International Conference on Space Optics—ICSO 2022

Dubrovnik, Croatia

3–7 October 2022

Edited by Kyriaki Minoglou, Nikos Karafolas, and Bruno Cugny,

COPERNICUS Sentinel-4: Calibration Campaign Results and Performances

International Conference on Space Optics — ICSO 2022, edited by Kyriaki Minoglou, Nikos Karafolas,
Bruno Cugny, Proc. of SPIE Vol. 12777, 1277735 · © 2023 ESA and CNES · 0277-786X · doi: 10.1117/12.2690338

COPERNICUS Sentinel-4: Calibration Campaign Results and Performances

G. Bazalgette Courrèges-Lacoste*[a], O. Seger[b], B. Oexl[c], M. Harlander[b], S. Riedl[b], S. Becher[b], J-F. Pittet[b], B. Ahlers[a], A. Chanumolu[a], M. Miler[a], Y. Aoun[a], A. Pasquet[a], M. Dobber[d], F. Ruethrich[d], S. Gimeno Garcia[d]

[a]ESA ESTEC, Keplerlaan 1, 2200AG Noordwijk The Netherlands; [b]Airbus Defense and Space GmbH, Robert-Koch-Straße 1, 82024 Taufkirchen, Germany; c Airbus Defence and Space GmbH, Claude-Dornier-Str., 88090 Immenstaad, Germany; [d]EUMETSAT, Eumetsat-Allee 1, 64295 Darmstadt, Germany

ABSTRACT

The Copernicus missions Sentinel-4 (S4) and Sentinel-5 (S5) will carry out atmospheric composition observations on an operational long-term basis to serve the needs of the Copernicus Atmosphere Monitoring Service (CAMS) and the Copernicus Climate Change Service (C3S).

Building on the heritage from instruments such as GOME, SCIAMACHY, GOME-2, OMI and S5P, S4 is an imaging spectrometer instruments covering wide spectral bands in the ultraviolet and visible wavelength range (305-500nm) and near infrared wavelength range (750-775 nm). S4 will observe key air quality parameters with a pronounced temporal variability by measuring NO2, O3, SO2, HCHO, CHOCHO, and aerosols over Europe with an hourly revisit time.

A series of two S4 instruments will be embarked on the geostationary Meteosat Third Generation-Sounder (MTG-S) satellites. S4 establishes the European component of a constellation of geostationary instruments with a strong air quality focus, together with the NASA mission TEMPO (to be launched end 2022) [9] and the Korean mission GEMS (launched 19 February 2020) [8].

This paper addresses the result of the final and crucial phase for the end to end performance of the PFM instrument: the extensive on-ground Characterization and Calibration of the instrument that is happening during the summer/fall 2022. The paper presents an overview of the calibration campaign objectives, the main performance verification and calibration measurements and preliminary performances of the PFM as-built instrument.

Keywords: imaging spectrometer, calibration, instrument performance, atmospheric mission

1. INTRODUCTION

Sentinel-4 is an imaging UVN (UV-VIS-NIR) spectrometer which will provide accurate measurements of key atmospheric constituents such as ozone, nitrogen dioxide, sulfur dioxide, methane, and aerosol properties over Europe and adjacent regions from a geostationary orbit (see Fig. 1) – hence the motto of Sentinel-4 "Knowing what we breathe".

In the family of already flown UVN spectrometers (SCIAMACHY [3, 4], OMI [5,6], GOME & GOME 2 [7]) and of those spectrometers recently launched (TROPOMI) and currently under development (Sentinel-5), Sentinel 4 is unique in being the first geostationary UVN mission, together with very similar geostationary UVN missions over other continents, which are being developed in parallel by NASA (TEMPO) and KARI (GEMS). Furthermore, thanks to its 60-minutes repeat cycle measurements and high spatial resolution (8x8 km^2), Sentinel-4 will increase the frequency of cloud-free observations, which is necessary to assess troposphere variability.

*gregory.bazalgette@esa.int; phone: +31 715654371;

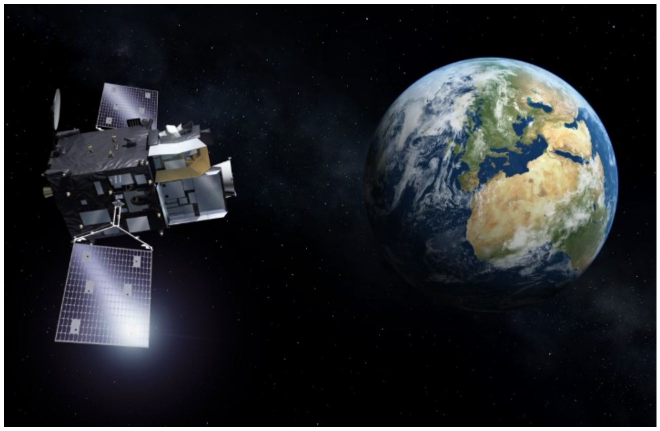


Fig. 1: artistic impression of Sentinel-4 embarked on Meteosat Third Generation-Sounder.

1.1 Instrument characteristics

The Sentinel-4/UVN instrument is a hyperspectral spectrometer operating with designated spectral bands in the solar reflectance spectrum. The prime Sentinel-4/UVN parameters are listed in **Table 1**.

Table 1: Sentinel-4/UVN instrument main design and performance parameters [2].

