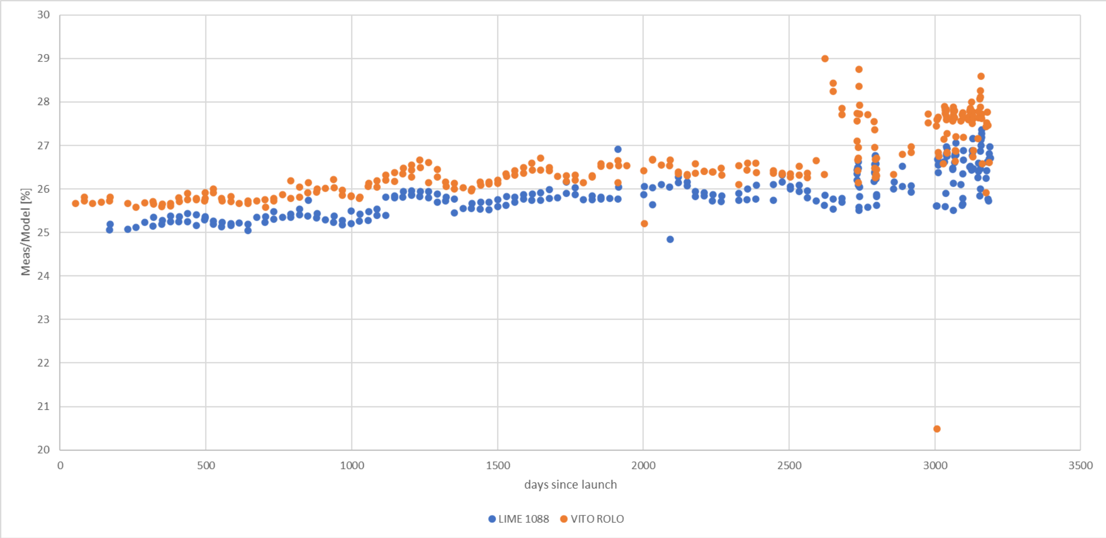

Figure 12 : PROBA-V SWIR irradiance compared to the 1088+933 lunar model

The tables below shows the averaged results and standard deviations.

Table 4: PROBA-V comparison to the 1088+933 lunar model

BAND	BLUE	RED	NIR	SWIR
%	450nm	645nm	834nm	1665nm
AVG	-2.060	-0.413	1.610	26.369
STDEV	1.453	1.564	1.132	6.045

Table 5: PROBA-V comparison with ROLO model implemented by VITO

BAND	BLUE	RED	NIR	SWIR
%	450nm	645nm	834nm	1665nm
AVG	2.658	3.631	5.481	27.098
STDEV	1.805	1.507	0.857	7.948

