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COMBINING TERRESTRIAL AND EXTRATERRESTRIAL TARGETS FOR RADIOMETRIC VALIDATION OF THE ENMAP IMAGING SPECTROMETER

14TH EARSeL WORKSHOP ON IMAGING SPECTROSCOPY

Thematic Session 1-2L: Novel approaches for the calibration and validation of spaceborne imaging spectrometers

LUMITUULI, Aalto University, Helsinki, Finland.

2026-06-02

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EnMAP

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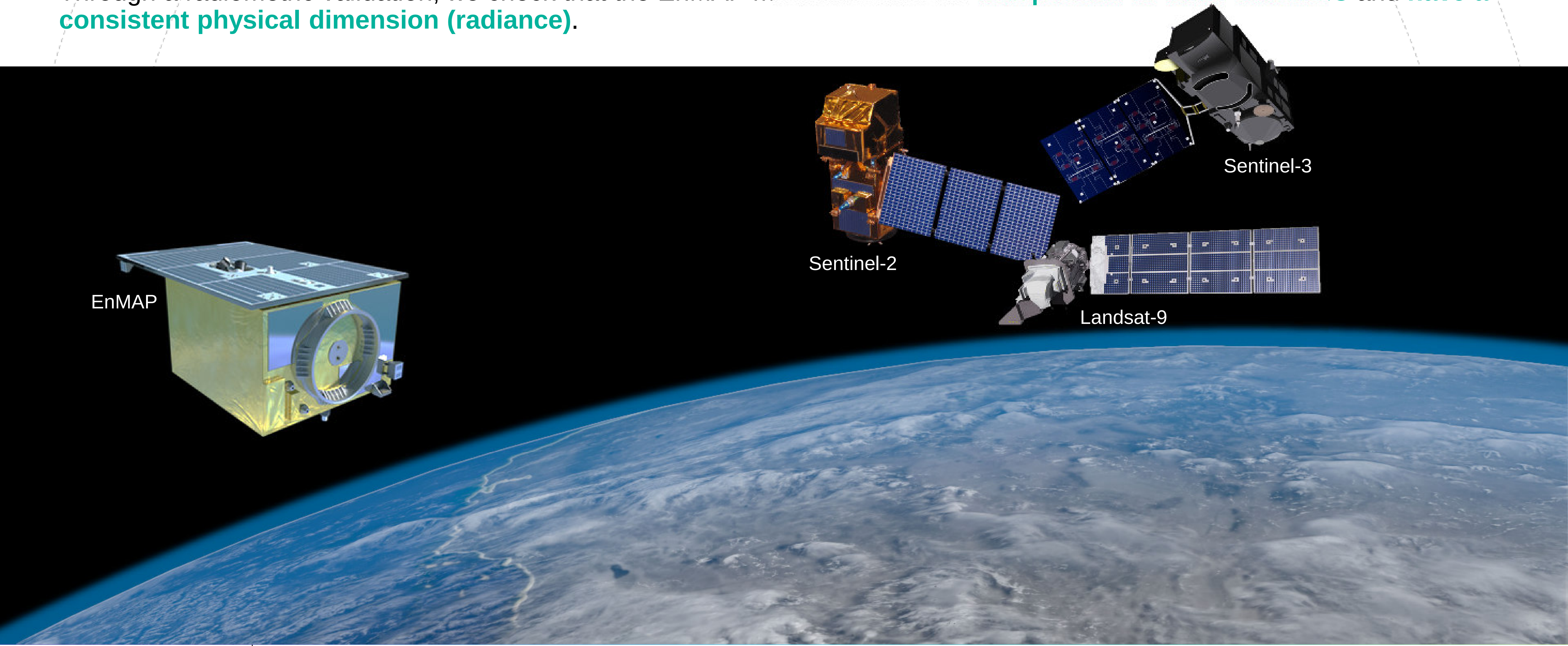
OUTLINE

01

TERRESTRIAL TARGETS

THE NEED FOR RADIOMETRIC VALIDATION

Through a radiometric validation, we check that the EnMAP measurements are **comparable to other satellites** and **have a consistent physical dimension (radiance)**.



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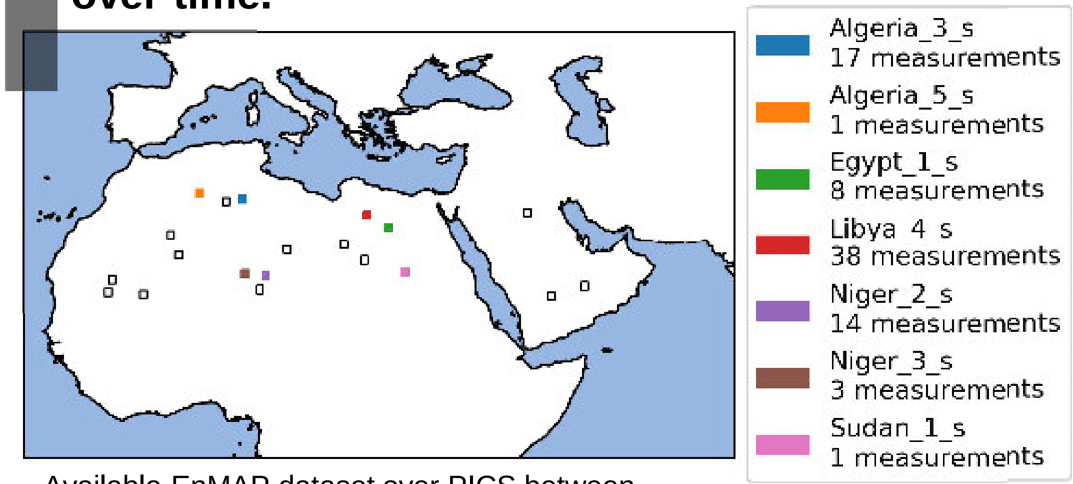
Earth Observation Center EOC of DLR. ENMAP artist view. **[Illustration]. In:** *ENMAP.org.* Available on: <https://www.enmap.org/_nuxt/EnMap_ArtistView3_284.webp>.
ESA/Copernicus and Rama, Maquette de Sentinel-2. 2015. **[Illustration]. In:** *Wikimedia.* Available on: <https://commons.wikimedia.org/wiki/File:Sentinel_2-IMG_5873-white_(crop).jpg>.
SkywalkerPL. Sentinel-3 spacecraft model. **[Illustration]. In:** *Wikimedia.* Available on: <https://commons.wikimedia.org/wiki/File:Sentinel-3_spacecraft_model.svg>.
NASA/Goddard Space Flight Center/Conceptual Image Lab, LANDSAT-9. **[Illustration]. In:** *Wikimedia.* Available on: <https://commons.wikimedia.org/wiki/File:LANDSAT-9.jpg>.

DO ENMAP AND SENTINEL-2 MEASURE THE SAME THING?

