EnMAP Moon observations for instrument monitoring and radiometric validation

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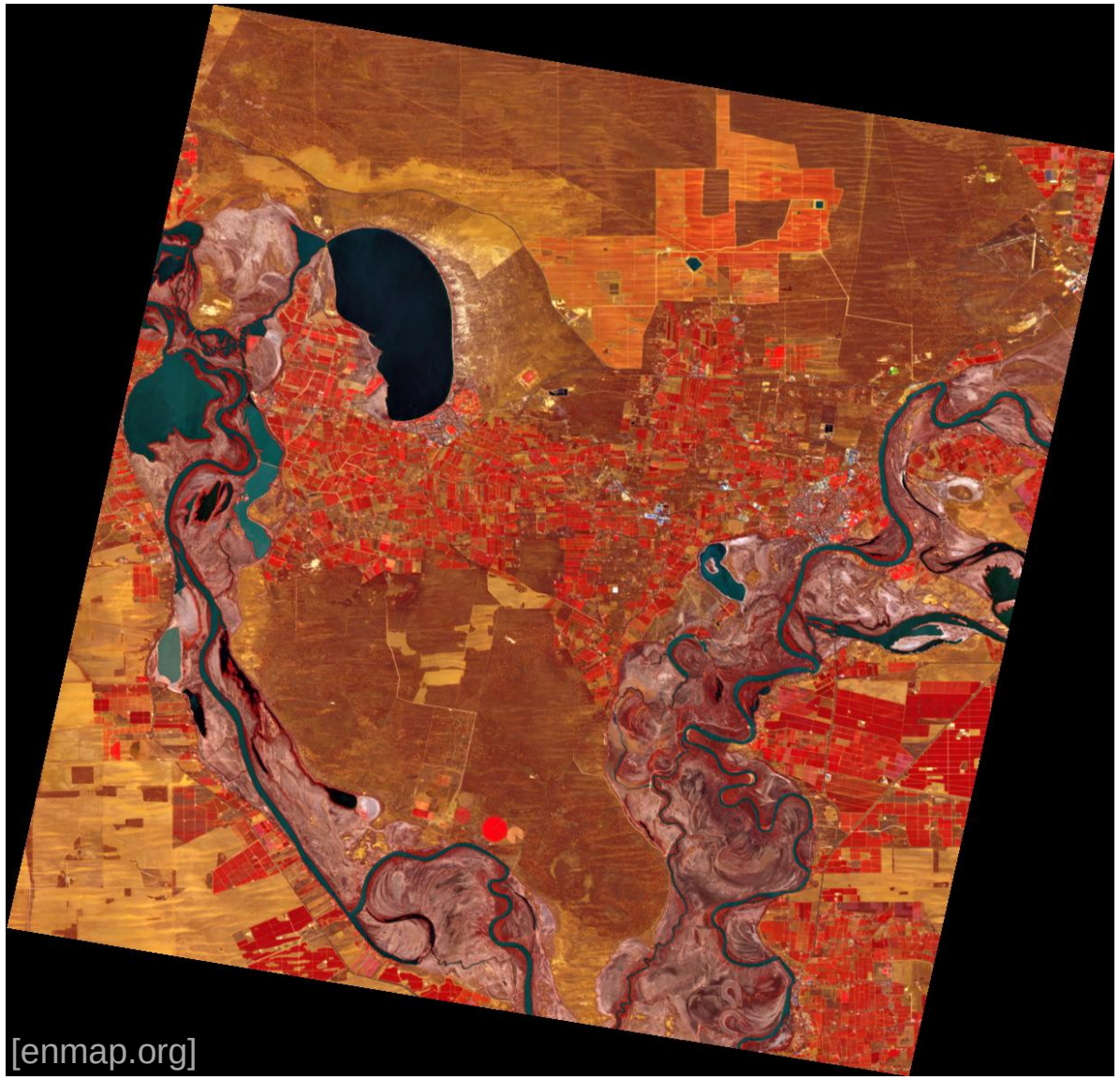
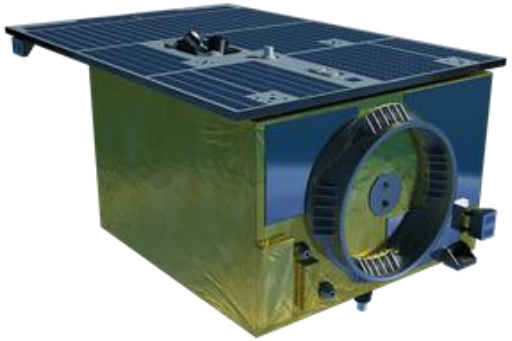
EnMAP mission: in a nutshell

https://www.enmap.org/


[enmap.org]

Earth observation data provided by EnMAP:

- 418–2450 nm, 224 bands, FWHM 6–11 nm
- 30 km x 30 km tiles, 30 m pixel size
- 4–27 days revisit time at 11:00 local time
- L1B: top of atmosphere radiances
- L1C: orthorectified top of atmosphere radiances
- L2A: orthorectified bottom of atmosphere reflectances (land and water)


[enmap.org]

EnMAP mission: in a nutshell

https://www.enmap.org/

EnMAP specification	VNIR	SWIR
Spectral range	420 – 1000 nm	900 – 2445 nm
Number of spectral bands	91	133
Spectral sampling distance	6.5 nm	10 nm
Spectral full width at half maximum	6 – 11 nm	7 – 11 nm
Spectral accuracy	0.5 nm	1 nm
Spectral stability	0.5 nm	
Spectral smile	<0.2 pix	
Signal-to-noise ratio	>500 (at 495 nm)	>150 (at 2200 nm)
Radiometric accuracy	<5%	
Radiometric stability	<2.5%	
Geometric accuracy	1 pix (30 m) with GCPs, otherwise 100 m	
VNIR/SWIR co-registration	0.2 pix	
L2A AOT, WV, BOA (land, water)	see Storch et al 2023	
Orbit type, altitude and inclination	Sun-synchronous, 653 km, 97.96°	
Orbit period and repeat cycle	1.6 h, 398 revolutions in 27 days	
Local time descending node	11:00 h ± 18 min	
Revisit time	4 days (±30° off-nadir tilt) 21 days (±5° off-nadir tilt)	
Ground sampling distance	30 m (at nadir; sea level)	
Swath width	30 km (2.63° across track)	
Swath length	1000 km / orbit; 5000 km / day	
Product size	30 km x 30 km	

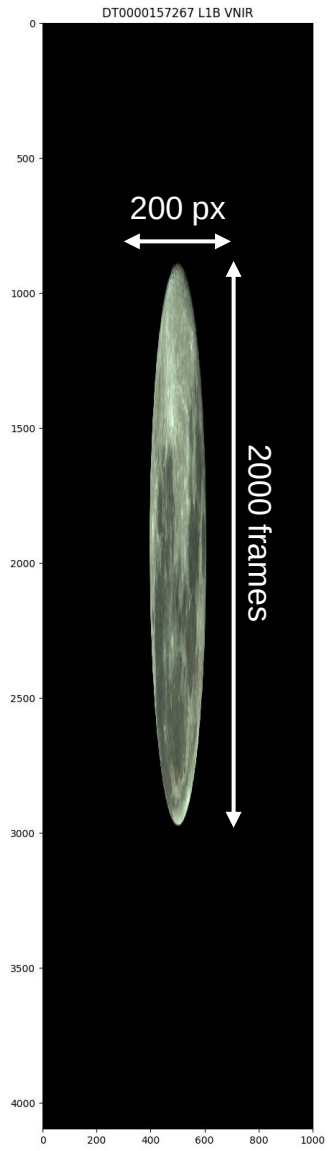
EnMAP in this conference:

- Mission overview (La Porta, Wed 11:30)
- Mission operations (Carmona, poster)
- Mission science (Chabrillat, poster)
- Cal/Val activities (Reiners, Tue 15:45)
- Spectral performance (Bachmann, poster)
- L2A land (Eckert, Tue 11:30)
- L2A water (Soppa, poster)
- and many more…

In-orbit calibration type	Mechanism	Frequency
Relative radiometric (lamp)	white spectralon	1x / fortnight
Absolute radiometric (Sun)	Sun diffuser	1x / 2 months
Spectral	doped spectralon	1x / fortnight
Linearity	focal plane LEDs	1x / month
Deep space	dark sky	1x / month
Dark frames	closed shutter	before/after imaging

EnMAP Moon observations

- EnMAP focus is Earth observation, but the mission is committed to performing regular Moon observations and is collaborating with lunar experts (USGS, CNES, ESS).
- Moon observations are useful for instrument monitoring, radiometric validation and lunar modelling.
- EnMAP Moon imaging capabilities:
  - variable lunar phase angle
  - along-track scan of Moon with 10x oversamping (Moon: 200 px, 2000 frames)
  - Earth observation mode used (spectral gaps at ~1400 nm and ~1800–1900 nm)
  - spectral data: VNIR: 418–993 nm, 91 bands, SSD 5–8 nm, FWHM 6–11 nm
    SWIR: 902–2445 nm, 133 bands, SSD 7.5–12 nm, FWHM 7–11 nm
  - space-based, high-quality and stable radiometric and spectral performance
- Current observation strategy: lunar phase angle ~7° every 2 months. This is well adapted for instrument monitoring and radiometric validation.
- Dedicated Moon observations campaigns to scan lunar phase angles and joint observations with other missions are being considered.



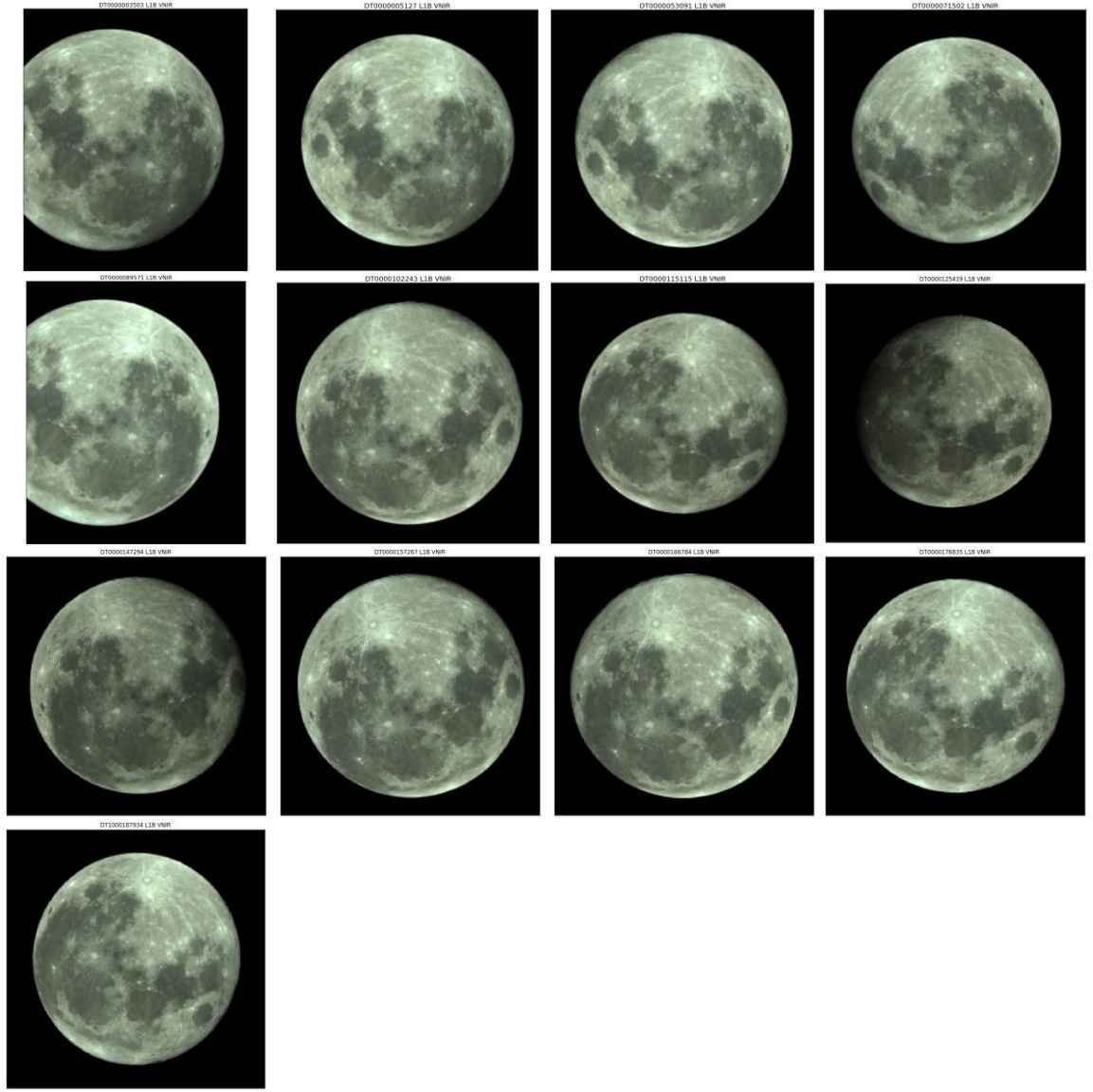
[Source: DLR]

EnMAP Moon observations

Datatake ID	Date	Number of tiles*	Lunar phase [°]
3503**	09.09.2022	3	-8.2
5127	07.11.2022	4	-6.1
53091	27.11.2023	12	5.6
71502	24.04.2024	4	6.8
89571**	19.08.2024	4	3.4
102243	16.11.2024	4	7.8
115115	13.02.2025	4	10.7
125419	10.04.2025	4	-23.0
147294	10.08.2025	4	15.4
157267	07.10.2025	4	7.4
166784	04.12.2025	4	-7.5
176835	02.02.2026	4	6.8
1000187934	02.04.2026	4	6.6
TBD	30.05.2026	4	-7 (TBC)

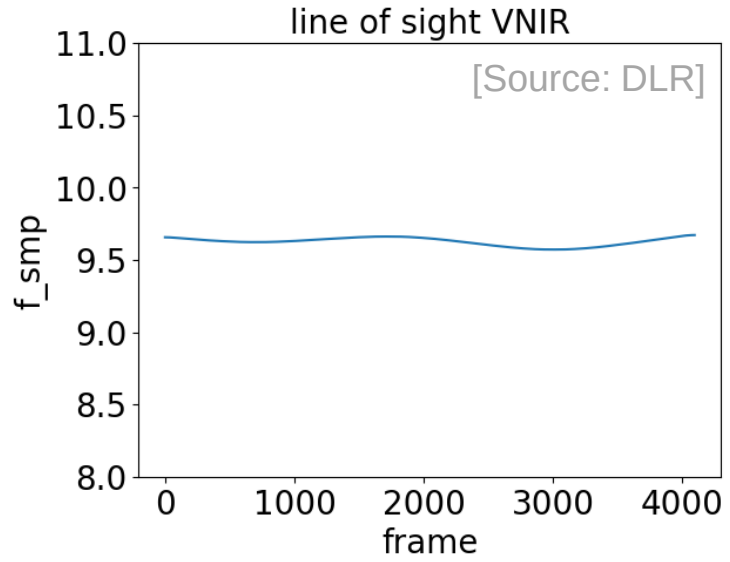
* EnMAP tile = 1024 along-track frames x 1000 across-track pixels
** Pointing innacuracy led to missing part of the Moon disk.