4.6 Result for PROBA-V with 1088 model

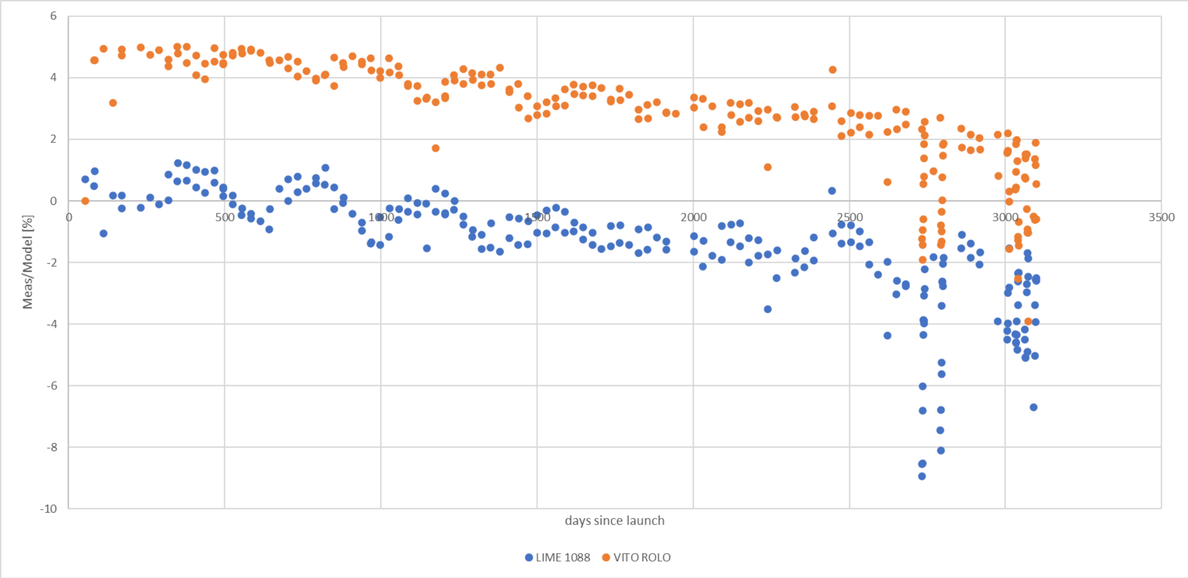

Figure 13 : PROBA-V BLUE irradiance compared to the 1088 lunar model

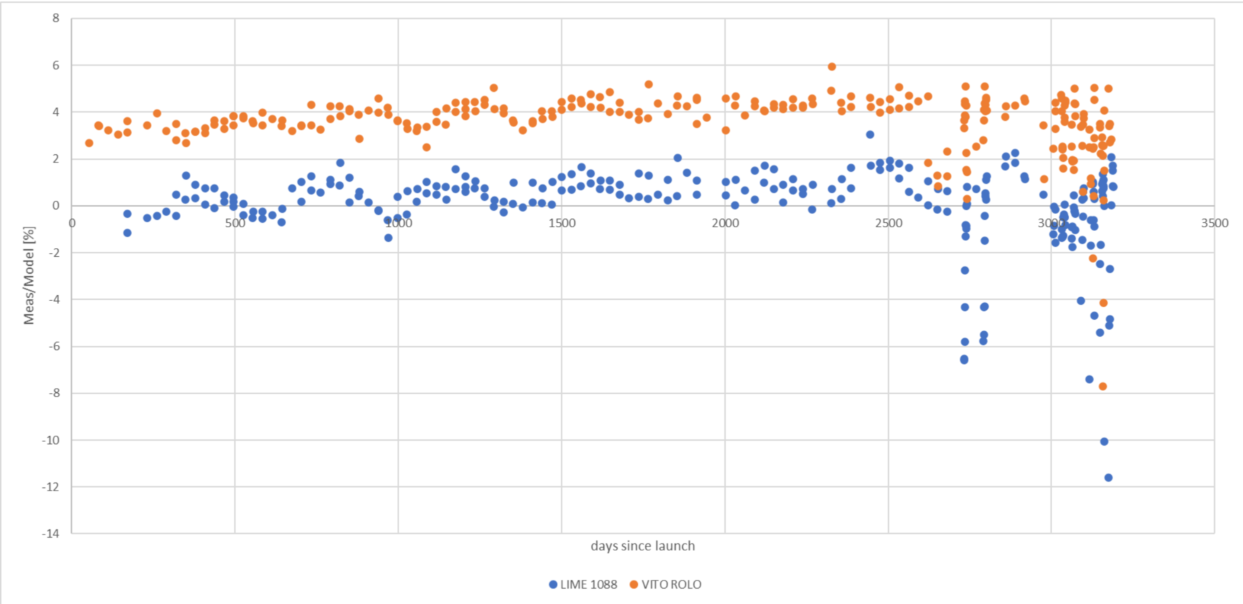

Figure 14 : PROBA-V RED irradiance compared to the 1088 lunar model

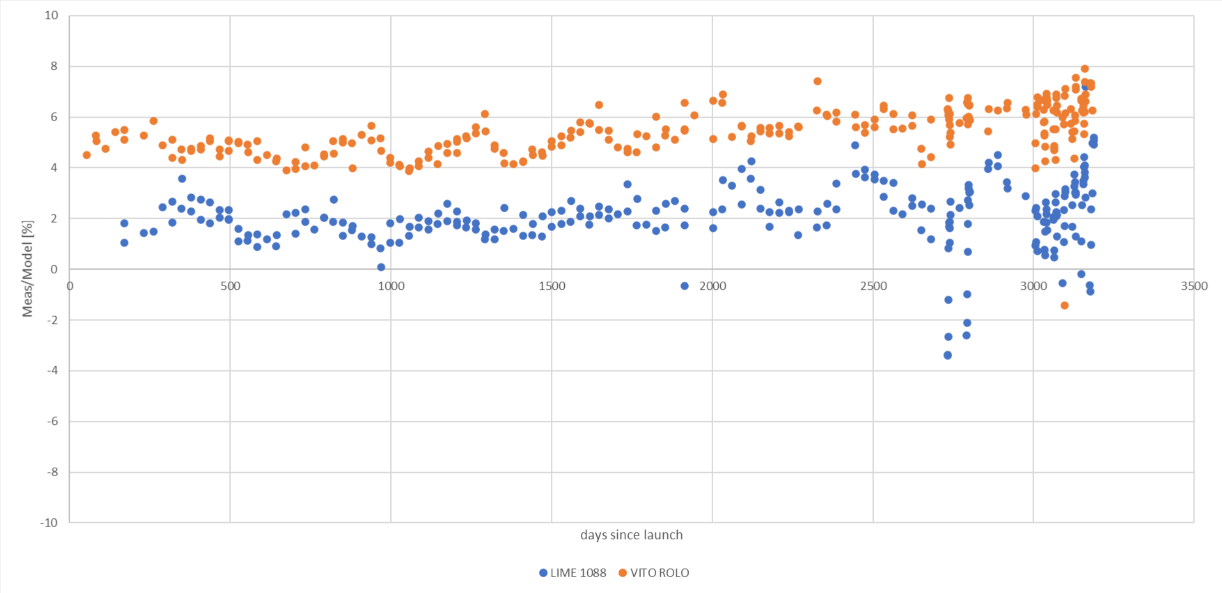

Figure 15 : PROBA-V NIR irradiance compared to the 1088 lunar model

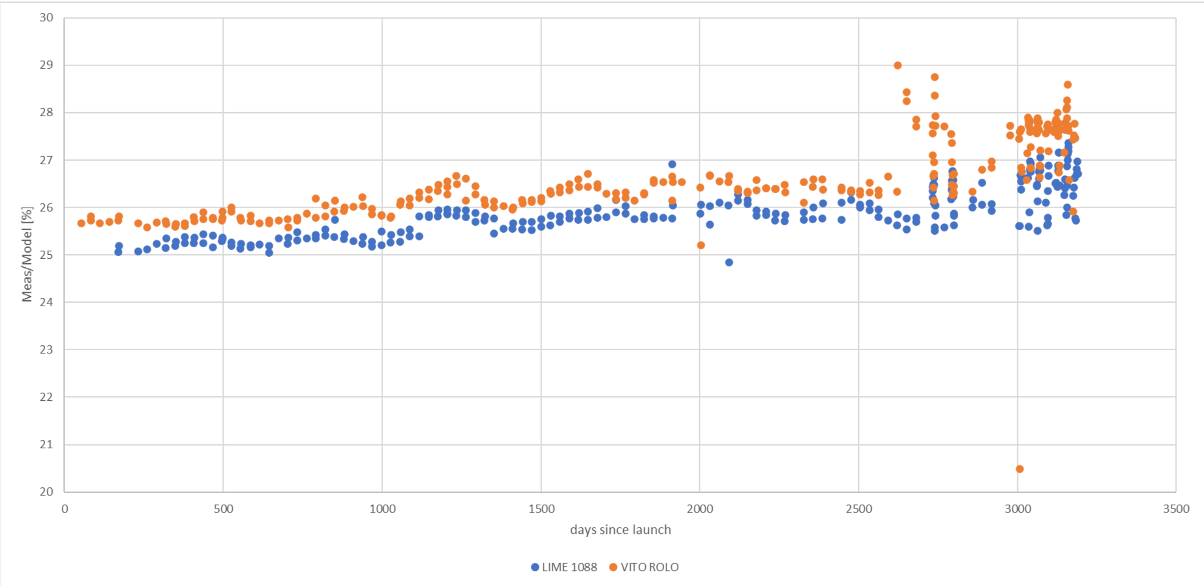

Figure 16 : PROBA-V SWIR irradiance compared to the 1088 lunar model

Table 6: PROBA-V comparison to the 1088 lunar model

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

4.7 Geometric considerations

The results presented in section 4.6, obtained with the 1088 model, show large temporal variations, compared to the results obtained with the 1088+933 or 'VITO-ROLO' results. In [AD2], a short paragraph is presented with the current status of the geometric coverage of the 1088 instrument measurements.

When analyzing the results in section 4.6, one can observer that the amplitude of temporal variation decreases around day 1700 since the launch of PROBA-V and that from that point on, the results are more in line with results of the 1088+933 or 'VITO-ROLO'.

Figure 17 shows the observer libration coverage (observer selenographic longitude and latitude) of both the 1088 measurements and the PROBA-V lunar acquisitions. The period of acquisitions between PROBA-V and the 1088 instrument measurements campaign overlap in the period March 2018 up to November 2019. No major difference is to be observed any longer between PV and CIMEL. The missing positions have been filled largely by the CIMEL measurements.

The model based on the 1088 measurements only, is built from a limited set of lunar irradiance data and by consequence it is not capable of simulating the geometric cases that fall outside this area. This will improve with the continuation of the measurements. In [AD2], a total period of 6 years of lunar measurements is suggested.

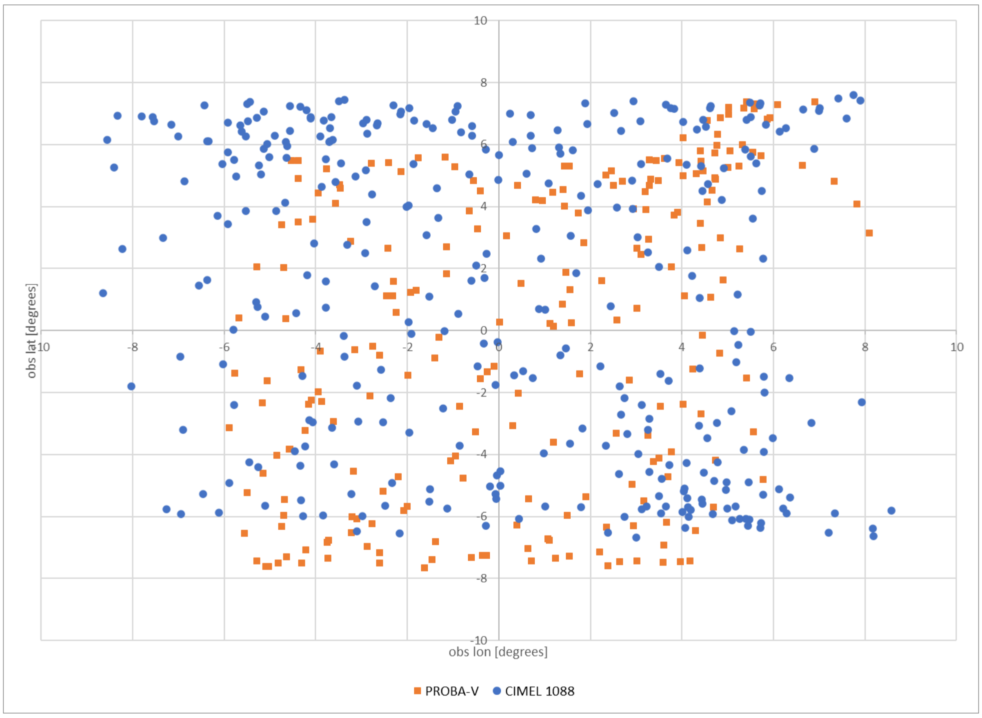

Figure 17: Selenographic lat/lon overlapping positions for the 1088 measurements and PV lunar acquisitions

4.8 Trending analysis

A limited analysis is done, to evaluate trending capabilities of the 1088+933 model. The ROLO lunar model has been applied in the past to evaluate possible instrument degradation. The moon has high reflectance/irradiance stability over time and consequently yearly trends of ~1% can be detected with sensor lunar acquisitions. PROBA-V has monthly lunar data over +5 years, therefore it is a good dataset to check the trending capabilities of the lunar model.

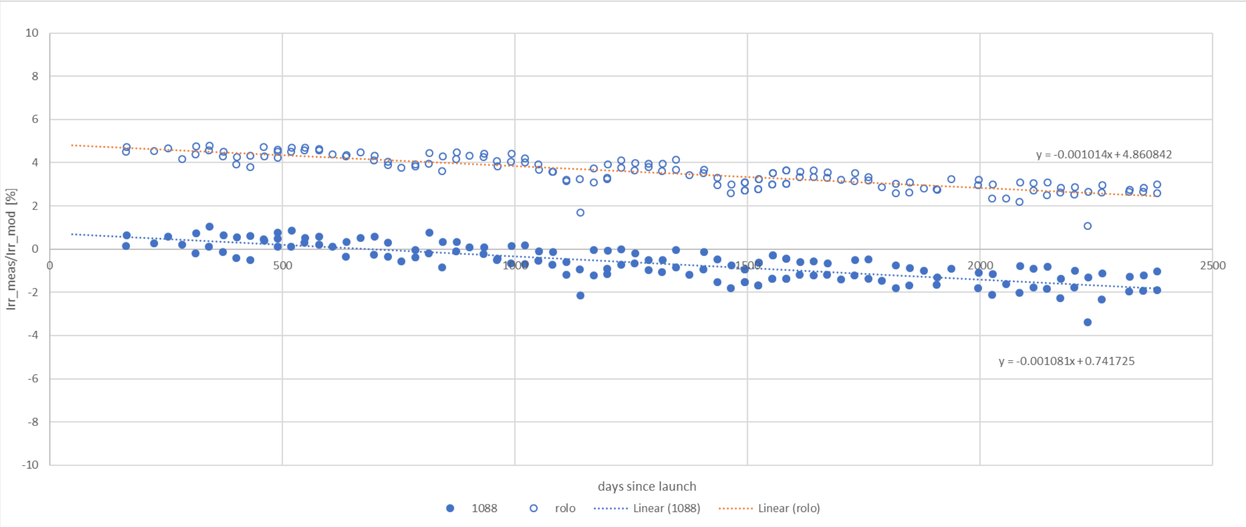

Figure 18: Trending analysis of both 1088+933 and ROLO models

When calculating the linear regression trend for both the 1088 and 'VITO-ROLO' model results, it is shown that both models give very similar trendlines, for all bands. As an example, the trendlines in of the BLUE results are shown in Figure 18.

These trends are cross checked and confirmed by application of other methods to PROBA-V sensor data, like PICS desert (Libya-4). More detailed results can be found in [RD5].

4.9 Conclusion PROBA-V comparison

One can observe that the absolute irradiance level of the 1088+933 lunar model lies around 3 % to 5 % above the VITO implemented ROLO model for the VNIR channels. This level appears to be quite in line with the instrument lunar observations irradiance level. The 1088 model has slightly lower absolute irradiance level, compared to the 1088+933 model.

In terms of relative stability, the 1088+933 model is 'as stable' as the VITO ROLO. The 1088 model clearly has more scatter. The fact that the model is currently less well defined with respect to the nonlinear part impacts results at lower phase angles. All PROBA-V lunar acquisitions have an absolute phase angle of around 7 degrees. With more 1088 instrument measurements and model updates, the model will be better defined in the lower phase angles. Trending analysis show good agreement between the 1088+933 and 'VITO-ROLO' model.

5 PLEIADES data

5.1 PLEIADES instrument

The Pleiades-1B HR imaging instrument (also called PHR1B) is a high resolution multi-spectral imager. It has five spectral bands in the VNIR region. The fifth band is a pan-chromatic band with a ground sampling distance (GSD) of 0.5 meter the other bands have a GSD of 2 meter.

