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## *On-ground re-calibration of the GOME-2 satellite spectrometer series*

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# On-ground Re-Calibration of the GOME-2 Satellite Spectrometer Series

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**Abstract**— The Global Ozone Monitoring Experiment-2[1] (GOME-2) represents one of the European instruments carried on board the MetOp satellite within the ESA's "Living Planet Program". Consisting of three flight models (FM's) it is intended to provide long-term monitoring of atmospheric ozone and other trace gases over a time frame of 15-20 years, thus contributing valuable input towards climate and atmospheric research and providing near real-time data for use in air quality forecasting.

The ambition to achieve highly accurate scientific results requires a thorough calibration and characterization of the instrument prior to launch. These calibration campaigns were performed by TNO in Delft in the Netherlands, in the "Thermal Vacuum Calibration Facility" of the institute.

Due to refurbishment and / or storage of the instruments over a period of a few years, several re-calibration campaigns were necessary. These re-calibrations provided the unique opportunity to study the effects of long term storage and build up statistics on the instrument as well as the calibration methods used.

During the re-calibration of the second flight model a difference was found in the radiometric calibration output, which was not understood initially. In order to understand the anomalies on the radiometry, a deep investigation was performed using numerous variations of the setup and different sources. The major contributor was identified to be a systematic error in the alignment, for which a correction was applied. Apart from this, it was found that the geometry of the sources influenced the results. Based on the calibration results combined with a theoretical geometrical hypothesis inferred that the on-ground calibration should mimic as close as possible the in-orbit geometry.

**Index Terms**—Calibration, Radiometry, slit-function, earth observation.

## I. INTRODUCTION

### A. The instrument

The GOME-2 instrument is a scanning grating spectrometer flying in low earth orbit LEO. The spectral bands are continuous in a range from 240nm to 790nm with a spectral resolution ranging from 0.2nm to 0.4nm. Additionally two polarization sensitive prism spectrometers are implemented measuring s and p polarization of the incoming light.

### B. Calibration approach

The GOME-2 instrument uses an extensive on-ground calibration in combination with on-board sources in a dedicated calibration unit. The on-ground calibration delivers key-data that is used in the on-ground processor to convert the raw data of the instrument into physical units. The on-board unit is used to monitor changes of the instrument while in orbit and to alter calibration key-data if necessary.

The instrument is calibrated on-ground for radiometry, polarization, spectral response, field of view, detector response and stray-light. The instrument is placed into a vacuum chamber ( $<10^{-5}$  mBar) and cooled down to its nominal in-orbit temperature. In this way the in-orbit conditions are simulated except for exact temperature gradients and gravity.

The position of the instrument in the chamber is fixed so that only nominal angles of incidence in the earth and sun port can be measured. Setups in ambient are used to determine the instrument response to different sun incidence angles on the on-board diffuser and to determine the scan mirror angle dependence.

### C. Storage approach

The MetOp mission consist of three satellites which were built in sequence. The instruments were all calibrated prior to

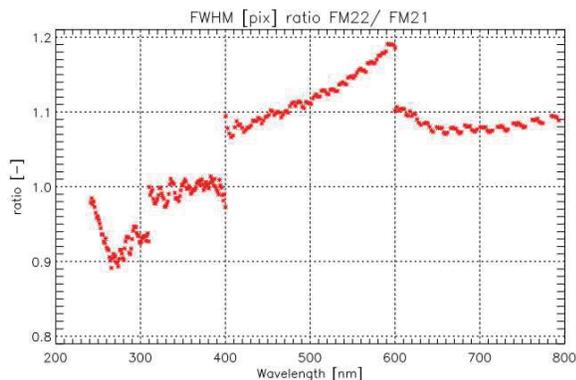


Fig. 1 Comparing the FWHM of the instrument slit-function measured during the delta calibration (FM22) w.r.t. the original calibration (FM21). On the x-axis the wavelength (200 to 800nm) and on the y-axis the ratio (0.8 to 1.2).

integration on the satellite. After the first MetOp launch in 2006 the GOME-2 instruments were dismantled from their satellites and stored at the instrument prime contractor's premises.

