Report
Study on validation of spectral band adjustment factors using lunar hyperspectral measurements
Activity 3

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Document number:
ESS-LUN-RP-003-Rev3
Version: 2017-06-07

Distribution:
EUMETSAT
Armamentarium
Earth Space Solutions
Tasty Chips Electronics
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ACTIVITY 3 DESCRIPTION

This section is copied from different locations in the SoW:

Lunar hyperspectral observations are available from Metop-A and -B with the GOME-2 instrument. In order to make use of those data the specific GOME-2 lunar observation geometries of these periods have to be taken into account. In addition, the Moon is passing through the GOME-2 instrument field-of-view in a way that shadowing effects of the instrument baffles, varying lunar illumination and surface characteristics play a significant role in the derivation of a stable GOME-2 Moon reference data set.

2.1 TASK 3.1.
Define a full list of information necessary to derive stable lunar irradiance spectra from GOME-2 – for example: instrument field-of-view baffling, lunar illumination and GOME-2 lunar viewing geometries, orientation of the Moon in the field of regard and radius of the lunar disc. The methodology to define this information shall also be defined.

2.2 OUTPUT 3.1.
The list of data sets necessary to derive stable lunar irradiance spectra from GOME-2, and proposed methodology to define this information, as a basis for the decision to exercise the option.

2.3 GOME-2 DATA AND READERS
EUMETSAT will provide two data sets of Level 1B lunar observations as acquired by GOME-2 aboard Metop-A and Metop-B. These data sets are in the EPS native format.

Additionally some information about the acquisition geometry for those observations will be provided: the phase angle at which the Moon is observed and the Moon crossing speed (using the Moon azimuth and the Moon elevation angles).

Any additional parameter that may be needed for making of GOME-2 data (such as the radius of the Moon as seen through the slit, or the orientation of the partly illuminated lunar disc with respect to the instrument entrance slit reference frame) shall be calculated by the contractor.

In order to access the Level 1B data, it is possible to use Python or C programs in conjunction with the Basic Envisat Atmospheric Toolbox (BEAT) (freely available on http://www.stcorp.nl/beat/). Some example programs will be provided by EUMETSAT.
3 METHODOLOGY

We intend to follow a similar methodology employed for SCIAMACHY for the GOME2 lunar irradiance calibration, extended with lessons learned. The method is related to the one described in Dobber et al. (1998) with adaptation to GOME-2 applied calibration.

3.1 FOV

GOME-2 observes the moon by tilting its scanning mirror to the side during specific parts of its orbit when the moon can be observed. Due to orbit mechanics this is only possible during certain phases of the moon. The GOME-2 slit of about 0.28 degree in dispersion direction and 2.75/2.78 degree in cross-dispersion direction, projected on the sky constituted its IFOV of about 0.28 degree in elevation direction and 2.75 degree in azimuth direction (MO-TR-TPD-GO-0095). This IFOV is narrower than the moon in elevation, as the moon is about 0.5 degree. The IFOV in azimuth direction is long enough however to cover the whole moon disk.

For a nominal moon observation sequence (scan) the moon moves in both azimuth and elevation directions (whole) through the IFOV while the detector is read out often enough to prevent saturation. See Figure 1.

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**Figure 1**

Single Moon measurement, during which the moon moves through the IFOV which is only partly filled by the Moon. Dimensions are not to scale.
Effectively a scan is made in the elevation direction across the moon disk. In order to determine the moon irradiance for that scan (with its phase, geometry, etc), these measurements have to be combined and corrected. Each measurement must be radiometrically corrected, preferably for all known instruments effects such as integration time, radiometric sensitivity, efficiency, polarization and degradation. Any correction not applied will have to be derived during this study (see below for degradation correction). Each measurement will then result in a radiometrically calibrated radiance spectrum in a number of photons sec^-1 nm^-1 sr^-1 cm^-2 for the part of the moon that is inside the slit.

This radiance can be converted in total photons detected (per nm and cm^2) by multiplying with the size of the IFOV (width b and length l) and the integration time (T).

By integrating or summing all measurements of a single scan an effective FOV (in sr) is created which contains the entire moon disk and provides all photons detected from the moon.