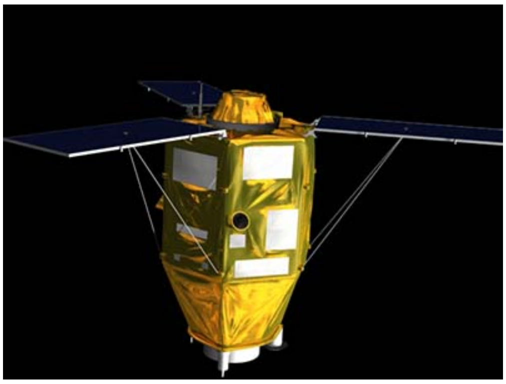

Figure 19: Pleiades 1B satellite

In Figure 20 you can see the spectral response functions of Pleiades 1B. All in the visible area of the spectrum : Blue: 430-550 nm Green: 490-610 nm Red: 600-720 nm and Near Infrared: 750-950 nm. Panchromatic band occupies 480-830 nm.

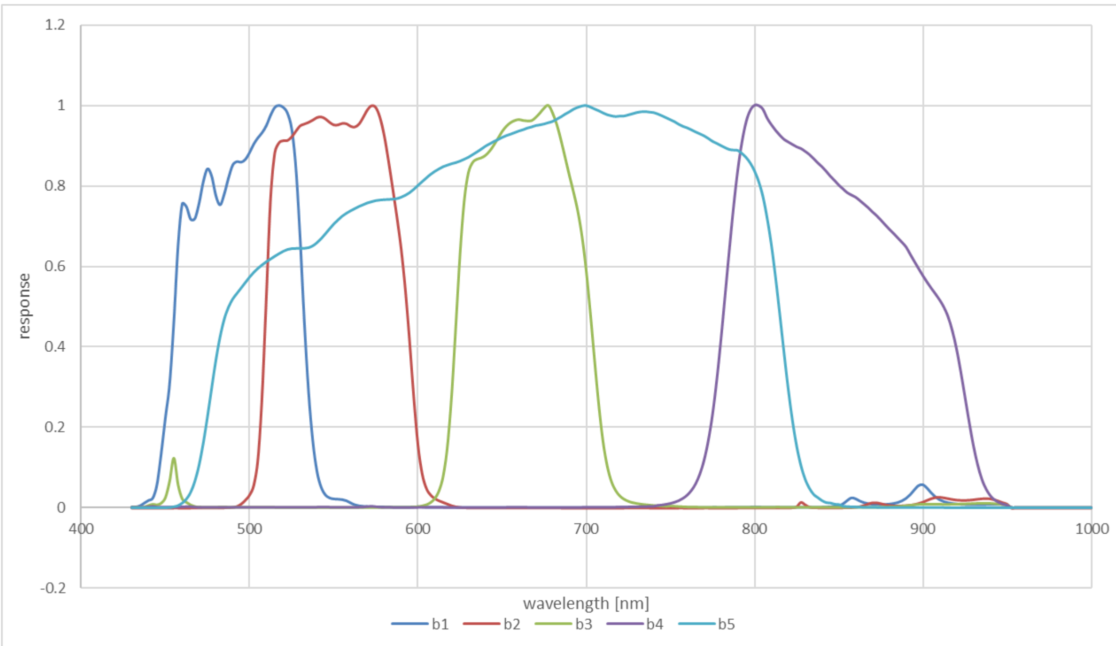

Figure 20: Pleiades-1B spectral response functions

comparison of the lunar spectral irradiance model to several datasets

5.2 Pleiades-1B lunar acquisitions

In total 68 lunar observations are provided to the project, spanning the period between 18/02/2013 until 07/04/2017. The measurements are a combination of 2 campaigns in 02/2013 and 03/2013 recording at sparse lunar phase angles over the entire cycle, added with more routine based observations around 40 degrees phase angle for several years, once every few months.

When looking at Figure 21, one can observe the sparsity or the measurements with respect to the lunar phase angle, but these cover a considerably wider range of phase angles than the PROBA-V observations.

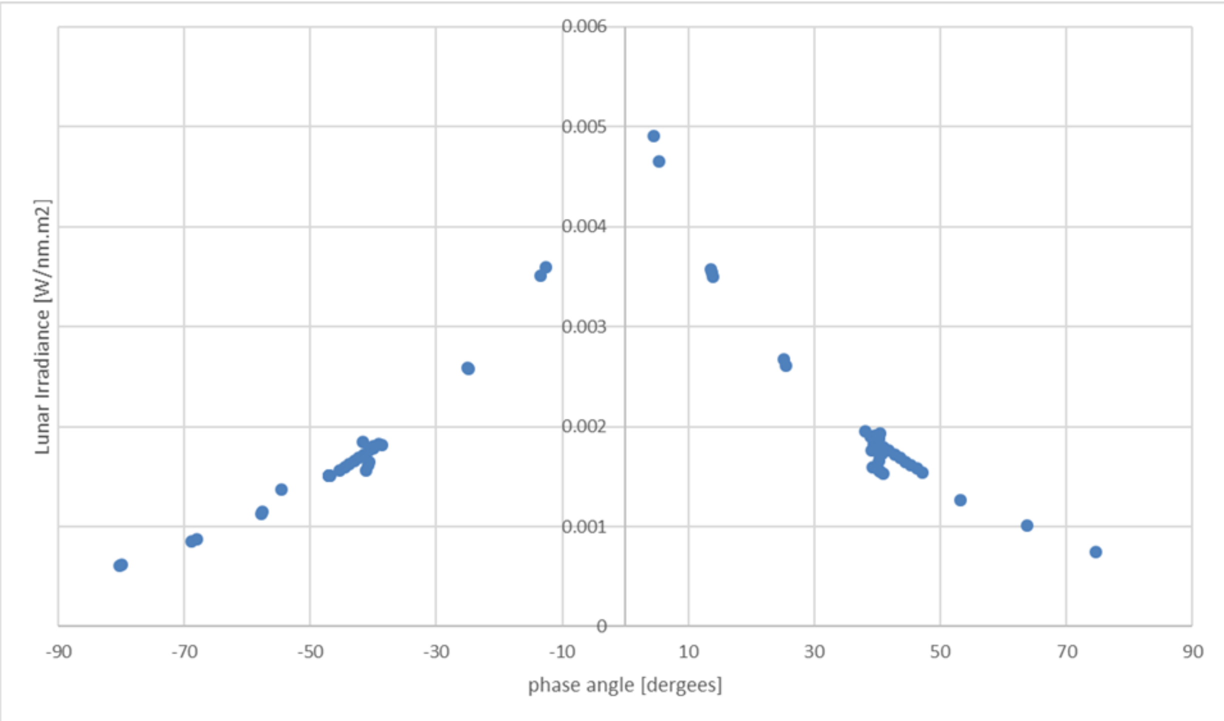

Figure 21: Pleiades Blue band lunar irradiance acquisitions

For every acquisition the model input parameters are delivered :

- Phase angle
- Observer selenographic latitude and longitude
- Sun selenogragphic longitude
- Geometric factor (distance sun and observer to the Moon)
- Timestamp of the observation
- Irradiance value for every band
- Irradiance value calculated with the version of the ROLO model, output provided by CNES

Apart from the necessary input parameters a set of calibration parameters is added for the period of the measurements. The so called PHR1B official calibration table :

Table 7: PHR1B calibration table

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

The calibration is applied to the Pleiades irradiance measurements, taking the temporal changes into account.

5.3 Results with 1088+933 model

For all Pleiades observations and spectral bands a model output is generated. The difference (in %) is calculated and plotted against the phase angle. With the Pleiades data, the results of the CNES implementation of the ROLO model are delivered as well. The comparison with these results is plotted as well (in blue) as an extra reference.

Important Notice : for the following figures 'rolo cnes' is the USGS ROLO model applied to the CNES output of the PLEIADES 1B Lunar observations.