For each next launch the corresponding instrument would again have to be calibrated before mounting it to the satellite. This was intended to be a delta campaign with respect to the original calibration to confirm stability.

## II. DELTA CALIBRATION OBSERVATIONS

### A. General

After a storage period of 6 years the calibration measurements of the second flight model were repeated. For most of the over 100 key-data the differences with the previous calibration were not significant, proving the stability of the instrument and its calibration. However some differences were more fundamental and forced a deeper investigation of the measurement method and the instrument design.

### B. Instrument spectral response function

The instrument spectral response function or "slit-function" describes how a spectral line of infinitely small bandwidth is imaged on the detector. This function was scanned spectrally on a sub-pixel level with a dedicated stimulus[2]. During the recent delta calibration the scan was repeated for the first time and a comparison was made with the full width half maximum (FWHM) of the function. Differences with the previous calibration up to 20% in FWHM were observed as can be seen in Fig. 1.

These changes were confirmed with independent measurements using a spectral line source, proving that this change is truly a change in the instrument.

The on-board calibration unit has a spectral line source, therefore this parameter can also be monitored in-orbit. This is what has been done for the currently flying model. The in-orbit

measurements showed that indeed the slit-function was not stable. This is surprising since the slit-function was expected to be very stable as it is purely determined by the mechanical configuration of the instrument optics.

After analyses of the optical design it was found that due to mechanical stress the grating inside the spectrometers could deform and therefore give optical power to the grating which leads to defocus.

### C. Radiometry

The GOME-2 instrument has an earth viewing port and a sun port. The radiometric response of both ports was to be absolutely calibrated. The response of the earth port is referenced to as radiance response and the response from the sun port is referenced to as the irradiance response. A NIST calibrated FEL lamp is used for this absolute calibration.

For the irradiance measurements the FEL lamp directly illuminates the instrument sun diffuser in the sun port. For the radiance measurements the FEL lamp illuminates an external diffuser to convert the FEL irradiance into a radiance (and simulate the earth as a diffuser). This diffuser is also calibrated in the absolute radiometric calibration facility at TNO. In both cases the distance between either external or instrument diffuser and the FEL lamp were varied.

As the FEL lamp is essentially a point source, it does not only illuminate the diffuser but also the surrounding. Therefore the cleanroom walls, ceiling and floor are all of black material. In addition to this, dedicated baffling is performed.

The first radiance measurements with the FEL lamp showed differences of several percent with the previous calibration. To confirm these results, measurements were repeated and again resulted in different values. It was found that the differences in the radiance measurements could be explained by a small alignment error, which was first corrected and later prevented by more stringent alignment procedures.

A small error was left between the measurements at different distances between FEL lamp and diffuser. This error could be explained if the size of the instrument detector

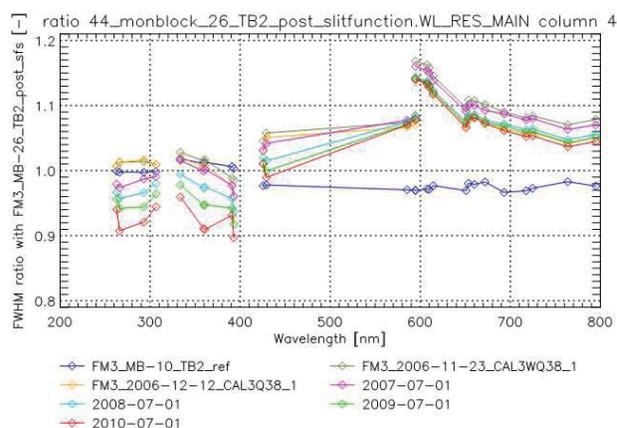


Fig. 2 Relative change of the slit-function FWHM of the current flying GOME-2 instrument. Reference is spectral line source measurement close to the dedicated slit-function measurement.