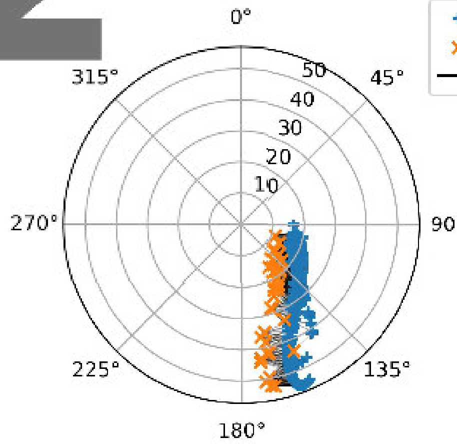
The most efficient way to **cross-calibrate** two sensors is to work on **Pseudo-Invariant Calibration Sites** (PICS).

1 Identify terrestrial targets which do not change over time.

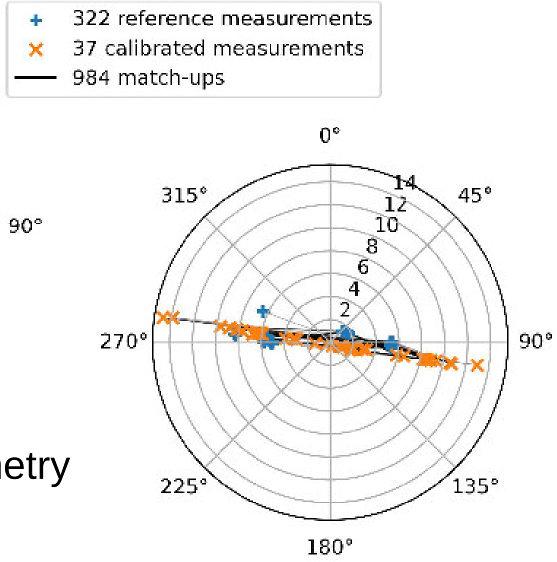


Available EnMAP dataset over PICS between 2022-07-29 and 2025-10-31.

2 Find acquisitions from both EnMAP and Sentinel-2 with matching angular conditions (discrepancy below 10°).



Solar geometry



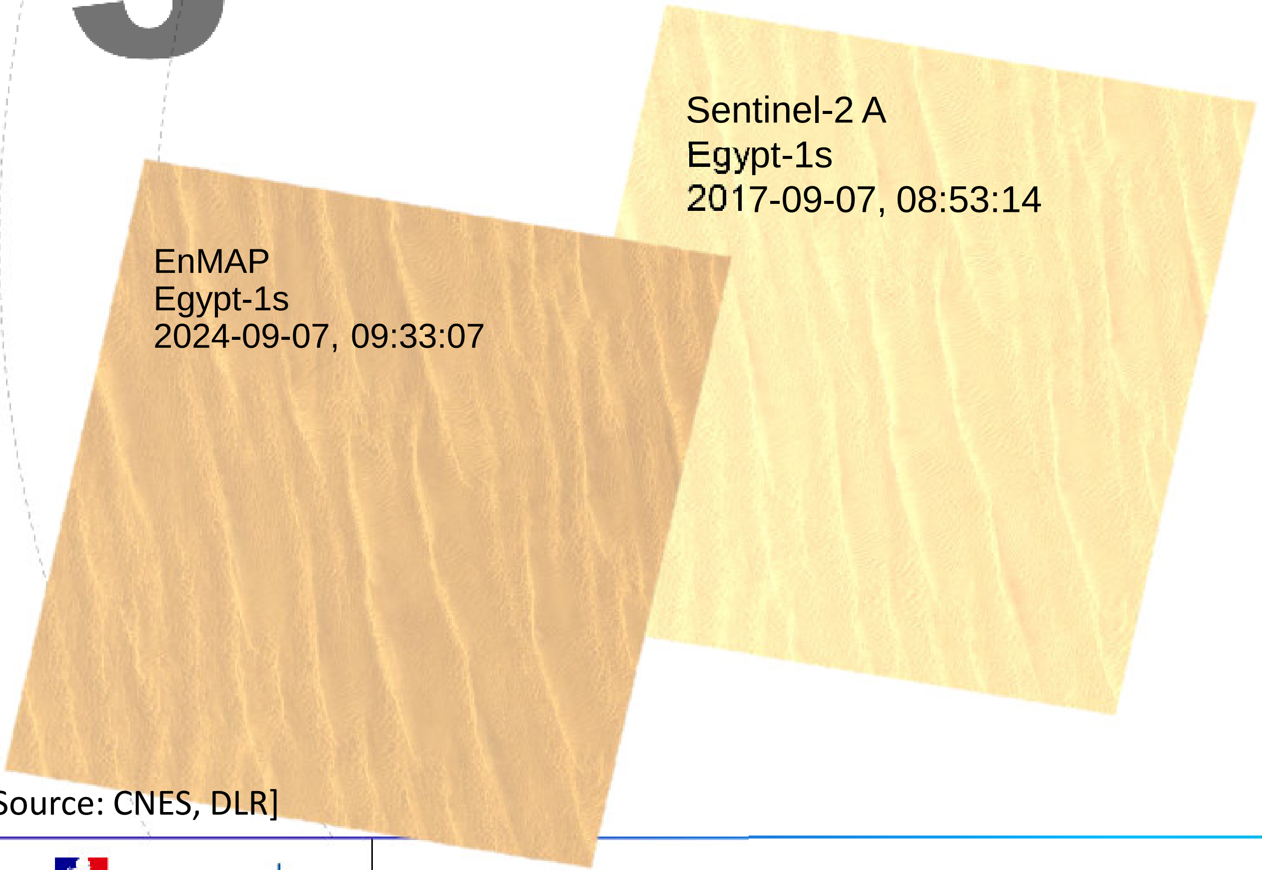
Viewing geometry

[Source: CNES, DLR]

DO ENMAP AND SENTINEL-2 MEASURE THE SAME THING?

The most efficient way to **cross-calibrate** two sensors is to work on **Pseudo-Invariant Calibration Sites** (PICS).

3 Compare the images.



[Source: CNES, DLR]

The CNES comparison algorithm over PICS [1] takes into account the following differences:

- the instrument **spectral response** between the sensors. A spectral interpolation is performed on the PICS bottom of atmosphere reflectance (assumed to be invariant in time) and helped by an a priori knowledge of the ground spectral shape.
- the change in **meteorological conditions** between the acquisition dates. This step entails a radiative transfer code to correct the atmospheric effects of the reference acquisition date and apply the atmospheric effects of the calibrated acquisition date. Note that aerosol optical thickness above 0.3 are filtered out.