Spectral			
Parameter	**UV-VIS values**	**NIR values**	**Comments**
Wavelength range	305-500 nm	750-775 nm	
Spectral Resolution / Spectral Oversampling	0.5 nm / 3	0.12 nm / 3	Oversampling is Resolution divided by spectral pixel sampling
Spectral Calibration Accuracy	0.0017 nm	0.0020 nm	
Geometric and Temporal Coverage			
Parameter	**Value(s)**		**Comments**
Spatial Sampling Distance (SSD)	8 km x 8 km (E/W) (N/S)		On-ground-projected SSD at reference point in Europe (45°N latitude; sub-satellite-point longitude)
Integrated Energy	70% over $1.47SSD_{EW}*1.13SSD_{NS}$ 90% over $1.72SSD_{EW}*1.72SSD_{NS}$		Integrated energy is a measure for the spatial resolution of the instrument
N/S slit field-of-view (swath)	4.0°		
E/W coverage & Repeat cycle	See Fig. 2		See Fig. 2
Daily Earth observation time	Summer max: 01:40 – 21:40 Winter min: 03:40 – 19:40		Adjusted to seasonally varying solar Earth illumination on monthly basis
Spatial co-registration	Intra-detector: 10% of SSD Inter-detector: 20% of SSD		2-dimensional (E/W & N/S) absolute co-registration
Radiometric			
Parameter	**UV-VIS values**	**NIR values**	**Comments**
Optical Throughput	~50% (in UV)	~60%	End-to-end scanner-to-detector
Radiometric Aperture	70 mm	44 mm	Circular diameter
Earth Signal-to-Noise-Ratio (SNR)	UV: >160 VIS: >1600	759-770nm: >90 Rest NIR: >600	For specified Earth radiance Reference scene
Earth Absolute RA	< 3%	< 3%	For Earth radiance & reflectance
Sun Absolute RA	< 3%	< 3%	For sun irradiance
Polarization Sensitivity	< 1%	< 1%	
Relative Spectral RA	< 0.05%	< 0.5%	For a spectral window of 3nm (UVVIS) and 7.5nm (NIR) and for reflectance only
Relative Spatial RA	< 0.25%	< 0.25%	For Earth radiance & reflectance

Power	212 W (average in operating mode)
Mass	200 kg
Data	25.1 Mbps (instantaneous, during acquisition)
Number of units	Three (3): • Optical Instrument Module (OIM), which contains the optical and detection part • Instrument Control Unit (ICU) • Scanner Drive Electronic (SDE)
Dimensions	OIM : 1080 x 1403 x 1785 mm ICU: 460 x 300 x 300 mm SDE: 300 x 200 x 100 mm

The requirement specifications of S4-UVN are amongst others set for level-0 and for level-1b data at End of Life (EOL) for the full signal dynamic range, for unpolarised spatially uniform scenes with a confidence level of one sigma. The requirement specifications have to be verified, partly on the ground and partly in orbit, during the commissioning phase (phase E1). ESA has implemented a number of requirements to be met before launch to assure a minimum of values to be met as apportionment of the total calibration. Some requirements, such as the instrument polarisation sensitivity, can on the other hand only be verified during an on-ground calibration phase, because the full set of required linearly polarized input light scenarios can only be offered to the instrument on the ground.

Figure 2 shows the S4 PFM instrument in its test configuration (at the Airbus OTN test facility prior to shipment to the RAL TVAC facility)

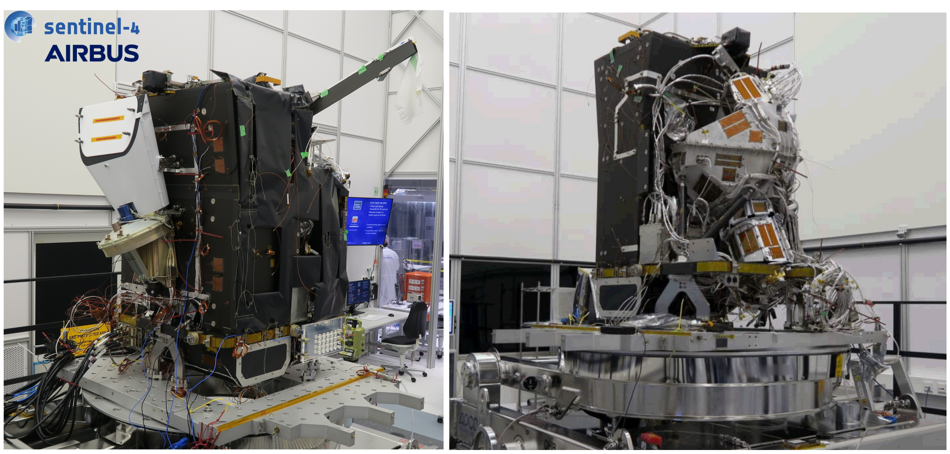


Fig. 2: S4 PFM instrument before shipment to the RAL TVAC facility.

1.2 Instrument Characterization and Calibration

After completion of the assembly, alignment and environment test phases in the 2020-2021 timeframe, the S4-UVN PFM instrument is ready for the crucial phase of Characterization and Calibration (C&C phase) at the RAL (UK) facility since early summer 2022. A full calibration is being performed on ground under flight representative thermal-vacuum conditions (i.e. thermal-vacuum environment with flight representative conditions for pressure, temperatures for detectors and optical bench).

Fig 3 shows the S4-UVN PFM integrated into the TVAC facility in RAL.