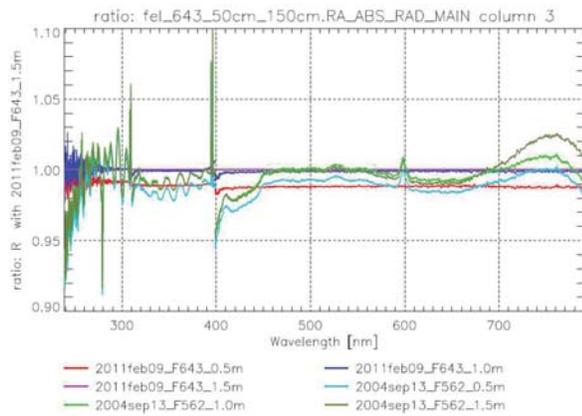


Fig. 3 Comparison of the determined radiance response between initial and delta calibration. The red blue and purple line are data from the new calibration with a distance between FEL lamp and diffuser of 0.5, 1.0 and 1.5m respectively. The turquoise, green and grey lines are data from the previous calibration with a distance between FEL lamp and diffuser of 0.5, 1.0 and 1.5m respectively. The wiggles are due to a not perfect detector etalon correction.

footprint on the diffuser is taken into account. In the analyses a homogenous illumination of the diffuser was assumed. As the FEL lamp resembles a point source this is only true at a far enough distance from the diffuser w.r.t. the size of the instrument detector footprint. Considering the field of view of 3 degrees (in one direction) and a distance of ~2.5m from the instrument, the footprint becomes about ~13cm. At the outer edges of the footprint the distance to the lamp is therefore about 0.85% larger than at the center, leading to a 1.7% lower irradiance at that point.

The assumed homogenous illumination leads therefore to a significant systematic error of ~1% at 0.5m distance. The data for the longest distance was used for the calibration key-data because at that distance the illumination is most homogenous.

The irradiance response measurements showed differences which were much larger and inconsistent. Unfortunately the irradiance measurements were carried out at a single distance, except for one case. Even though the results also indicated an alignment error similar to the radiance measurements, the order of magnitude of this error was improbably large and was not consistent with the other measurements. Therefore a more deep investigation was performed.

### III. INVESTIGATION OF IRRADIANCE RESPONSE ANOMALY

#### A. Setup

As stated previously the radiometric anomaly was found to be in the irradiance measurements. Therefore this setup is described here in greater detail.

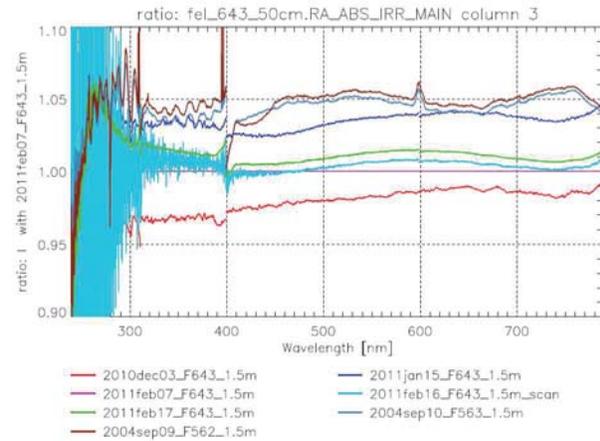


Fig. 4 Comparison of the determined irradiance response between initial and delta calibration. All measurements were performed with the FEL lamp at 1.5 meter distance from the instrument diffuser. The dark brown line and the grey-blue line are from the previous calibration.

The FEL irradiance setup is relatively simple: the source is placed at a known distance from the instrument diffuser. The instrument itself is inside a thermal vacuum chamber (TVC). The light enters the TVC via a vacuum window. Just in front of this window there is a baffle to block all unwanted light into the vacuum chamber to minimize stray-light. In practice this means that only the diffuser and the sun port baffle will be illuminated.

Behind the lamp a dark plastic plate (PE-plate) is placed at an angle w.r.t. the axis diffuser source. This is done to avoid specular reflections towards the diffuser. In some of the test cases the PE-plate was removed or replaced by a mirror.