The result is given per spectral band k as

$$\Delta A_k = \frac{\text{EnMAP measurement}}{\text{Sentinel}-2\text{ measurement}}$$

[1] S. Lacherade, B. Fougnie, P. Henry, and P. Gamet, ‘Cross Calibration Over Desert Sites: Description, Methodology, and Operational Implementation’, *IEEE Transactions on Geoscience and Remote Sensing*, vol. 51, no. 3, pp. 1098–1113, Mar. 2013, doi: 10.1109/tgrs.2012.2227061.

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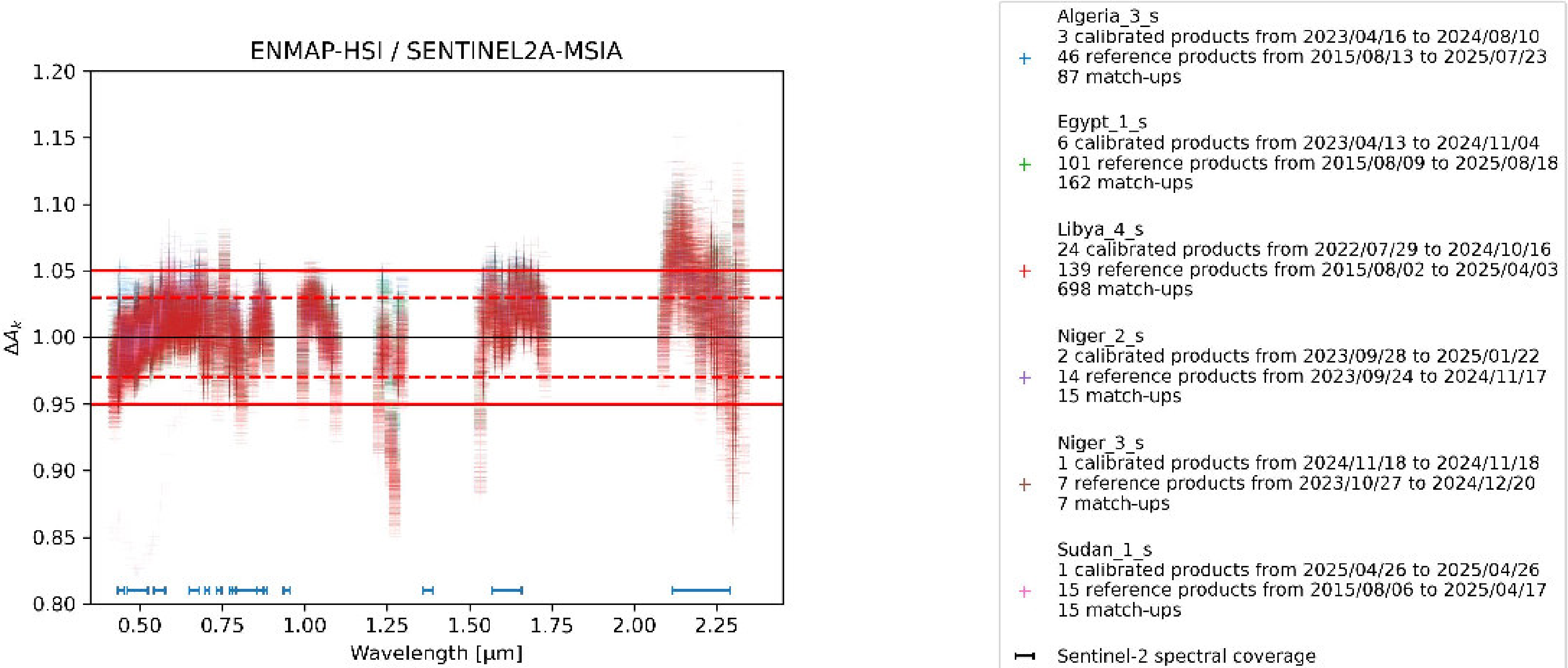
DLR. ENMAP Egypt-1s PICS acquisition. **[Satellite image].** 2024-09-07.
European Space Agency – Copernicus Sentinel-2 A. Egypt-1s PICS acquisition **[Satellite image]**. 2017-09-07.

RESULTS

A comparison ratio between EnMAP and Sentinel-2 A (taken as a reference sensor) is available for all wavelengths, all sites and all matching products, providing a **large statistics**.



[Source: CNES, DLR]

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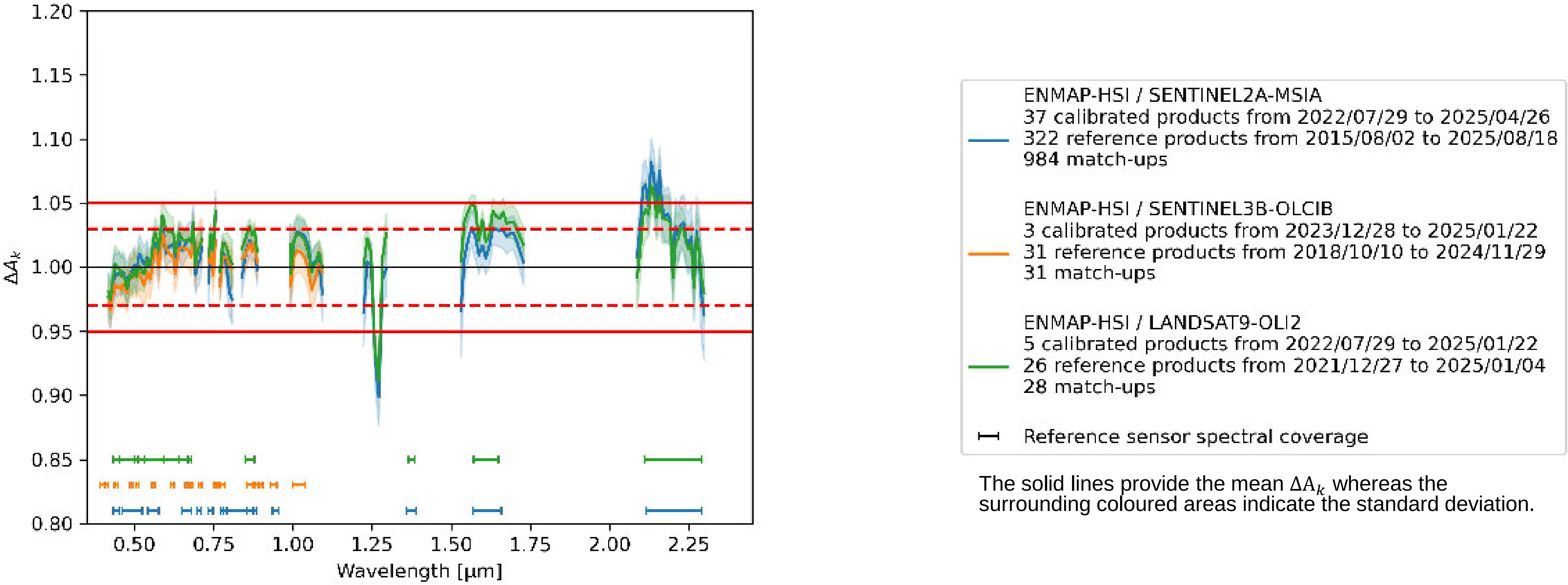
RESULTS

Besides, this comparison can be performed with various reference sensors. On average, **EnMAP measurements are coherent with Sentinel-2 A, Sentinel-3 OLCI B and LANDSAT9 within 5 %**. The **SWIR range** seems to be a bit **brighter** than the reference sensors. Atmospheric absorption bands cannot be processed with this technique.