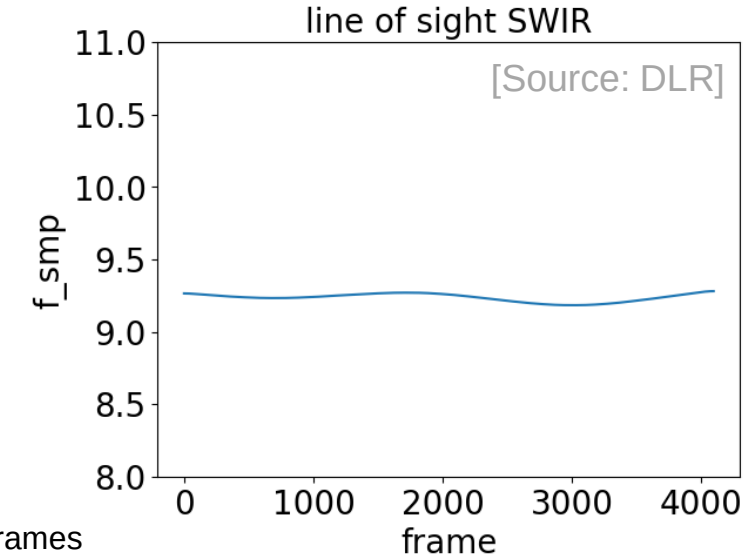
[Source: DLR]



Moon data processing

- Moon observations are processed in a dedicated pipeline, delivering internal products with at-sensor radiances (L1B) and extensive auxiliary information for post-processing.
- Time (UTC) and spacecraft position (ECEF/WGS84, ICRF/J2000) are computed from GPS data.
- Line of sight (ECEF/WGS84, ICRF/J2000) is computed from attitude data (single band for each detector since keystone is small: <0.2 pixel).
- Oversampling is estimated from line of sight (filtered to remove noise): $f_{\mathrm{smp}} = \frac{\mathrm{IFOV}}{\Delta}$, $f_{\mathrm{smp}} \approx 10$, Moon: 2000 frames
- Lunar phase angle, observer and Sun selenographic coordinates, Moon-Sun and Moon-EnMAP distances derived from JPL Horizons using time and spacecraft position at Moon center imaging in VNIR.





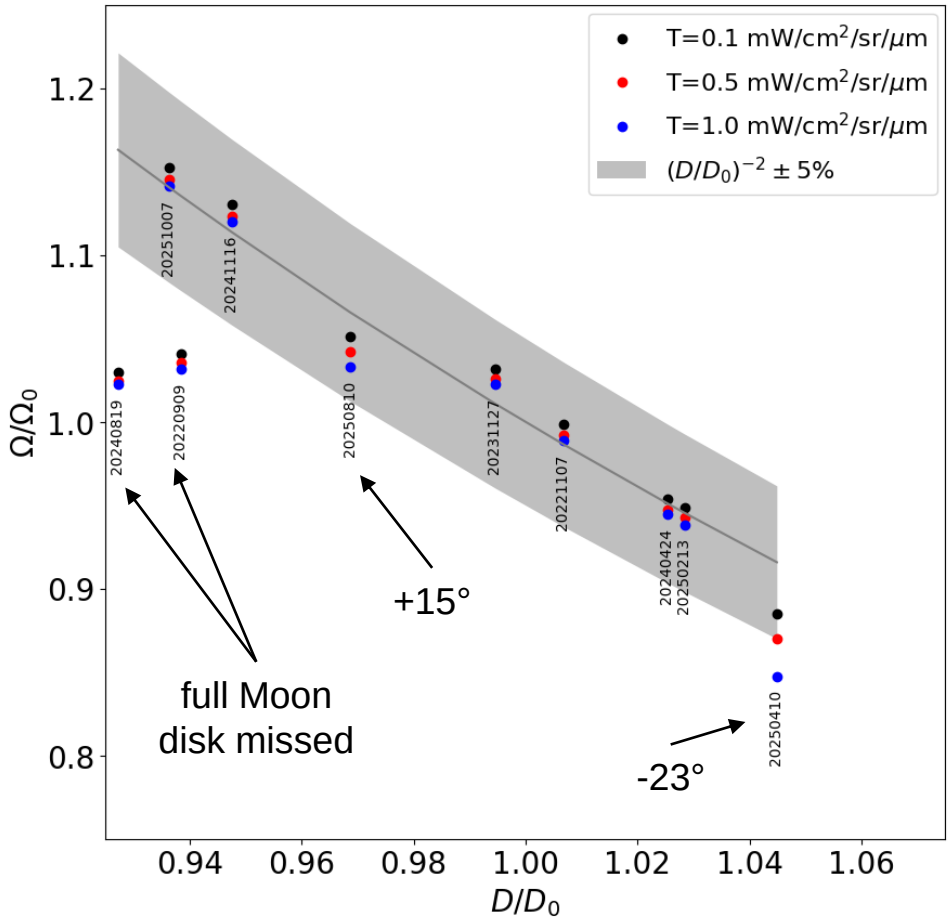
IFOV: along-track instantaneous field of view
Δ: angle between pixel line of sights in consecutive frames

Moon data processing

- Moon mask is derived by thresholding VNIR average radiance and removing isolated pixels. Simple procedure is adequate for phases below ~25°.
- Lunar radiance: $L_M(\lambda) = \frac{1}{N_M}\sum_{(f,p)\in M} L(f,\lambda,p)$
  - Defective pixels removed from averaging
- Lunar irradiance: $E_M(\lambda) = \frac{\Delta\Omega}{f_\mathrm{v}}\sum_{(f,p)\in M}\frac{L(f,\lambda,p)}{f_\mathrm{smp}(f,p)}$
  - Defective pixels replaced by average irradiance of valid pixels
  - Per-frame and per-pixel oversampling considered
- Effective lunar disk reflectance: $\rho_M(\lambda) = \frac{\pi E_M(\lambda)}{\Omega_M E_S(\lambda)}$
  - Sun model used in EnMAP (Fontenla et al, 2011) factored out
- Distance correction applied a posteriori:

$$E_{M,0}(\lambda) = E_M(\lambda)\left(\frac{D_{S-M}}{1\ \mathrm{AU}}\right)^2\left(\frac{D_{O-M}}{384\,400\ \mathrm{km}}\right)^2$$