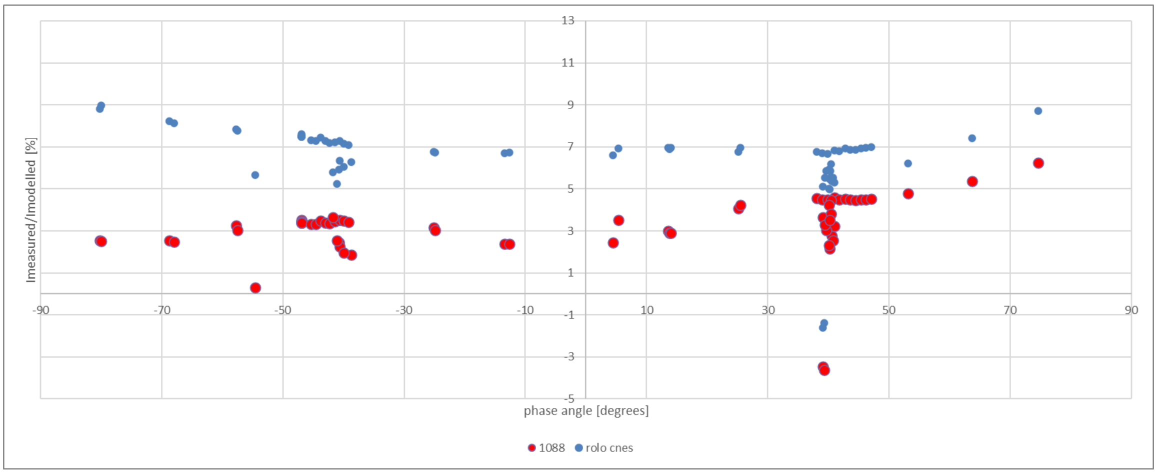

Figure 22: PHR1B band 1 (blue) result – 1088+933 model

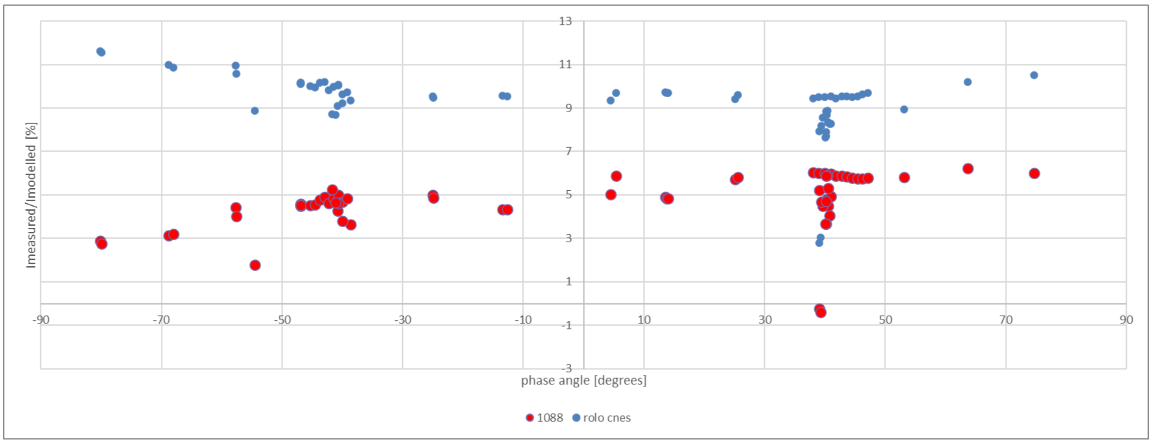

Figure 23: PHR1B band 2 (green) result – 1088+933 model

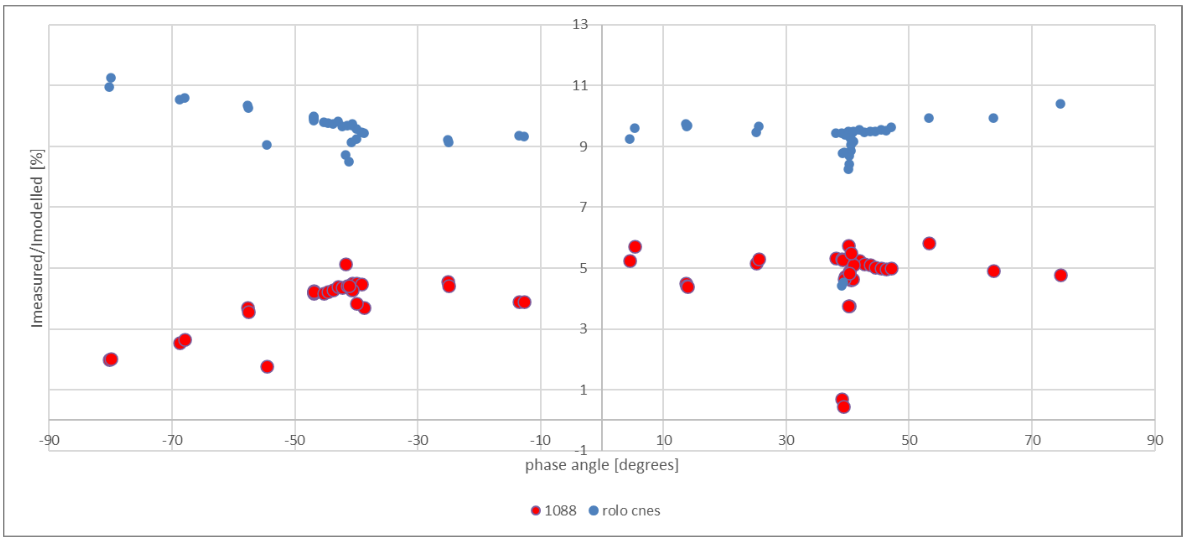

Figure 24: PHR1B band 3 (red) result – 1088+933 model

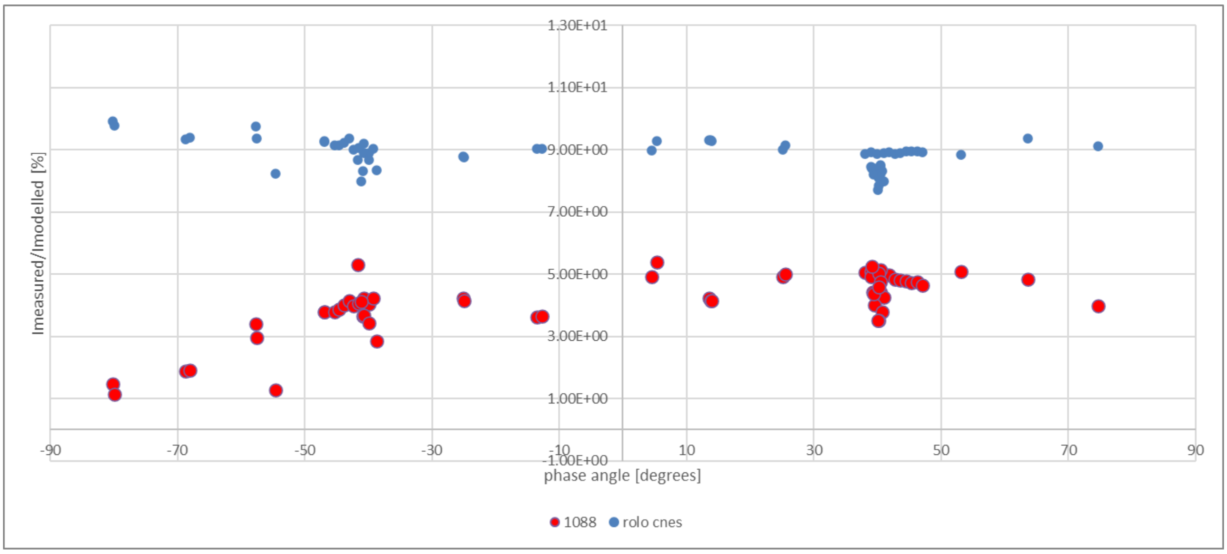

Figure 25: PHR1B band 4 (nir) result – 1088+933 model

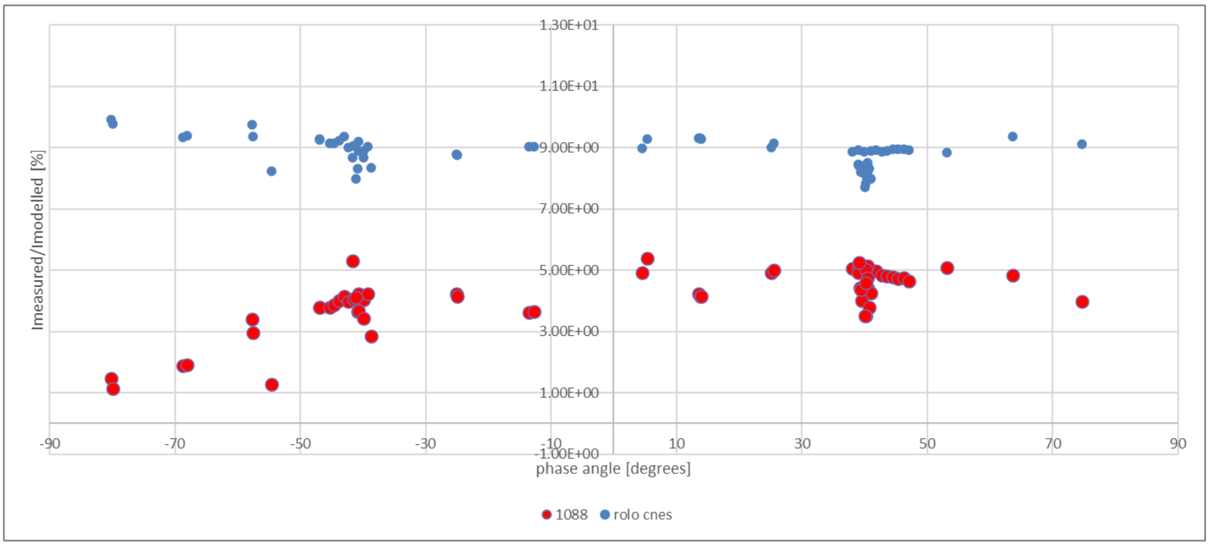

Figure 26: PHR1B band 5 (pan) result – 1088+933 model

Tables with averages :

Table 8: Average and Stdev of Pleiades data agains the 1088+933 model

%	BLUE	GREEN	RED	NIR	PAN
AVG	3.099	4.614	4.342	6.630	5.773
STDEV	1.414	1.138	0.940	1.173	9.505

comparison of the lunar spectral irradiance model to several datasets

Table 9: Average and Stdev of Pleiades data against the USGS model

%	BLUE	GREEN	RED	NIR	PAN
AVG	6.512	9.323	9.406	11.151	8.853
STDEV	1.663	1.398	1.016	1.295	0.471

5.4 Result with 1088 model

Important Notice : for the following figures 'rolo cnes' is the USGS ROLO model applied to the CNES output of the PLEIADES 1B Lunar observations.