The solid lines provide the mean ΔA_k whereas the surrounding coloured areas indicate the standard deviation.

[Source: CNES, DLR]

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02

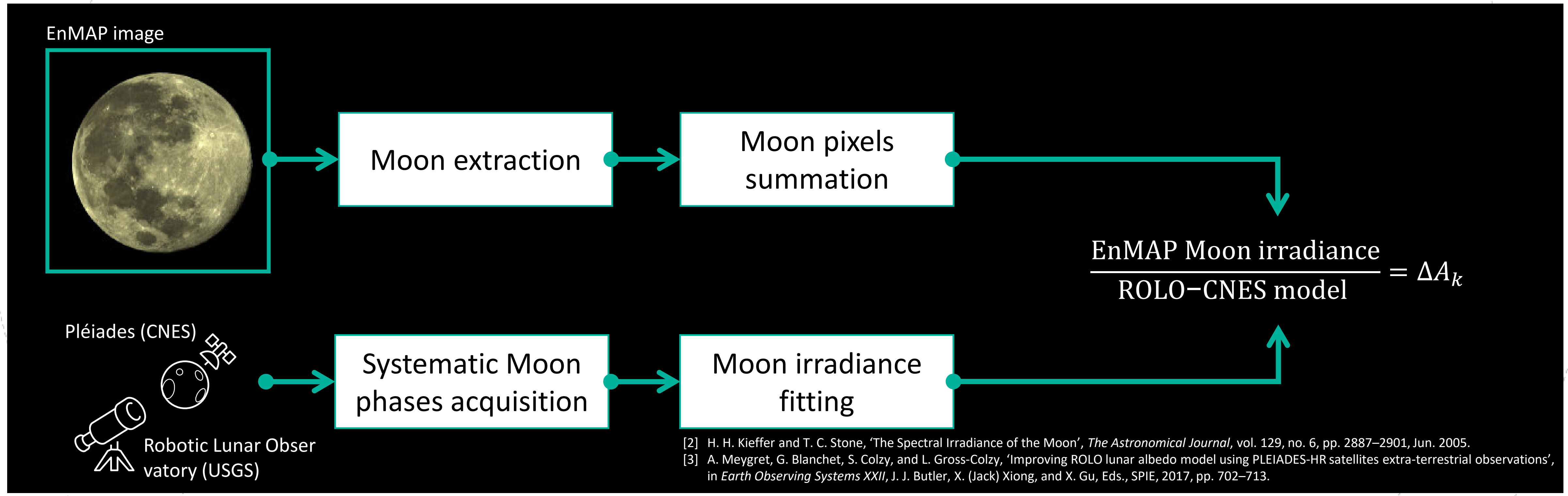
EXTRATERRESTRIAL TARGETS

MOON ACQUISITIONS

Acquiring the Moon has two main advantages:

- **characterise various acquisition artefacts** (such as straylight, pixel equalisation residuals, etc.) thanks to the strong contrast between the Moon and the dark background;
- **check the radiometry**, especially in the atmospheric absorption bands.

The CAL/VAL on Moon images is as follows:



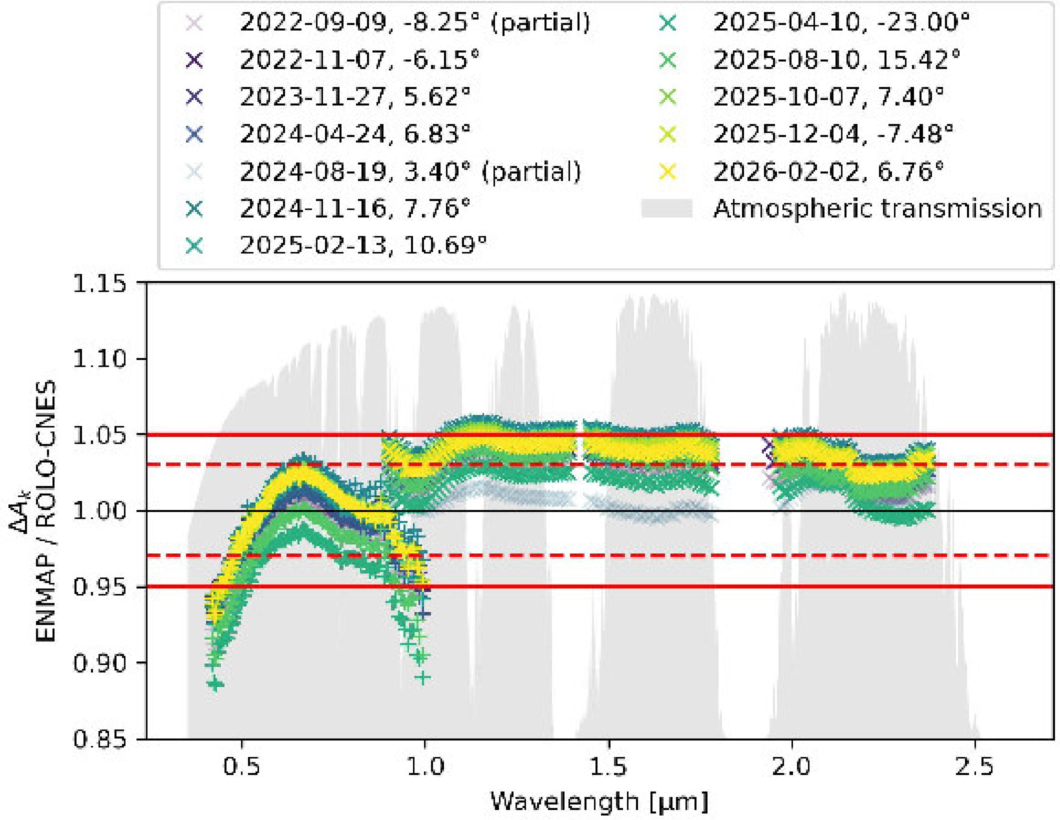
[2] H. H. Kieffer and T. C. Stone, 'The Spectral Irradiance of the Moon', *The Astronomical Journal*, vol. 129, no. 6, pp. 2887–2901, Jun. 2005.
[3] A. Meygret, G. Blanchet, S. Colzy, and L. Gross-Colzy, 'Improving ROLO lunar albedo model using PLEIADES-HR satellites extra-terrestrial observations', in *Earth Observing Systems XXII*, J. J. Butler, X. (Jack) Xiong, and X. Gu, Eds., SPIE, 2017, pp. 702–713.

