Summary of the Fourth Joint GSICS/IVOS Lunar Calibration Workshop

4-8 December 2023

EUMETSAT Headquarters - Darmstadt - Germany

Between the 4th and 8th of December 2023, EUMETSAT hosted the Fourth Joint GSICS/IVOS Lunar Calibration Workshop. Organised in collaboration with USGS, the workshop gathered more than 35 participants on site and about the same amount online, representing a total of 30 agencies, institutes or companies from the New Space.

The main objectives of the workshop were to exchange on the following topics:

- Measurements and Moon observations, with the goal of achieving SI traceability
- Lunar calibration systems and model development
- Instrument monitoring using lunar calibration, including discussions on best practices for estimating the lunar irradiance from the measurements
- Thermal Infrared and microwave remote sensing and lunar observation
- Inter-calibration using lunar observations
- Alternative applications of lunar observation, including geometric and MTF post-launch characterization

The large number of topics and contributions addressed during the workshop led to extending the meeting to five days, whereas the previous editions lasted four days, with the following agenda:

- **Monday (morning + afternoon)**: Measurements and Moon Observations (chaired by S. Maxwell - NIST, in replacement of K. Turpie - UMBC)
- **Monday (afternoon) and Tuesday**: Lunar Calibration Systems and Model Development (chaired by T. Stone - USGS)
- **Wednesday:** Instrument Monitoring using Lunar Calibration (chaired by S. Wagner - EUMETSAT)
- **Thursday (morning + afternoon)**: Thermal infrared and Microwave (chaired by T. Hewison - EUMETSAT)
- **Thursday (afternoon)**: Alternative Applications of Lunar Observations (chaired by F. Yu - UMD)
- **Friday**: Discussions, Review of actions/recommendation/way forward and Conclusions of the workshop (chaired by S. Wagner - EUMETSAT and T. Stone - USGS).

Measurements and Moon Observations

The status of a series of projects was presented to the group. They include ground-based, airborne and satellite measurement datasets. Those measurements are meant to serve as reference measurements and provide absolute and relative anchor points to the lunar irradiance models. The following datasets and activities were discussed:

- SCIAMACHY lunar measurements: a new processing version (v10.1) of those measurements has been prepared by Earth Space Solutions and DLR, in the context of an ESA project. This dataset covers phases between -80 and +20 degree phase. The uncertainties are claimed to be less than 2% for absolute lunar reflectance and slightly

above 2% for absolute lunar radiance. Relative uncertainties are estimated to be about 2% and 0.5% at the most, respectively for reflectance and radiance.

- Air LUSI: since the 3rd Lunar Calibration Workshop, Air-LUSI has undergone a series of design improvements and four additional measurements flights took place in March 2022. Data quality and accuracy has been conducted and the observations are expected to be available for distribution in 2024. The uncertainty budget has been revised and the uncertainties are estimated to be now about 0.8% (k=1).
- Mauna Loa LUSI (project led by NIST): the instrument and the infrastructure were commissioned in Fall 2022 and provided some initial lunar measurements. However, the volcanic eruption from November 2022 interrupted the execution of the campaign and access to the site is not expected before the end of 2024. A SWIR instrument has been developed and was tested in September 2023.
- The measurement campaign at the Lijiang observatory - China: initiated in 2015, the campaign led by CMA, in collaboration with other Chinese institutes (Naning University of Aeronautics and Astronautics, Xi'an Institute of Optics and Precision Mechanics, and Shanghai Institute of Technical Physics), continues to gather lunar measurements. A set of three instruments has been deployed on the site: a VIS/NIR lunar imaging spectrometer since 2015 (400-1000 nm), a SWIR lunar observation infrared spectrometer since 2020 (1000-2400 nm), and a VIS/NIR lunar and earth spectral imager radiometry benchmark since 2019 (400-1000 nm). In complement, a important set of lunar observations is collected from with two sensors in space: the PMS-2 (Panchromatic and Multispectral Sensor) instrument on-board the JiLin-1 small commercial satellite, and the HAOC (High Accuracy On-Board Calibrator) instrument on-board FY-3G. Those datasets will be used to develop new lunar irradiance models. It is also envisaged to infer models purely using data driven approaches.
- The campaign led by ESA to acquire lunar observations in support to the development of the LIME model: initially based on CIMEL acquisitions of the lunar irradiance at night, the instrument set-up has been complemented by a limited series of hyperspectral measurements with an ASD FieldSpec spectrometer. Those hyperspectral acquisitions will be extended for three months to anchor the CIMEL observations. The spectral coverage of the CIMEL instrument is also foreseen to be complemented in the SWIR with a filter at 2.1 µm. ESA mentioned that the funding for the campaign is secured till 2028.