This total number of photons can be converted into an irradiance by dividing by the total time each part of the moon is in view, which is the time it takes the moon through move through the slit (which can be derived from the scanning speed in elevation direction v_elev) equal to b/v_elev. This corrections combined provides the lunar irradiance. See Figure 2.

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**Figure 2**
Moon Scan, during which the moon has completely moved through the IFOV, or the IFOV over the moon, creating an effective FOV
Dimensions are not to scale.
Correcting the summed measurements with these ratios will result in the desired lunar irradiance as seen by the satellite. The advantage of this approach is that it is insensitive to any inaccuracies of the IFOV pointing, as preliminary results show (see Appendix).

### 3.2 IMPERFECT SCANS

Some scans in which the moon did not properly cross the IFOV of GOME-2, either by not sampling the whole disk or because the moon did not cross the IFOV monotonically in elevation direction, can be detected by studying the geometries involved or the expected measurements behavior over the scan. The monotonically increasing elevation direction can be established from the (center) lunar elevation angle, while proper crossing can be determined from the 5-point (top, bottom, edge, dark edge and center) lunar azimuth and elevation angles which all must fill within the FOV. These angles are available in the GOME2 observations (EPS.SYS.SPE.99001). Dedicated tools will be designed for this verification purpose (to be delivered as prototype software) and these improper scans will be studied and flagged. Due to scanning or orbit inaccuracies the available lunar angles are not always correct, as such all measurements must be studied for possible behavior similar to an improper sampling and flagged if needed.

See Figure 3.

![Diagram of Moon scan where IFOV does not sample entire moon. Dimensions are not to scale.](image-url)
3.3 GIRO
This results in a dataset of GOME-2 lunar irradiance where geometry such as sun-moon, moon-satellite distance and lunar variation such as phase and libration are still uncorrected for. This lunar irradiance based upon satellite viewing conditions (@satellite) can be used to compare with GIRO (which also provides lunar irradiance @satellite). Therefor GIRO will be employed to calculate a (reduced resolution) model spectrum for each valid lunar scan and derive required lunar parameters for later steps not provided in the GOME-2 measurements. The GIRO results will be later compared to the GOME2 derived lunar irradiances.

3.4 GEOMETRY
In order to derive stable lunar irradiance as seen from a stable earth (@nominal), geometry corrections will be determined. Distance effects will be normalized to the average earth-moon distance and earth-sun distance. See Figure 4. The moon-satellite variation can be removed by multiplying with average $d^2_{\text{earth-moon}}/d^2_{\text{sat-moon}}$, while the sun-moon variation can be removed by multiplying with average $d^2_{\text{earth-sun}}/d^2_{\text{sun-moon}}$. Intrinsic lunar variation (phase and libration) will not be removed from the lunar irradiance in this phase. The geometric phase angle is provided by EUMETSAT. See Figure 5.

![Diagram showing Sun-Moon, Earth-Moon, and Satellite-Moon distances](image)

**Figure 4**
Underlined distances are distances to which average value will be normalized for Earth reference frame. Distances not to scale.
3.5 DEGRADATION

As indicated by EUMETSAT, no degradation correction valid for the lunar observation is currently available, but is required for a stable lunar irradiance. As GOME-2 observes only under a limited number of geometries this relative correction can be derived from the lunar measurements itself by combining stable observations with (very) similar viewing and lunar phase and libration geometries (@nominal). As no degradation of the lunar irradiance itself is expected, all changes can be attributed to degradation. Repeating this for other viewing and lunar geometries (@nominal) allows determining the precision of the correction. More precision on the degradation would be gained by modelling the degradation together with the phase angle and libration (and any other) dependencies. Given the degradation behavior of GOME-2A and GOME-2B, and the large impact of the GOME-2A (second) throughput test of September 2009, after which degradation and degradation behavior changed significantly, the model would consist of 3 degradation models (GOME-2B, GOME-2A before Throughput test, GOME-2A after Throughput test), where degradation is separately determined for each, but all other parameters are the same and linked (hopefully). However lunar variation can no longer be determined independent from the degradation, though expected correlation is low.

Alternatively we use the high relative accuracy of GIRO to monitor the GOME-2 degradation. This supposes that all observables are under control. However this does not have preference as the GIRO comparison is then no longer fully independent.