DLR. ENMAP Moon image with phase angle 6.9°. [Satellite image]. 2024-11-16.

MOON RESULTS

Here are the results already shown on the previous presentation by Miguel Pato. Globally, EnMAP and the ROLO-CNES model **agree within 5 %** except near the VNIR focal plane boundaries.

Let's focus on the partial Moon processing.



[Source: CNES, DLR]

ENMAP PARTIAL ACQUISITION

If only a **Moon subpart** is acquired, the **Moon irradiance cannot be computed anymore**.

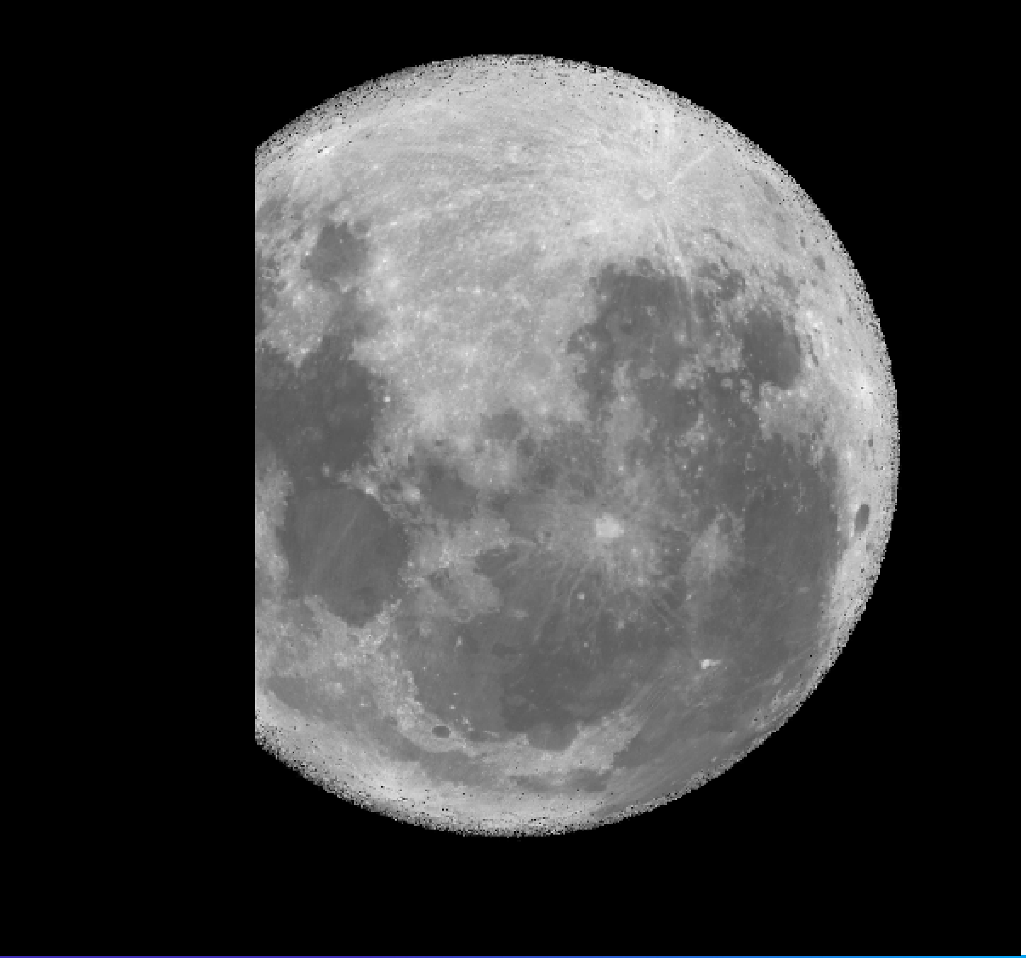
Obviously, the missing part of the Moon makes the EnMAP measurement different from the model.

$$\Delta A_k = \cancel{\frac{\text{EnMAP Moon irradiance}}{\text{ROLO-CNES model}}}$$

DLR. ENMAP Moon image. [Satellite image]. 2024-08-19.

EQUIVALENT SIMULATION

High-resolution simulation



To go further, a model able to output a **full image of the Moon** was developed. The model takes as input:

- the ROLO-CNES irradiance model [2][3];
- the Digital Elevation Map and albedo of the Moon (measured by the Lunar Orbiter Laser Altimeter, USGS) [4];
- the EnMAP acquisition conditions taken from metadata (satellite position, line of sight, etc.).

A pixel-resolved model is of interest for:

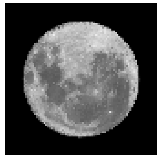
- optical-instrument design;
- nonlinearity assessment with a per-pixel ratio;
- calibration on partial Moon acquisition.

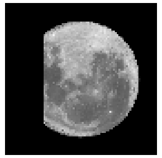
[2] H. H. Kieffer and T. C. Stone, 'The Spectral Irradiance of the Moon', *The Astronomical Journal*, vol. 129, no. 6, pp. 2887–2901, Jun. 2005.
[3] A. Meygret, G. Blanchet, S. Colzy, and L. Gross-Colzy, 'Improving ROLO lunar albedo model using PLEIADES-HR satellites extra-terrestrial observations', in *Earth Observing Systems XXII*, J. J. Butler, X. (Jack) Xiong, and X. Gu, Eds., SPIE, 2017, pp. 702–713.
[4] Smith, D. E., Zuber, M. T., Neumann, G. A., Mazarico, E., Head III, J., Torrence, M. H., & LOLA Science Team (2011). *Results from the Lunar Orbiter Laser Altimeter (LOLA): global, high-resolution topographic mapping of the Moon*. Paper presented at the 42nd Lunar and Planetary Science Conference, Lunar and Planetary Institute, Houston, TX. https://www.lpi.usra.edu/meetings/lpsc2011/pdf/2350.pdf.

RECOVER THE MISSING PART THANKS TO SIMULATION

The simulation advantage is to be able to **recover the missing part** of the Moon! A correction factor can thus be computed as a ratio between the partial acquisition and the full acquisition.