The FEL lamp itself is placed upon a rail which is used to adjust the distance between lamp and diffuser. This rail itself has a high accuracy of a few micrometers. The distance between FEL and diffuser is between 1.5 and 2.5 meters. This distance is determined by triangulation of the sun port baffle and the lamp alignment jig using a theodolite. The accuracy of this technique is well within a few millimeters.

Most of the light of the FEL lamp will illuminate the environment and not the instrument diffuser. This means that there will be a considerable amount of environmental stray-light. To characterize this a background measurement was performed using a background shutter that only blocks the direct light. Preferably the shutter should be close to the lamp, however this would influence the temperature of the lamp and therefore invalidate the NIST calibration. The background shutter is therefore placed further from the lamp blocking more of the environmental stray-light. The background level measured in this way is about 3 orders of magnitude lower than the exposure measurements so it is assumed that the influence of the position of the shutter is small.

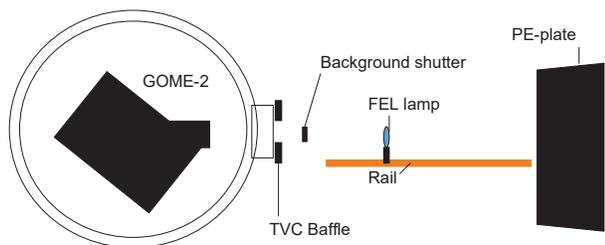


Fig. 5 Principle setup for the GOME-2 FEL irradiance calibration measurement. The PE-plate was in some case removed or replaced by a mirror.

A number of potential sources of the deviations were investigated; namely environmental stray-light, instrument stability and alignment error.

*B. Environmental stray-light*

The influence of environmental stray-light was investigated by changing the baffling behind the FEL lamp. Three case were investigated:

1. The default configuration with the PE-plate
2. The PE-plate replaced with a mirror at an angle such that it views towards a dark area inside the cleanroom at a long distance.
3. No PE-plate or mirror, in this case the cleanroom wall will generate a specular reflection towards the instrument diffuser

The measurement results reproduced very well (within 1%). It was therefore concluded that the influence of the environmental stray-light was very well under control.

*C. Instrument stability*

The instrument stability was tested by performing environmental cycles while leaving the setup intact. The instrument was switched off and on and sent through thermal cycling and vacuum cycling. The irradiance response after any of these environmental changes showed no deviation at all (within 1 %). It was therefore concluded that the instrument was stable and was not the cause for the anomaly.

*D. Alignment error*

The distance measurement using triangulation was considered very accurate based on the accuracy of the theodolite. However after doing many repetitions of the measurement it was found that the only time a major difference in irradiance response was observed, was after re-alignment of the setup. On one occasion, when the instrument was back in ambient condition with the setup still aligned, the alignment was checked using a ruler. A difference was found of no more than 5mm. A misalignment of 5 mm could not explain the differences in the irradiance response, for that a distance error of more than few centimeters was needed.

As the differences in irradiance response of the instrument were wavelength independent, an alignment error was still considered the most likely cause. Focus was therefore given to the target on the instrument used for the triangulation. The

edges of the instrument sun port baffle have a well-known separation distance to each other and to the diffuser. Theoretically they pose a very accurate target. However the baffle is black and placed into a dark vacuum chamber.

The mechanical lay-out is shown in Fig. 6. As can be seen in when viewing the baffle (top left view) from outside the chamber there are many edges visible close to the target edges. A distance error of  $129/126-1=2.4\%$  is introduced when the nearest edges are mistakenly used for triangulation. The theodolite is typically placed at a distance of  $\sim 3m$  (typical), which can lead to an distance error of  $\sim 7cm$ . The FEL lamp is calibrated at a distance of 50 cm. The point-source like behavior is used to determine the absolute irradiance at other distances (using the  $r^2$  rule). With the lamp at 150cm this leads to an error in irradiance response of 9.5%. This makes it plausible that the deviations in irradiance response found (see Fig. 4) are indeed from alignment errors.