If precision is low and the extra information (unfitted earth radiance degradation measurements) is provided by EUMETSAT, an attempt can be made to scale the expected behavior of a slightly contaminated mirror (Krijger et al. 2014) to the observed earth radiance and solar irradiance degradation, allowing extrapolation to the lunar observation viewing angles. However the exact behavior of GOME-2 mirror might be different than expected at the larger viewing angles resulting in erroneous corrections. A full analysis of the mirror contamination and its scan-angle effect, which would allow exact determination of lunar degradation is outside the scope of this study.

Figure 5
Difference between geometrical lunar phase and (Earth) lunar phase for which must be corrected for Earth reference frame.
If all approaches fail to provide a degradation correction with the desired precision, the degradation of the most-extreme nadir viewing angle earth radiance degradation will be extrapolated to lunar viewing conditions. The degradation results derived will be employed to correct all lunar measurements for degradation (both @nominal and @satellite frames).

The degradation corrected irradiances (@satellite ) can now be compared to the GiRO model spectra for the valid wavelengths of GiRO. Outliers and deviations can be determined and studied. No predictions can be made what results will be obtained. If large deviations are found the choice can be made to use GiRO spectra to re-calibrate the GOME2 spectra, however this is not preferred.

3.6 LUNAR VARIATIONS

Assuming no show-stoppers, with the degradation corrected irradiance the lunar geometry variations can be studied (and removed) and dependencies on phase angle and irradiance derived (if data quality allows), either directly on the GOME2 lunar irradiance or relative to GiRO. The variations will be fitted to a model. Either a model containing only phase angle and libration, or a more extensive one containing remaining degradation, selenographics longitude, viewing mirror, etc (See Kieffer et al 2005 and Activity 1&2). This is dependent on the data amount and quality. Possibly this variation has already been derived in order to determine degradation (see above).

Having compared the GOME2 spectra relative to GiRO and determined the lunar variations, now GOME2A and GOME2B lunar irradiance measurements can be compared to each other. Little difference is expected, because geometry, degradation, radiometric response is all corrected. Earlier studies [Eumetsat Contract. EUM/CO/04/1298/RM] have shown that GOME-2A and GOME-2B have different slitfunctions, but this is expected to have little impact on intrinsic lunar variations that vary only slowly over wavelength. If any differences are understood and small enough, the measurements can be combined. Combined lunar variations can again be determined but with higher confidence due to the increased number of observations.

Understanding all intrinsic lunar variations in the GOME2 observations (either irradiance or relative to GiRO), allows to construct a reference lunar irradiance spectrum at (various) reference phase and libration angles. Zero libration angles are a natural choice, however the often employed 7 degree phase angle might not be possible with the limited phase angles observed by GOME2. Instead a reference phase angle representative of the GOME2 observations will be provided. Together with the spectral dependencies on phase angle and libration (and any other parameters) this will allow comparison with other missions.

3.7 LUNAR ALBEDO

In all of the above it is possible, in case of data issues, to examine lunar albedo instead of lunar irradiance, as many instrument effects are divided out with albedo. For these cases the identical calibrated GOME2 solar irradiance spectra are required, together with the applied diffuser (BSDF) calibration. However this is not foreseen at the moment.

3.8 OUTPUT

All of the above will result in a database containing for each GOME-2 lunar scan:

1. Lunar observed irradiance spectra (@satellite, without degradation)
2. GiRO spectra (@satellite)
3. Geometry Correction
4. Degradation Correction
5. Stable Lunar observed irradiance spectra (@nominal and degradation corrected)

And a GOME2A&B (separate or combined) reference lunar irradiance at typical GOME2 phase angle with all its dependencies, independent and relative to GiRO.
LIST OF DATA SETS

Below we indicate all information required. All information, except those indicated missing, is present in the sample GOME2 lunar observation files received. However due to reader issues (see below) no check of the validity of the information could be performed. Some information is indicated optional, as this information is not required for the desired minimum output but might be very helpful with any further analyses of the results.