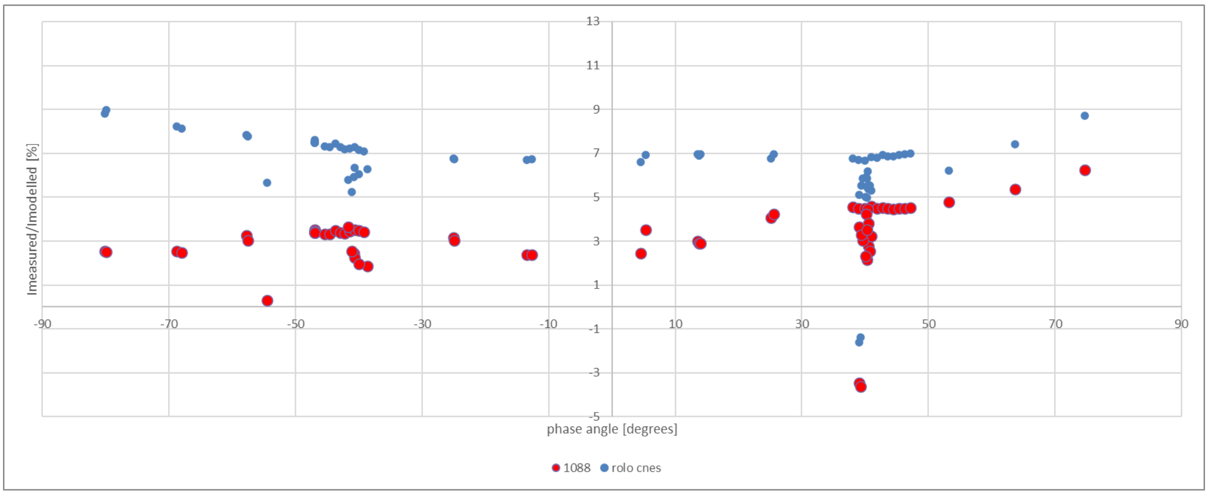

Figure 27: PHR1B band 1 (blue) result – 1088 model

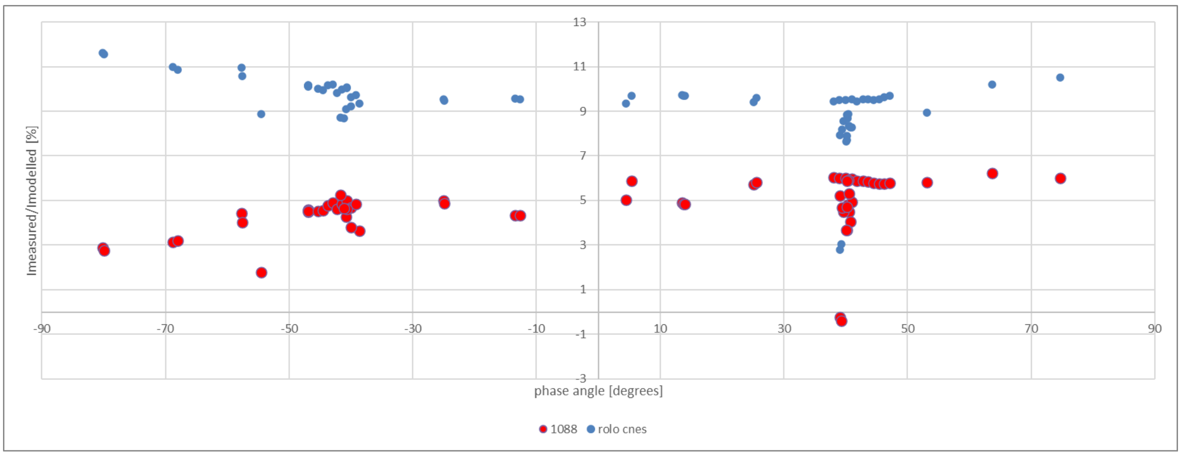

Figure 28: PHR1B band 2 (green) result - 1088 model

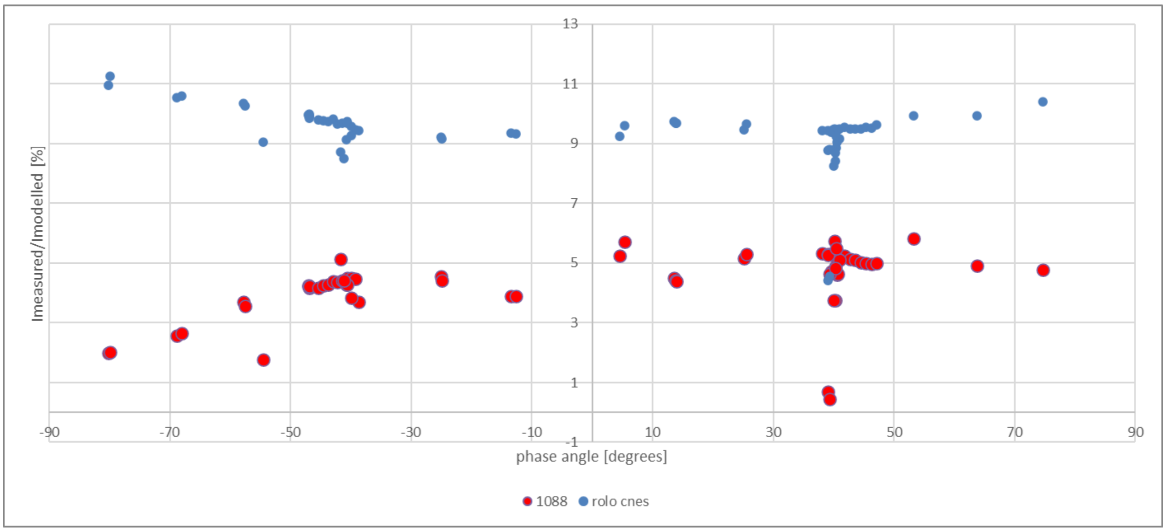

Figure 29: PHR1B band 3 (red) result - 1088 model

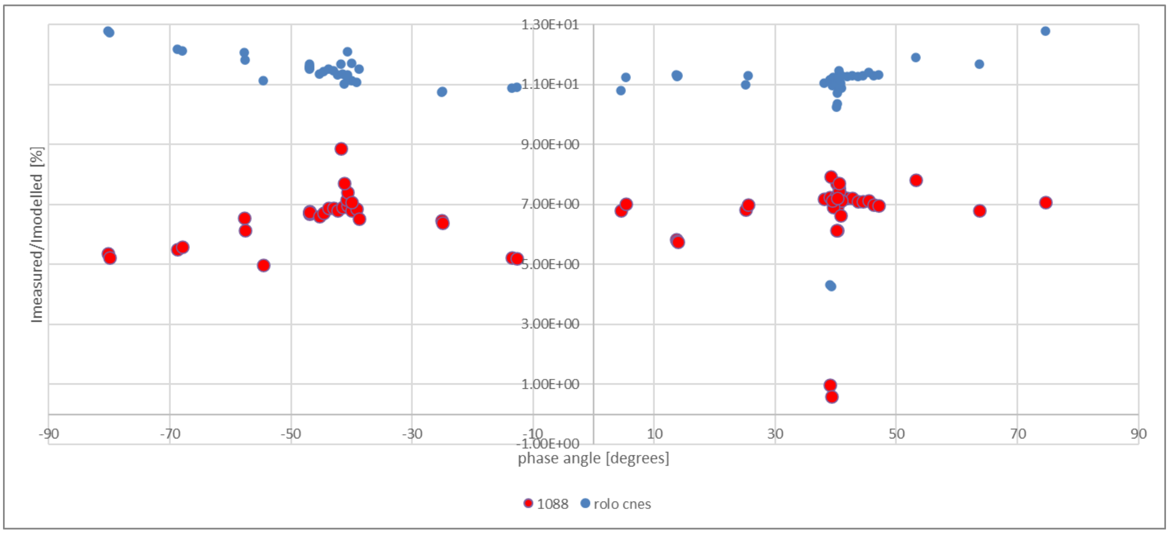

Figure 30: PHR1B band 4 (nir) result - 1088 model

comparison of the lunar spectral irradiance model to several datasets

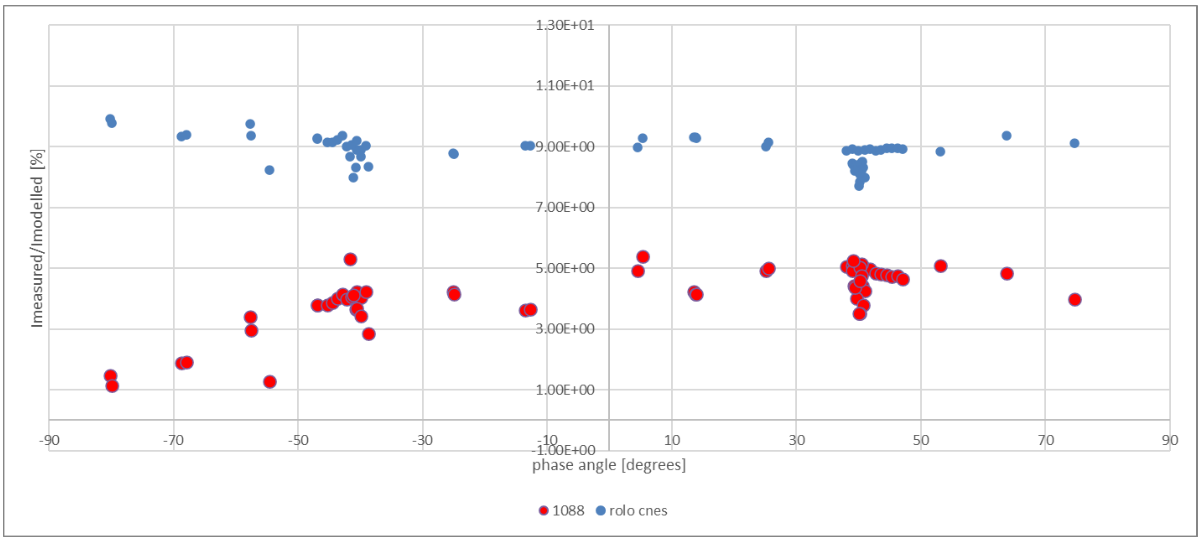

Figure 31: PHR1B band 5 (pan) result - 1088 model

Table with the overview of the comparison between the Pleiades 1B and 1088 lunar model.

Table 10: Average and Stdev of Pleiades data agains the 1088 model

%	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

5.5 Conclusion Pleiades 1B comparison

The comparison with Pleiades shows that :

- General shape of the phase angle graphs is the same for both models, however small differences can be observed with varying phase angle and wavelength. Looking at the standard deviation, the models are quite in line.
- The output of the 1088+933 instrument measurement derived lunar irradiance model is slightly lower than the PLEIADES irradiance levels, calibrated with other vicarious calibration methods. The comparison with the instrument shows differences of the order of 5 %.
- The absolute level of the 1088+933 ESA lunar model is between 3 % and 5 % higher than the ROLO model implemented by CNES
- And the 1088 model appears to be reasonably in the same absolute range, but with increased phase angle variations.

6 Comparison with the GIRO model

The GIRO model was developed at EUMETSAT in collaboration with T. Stone to create a functional copy of the original USGS ROLO model as a second reference implementation. Benchmarks have shown numerical “identity” between both models.

The GIRO model is distributed to parties that incorporate data into the GLOD, a database with several sets of lunar acquisitions, formatted and stored by EUMETSAT. The agreement was made to share data of the current project with the GLOD, in order to get a license to use the GIRO as a comparison to the currently developed model.

Both models are setup the use the PROBA-V sensor spectral responses. In this comparison, version 1.0.0, fourth release, is applied.

6.1 Input data

Both models require as an input the time and location for which a lunar irradiance has to be simulated. For a period of 1456 days, PROBA-V observer geometries have been simulated and stored together with its timestamp. This has resulted in 465 lunar positions with phase angles ranged between the limits of the model (-90 and +90 degrees phase angle). Angles smaller than 2 degrees absolute phase angle have been discarded as well.

These geometries have been applied to both the GIRO and the 1088+933 lunar model. Relative plots are shown in the next section, comparing the 1088+933 irradiance directly to the GIRO irradiance output for all 4 PROB-V spectral channels.