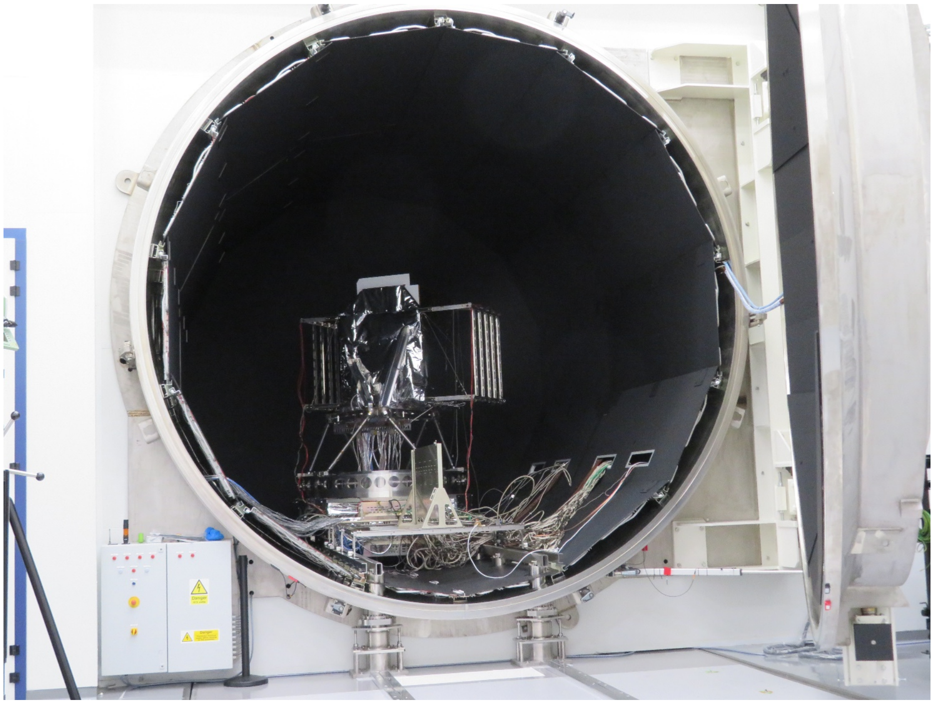


Fig.3 : S4 PFM instrument inside RAL TVAC chamber.

The aim of the calibration and on-ground characterization activities for the S4-UVN instrument performed during the combined characterization and calibration campaign is twofold: the verification of the performance related customer requirements at L0 and L1b and the provision of measurements needed to derive the calibration keydata. The latter ones are required by the science processor for the L0 to L1b processing [1].

The strategy and rationale to verify the S4-UVN requirements are based on the on ground measurements list specified in the S4-UVN requirement specification. This is a comprehensive list of measurements established by ESA based on past experience from similar missions like SCIAMACHY, OMI, GOME & GOME 2. This list is provided in **Table 2**. The on-ground measurements list is completed with requirements related to specific characterizations of the instrument such as straylight, Instrument Spectral Response Function (ISRF), absolute radiometry traceability, …

Table 2: list of the instrument parameters that shall be calibrated on-ground with sufficient accuracy to meet all requirements on the accuracy of the level 1b data products.

Number	Parameter
1.	**Detection chain**
1.1	Dark current as a function of detector temperature
1.2	Pixel-to-pixel dependent non-linearity response
1.3	Detector read-out noise
1.4	Detector Pixel-to-pixel Response Non-Uniformity (PRNU)
1.5	Detector Pixel-to-pixel Dark Signal Non-Uniformity (DSNU)
1.6	Memory effect

1.7	Pixel cross-talk calibration
1.8	Detector bad and dead pixel list
1.9	Detector Random Telegraph Signal (RTS) pixel list
1.10	Electronics offset correction (dynamic and theoretical)
1.11	Detector smear
1.12	Electronic conversion
1.13	Electronics stability in time (short term and long term)
1.14	Characterisation / quantification of binning and temporal oversampling effects
1.15	Fixed pattern noise
1.16	Quantum efficiency
1.17	Detector (chain) non-linearity
2.	**Spectral**
2.1	Spectral calibration in vacuum wavelengths
2.2	Spectral slit functions
2.3	Spectral slit functions optical bench temperature dependence
2.4	Spectral resolution
2.5	Spectral resolution optical bench temperature dependence
2.6	Spectral calibration optical bench temperature dependence
2.7	Spectral slit functions for non-uniform illumination of the spectrometer slit
2.8	Spectral smile assignment
3.	**Radiometric**
3.1	Absolute radiance calibration
3.2	Swath angle dependence calibration radiance
3.3	Absolute irradiance calibration
3.4	Swath angle dependence calibration irradiance
3.5	Instrument BSDF calibration
3.6	Swath angle dependence calibration BSDF
3.7	Spectrometer entrance slit irregularity correction calibration
3.8	Calibration data of all radiance standards used in the on-ground instrument calibration
3.9	Calibration data of all irradiance standards used in the on-ground instrument calibration
3.10	Transmission of the thermal-vacuum chamber windows over the applicable wavelength range
3.11	Absolute radiance calibration optical bench temperature dependence
3.12	Absolute irradiance calibration optical bench temperature dependence