All measured GOME2A&B lunar irradiances, corrected for
- Radiometric response (including scan-angle)
- Polarisation
- Degradation [missing, to be provided by EUMETSAT, or derived during study]
- Other Instrument effects

For each measurement the following information is required
- Time
- Wavelength
- Integration time
- Viewing angle
- Lunar azimuth (5-point, from satellite)
- Lunar elevation (5-point, from satellite)
- Solar azimuth (from satellite)
- Solar elevation (from satellite)
- LOS azimuth (5-point, from satellite) [missing, can be derived viewing angle and documentation]
- LOS elevation (5-point, from satellite) [missing, can be derived viewing angle and documentation]
- Distance sun-moon
- Distance satellite-moon
- Average distance sun-earth [missing, available from SPICE in GIRO]
- Average distance earth-moon [missing, available from SPICE in GIRO]
- Lunar radius [missing, can be derived from distance satellite-moon]
- Lunar phase [missing, available from SPICE in GIRO]
- Lunar geometrical phase angle (from satellite)
- Lunar disk fraction (from satellite)
- Lunar libration longitude [missing, can be derived from GIRO]
- Lunar libration latitude [missing, can be derived from GIRO]
- Elevation scanning speed (from satellite) [missing, promised to be delivered by EUMETSAT, can be derived from lunar elevation angles]
- Polarisation q-value spectrum [optional]
- PMD readouts [missing, optional]
- Calibrated solar irradiance spectrum [missing, optional]
- Earth radiancde degradation measurements [missing, optional]

The following general information is required (for each wavelength)
- GOME2A&B IFOV (slit) dimensions in degrees [missing, but documentation provided]
- GOME2A&B FOV dimensions [missing, but documentation provided]
- GOME2A&B BSDF calibration [missing, optional]
- X,Y,Z position of GOME2 for each measurement [missing, alternative Two-line element (TLE) orbit information]
- Roll, Yaw, Tilt accuracy of GOME2 (or uncertainties IFOV pointing)

For all of the above information accuracy information is optional but would aid in determining total accuracy of the GOME2 derived lunar irradiances.
4.1 MISSING INFORMATION

- The missing elevation scanning speed, mentioned in ITT, can be derived from the provided lunar elevation, however at a lower accuracy than if directly derived from EUMETSAT orbit software. For follow-on studies the option of support from EUMETSAT flight dynamics should be investigated.
- The missing degradation information can be derived as described in the methodology from either the moon measurements itself or from EUMETSAT determined earth radiance degradation or from earth radiance degradation measurements possibly combined with solar irradiance measurements and a mirror model.
- The X,Y,Z position of GOME2 should be delivered at the start of the project, though can be derived more inaccurate from the TLE
- The accuracy information should be delivered at the start of the project, though can be roughly estimated resulting in less accuracy and precision.
- All other missing information can be derived from documentation provided or online available

4.2 DATA & READERS

At the start of this Activity the BEAT software did not read lunar observations. The BEAT software team has been informed of this, and with good communication, immediately corrected this situation. However the resulting read-in radiances were all invalid numbers, which EUMETSAT indicated was due to writing error their side.

Alternative preliminary test ASCII-files have been delivered by EUMETSAT, however no dedicated reader has been made available. With a temporary reader the test ASCII-files have been checked, which contain the required information, however the validity of the information has not and sometimes cannot be verified.

In all cases this will mean that any reader has been not extensively tested yet. In addition EUMETSAT has also indicated the information in the files might not be correct at this point in time and will be updated in the final consolidated delivery. Some effort is foreseen verifying the information provided.
### 5 Detailed Plan

Detailed calibration plan including outputs

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<td>2</td>
<td>Create earth/sun/lunar geometry software</td>
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<td>3</td>
<td>Create IFOV+moon trajectory verification software</td>
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<td>4</td>
<td>Select and read in all measurements of a single lunar observation (scan)</td>
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<td>Correct measurements for instrument effects if needed</td>
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<td>Verify polarisation correction</td>
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<td>Total measurements while moon is in view (minimum signal above noise)</td>
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<td>10</td>
<td>Determine geometry correction average $d^2_{\text{earth-moon}}/d^2_{\text{sat-moon}}$</td>
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<tr>
<td>11</td>
<td>Determine geometry correction average $d^2_{\text{earth-sun}}/d^2_{\text{sun-moon}}$</td>
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<td>Flag scan in case the moon did not monotonically increase elevation</td>
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<td>17</td>
<td>Calculate GIRO spectra &amp; lunar information for each GOME2A&amp;B observation at GOME2A&amp;B (reduced) spectral sampling, using observation time and GOME2 TLE.</td>
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<td>Determine degradation correction by modelling all variation (degradation, phase, libration, etc) (@nominal)</td>
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<td>Create database of (task 4.1) [output]</td>
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<td>- Lunar observed irradiance spectra (@satellite, without degradation)</td>
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<tr>
<td></td>
<td>- GIRO (@satellite)</td>
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<td>- Geometry Correction</td>
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<td></td>
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<td></td>
<td>- Stable Lunar observed irradiance spectra (@nominal and degradation corrected)</td>
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### Report Activity 3
Study on validation of spectral band adjustment factors using lunar hyperspectral measurements