6.2 Results GIRO model

Comparison is done for the 4 PROBA-V spectral bands, with central wavelengths 450, 645, 834 and 1665 nm.

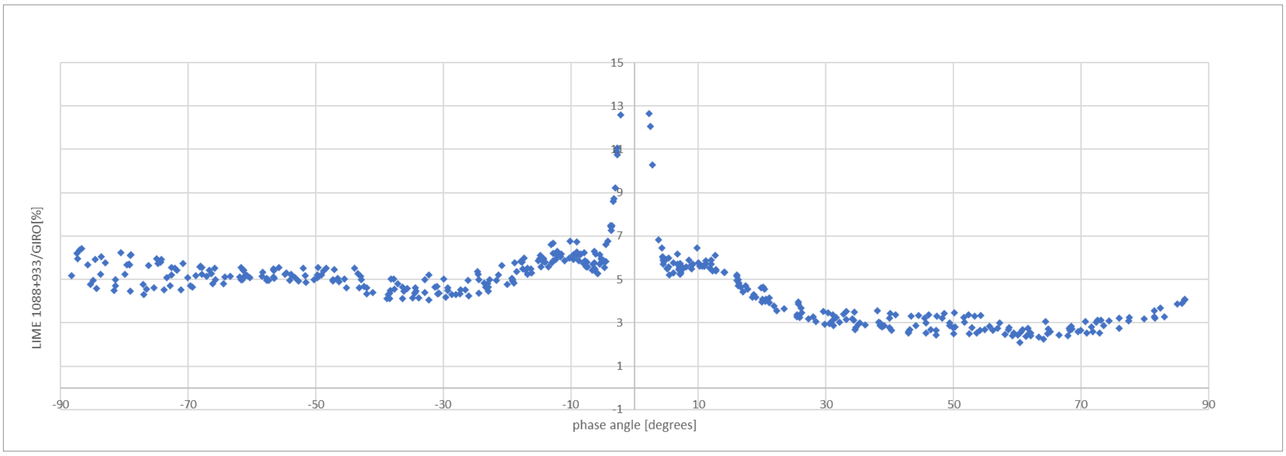

Figure 32: 1088+933 model to GIRO 461 nm

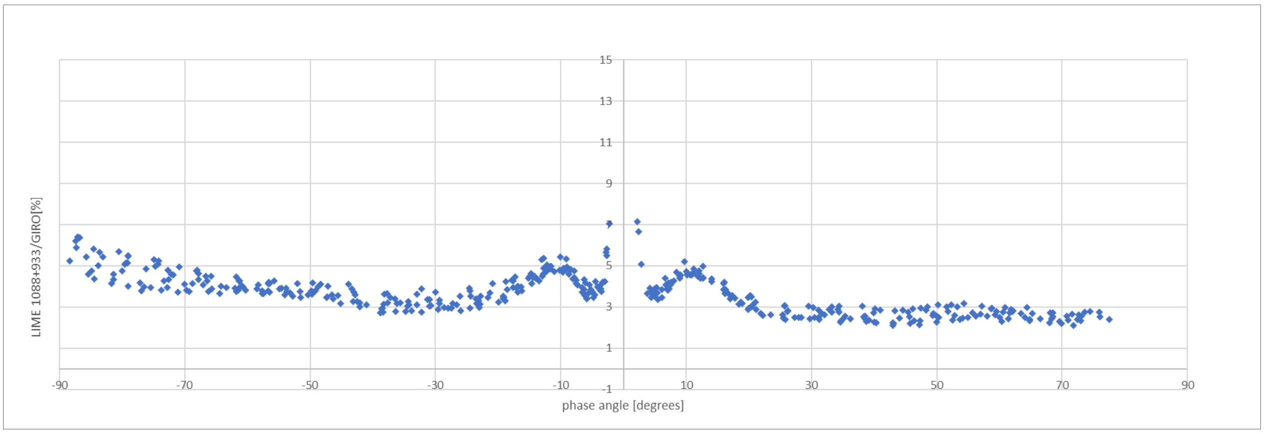

Figure 33: 1088+933 model to GIRO 650nm

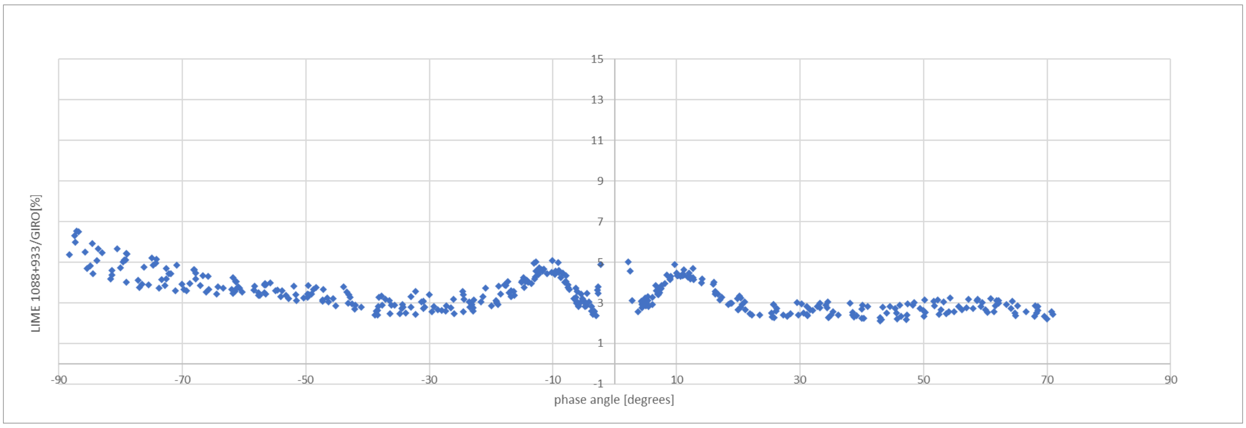

Figure 34: 1088+933 model to GIRO 840 nm

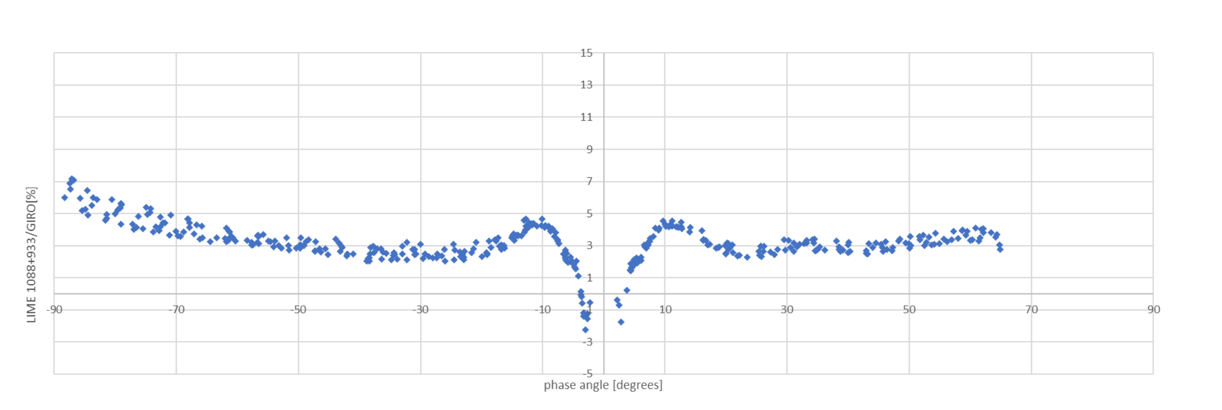

Figure 35: 1088+933 model to GIRO 1604 nm

Table 11: overview of 1088+933 model compared to GIRO

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

6.3 Conclusion GIRO comparison

In general three important conclusions can be taken from this comparison:

- For all bands the ESA model gives higher lunar irradiance than the GIRO model in the VNIR and SWIR
- This difference increases with wavelength
- For very low phase angles, the two models are in closer agreement, apart from for wavelengths below 440 nm

The 1088+933 model and the GIRO have different solutions, both for the absolute level as the dependency on the phase angle. When looking at the PROBA-V and Pleiades results, the absolute level of the 1088+933 model is closer to the sensor compared to their specific ROLO implementations. What is observed from the GIRO results, they appear to be quite in-line with that conclusion.

The phase angle dependency of both models (1088+933 and the GIRO) is quite different. The GIRO model is based upon much more geometric cases and therefore is expected to be more stable. Both PROBA-V and PLEIADES results seem to confirm this. Model regression iterations with more measurements available for the 1088+933 model should improve (lower) this dependency.

7 Conclusions

7.1 Conclusions for the 1088+933 model

For the absolute level of the model the following conclusions can be drawn :

- The absolute model level agrees quite well with the Pleiades instrument,
- Compared to the CNES ROLO version, around 3 to 5 percent difference is observed,
- This absolute difference is also confirmed through the PROBA-V comparison, with a different reference.
- Comparison with the GIRO reveals a comparable absolute difference, except in lower phase angles.

To summarize the comparison, it is the current version of the lunar model has some issues :

- In general a phase dependency is observed for all bands
- Especially low phase angles (<10 degrees) appear to have larger than average deviations
- In general, the irradiance level difference between the ESA model and VITO/CNES or GIRO implementations of the ROLO appear to be constant and around 5% in the VNIR.
- PROBA-V lunar data processing is to be re-assessed, as the results do not agree with knowledge of other absolute calibration methods

7.2 Conclusions for the 1088 model

- The 1088 model agrees quite well in absolute value with the 1088+933 model.
- When looking at the PROBA-V results, the 1088 model appears to have an increased standard deviation. The model appears to have less ability to reproduce low phase angle results.
- Looking at the Pleiades results, in absolute terms, the model is closer to the instrument than the 'CNES-ROLO4. However, there is a larger phase angle dependency observed.

This study isn't final :

- More measurements with the 1088 instrument are needed, so the developed model has full traceable calibration
- After deriving new parameters for the model from the 1088 instrument data this comparison will be reproduced and re-assessed.
- Comparison with other references is to considered (i.e. from the GLOD)

APPENDIX A – MODEL IMPLEMENTATION VALIDATION

As an extra test, a comparison between the implementation described in paragraph 3.2 done within the project is compared to the GIRO model output. Simply feeding the ROLO model coefficients from [RD-1] into the software allows comparison of both implementations.