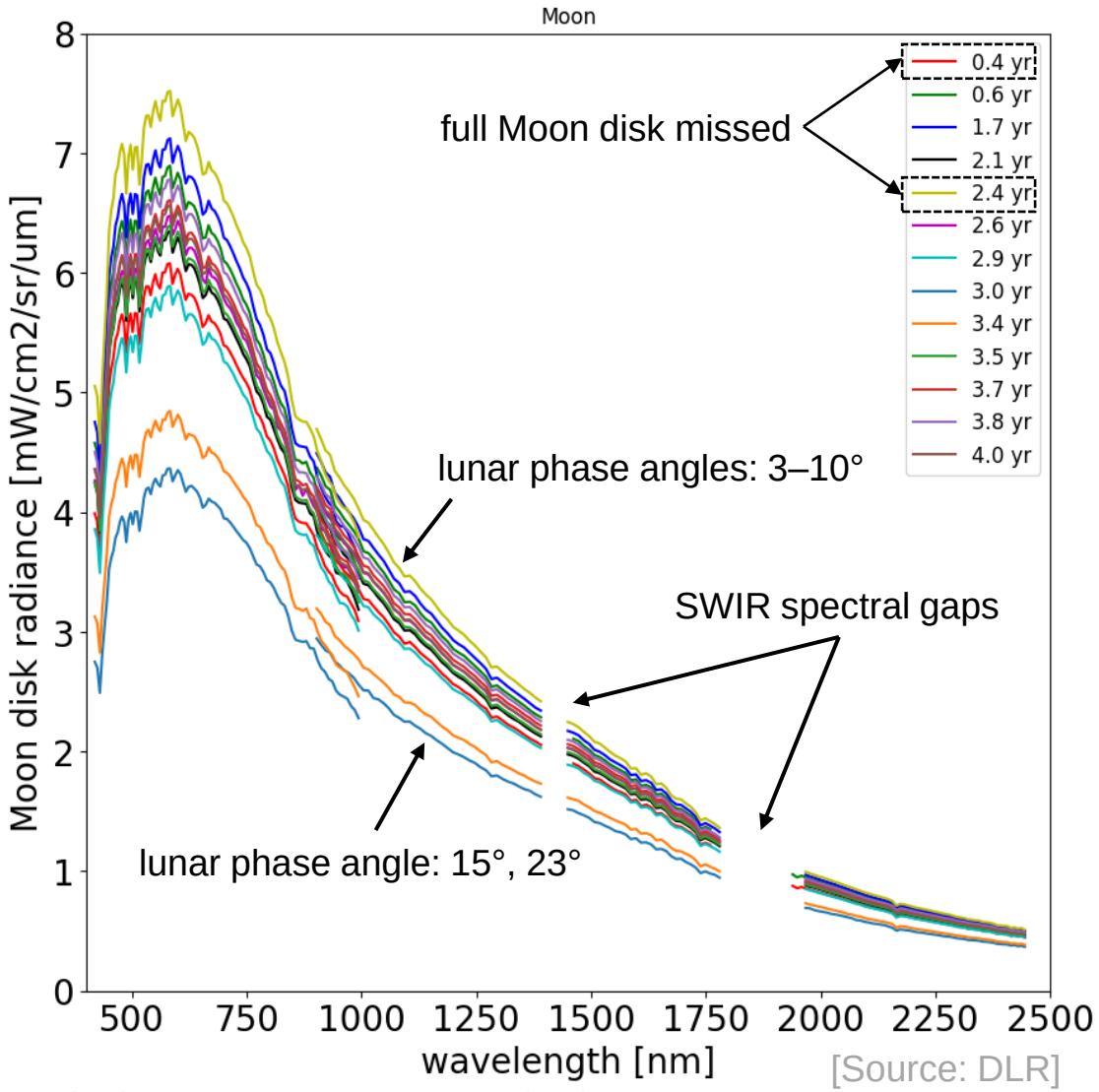
[Source: DLR]



L: at-sensor radiance spectral image f: frame, p: pixel
M: Moon mask without defective pixels,
f_v: fraction of valid pixels in the Moon mask
$\Delta\Omega \approx$ IFOV×GSD: pixel solid angle
E_S: solar irradiance model used in EnMAP
$\Omega_M = \pi R_M^2/D_M^2 = 6.4177\times10^{-5}$ sr

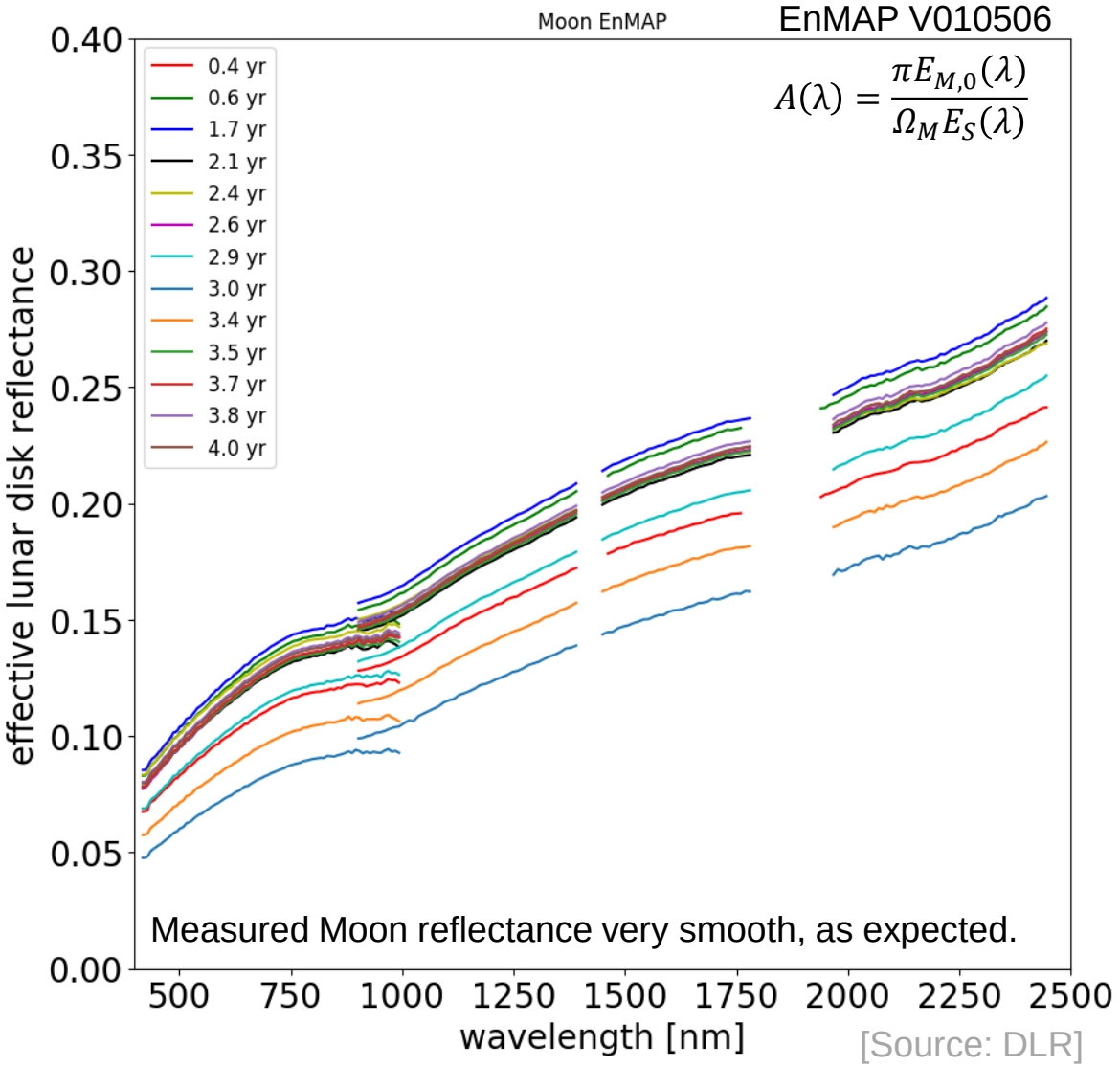
Moon data processing

At-sensor radiance averaged over Moon



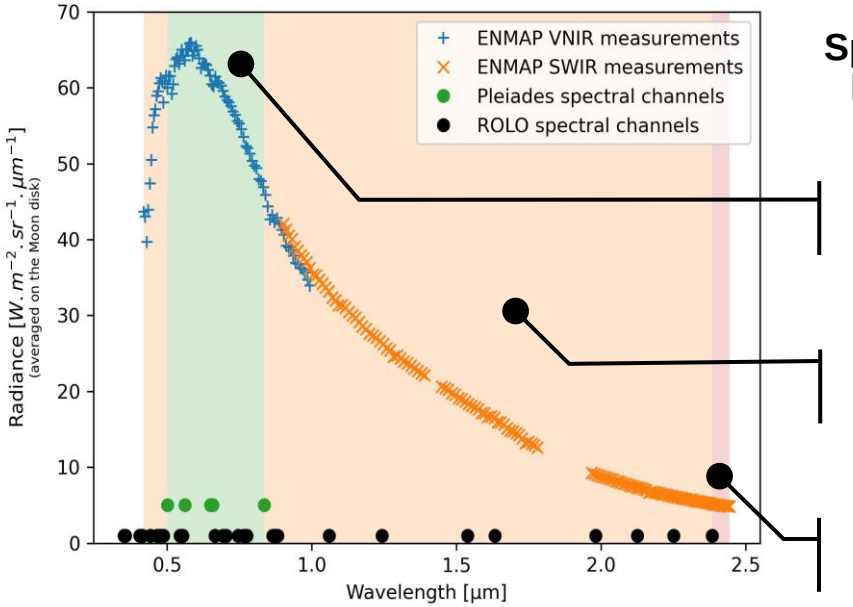
[Source: DLR]