In addition to those activities, the participants of the workshop were updated with the status of upcoming mission ARCTONE. ARCSTONE is foreseen to be launched in the Summer 2025. The mission will acquire lunar reflectance for phases ranging from -90 to +90 degrees, for nominal acquisitions, over 3 years. But one goal is to extend that range to +/-135 degrees. The objectives of the missions are "to enable on-orbit high accuracy absolute calibration for the past, current and future reflected solar sensors", and to achieve "high-accuracy measurements of the lunar reflectance (better than 0.5% with k=1)". One specific issue to the ARCSTONE mission is that it requires lengthy background-signal measurements and a good thermal stability over about 20 minutes. An analysis of the ARCSTONE InVEST characterisation was presented, with a list of identified improvements for the mission.

Finally, the workshop was an opportunity to learn from groups using the Moon as a source of light to measure at night aerosol content in the atmosphere. In particular, N. Kouremeti gave a presentation of the work done at PMOD on the traceability of lunar direct irradiance measured with a precision filter radiometer. Those activities raised a strong interest among the participants and can benefit the GSICS/IVOS development to establish more accurate lunar irradiance models.

Lunar Calibration Systems and Model Development

This session was split between i) a couple of presentations on the LIME (ESA) and LESSSR (EUMETSAT) models to update the group on the current development status, ii) a series of presentations and discussions on the development of the LSICS framework, and iii) the outcome the lunar model inter-comparison.

The LIME model keeps being regularly updated as more measurements are available from the Cimel instrument. The project has been addressing more recently the question of polarisation and how to model it. ESA also announced the release of the LIME Toolbox early 2024, which would allow users to simulate the lunar irradiance for their own instrument configuration via a GUI interface. It would be also possible to plug the underlying Python package into scripts for operational purposes.

The LESSSR model is also being revisited. An uncertainty analysis is done to assess the relevance of the terms (also called base functions) chosen for the lunar reflectance parametrization. The project, funded by EUMETSAT, and done in collaboration with ESA, will continue in 2024. The goal is to derive a more advanced version of the LESSSR model and to use it to inter-calibrate SCIAMACHY and the GOME-2 series of instruments in support of the ESA FDR4ATMOS project.

The LSICS (Lunar Spectral Irradiance Calibration System) will replace the GIRO. It is python-based and it will offer a framework where lunar disk reflectance models could be plugged in. A first version of LSICS is expected at the end of 2024, with the SLIM model as a first demonstrator for an end-to-end calibration chain. Therefore, model developers were encouraged to build modules compatible with the LSICS interfaces to allow future integrations (for instance for benchmarking purposes). Discussions highlighted the point that LSICS is meant to be used for monitoring instruments that can observe the Moon and not to support the generation of models. The framework could be run with different lunar reflectance models.

Model traceability needs to be ensured at this point. The group agreed on the absolute need to document in detail the models and to have the ATBDs and ASDs (Algorithm Specification Documents) reviewed by the GSICS lunar community, in a separate process from peer-review publications.

Finally, T. Stone (USGS) presented the outcome of the lunar reflectance model inter-comparison. Six models participated in the exercise (ROLO, CLIMES, SP, GIRO, SLIM, LIME and LESSSR). ROLO was taken as the reference model for the comparisons. Models show a large variability in general. Further analysis is needed to fully understand those differences. The inter-comparison exercise will be continued and some ideas for improvement have been discussed, such as covering an additional part of the spectrum with additional

spectral response functions or asking the modeller to implement the TSIS-1 HSRS in their model.

Instrument Monitoring using Lunar Calibration

As in previous editions of the lunar calibration workshop, one part of the meeting was dedicated to the monitoring of the missions in space, using lunar calibration. A number of agencies presented an update on their activities, for both Low Earth Orbit sensors (GOSAT/CAI-2 and FTS-2, Proba-V, S3-OLCI, Jilin-1, MODIS, or NOAA-20/VIIRS) and Geostationary sensors (Himawari-8 and 9, SEVIRI, MTG/FCI and LI and FY4A/AGRI). In particular, JMA showed the very impressive set of observations with AHI (more than 30000 observations with Himawari-8 and 4000 observations with Himawari-9, within the domain of applicability of the lunar models i.e. [-92,92] degree phase).