3.13	Instrument BSDF calibration optical bench temperature dependence
3.14	BSDF of on-board bare diffusers for sufficient angle combinations
3.15	Irradiance goniometry
3.16	Smear effect for non-uniform illumination
3.17	Radiometric correction for non-uniform illumination of the spectrometer slit
4.	**Geometric**
4.1	Sun port azimuth range (season)
4.2	Sun port elevation range (orbit)
4.3	Instrument alignment of elevation and azimuth angles (normal of diffuser) with respect to IAC (Instrument Alignment Cube)
4.4	Instantaneous Line Of Sight (ILOS) azimuth (cross-scan direction) with respect to IAC
4.5	Instantaneous Line Of Sight (ILOS) elevation (scan direction) with respect to IAC
4.6	Instantaneous Field Of View (IFOV) and PSF in scan direction
4.7	Instantaneous Field Of View (IFOV) and PSF in cross-scan direction
4.8	Intra-band spatial co-registration
4.9	Inter-band spatial co-registration
4.10	Spatial slit function response (cross-scan direction)
4.11	Instrument alignment from boresight to mechanical datum
4.12	Instrument alignment knowledge from pixel Line Of Sight (LOS) to IAC (Instrument Alignment Cube)
4.13	Quantification of viewing properties of the polarisation scrambler
4.14	Solar zenith angle
5.	**Other**
5.1	Spectral features of all on-board diffusers
5.2	Spectral features of polarisation scrambler
5.3	Radiometric stability assessment / monitoring.
5.4	Spatial and spectral straylight calibration (incl. BSDF/BTDF of flight optical/mechanical components)
5.5	Polarisation characterisation

The C&C campaign logic is such that in advance to the calibration phase, directly after the TB/TV phase, a series of Performance Verification measurements (occurring during the so-called debugging phase) are being performed on one hand as instrument and OGSE health check and on the other hand to ensure that the anticipated L0 instrument performances (for instance polarization sensitivity) are as expected. From this point in time the instrument configuration is frozen (i.e. no possible change in configuration anymore unless all acquired Calibration Key Data will have to be measured again) and the start of the calibration with the generation of the corresponding instrument key data is kicked off.

This paper describes the performance verification and calibration measurement program, its rationale and presents preliminary results from the S4-UVN PFM C&C campaign.

2. S4-UVN CALIBRATION

The instrument calibration and level-0 to level-1b data processing can be separated into three main categories: radiometric calibration, spectral calibration and geometric characterisation.

The radiometric calibration includes all parameters that play a role for calibrating the instrument signal binary units into radiometrically calibrated radiances (in photons/(s.nm.cm^2.sr)) and irradiances (in photons/(s.nm.cm^2)). In turn, this includes all optical effects (radiometric throughput, gratings, stray light), detector effects and electronic effects. The radiometric calibration also includes the Earth reflectance calibration via the so-called instrument Bi-directional Scattering Distribution Function (BSDF) that radiometrically calibrates the earth radiances observed in orbit with respect to the on-board diffusers used for sun irradiance observations.

The spectral calibration transfers the detector pixel data into wavelengths and calibrates the Instrument Spectral Response Functions that are essential for spectral calibration and for L1b-L2 data processing.

The geometric characterisation encompasses amongst others the co-registration, the spatial resolution and the geolocation, which attaches geolocations on the earth to the observed ground samples and provides all required angular information for the illumination conditions that can in turn have an impact on the radiometric calibration; these will include satellite position and pointing, landmarks and preliminary spatial sample classification (e.g. land/water/cloud mask).

The following sections are addressing these different aspects separately, with special emphasis of the S4-UVN key calibration measurements: absolute and relative radiometry, straylight, polarisation, detection chain, spectral calibration and instrument spectral response function, Point spread function, integrated energy and co-registration.

2.1 Radiometric calibration

The radiometric calibration includes the calibration of the radiometric goniometries for Earth radiance and sun irradiance measurements prior to launch with an accuracy that is compliant with the in-flight absolute radiometric accuracy requirements of the Earth spectral radiance, on absolute irradiance and absolute Earth reflectance, and the relative viewing angle dependencies thereof. The viewing properties of the instrument (i.e. lines of sight, fields of view, intra-channel co-alignment and inter-channel co-alignment) will be included, as well as the illumination angles of the diffusers, in the calibration prior to launch to accuracies that are compliant to the in-flight accuracy requirements of these viewing properties. The absolute radiometric radiance and irradiance are traceable to primary radiometric standards used during on-ground calibration.

The radiometric requirements of S4-UVN are per nature difficult to achieve. For instance the instrument response in Earth observation mode shall be calibrated on the ground to an accuracy better than 1.0% and the instrument response in sun calibration mode shall be calibrated on-ground to an accuracy better than 0.8% (all values apply on a one sigma confidence level).

Based on experience from previous similar instrument calibrations, in order to meet such demanding requirements it is required to combine the results of the measurements obtained with different illumination sources (Optical Ground Support Equipment - OGSE) in order to increase the accuracy of the calibration keydata and in order to minimize errors originating from peculiarities associated with each illumination source, such as light flux level, distance to instrument, homogeneity of illumination, generated straylight, representativeness of in-orbit illumination, temporal stability, polarization, absolute radiometric calibration status. Each of these parameters contributes to the overall error for that specific illumination source, and by combining the results from different sources the final errors can be reduced considerably. In order to achieve this target, it is necessary to properly commission the different light sources and perform measurements where the radiometric dependencies on the parameter that is varied are investigated. For this purpose the following set of OGSE is used in combination for the radiometric calibration measurements (see **Table 3 and 4**). In accordance with this approach the absolute radiometric calibrations and their angular dependencies are calibrated separately.