Effective Moon disk reflectance



[Source: DLR]

EnMAP Moon data and ROLO-CNES



[Source: CNES]

Spectral validity of the ROLO-CNES model

Reliable model with CNES correction

Model with **extrapolated CNES correction**

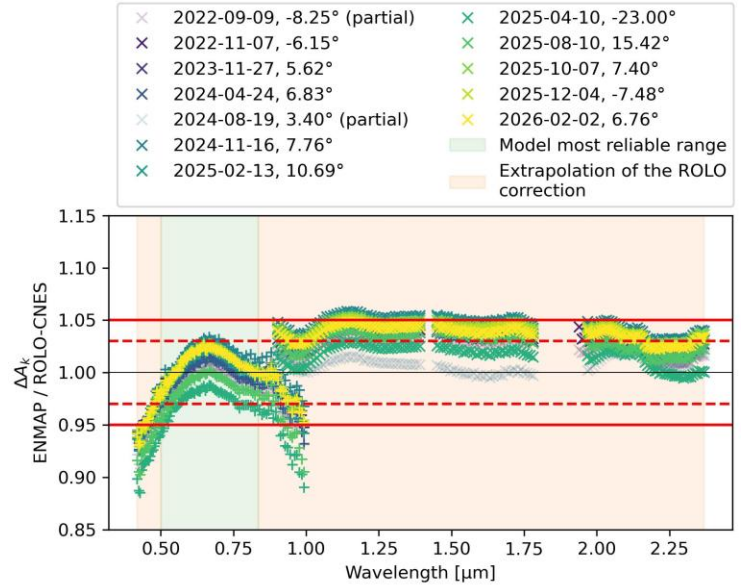
Extrapolated ROLO model

ROLO-CNES model:

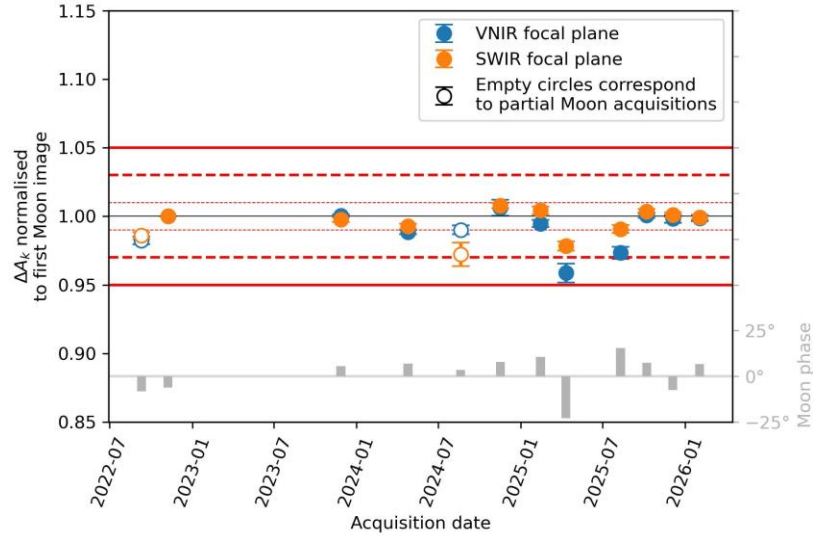
- The model combines:
  - **ground observations** from USGS (the ROLO model) [H. H. Kieffer and T. C. Stone, 'The Spectral Irradiance of the Moon', *The Astronomical Journal*, vol. 129, no. 6, pp. 2887–2901, Jun. 2005]
  - **space observations** from the Pleiades satellites (1400 acquisitions in the VNIR range to correct for Moon phase dependency and a radiometric bias) [A. Meygret, G. Blanchet, S. Colzy, and L. Gross-Colzy, 'Improving ROLO lunar albedo model using PLEIADES-HR satellites extra-terrestrial observations', in *Earth Observing Systems XXII*, J. J. Butler, X. (Jack) Xiong, and X. Gu, Eds., SPIE, 2017, pp. 702–713.]
- The model provides the total Moon irradiance.
- For partial Moon acquisitions, a **pixel-resolved** model was developed. The pixel-resolved model is not yet as accurate as the total irradiance model.

EnMAP Moon data and ROLO-CNES

Spectral results



Temporal results



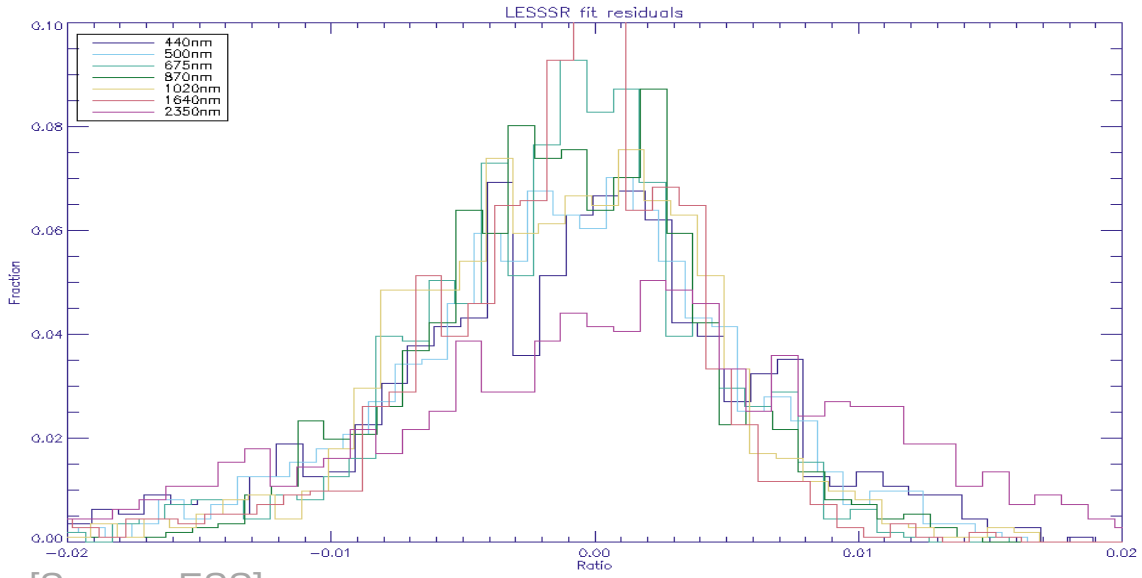
[Source: CNES]

Comparison to ROLO-CNES:

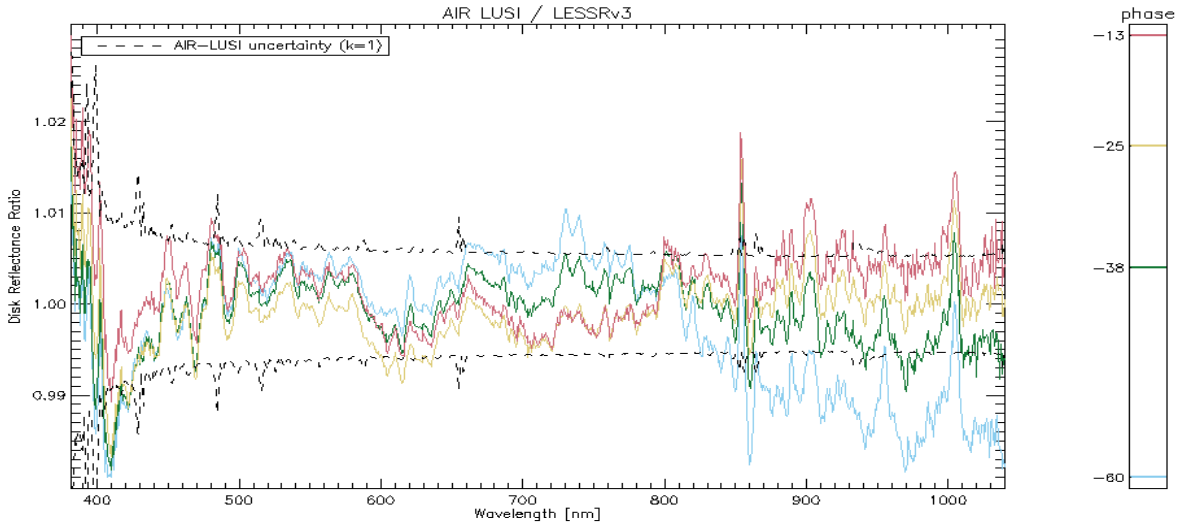
- In **VNIR [600-900] nm**, EnMAP is within ±3%. Outside the most reliable range, the discrepancy increases significantly only in VNIR. The spectral bell shape of the results is not yet understood (and is also observed during calibration with other sensors).
- In **SWIR**, EnMAP is above the model by 2–5%.
- **Spectral shape** is consistent among all observations.
- Except on 2 dates, the **time series** is stable within 1% over the 4 years of operation.
- The **two focal planes** do not match over the range 900–1000 nm with a nonlinear bias of ~5%.
- Globally, EnMAP and the ROLO-CNES model **agree within 5%** except near the VNIR focal plane boundaries.

See also the presentation by Damien Rodat (next talk!), in particular for the partial Moon processing.

EnMAP Moon data and LESSRv3



[Source: ESS]

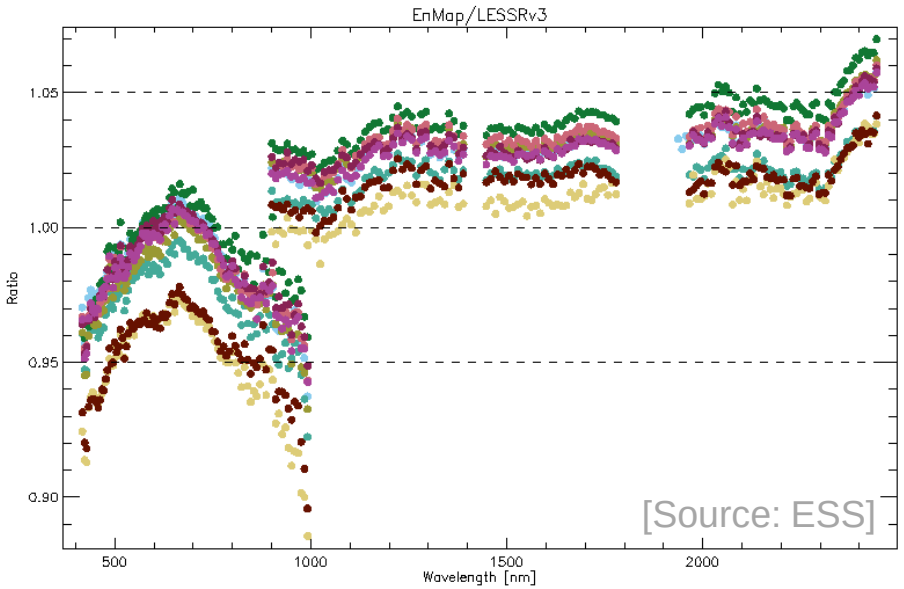


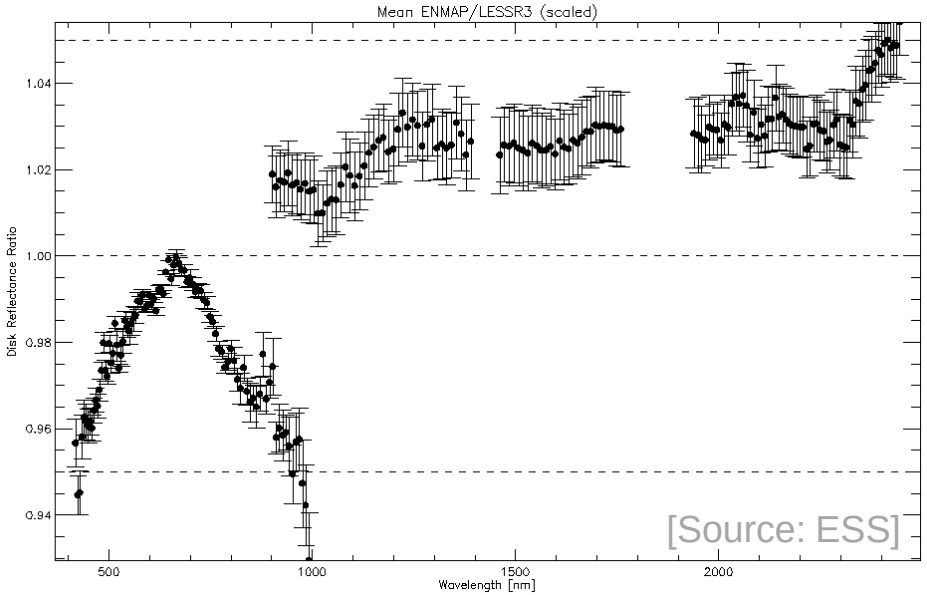
[Source: ESS]

LESSR model:

- LESSRv2 (EUMETSAT)
- LESSRv3 (Earth Space Solutions):
  - Based on ESA SCIAMACHY (satellite)
  - 250–2600nm (5nm resolution)
  - Libration per wavelength
  - Lunar phases: -80° to +20°
  - <1% uncertainty (<1000nm)