Models like the LIME, SP or LESSSR are now more routinely used for mission monitoring, in addition to the ROLO and the GIRO. The SP model, applied to GOSAT-2 instruments, showed its potential not only for radiometric performance monitoring but also for other purposes such as MTF post-launch assessment, spectral modelling to support hyperspectral missions, etc.

However, the mission monitoring assessments certainly need to be further analysed in view of the results of the lunar model inter-comparison exercise. There is also a need to realign the models with respect to the solar irradiance spectrum, which is now recommended by GSICS and CEOS WGCV IVOS to be the TSIS HSRS spectrum.

For the first time, the group discussed monitoring hyperspectral missions after a series of presentations by NASA JPL on their activities with OCO-2 and OCO-3 lunar measurements. Those presentations raised the question of having polarisation models of the Moon. In order to establish such models, the group recommended acquiring new sets of reference measurements.

Finally, this session addressed again the question of how the instrument teams derive the lunar irradiance observed by their sensors. It implies a good determination of parameters such as the oversampling factor and the solid angle of the detectors acquiring the lunar signal. The participants reiterated the need to define best practices and guidance. An action has been formalised and it was agreed that the group would start working on those best practices in 2024.

Thermal infrared and Microwave

The use of lunar observations in the thermal infrared and in the microwave part of the solar spectrum has made spectacular progress on the front of model developments and usage for the radiometric assessment of space-born instruments.

Among other applications, the workshop was the opportunity to have presentations on topics such inter-calibration using the Moon as a transfer target, inter-band calibration, radiometric performance and detector monitoring, or antenna pattern mapping. Despite the question of the signal saturation for part of the sensors, encouraging results showed the need to further explore the usage of lunar imagery in those spectral domains.

But most importantly, the session had extensive talks and discussions on the question of model development for IR and MW applications. This is a major development in the field of lunar calibration. Thermo-physical models of the Moon are now available and allow the simulation of

lunar radiance to derive maps of the Moon in the IR, which could be extended to the MW domain. Research and development is also needed on the uncertainty assessment and how accurately the models can address mission radiometric requirements in terms of absolute and relative accuracy. Those questions relate to the definition and the validation of an emissivity model for the Moon and potential effects of libration.
Even though the session was focused on usage of lunar imagery, two presentations were given by the University of Hamburg and the Technical University of Dortmund on the use of planets, namely Venus and Mercury, as potential calibration targets for Earth observing sensors. One major advantage of using those planets is that the signal does not saturate. Despite the low availability of observations, the potential offered by those planets to monitor the radiometric performances of IR and MW sensors is worth further exploration.

Alternative Applications of Lunar Observations

Even though this session was short, it gave more insight on how lunar imagery can support in-flight assessment in addition to radiometric performance analysis. The session addressed topics such as MTF post-launch assessment using the Moon, straylight corrections, and moon measurements to retrieve aerosol optical thickness at night using the Moon as a source of light.
Regarding MTF post-launch assessment, several algorithms were presented. The choice of the fitting function for the ESF with lunar albedo flatting may impact significantly the end result. So the group recommended continuing with the comparison of the methodologies adopted by the various agencies who perform in-flight assessment with the Moon.
NOAA also presented their analysis of the impact of straylights on the ABI lunar irradiance as estimated from the measurements, in particular when looking at the response versus scan-angle. Even though the straylights, when present, are negligible at sample level, the effect may be significantly amplified when integrating the signal to infer the observed lunar irradiance. Therefore, careful straylight corrections are applied in order to reduce those uncertainties in the radiometric performances assessment of the instruments. Even though these corrections are instrument specific, some general recommendations were listed, such as ensuring sufficient distance to Earth disk to avoid residual signal scattered by the Earth, or considering a broader coverage around the Moon to integrate scattered moon light.
Finally, CNR/ISAC presented their work with the Skynet network to retrieve the atmospheric aerosol optical depth from lunar measurements acquired with sun-sky photometers. The participants showed a great interest in this project as the dataset constitutes a very large database of good quality lunar observations that could support model development. Skynet is a good example of alternative lunar observations that could help the lunar calibration community in its research and development activities on lunar irradiance modelling.