The used OGSE are designed to optimally calibrate both the absolute Earth radiance and sun irradiance, as well as calibrate the Earth reflectance via the instrument Bi-directional Scattering Distribution Function (BSDF). The requirements on the instrument BSDF (reflectance) are most stringent, because the earth reflectance is used for most of the L1b-L2 data processing algorithms, and a number of error contributions in radiance and irradiance absolute radiometric calibrations cancel in the instrument BSDF / earth reflectance.

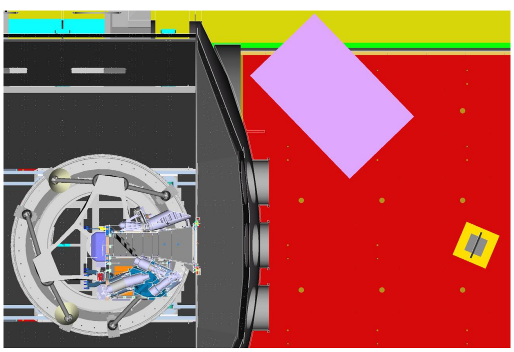
Table 3: OGSE used during Radiometric measurements.

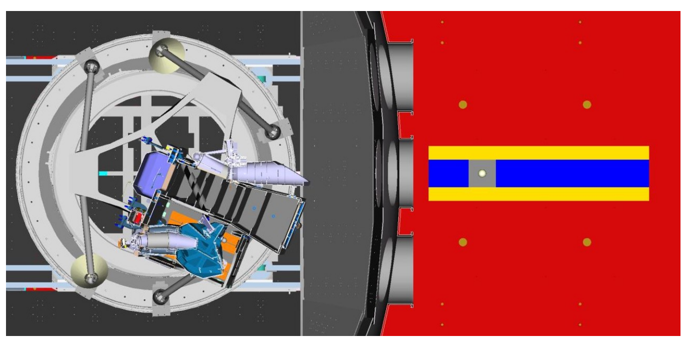
OGSE	Earth Radiance mode	Solar Irradiance mode
FEL lamp	1R	1I
Sun Beam Simulator - SBS	2R	2I
Integrating sphere - ISP	3R	3I

Table 4: Radiometric measurements and their objectives.

Key Data	Measurement	Objectives
BSDF	2I/2R	Instrument BSDF with SBS, expected most accurate result for instrument BSDF due to optimal illumination and optimal signal levels for SBS radiance and SBS irradiance measurements.
Refl_FEL	1I/1R	Analysis result from measurement expected to be less good due to non-optimal FEL lamp illumination.
Abs-Rad	1R	Calibration Key Data (expected to be the most accurate key parameter to be used for 0 to 1 processing).
Abs_Irrad	Abs_Rad x BSDF	Best (expected to be the most accurate key parameter to be used for 0 to 1 processing)
Abs_Irrad_FEL	1I	Analysis result from measurement expected to be less good due to non-optimal FEL lamp illumination and low signals in UV.
Ang_dept_sphere	3R	Radiance angular dependence.
Refl_sphere	3I/3R	Instrument BSDF with ISP, low signals in UV.
Abs_Rad_2	3R	Radiance angular dependency + Calibration Key Data (to be used in 0 to 1 processing in case more accurate than Abs_Rad).
Abs_Irrad_2	Abs_Rad_2 x BSDF	Calibration Key Data (to be used in 0 to 1 processing in case more accurate than Abs_Irrad).

Examples of the implemented OGSE measurements configurations are presented in **Figure 4.**





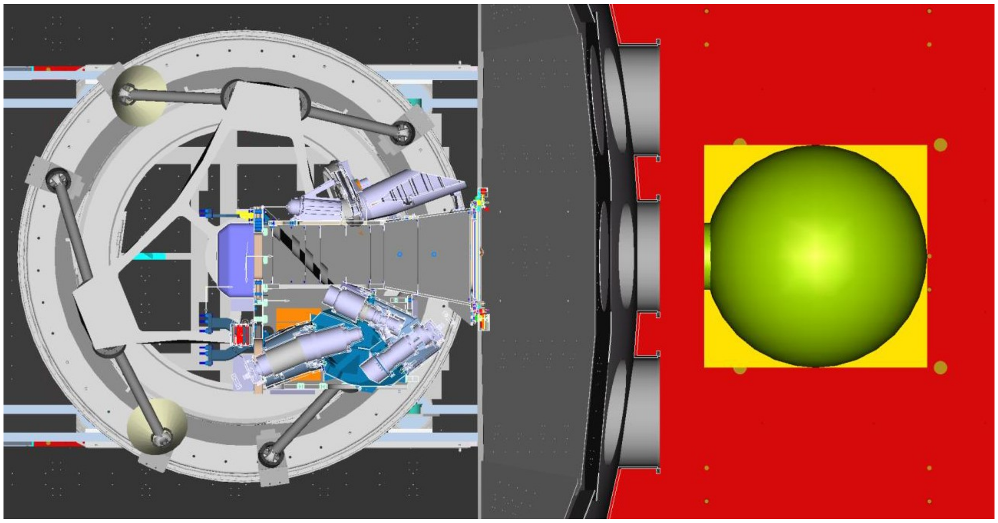


Fig. 4: **Top Left** Sun Beam Simulator (SBS) [pink] + OGSE diffuser [yellow] on the Earth port (configuration 2R). **Top Right**: FEL lamp [yellow/blue] in front of the sun port configuration layout (configuration 1I). **Bottom:** Integrating Sphere (ISP) [green] on the Earth port configuration (configuration 3R).