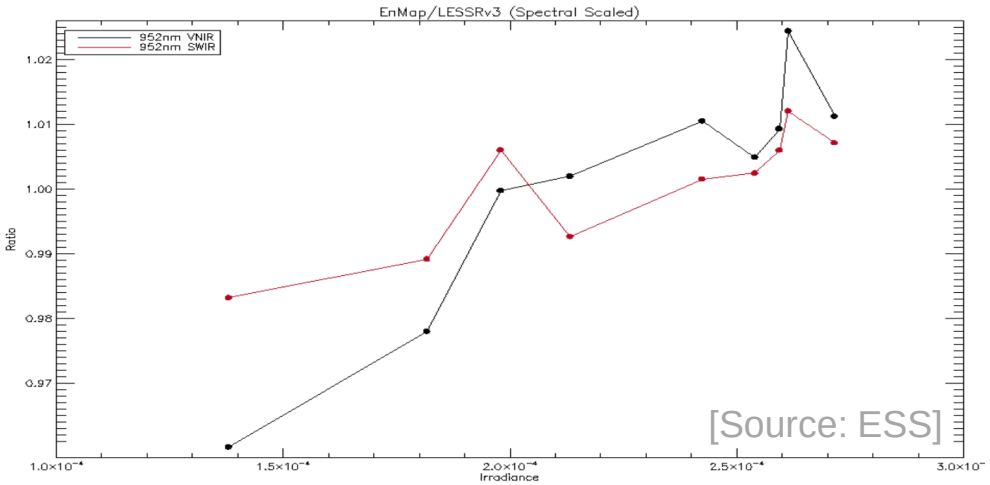
EnMAP Moon data and LESSRv3



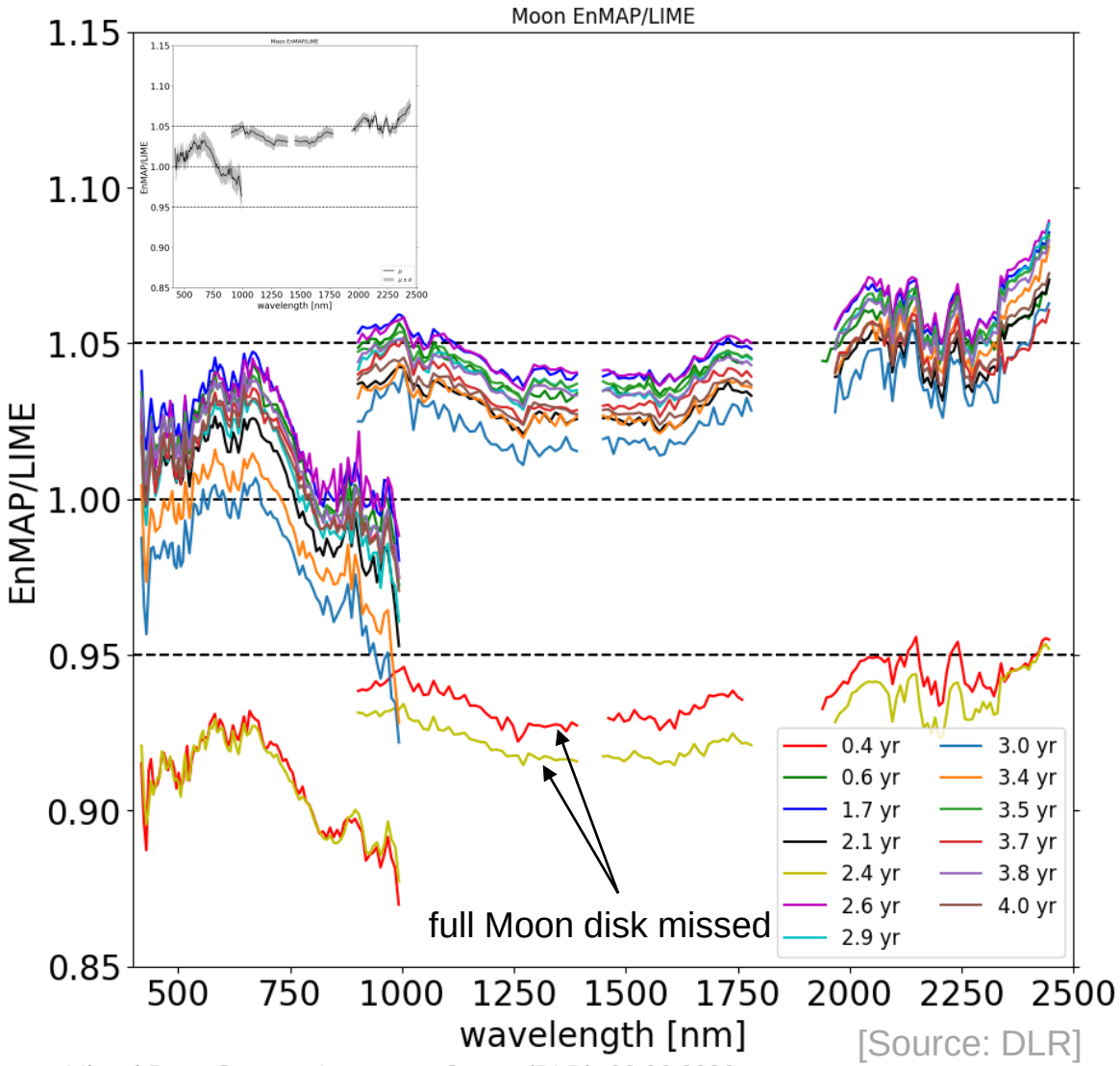


Comparison to LESSRv3:

- Analysis of Moon mask, oversampling, distance correction and calibration artifacts (all negligible).
- Analysis of VNIR/SWIR mismatch at 900–1000 nm and correlation with irradiance level.
- Spectrally similar results (intrinsic noise <1%).
- VNIR within ±2% at 600–900 nm, but below model at <600 nm and >900 nm.
- SWIR 0-5% above model.



EnMAP Moon data and LIME 1.4.1



[Source: DLR]

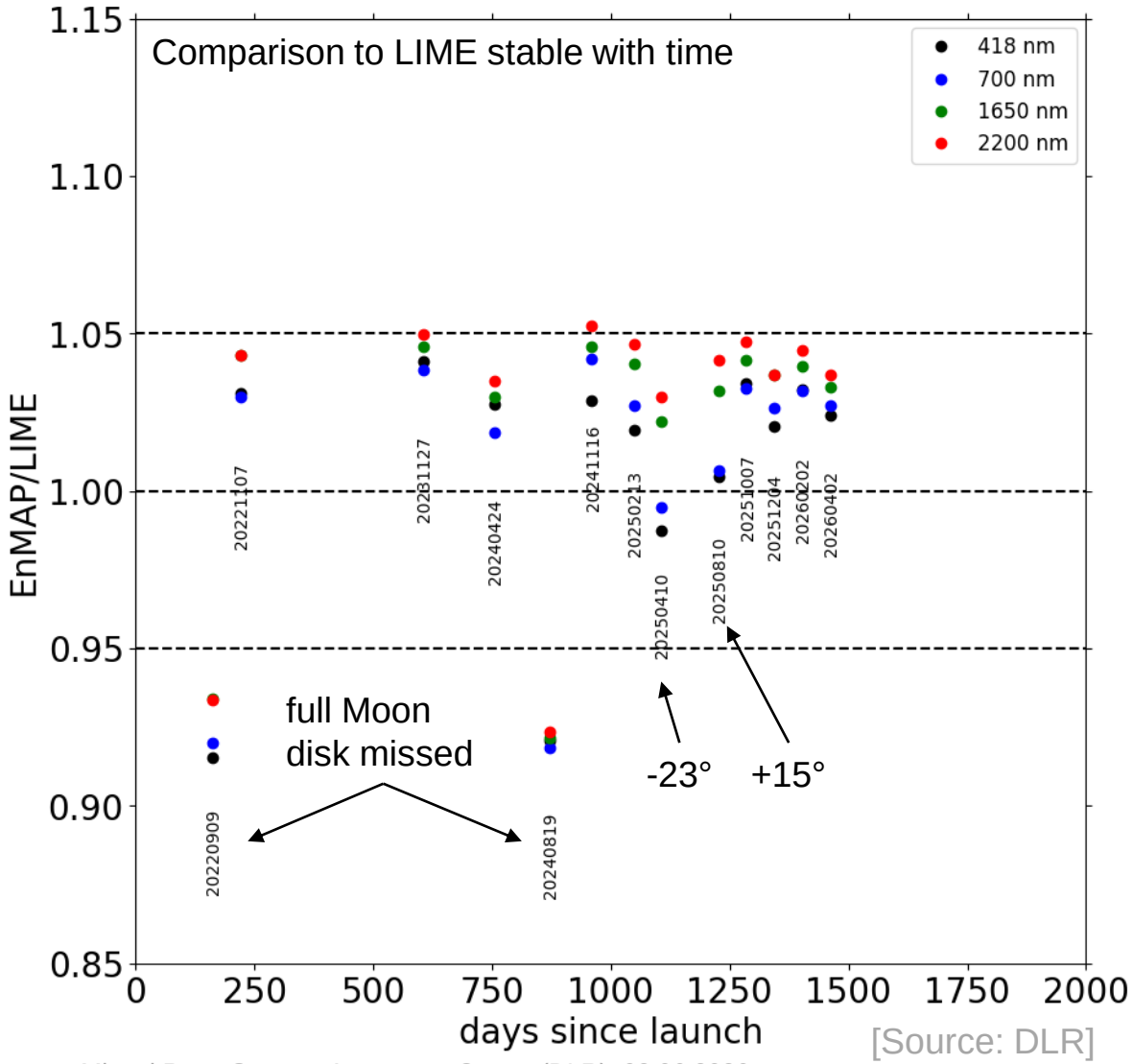
LIME model (ESA): https://lime.uva.es/

- Based on multi-spectral (CIMEL) and hyperspectral data from Tenerife, Spain, Apollo spectra and data from various missions.
- 400–2500 nm, <2% radiometric uncertainty.