Visual inspection of intermediate results show that the calculation of the ROLO reflectance values are identical for both GIRO and the project software. Differences exist between the output irradiances of both implementations, are thus due to the model 'post-processing' of paragraph 3.2.

In the next figures one can observe, that for the PROBA-V bands, there is generally a very small difference (~0.1 % absolute), except for the blue band. In the blue band, the offset between both implementations is about 1 %.

Following possible reasons are identified :

- Different reflectance interpolation for model central wavelengths (no knowledge of responses is available for the ROLO channels)
- Slightly Different procedure :
  - Spline interpolation implementation
  - Least Absolute Difference regression implementation

There is currently no conclusion yet on the exact reason. There appears to be a dependency on wavelengths. This needs further investigation in one of the next model iterations.

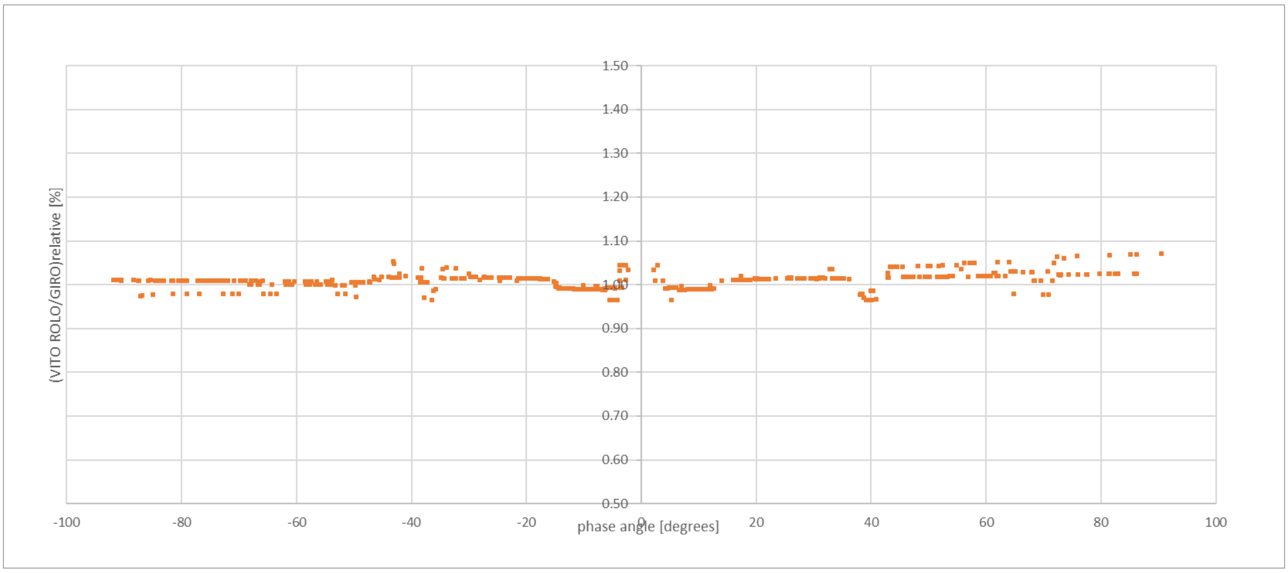

Figure 36: Relative difference between project software and GIRO for 461nm

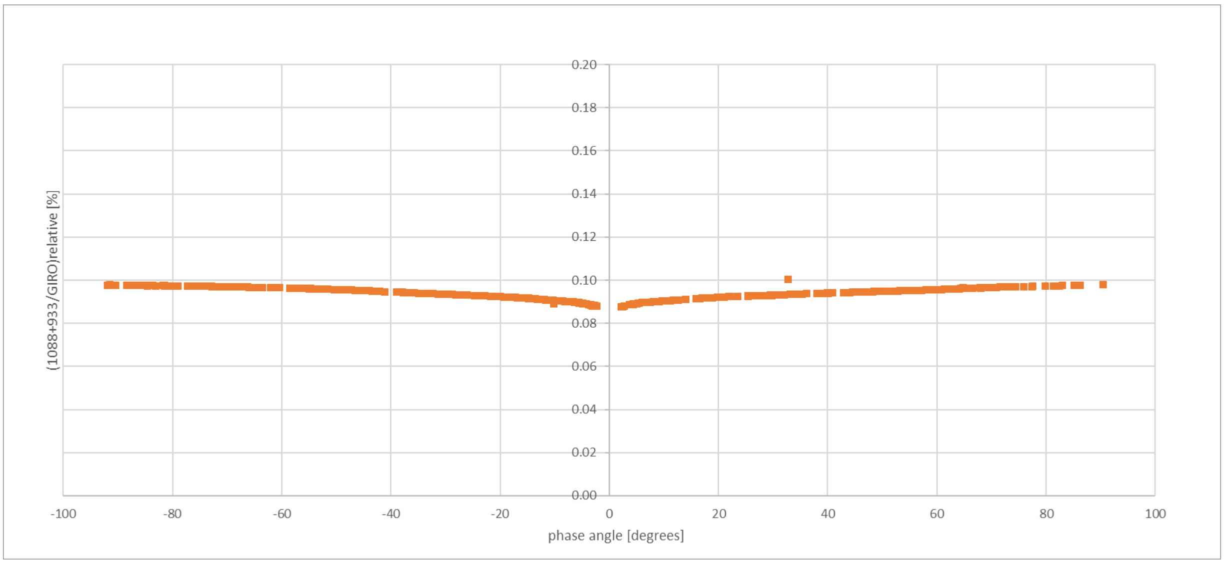

Figure 37 : Relative difference between project software and GIRO for 650nm

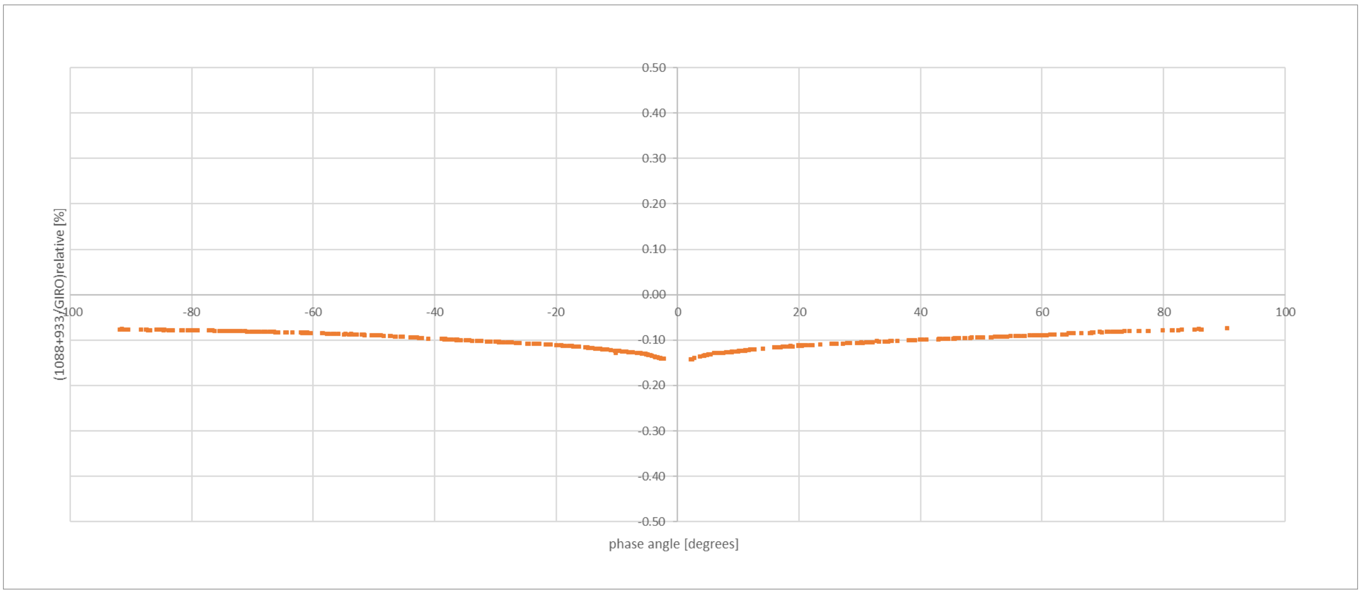

Figure 38 : Relative difference between project software and GIRO for 840nm

comparison of the lunar spectral irradiance model to several datasets

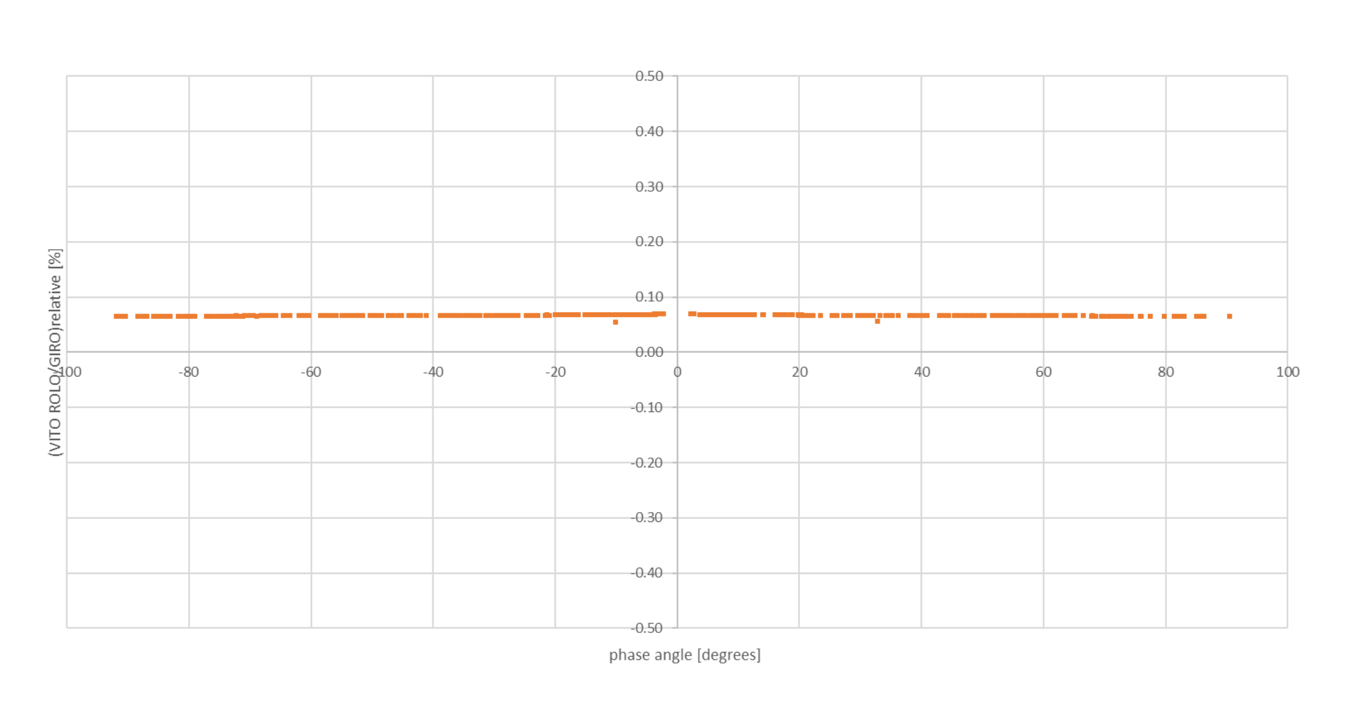

Figure 39: Relative difference between project software and GIRO for 1604nm

APPENDIX B – Comparison Sentinel 3 OLCI with LIME

In this paragraph Sentinel-3 lunar acquisitions are compared with the most the LIME model. Two acquisitions have been performed, one for S3A and one for S3B.