Fig. 5 presents the preliminary results for the ISP measurements during the debugging phase for Abs_Rad_2 (config 3R) and Refl_sphere (config. 3I/3R).

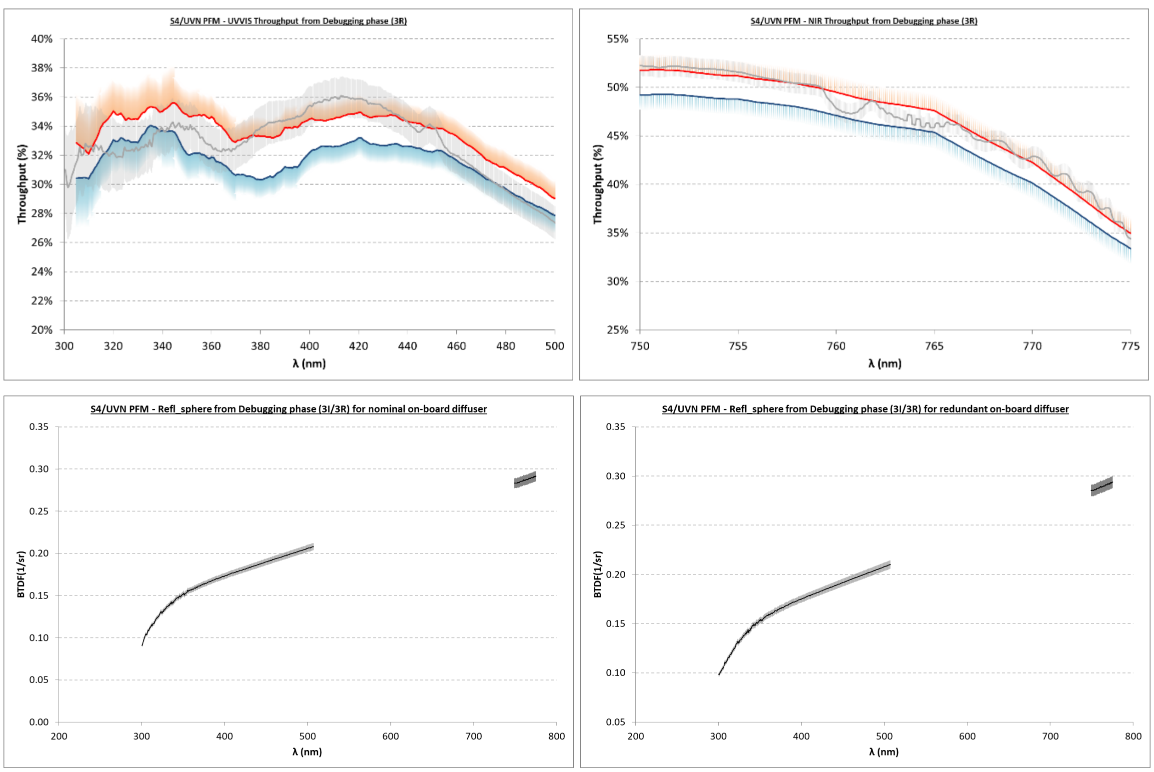


Fig. 5: Top Preliminary Abs_Rad_2 from debugging phase (ISP) [gray] + MIN [blue] + MAX [red] predictions on the Earth port (config 3R) **Left**: UVVIS channel / **Right**: NIR channel. **Bottom**: Preliminary Refl_sphere from debugging phase (ISP) [black] (config 3I/3R). **Left**: Nominal on-board-diffuser / **Right**: Redundant on-board diffuser. All preliminary measurements from the debugging phase lie within the predictions accounting for the measurement precision.

Straylight:

Spectral stray light, spatial stray light and combinations thereof are being considered. The spectral stray light calibration extends beyond the optical channel boundaries. For the UV-VIS-NIR source wavelengths in the range from 300 to 1100 nm are considered due to the sensitivity of the detectors in this wavelength range. The accuracy of the pre-launch stray light calibration shall be compliant to the pre-launch accuracy requirements of absolute radiance, absolute irradiance and absolute Earth reflectance, as well as to the absolute radiance, irradiance and reflectance radiometric accuracy requirements for the level 1b data in-orbit. Stray light contributions from inside the instrument field of view and from outside the field of view are considered. For internal stray light the effects from near-field stray light (the area where the spectral and spatial response functions go over into stray light) and far-field stray light are considered. Far-field stray light can be separated into uniform stray light (over spectral and/or spatial pixels) and ghost-type stray light (localised at certain groups of spectral or spatial pixels). For the Sentinel-4/UVN instrument stray light is particularly challenging for the wavelength regions below 320 nm and around 760 nm, due to the low Earth radiance signals originating from ozone and O_2 A-band, respectively, and for unclouded ground scenes with low albedos (<5%), which may collect significant fractions of spectral spatial stray light from clouded ground scenes observed at the same time on the CCD detectors at other wavelengths and viewing positions. On the other hand, the above areas are also the ones that are most interesting from a data usage perspective for tropospheric ozone and NO_2 and cloud and aerosol information from the O_2 A-band spectral region, underlining the importance of proper and sufficient stray light reduction in the level-1b data.