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<td>Verify and study results</td>
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<td><strong>36</strong></td>
<td>Create GOME2A&amp;B (separate or combined) reference lunar irradiance at typical GOME2 phase angle with dependencies [output]</td>
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<tr>
<td><strong>37</strong></td>
<td>Create GOME2A&amp;B (separate or combined) reference lunar irradiance at typical GOME2 phase angle relative to GIRO [output, if possible]</td>
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6 REFERENCES

- MO-TR-TPD-GO-0095, issue 1, 2004, GOME-2 FM3 Calibration: Field of View
- EPS.SYS.SPE.99001, issue 7, 2010, EUMETSAT POLAR SYSTEM GOME-2 Level 1 Product Generation Specification
Below some (uncaptioned) preliminary plots are shown, derived from the test (asci) dataset provided by EUMETSAT.

Figure 6 Lunar brightness (color) as function of elevation and azimuth (in satellite frame). Only measurements around 90 azimuth provide actual measurements (as these are the measurements where the mirror looking to the side can see the moon passing through the IFOV. A curved stripe of dots touching each other form a single scan. The moon moves in a circular fashion as seen by the (earth rotating) satellite.

Figure 7 Same as previous figure, but now for single moon scan and the IFOV (solid curve). The colored dots indicate the center of the moon for each measurement. The moon can be seen moving into and then out of view.
Figure 8 Measured Lunar brightness as function of phase angle. The moon can be seen (for each scan) to move into view, then reach maximum brightness (middle IFOV) and move out of IFOV again. The maximum brightness per scan is (as expected) decreasing for the higher phase angles.

Figure 9 Phase angles as function of time. Orange color indicates measurements that are not zero brightness. What can be observed is the slight variation in phase during a scan, with several scans per day. This is then repeated a few days later. However many observations do not observe the actual moon (and observe zero brightness).
Figure 10 Measured lunar brightness (for several scans) as function of azimuth, where the moon can be seen moving into the IFOV and the moving out of the IFOV. For these scans the response is identical for each scan (due to orbit mechanics) and are an indication of the noise in the data.

Figure 11 Measured lunar brightness for same scans as previous figure, but now as function of elevation. Again the moon can be soon to move through the IFOV for each scan and reaching maximum measured brightness halfway. The decrease in maximum brightness is due to change in phase angle.
Figure 12 Measured lunar brightness as function of pixel number for a single sample measurement. Channel overlaps every 1024 pixels are clearly visible.

Figure 13 Same lunar spectra as previous figure, but now as function of wavelength. No unexpected behaviour is visible and the channels overlaps appear to match. Colors indicate the different GOME2 channels.
Figure 14 Same spectrum as previous image but now divided by a spectrum earlier in the provided test data set under similar viewing conditions. This ratio shows the (approximate) degradation during this 5 months period. Colors indicate the different GOME2 channels.

Figure 15 Same information as previous figure, but now as function of pixel number.
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Figure 16 Mirror viewing angle as function of time. The mirror angle for a single scan is fixed (multiple dots at same location, not visible here). For the next scan the mirror is moved slightly and fixed again. This process is repeated every few weeks.

Figure 17 Lunar phase as function of Mirror viewing angle. As can be seen there is a correlation between viewing angle and lunar phase (due to orbit mechanics). As both the polarisation sensitivity changes due to different mirror viewing angle, and the polarisation changes with a different lunar phase, special care must be taken to separate the effects. This makes an accurate provided polarisation correction all the more important.