Conclusions and way forward

The Fourth Joint GSICS / IVOS Lunar Calibration Workshop gathered again many organisations and researchers working in the field of lunar calibration. It addressed a broad range of activities, such as the acquisition of reference measurements and how to infer new lunar models or improve existing ones using those measurements, how to extend lunar calibration in the thermal

infrared and microwave parts of the solar spectrum, and how to use lunar imagery to support additional in-flight assessment of the instruments performances. As part of the community effort to improve the lunar models, the results of an inter-comparison exercise between six different models were discussed and will lead to further understanding on what can be further improved in the numerical description of the lunar irradiance signal. The GIRO, which was initially developed to serve as a common baseline between agencies for instrument monitoring, will be replaced by the LSICS framework.
Finally, the broad range of activities addressed by the workshop led the Lunar Calibration Community to propose to the GSICS Executive Panel the creation of a subgroup on lunar calibration activities within the GSICS Research Working Group.

The detailed minutes of the meeting are available on:
http://gsics.atmos.umd.edu/bin/view/Development/LunarCalibrationWS2023

In total, 7 decisions, 17 actions and 23 recommendations were listed. Following the GSICS action tracker standards, they are reference according to the meeting (LCWS, Lunar Calibration Workshop), the year (2023), the presentation number (number + letter, for instance “1b”), the action/recommendation number taken during the course of the discussions raised by the presentation (starting at 1). For more information about the background discussions please refer to the corresponding presentation and the minutes of the meeting as available on **http://gsics.atmos.umd.edu/bin/view/Development/LunarCalibrationWS2023**

List of decisions

D.LCWS.2023.1b.1: SLIMED model to be officially known as SLIM from now on.

D.LCWS.2023.2i.1: GSICS LSICS model will be developed as a GSICS deliverable tool.

D.LCWS.2023.2i.2: GSICS LSICS model will be coded in python.

D.LCWS.2023.2i.3: future version of GSICS LSICS model output will include uncertainties.

D.LCWS.2023.5a.1: The Lunar Calibration Community proposes the formation of a sub-group on lunar calibration within the GSICS Research Working Group - cross-cutting spectral bands, and will ask the GSICS Executive Panel for endorsement at the next EP meeting (March 2024). Proposal of chairs to follow EP endorsement.

D.LCWS.2023.5a.2: The Lunar Calibration Community agrees to continue joint GSICS/IVOS lunar calibration workshops in person every year or 2 years.

D.LCWS.2023.5a.3: Schedule regular web meeting slots - with the objective of holding a meeting every 2 or 3 months - in coordination with other GSICS sub-groups. With one meeting in person every second year (see **D.LCWS.2023.5a.2**)

List of actions

A.LCWS.2023.1p.1: ESA/VITO to check on the uncertainty in the lower phase angle of the model and report back to GSICS.

A.LCWS.2023.1q.1: Model developers shall provide a detailed description of how their model is derived and a detailed functional description of their model.

A.LCWS.2023.2b.1: T. Stone to coordinate with the group involved in the first lunar model inter-comparison to define a way forward for the next iteration on the model inter-comparison.

A.LCWS.2023.2f.1: Teams involved in software development to liaise with LSICS development group on what are the typical disclaimers for distributing software.

A.LCWS.2023.2i.1: T. Stone (USGS) to report the scope of LSICS to EP in the 2024 annual meeting. The GSICS LSCIS will be modularly implemented with open source code of Python and accessible to the public pending on Github.

A.LCWS.2023.2i.2: GDWG (Masaya T.) to seek the corresponding information from WMO and GDWG members to provide guidance on the version control of the GSICS LSICS deliverable. Report at the 2024 annual meeting.

A.LCWS.2023.2i.3: EUMETSAT & NOAA to continue to develop spec & circulate, then iterate with group. Seb Wagner needs to check with EUMETSAT.(due: 2024 annual meeting)

A.LCWS.2023.2i.4: Revise variable naming conventions, provide the documentation for review (due: 2024 annual meeting)

A.LCWS.2023.2i.5: GDWG to provide guidance on the method to implement for flagging that LSICS products came from official LSICS run.

Action A.LCWS.2023.3c.1: Jason to report at a future Lunar Calibration sub-group web meeting about the issues with the F-factor (due: by 2025 annual meeting).

Action A.LCWS.2023.3n.1: Martin Burgdorf to coordinate a presentation on using stars to monitor Himawari-8 and 9 at a future Lunar Calibration sub-group web meeting (due: by 2025 annual meeting).