$\gamma_{correction} =$





And,

$$\Delta A_k = \frac{\gamma_{correction} \times \text{EnMAP partial Moon irradiance}}{\text{ROLO−CNES model}}$$

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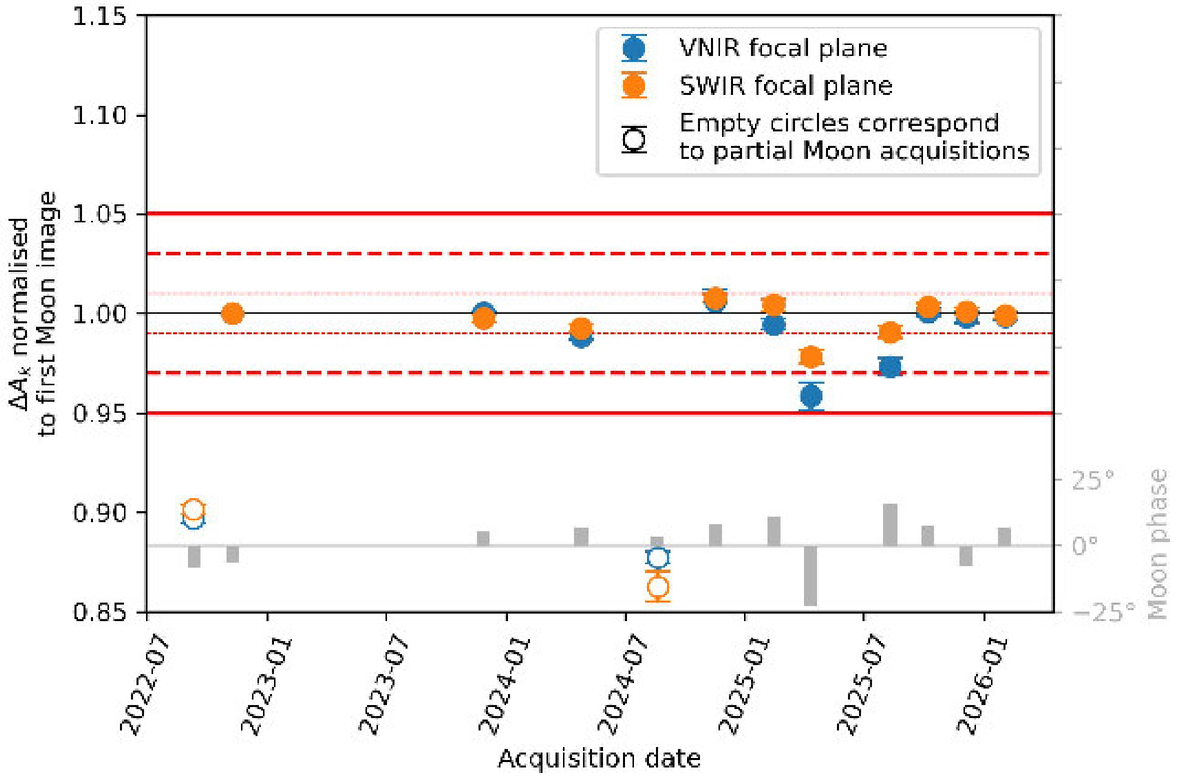
RESULTS

Based on the temporal series, the partial Moon processing reliability can be estimated: the additional **uncertainty is around 1-2 %**.

Before correction



Each point corresponds to the average evolution of the spectral channels of a given focal plane and the error bars indicate the dispersion among spectral channels.

[Source: CNES, DLR]

RESULTS

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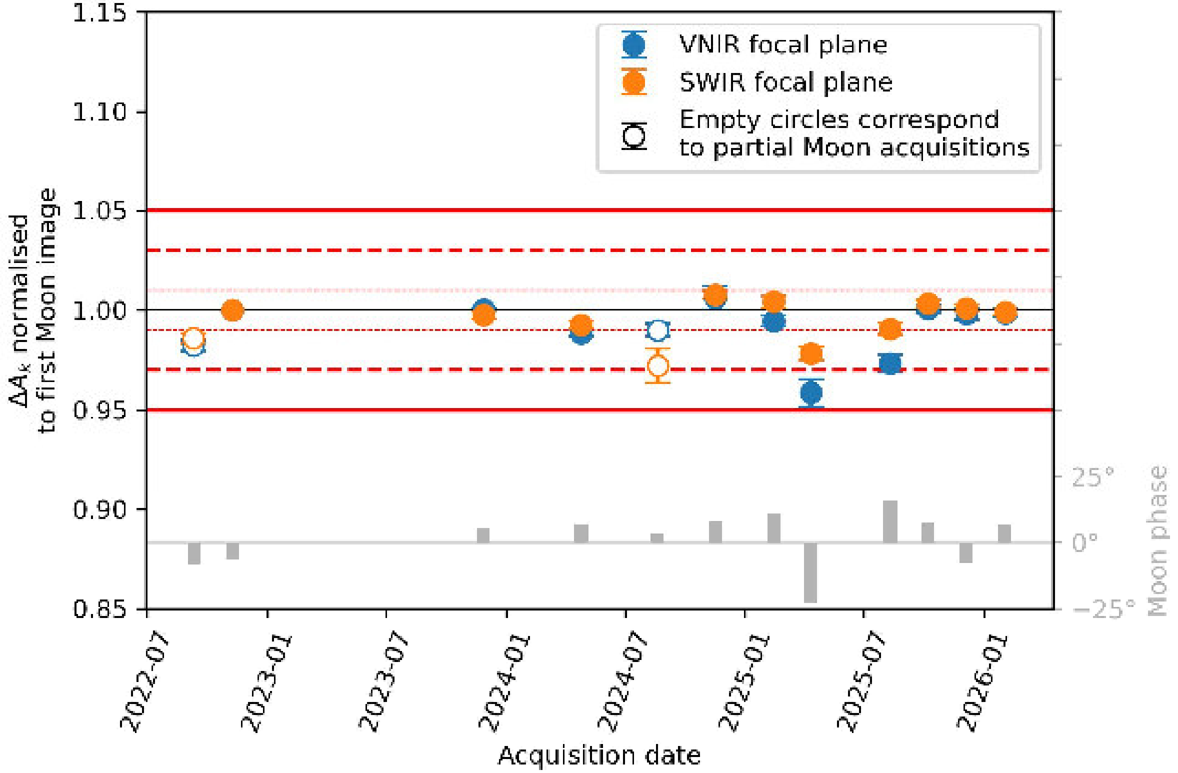
After correction



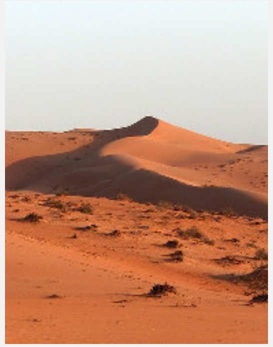
Each point corresponds to the average evolution of the spectral channels of a given focal plane and the error bars indicate the dispersion among spectral channels.