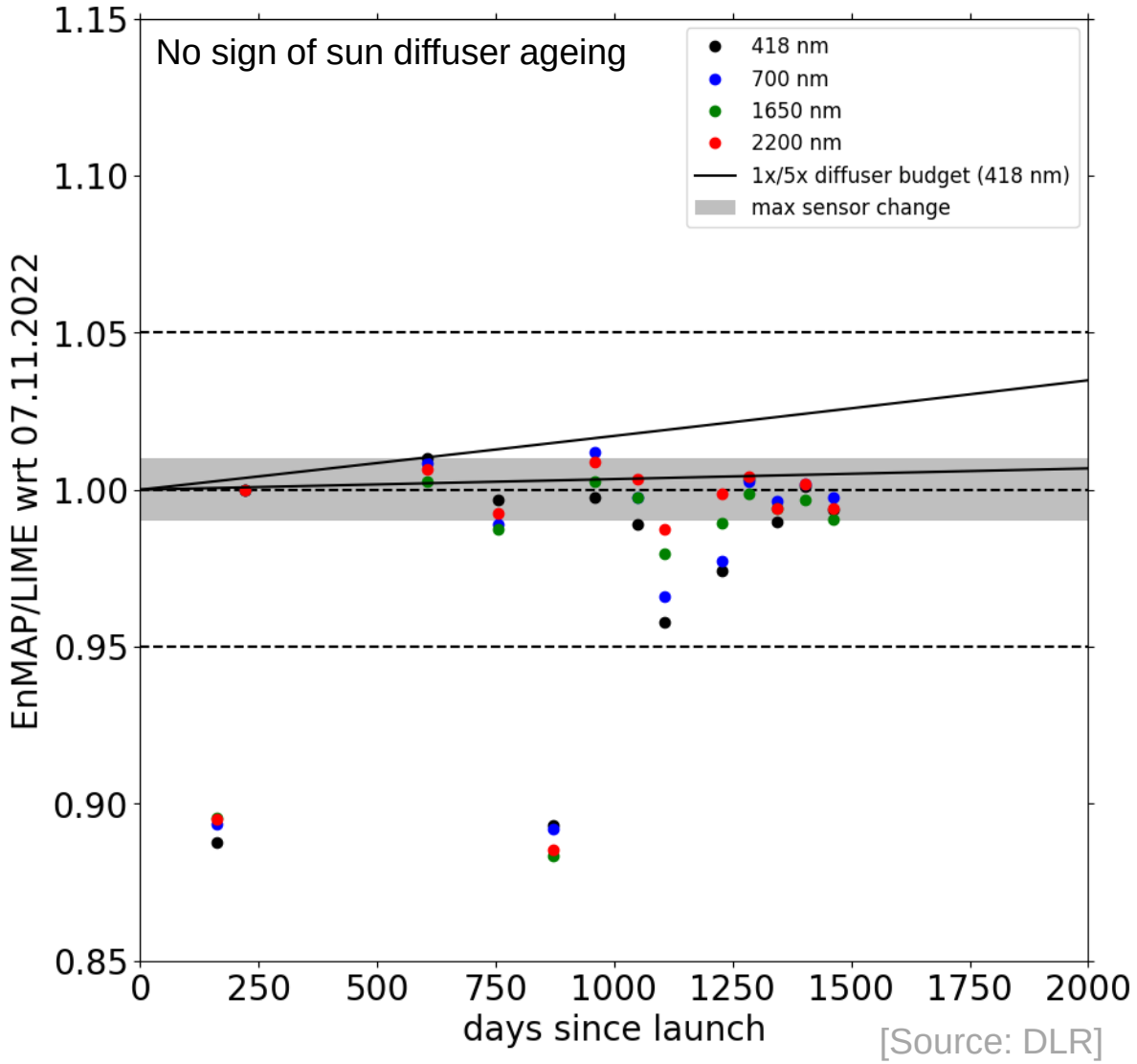
Comparison to LIME 1.4.1 (Nov 2025):

- Spectrally stable results for ~7° observations
- VNIR within 5% of LIME with bump-like feature
- SWIR consistently above LIME
- VNIR/SWIR mismatch at 900–1000 nm
- No sign of sun diffuser ageing

EnMAP Moon data and LIME 1.4.1



[Source: DLR]



[Source: DLR]

Conclusion

Summary:

- EnMAP Moon data have proven very useful for instrument monitoring and radiometric validation, hopefully they will also become useful for lunar modelling in the future.
- EnMAP is within 5% of lunar models (ROLO/CNES, LESSRv3, LIME) with small intrinsic noise.
- Consistent deviations in VNIR (<600 nm, >900 nm) and SWIR (overall) also observed in Earth data and will be mitigated by on-going major calibration update (stay tuned!).

Outlook:

- After more than 4 years in space, EnMAP is in a mature phase with in-orbit calibration facilities working nominally and both VNIR and SWIR instruments stable.
- Five-year mission extension (Oct 2027 – Sep 2032) currently being considered.
- Moon observations routinely performed every two months and further acquisitions possible.
- We expect to operate EnMAP for many years and continue providing high-quality data!

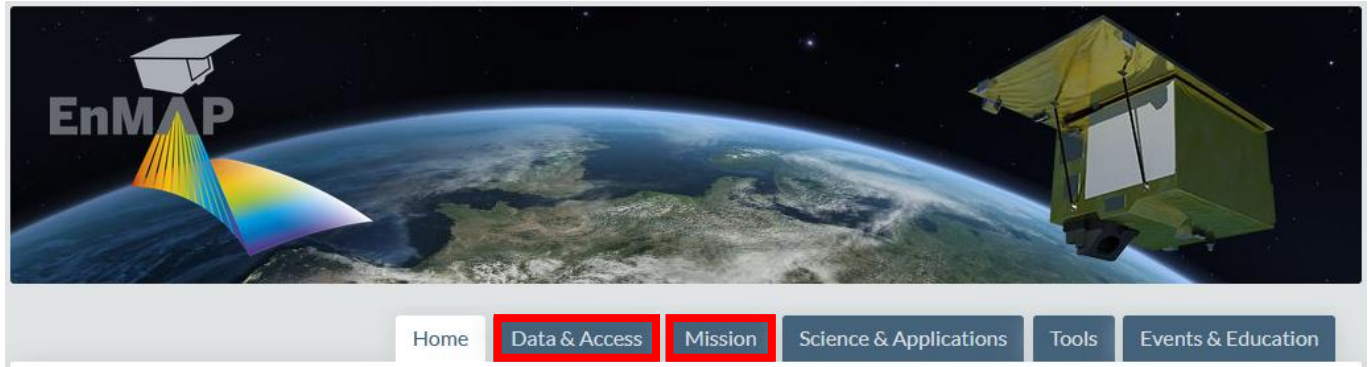
Acknowledgements

This research was supported by the DLR Space Agency with funds of the German Federal Ministry of Research, Technology and Space on the basis of a decision by the German Bundestag (50 EE 0850, 50 EE 1923 and 50 EE 2108).

Useful links:

- Tasking orders and catalog browsing:
  https://planning.enmap.org/
- Mission quarterly reports:
  https://www.enmap.org/mission/
- ICDs, ATBDs, FAQ, change log:
  https://www.enmap.org/data_access/

https://www.enmap.org/



Imprint

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