A.LCWS.2023.4j.1: Fangfang Yu (UMD) to invite Diogo Rio Fernandes (OroraTech) to GSICS annual meeting to present inter-calibration of SAFIRE thermal IR imagers

A.LCWS.2023.4l.1: Jack Xiong (NASA) to report back on result of comparison of comparison of TPMs with MODIS/VIIRS

A.LCWS.2023.4d.1: Tiger Hu (UMD) to share AMSU and ATMS Moon observations with Thomas Müller

A.LCWS.2023.5a.1: Hugh Kieffer to propose section titles for Best Practice Guideline on lunar calibration by 2024-03-01

A.LCWS.2023.5a.2: Seb Wagner (EUMETSAT) to propose way forward with GSICS Lunar Observation Dataset (GLOD) by 2024-03-01

A.LCWS.2023.5e.1: Thomas Müller to analyse impact of libration on thermal signal and report by 2024-12-31

List of recommendations

R.LCWS.2023.1f.1: Lunar Calibration Community to investigate in coordination with the GSICS Research Working Group how to raise visibility of the lunar (measurement) activities, and how to show the usefulness of those activities for climate monitoring.

R.LCWS.2023.2i.1: The inputs/outputs of the LSICS should maintain GIRO compatibility

R.LCWS.2023.1j.1: Agencies acquiring lunar observations to share data with documentation and uncertainties as far as possible.

R.LCWS.2023.1j.2: GSICS to define a mechanism to share observations (jointly with IVOS) - e.g. assigning a DOI, linked to a URL. Share recommendation with WGCV (actionee: Jack Xiong - NASA)

R.LCWS.2023.1n.1: Encourage more observations of lunar polarisation to allow development of improved lunar polarisation model

R.LCWS.2023.1p.2: a detailed documentation on all lunar models and their implementation should be provided for review by the Lunar Calibration Community

R.LCWS.2023.1q.1: GSICS community should review and validate the methodology (related to **A.LCWS.2023.1q.1**). Peer review process is secondary.

R.LCWS.2023.2a.1: Additional spectral bands should be added to the existing SRF dataset available for the inter-comparison exercise, in particular in spectral domains subject to gaseous absorption.

R.LCWS.2023.2a.2: NIST to share fully processed Air-LUSI data with the Lunar Calibration Community. This will support the understanding of model differences.

R.LCWS.2023.2a.3: Tom Stone to iterate with the Lunar Calibration Community on the need to generate time series of model lunar irradiance differences for a synthetic instrument

R.LCWS.2023.2i.1: LSICS should maintain GIRO compatibility for input and output files

R.LCWS.2023.2i.2: LSICS should implement a capability to account for the solar spectral irradiance variability.

R.LCWS.2023.2i.3: The LSICS lunar disk reflectance module should consider generating the lunar disk reflectance spectrum as an intermediate product.

R.LCWS.2023.2i.4: LSICS should implement the GSICS-endorsed solar spectrum

R.LCWS.2023.4k.1: Jack Xiong (NASA) to report on outcome of the analysis of the ABI lunar data in thermal infrared

R.LCWS.2023.4n.1: EUMETSAT and VITO are invited to test more fitting functions and share results with the Lunar Calibration Community

R.LCWS.2023.4o.1: as a continuation of **R.GVNIR.2020.19d.1** (see Notes), NOAA is encouraged to coordinate the Lunar Calibration Community efforts to define best practices for post-launch assessment of MTF using lunar imagery.

R.LCWS.2023.4s.1: GDWG to review how to host the new lunar irradiance data such as air-LUSI, skynet lunar irradiance data

R.LCWS.2023.5b.1: EP to promote acquisition of SI-traceable observations of the Moon to support further operation of Mauna Loa-LUSI, and to include the aerosol retrieval application to raise visibility of lunar calibration by tying it to a key climate data record

- Seb Wagner (EUMETSAT) and Tom Stone (USGS) to interface with Monica and Natalia to formulate the latter

R.LCWS.2023.5b.2: GSICS Exec Panel to support acquisitions of more polarisation-diverse observations of the Moon.

R.LCWS.2023.5b.3: GSICS recognises the additional value in disk-resolved lunar observations to support the further development and validation of lunar radiance models.

R.LCWS.2023.5e.1: Agencies operating microwave instruments observing the Moon are encouraged to compare these with the model presented by Tiger Hu (UMD), which is fitted to ATMS data. This would allow instrument comparison, covering more phase angles.

Notes:

R.GVNIR.2020.19d.1: NOAA is encouraged to pursue its initiative on comparing approaches for post-launch assessment of MTF using lunar imagery. This initiative, in collaboration with other agencies, would lead to the definition of best practices for MTF assessment using the Moon.