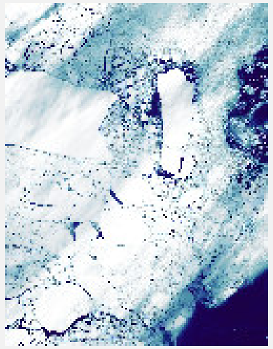
[Source: CNES, DLR]

03
RESULTS COMBINATION

SADE/MUSCLE, THE CNES CAL/VAL ENVIRONMENT

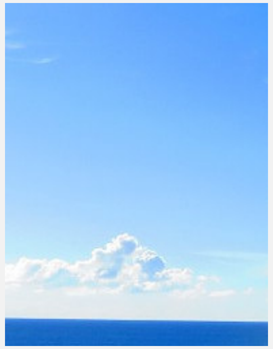
Depending on the sensors and the validation objectives, various methods will be combined:


Desert


Dome

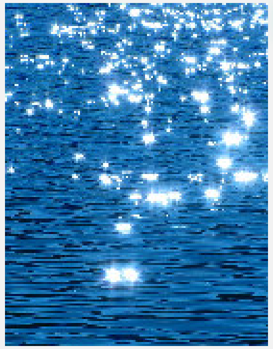

Moon


Stars


Rayleigh


Instrumented site


Cloud


Glitter

All the vicarious calibration methods developed in CNES are included into a **unified software** called Muscle and a **common database** called SADE which:

- ensure traceability;
- perform massive cross-comparison between sensors (more than 33,000,000 reference measurements coming from 50 different sensors);
- reduce validation time and costs to integrate new sensors;
- propagate any methodology improvement to all available sensors.

MUSCLE

SADE/MUSCLE will soon be opened online for CNES partners.

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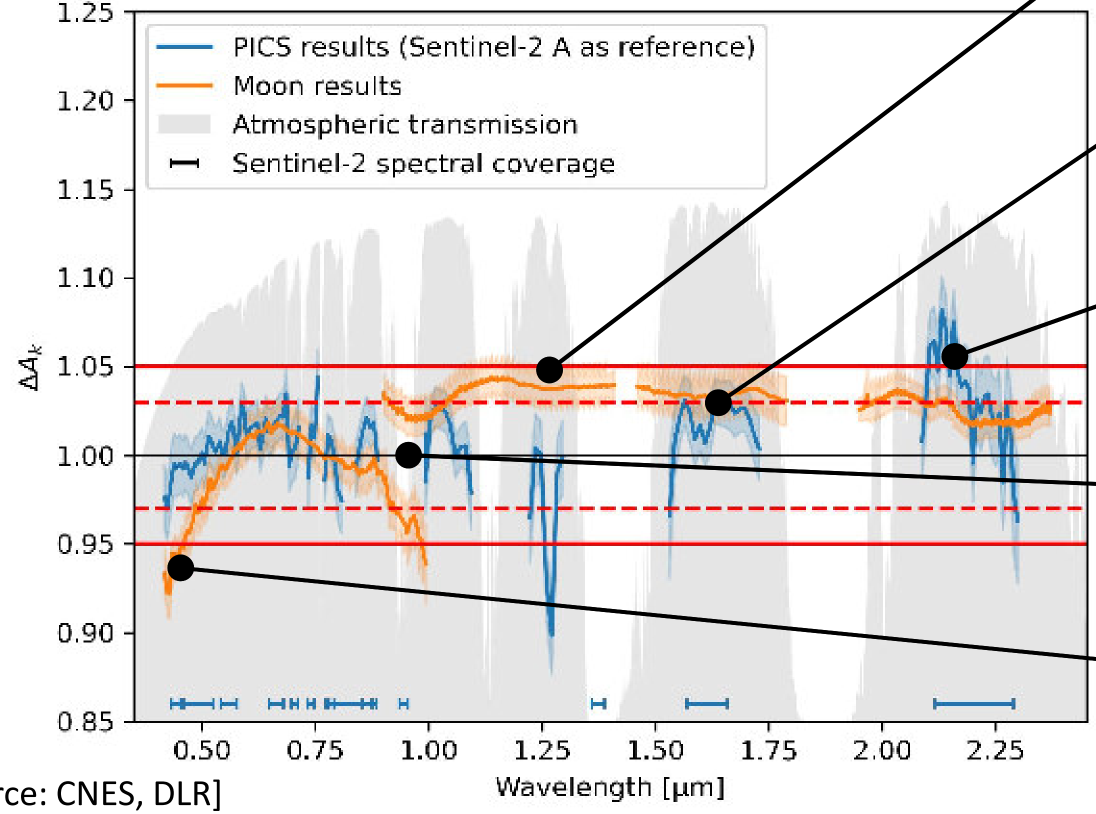
Fransoo. Désert dunes dune Oman paysage. **[Photographie]. In**: *Pixabay*. Disponible sur : <https://cdn.pixabay.com/photo/2019/02/09/15/52/desert-3985416_960_720.jpg>.
European Space Agency – Copernicus Sentinel-2 B. Antarctica coast - 2020-02-19 **[Photographie].** (S2B_MSIL1C_20200218T232349_N0209_R101_T54DXM_20200219T000933).
Maigler. Clouds Ocean Sky. **[Photographie]. In** : *Pixabay*. Disponible sur : <https://pixabay.com/photos/clouds-ocean-sky-horizon-scenic-91440/>.
CNES. Instrumented site in Namibia. **[Photographie].**
Potsclam Barro. Heavy clouds. **[Photographie]. In** : *Pexels*. Disponible sur : <https://www.pexels.com/photo/heavy-clouds-1828305/>.
Revera, Gregory H. Full Moon photograph taken 10-22-2010 from Madison, Alabama, USA. **[Photographie]. In**: *Wikipedia*. Disponible sur : <https://en.wikipedia.org/wiki/File:FullMoon2010.jpg>.
Akira Fujii. Ground-based image of Sirius. (2005) **[Photographie]. In**: *EsaHubble*. Disponible sur : <https://esahubble.org/media/archives/images/original/heic0516f.tif>.
Bokeh lights photograph of body of water. **[Photographie]. In**: *PickPik*. Disponible sur : <https://i1.pickpik.com/photos/776/729/281/sparkles-water-surface-water-aqua-53f125eb062438a9d49333d5eedd20a2.jpg>.

EXAMPLE OF RESULT COMBINATION ON ENMAP

Globally, the results are coherent within 5 % with PICS (CNES methodology [1]) and ROLO-CNES. Local discrepancy are analysed to evaluate instrument-related effects from method-related effects.



[Source: CNES, DLR]

The PICS results differ from Moon ones around 1.25 µm because the **Sentinel-2 A reference has no spectral channel over this range** (so PICS results are less reliable).

The **small positive bias over the SWIR** range is observed by both methods.

The **PICS method is less reliable for large wavelengths** due to a lack of spectral coverage by reference sensors (Sentinel-2 has a large bandwidth on B12).

Without atmospheric perturbations, the Moon results are very efficient to characterise the **VNIR/SWIR bias**.

The Moon calibration on the bluest spectral channel is not coherent with the PICS one; **the Moon model must be improved for short wavelengths**.

[1] S. Lacherade, B. Fougnie, P. Henry, and P. Gamet, 'Cross Calibration Over Desert Sites: Description, Methodology, and Operational Implementation', *IEEE Transactions on Geoscience and Remote Sensing*, vol. 51, no. 3, pp. 1098–1113, Mar. 2013, doi: 10.1109/tgrs.2012.2227061.