Different measurement approaches and OGSE use for on-ground calibration and keydata generation for the uniform and ghost straylight correction are considered. The rationale of these various measurements and their implementation is explained below:

- "ISRF-type straylight measurements": these illuminate 2 times [each] half of the slit height (lower-edge, upper-edge). They are made for a limited number of spectral points, with very long integration times. These measurements are covered by the monochromatic variable light source (VLS, a laser) with the collimation optics (COL) flat field illumination imaged on half the slit.
- "monochromatic point-source measurements": these illuminate the full slit width and ~2 spatial pixels with a laser. They are made for a limited number of (spectral, spatial) grid points, with very long integration times. These small kernel measurements will be performed with the straylight optic (SLO).

Additional measurements types are also envisaged for characterization/verification of straylight following the knowledge obtained during the projects evolution.

5-Reflection (5R) ghost measurements: The 5R ghost in NIR was identified via optical simulation and its presence was confirmed in the frame of the lower level Telescope-Spectrometer-Assembly (TSA) optical test. Three dedicated straylight measurements are planned to fully characterize it:

- Monochromatic light source with full slit illumination, where the wavelength is scanned over a range of wavelengths to determine the central wavelength of the 5R ghost peak.
- Monochromatic light source with half slit illumination at the central wavelength of the 5R ghost for field dependence measurement
- As alternative light source to the VLS, two band-pass filters are implemented into the Filter Light Source (FLS). With this light source the spectral resolution is not as good as with the VLS. These calibration measurements are essential to inject more photons into the instrument to assess the accuracy of the 0-1b stray light corrections and stray light key data.

Out of field straylight characterization measurements: although the out of field straylight is not planned to be corrected the following measurements for characterization are planned.

- Monochromatic light and white light source with flat field illumination, where the object target is scanned across the instruments slit in E/W direction in a step and stare mode.

Near slit straylight feature measurements: a characterization of the near slit straylight features is foreseen to measure the illumination dependence of the features observed in the vicinity of the instrument slit (See **fig 6**)

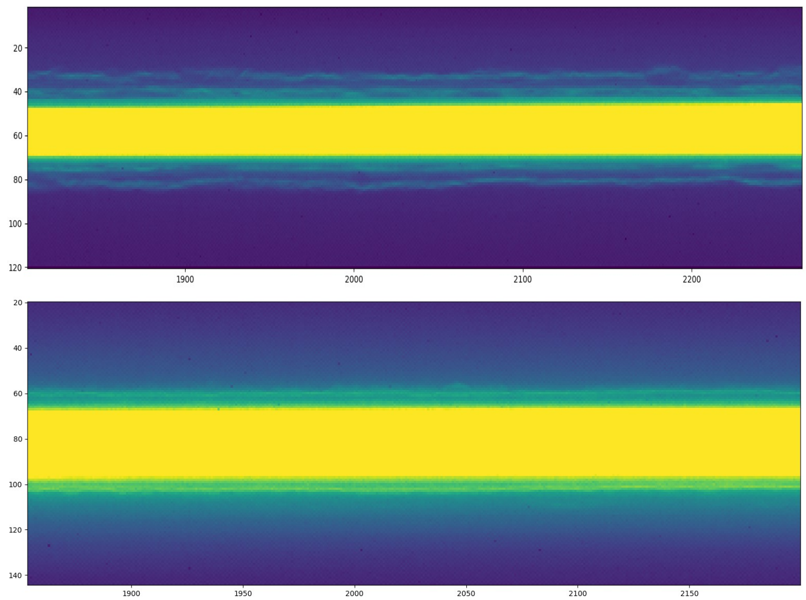


Fig. 6: Short range slit straylight observed during the lower level TSA measurements **Top** UVVIS full slit zoom/rescaled. **Bottom**: NIR slit zoomed/rescaled

- Monochromatic illumination in flat field of half the entrance slit in E/W, thus illuminating only one of the slit edges.

In addition to these measurements that are mandatory based on the current status of analysis and instrument testing, there are a few measurements additionally planned for straylight characterisation and end to end performance verification:

- A “white light point source” stimulus. Here a polychromatic (white light) input illuminates a few pixels in the spatial direction to detect spatial ghost straylight.
- A "broad-band source" stimulus illuminating the full slit, with spectral band pass filters used to limit the spectral bandwidth. These measurements are not used to derive straylight calibration key parameters, but to verify the correctness and completeness of the straylight calibration parameters derived from the above measurements, as well as to check the correctness and completeness of the correction algorithm. These measurements will support the end to end performance verification of the instrument.
- A combination of the above, i.e. a “broad-band point source” where filters are used in addition to the Continuous Light Source (CLS) to limit the spectral bandwidth.
- A monochromatic partial slit illumination with the SLO optics, where 30 spatial pixels are illuminated. This measurement is similar to the one with a monochromatic half slit measurements for large kernel retrieval, however using the SLO optics. It allows achieving a better SNR while constraining the illumination region to a (larger) spot.

<u>Detection chain:</u>

A complete on-ground calibration of detector properties and electronic properties will be performed. The parameters that are of relevance for the Sentinel-4/UVN instrument are listed in **Table 2**. Detector exposure smear will be calibrated for non-homogeneous illumination of the spectrometer’s entrance slit.

Polarization

The instrument's polarization sensitivity is required to be less than 1% at level-0, also because the 0-1b data processing doesn't foresee radiometric correction steps for polarization. In the instrument design this is realized using a weak polarization scrambler and transmission optics, in combination with small incidence angles for the geostationary mission. The focus of the dedicated on-ground polarization measurements will be to show compliance to this requirement and characterize remaining polarization spectral features.