The Sentinel 3B spectral response functions of the instrument are shown in Figure 40. There are 21 bands over the visible range between 400 and 1050nm roughly. The spectral bands are 40,20,10 and 7.5 nm wide. Three specific narrow bands in the area of 765nm are 2.5,3.75 and again 2.5 nm wide. These are spectral bands for specific application of atmospheric correction purposes.

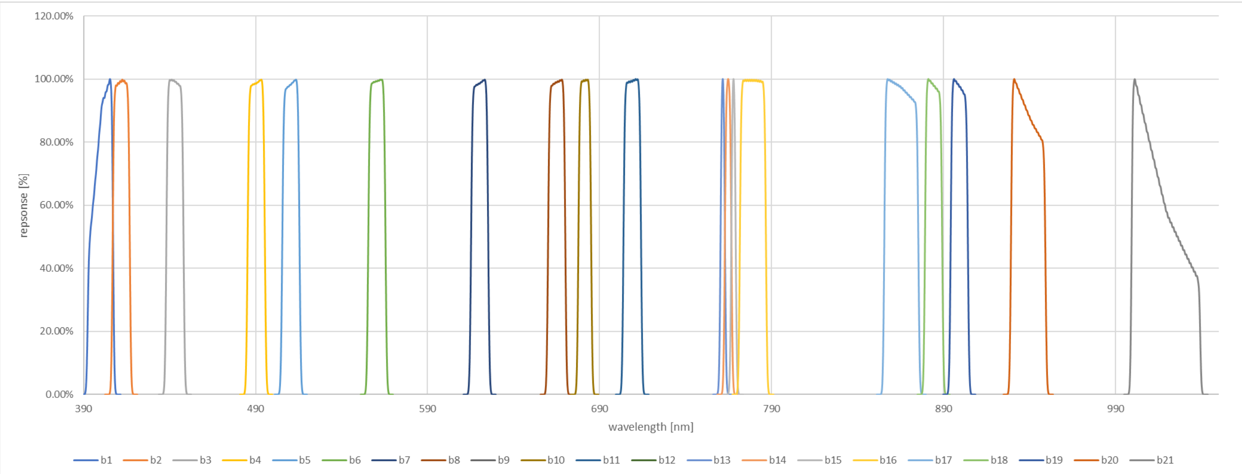

Figure 40: Sentinel 3B OLCI mean Relative Spectral Response curves

comparison of the lunar spectral irradiance model to several datasets

Timestamps and sensor locations are :

Sensor	Timestamp	X(J2000) [km]	Y(J2000) [km]	Z(J2000) [km]
S3B	2018-07-27T05:22:43	956.429	-6474.182	-2969.739
S3A	2020-07-04T16:13:05	-1367.947	-6186.552	-3386.554

Table 12:Timestamp and location of S3A/B lunar observations

The push-broom imager performs a line-by-line scan of the Moon during a rotational maneuver of the platform. This approach requires specific processing of the data, taking into account the oversampling factor for every line, using the platform telemetry. The processing to retrieve the irradiances from the image is performed by Maciek Neneman of ESA-ESTEC. His results and the comparison of the S3B and the previous version of LIME is published :

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.

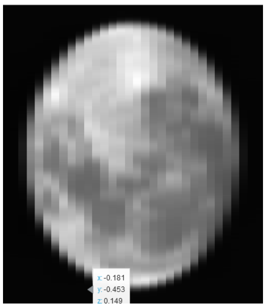

Figure 41: S3B lunar acquisition quicklook for band 5

Figure 41 is a quicklook of the spectral band 5 in DN values. The processing that is performed is comparable to the PROBA-V processing sequence, apart from specific implementations like DN to Radiance conversion sensor model. The Irradiance values for both sensors is plotted in Figure 42. The differences that are observed are due to the difference in observation geometry (phase angle, libration) and sensor differences. The irradiances are normalized for distances between Sun, Moon and observer.

comparison of the lunar spectral irradiance model to several datasets

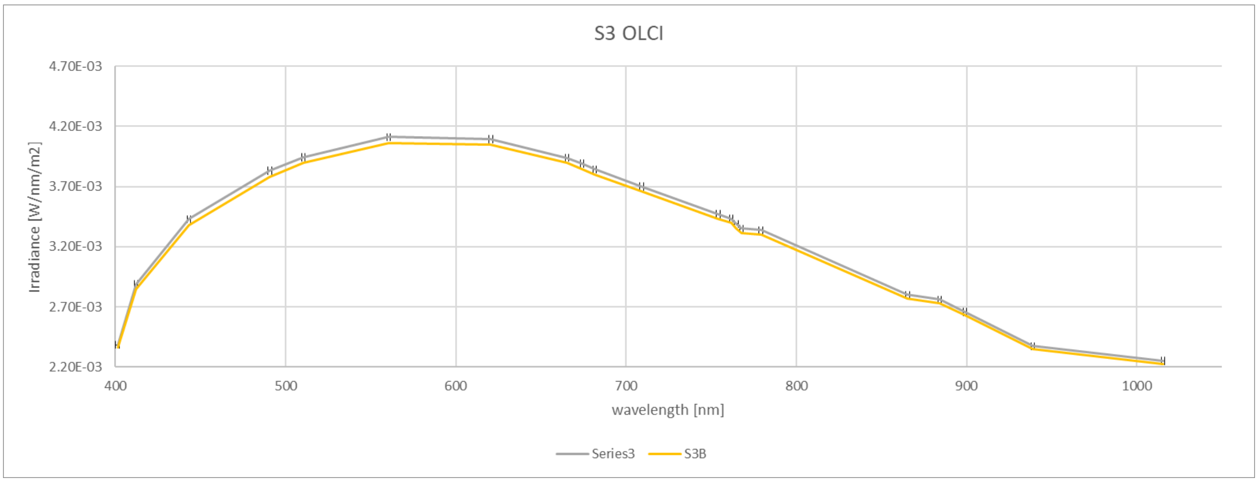

Figure 42: Irradiance levels for both S3A and S3B Lunar acquisitions

Direct comparison between LIME and the observations of both S3A and B are plotted in Figure 43.

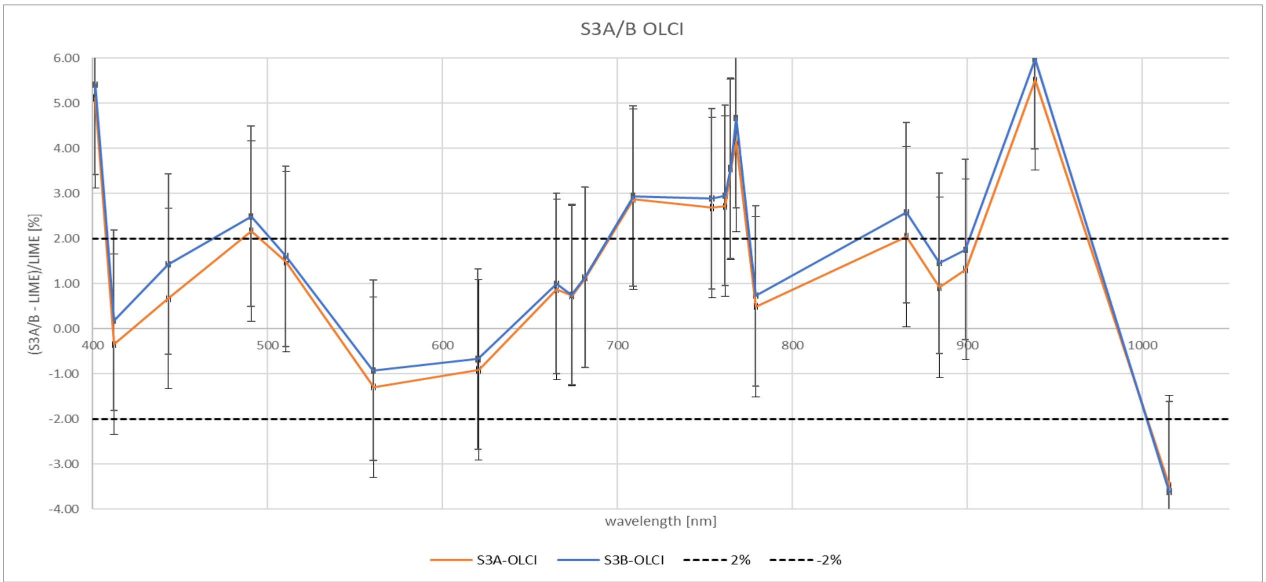

Figure 43: Comparison between S3A and B OLCI and LIME

When taking the 2% model uncertainty into account, the plot shows that for both S3A and B most bands fall within the 2% absolute requirement level. In general, S3A appears to be slightly higher then S3B. However, taken the model uncertainty into account, differences are too small to confirm them.