CONCLUSIONS

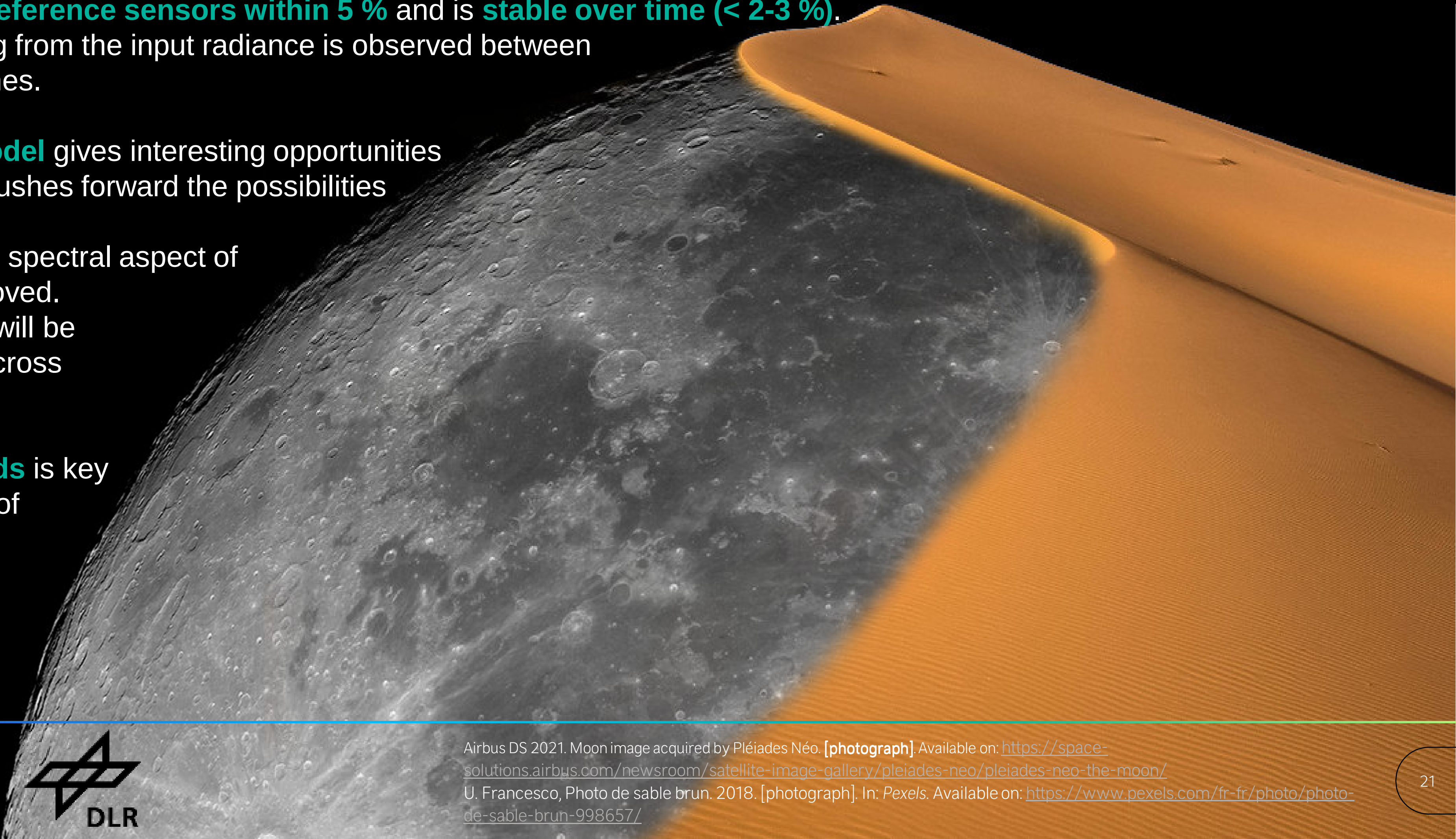
CONCLUSION

Based on CNES methods, the EnMAP results are compared to vicarious calibration/validation targets both terrestrial (PICS) and extraterrestrial (Moon):

- EnMAP is aligned with other **reference sensors within 5 %** and is **stable over time (< 2-3 %)**.
- A **radiometric bias** depending from the input radiance is observed between the **VNIR** and **SWIR** focal planes.

- The **pixel-resolved Moon model** gives interesting opportunities to process partial Moon and pushes forward the possibilities offered by Moon images.
- Based on EnMAP images, the spectral aspect of the Moon models will be improved.
- Combined Moon acquisitions will be organised to go further in the cross -calibration exercise.

- **Combining CAL/VAL methods** is key for a comprehensive analysis of the radiometry.



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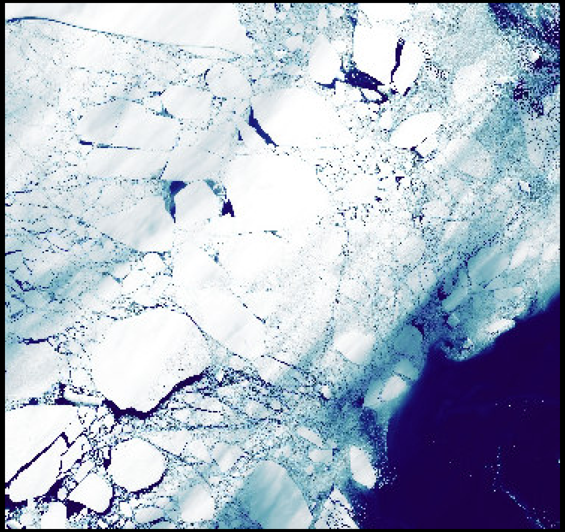
Airbus DS 2021. Moon image acquired by Pléiades Néo. [photograph]. Available on: https://space-solutions.airbus.com/newsroom/satellite-image-gallery/pleiades-neo/pleiades-neo-the-moon/
U. Francesco, Photo de sable brun. 2018. [photograph]. In: *Pexels*. Available on: https://www.pexels.com/fr-fr/photo/photo-de-sable-brun-998657/








THANK YOU FOR YOUR ATTENTION

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Fransoo. Désert dunes dune Oman paysage. **[Photograph]. In**: *Pixabay*. Disponible sur : <https://cdn.pixabay.com/photo/2019/02/09/15/52/desert-3985416_960_720.jpg>.
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Akira Fujii. Ground-based image of Sirius. (2005) **[Photograph]. In**: *EsaHubble*. Disponible sur : <https://esahubble.org/media/archives/images/original/heic0516f.tif>.
Bokeh lights photograph of body of water. **[Photograph]. In**: *PickPik*. Disponible sur : <https://i1.pickpik.com/photos/776/729/281/sparkles-water-surface-water-aqua-53f125eb062438a9d49333d5eedd20a2.jpg>.