*E. The absolute irradiance response*

After reaching the conclusion that the deviations were caused by alignment errors, the question remained to find the true irradiance response of the instrument. Fortunately the FEL source was not the only source used for radiometric calibration. Additionally a sun simulator was used for both radiance and irradiance measurements.

The sun simulator is a highly collimated source which in theory has no distance dependence. Due to inhomogeneity of the beam some minor distance dependent effect can be observed.

The sun simulator is not absolutely calibrated but can be used for relative measurements. The ratio between the instrument response of the earth port and the sun port to the sun simulator was determined. This ratio is referred to as the instrument BSDF. As the radiance response of the instrument to both sources (FEL and sun simulator) was consistent, the

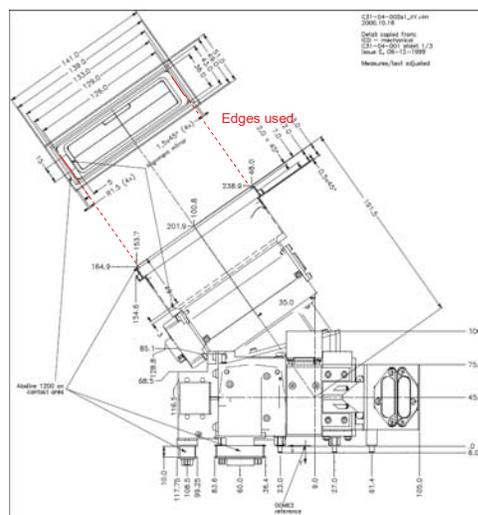


Fig. 6 Mechanical drawing of the GOME-2 calibration unit.

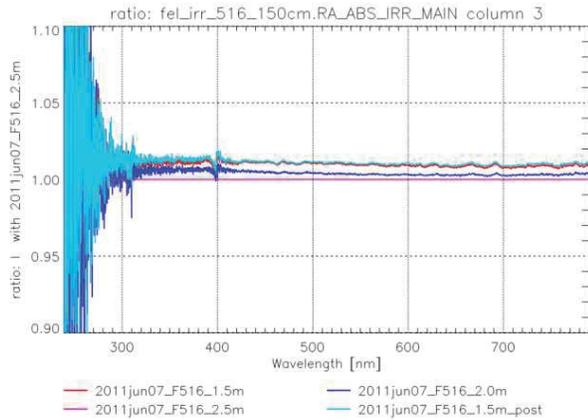


Fig. 7 Ratio of the irradiance measurements for different distances. The reference is the measurement at the largest distance. Noise levels in the UV are high because of short measurement time.

correctly aligned irradiance results using the FEL lamp could be chosen.

#### F. Source distance effect

During the investigation of the irradiance anomaly with the FEL lamp, the distance between diffuser and lamp was varied. In these measurements the FEL lamp seemed to not behave like a point source. Given the geometrical configuration of the setup this was not expected. It was found that the measurement at the longest distance resembled best the sun simulator measurements. The explanation was found in considering that the divergence of the light beam illuminating the diffuser changes with distance. The divergence of the sun is about  $0.5^\circ$  and therefore the source should have a similar divergence. Considering the size of the diffuser and the FEL lamp a distance of about 1.8m would be required.

Additionally, the baffle structure in front of the diffuser will give some stray-light. If the divergence of the illumination is similar to the sun, the stray-light will resemble the in-orbit conditions. If, however, the FEL lamp is placed too close to the sun port, the effective divergence of the beam is larger and more stray light is produced by the baffle. This was proven by a measurement with the sun simulator were first the baffle and diffuser was illuminated and then only the diffuser. A change of 0.5 to 1% in signal was observed. For a more divergent source as the FEL this is most likely higher.

#### IV. CONCLUSION

The GOME-2 instrument seems to be stable after many years in storage. Many of the results could be reproduced. The only instability found in the instrument was the shape of the instrument spectral response function. This however was never required for this instrument.

The delta calibration period as performed showed that taking a short cut on absolute radiometry and reducing measurements will jeopardize accuracy. Redundancy is an absolute must for highly accurate on-ground calibration.

#### ACKNOWLEDGMENT

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