Spectral features originating in the instrument, e.g. from the on-board diffusers as observed in predecessors missions, as well as the above mentioned remaining polarization spectral features, may hamper the analysis of atmospheric trace gases in the L1b-L2 data processing. These features have as much as possible to be eliminated by the instrument design since correction of the polarization spectral features based on an unknown polarization state of the Earth light is not possible with the Sentinel-4 UVN design. The relative spectral radiometric accuracy (peak-to-peak) are considering small spectral window widths of a couple of nanometers, which for compliance of the requirement incorporate these spectral features next to other relevant errors for the instrument response in sun irradiance and Earth radiance observation modes, as well as for Earth reflectance (ratio radiance over irradiance). As example, in the UVVIS between 315 and 500 nm, the maximum relative radiometric spectral accuracy error over a spectral window width of 3 nm is required to be smaller than 0.05%.

In order to characterize the PFM polarization (sensitivity and polarization spectral features), two types of measurements are implemented with the Polarization (POL) OGSE:

- The measurement focused on the verification of the polarization sensitivity of the Instrument (below 1%). The verification is performed with the so-called Polarization Optics (POL) used with the Continuum Light source. The test is performed by rotating the polarization state at the exit of the Polarization Optics. The full spectral range of the Instrument is covered in one measurement for each polarization state with the use of the Continuous Light Source (CLS). This measurement is mainly limited by the stability and knowledge accuracy of the CLS with the POL optics during rotation. **Fig. 7** presents the first preliminary polarization sensitivity results for 3 North/South measurement sets covering the ±2° Field of View

- Instrument polarization data (relative Müller matrix elements) are needed as Calibration Key Data for mitigation at Level-2 by co-fitting dedicated pseudo-absorbers. To determine the Müller-Matrix elements polarization measurement using monochromatic laser light with the POL OGSE are used. These are the dedicated measurement to perform a check on the polarization spectral feature contribution to the relative spectral radiometric accuracy.

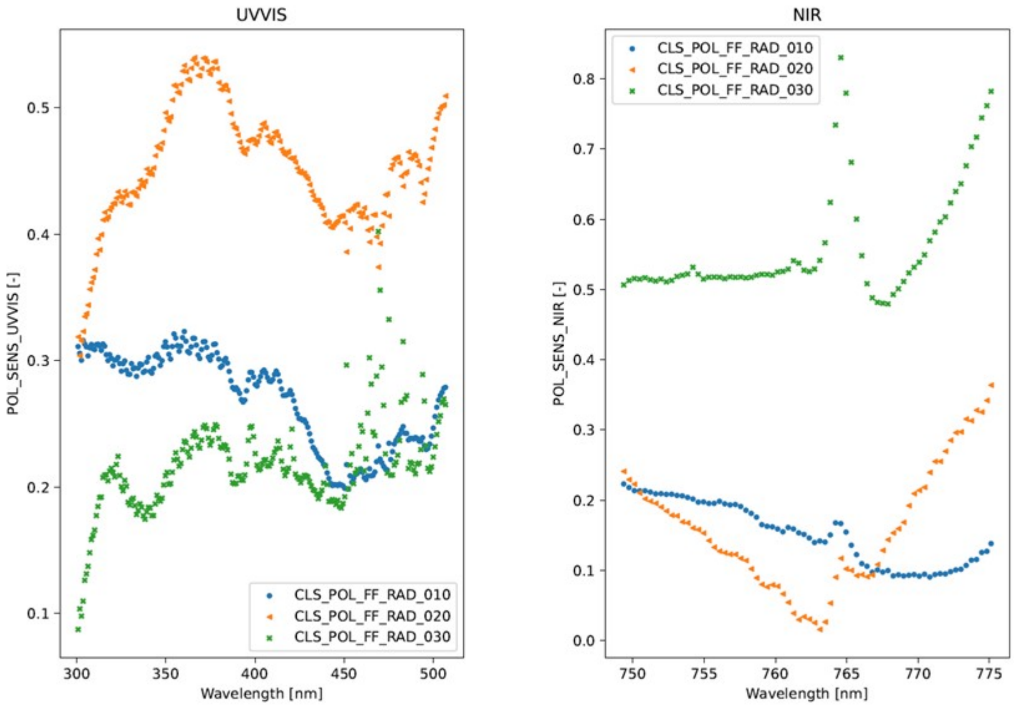


Fig. 7: Polarization sensitivity in UVVIS and NIR bands (preliminary results). The achieved polarization sensitivity is well below the specified 1%. Note: the feature in NIR around 765nm is an artefact. Assumption is that it is caused by imperfection in compensation of signal variation.

2.2 Spectral calibration

On-ground Spectral calibration will be performed with dedicated spectral calibration sources and in flight with the knowledge of the solar Fraunhofer lines and the atmospheric absorption lines. The spectral calibration will also be checked for its dependence to non-homogeneous illumination of the instrument's entrance slit (in east-west scan direction): inhomogeneously illuminating the instrument entrance slits will introduce a shape change of the spectral response function, which may in turn introduce an apparent spectral shift of the observed spectral absorption lines in the spectra. In addition, the spectral response function (spectral slit function) of the instrument will be calibrated on the ground. The spectral response functions are used to establish the spectral resolution and for the spectral calibration algorithms in the level-0 to level-1b data processing, as well as for the level-1b to level-2 data retrievals. Most of the level-1b to level-2 data retrievals convolve high-resolution absorption cross section spectra of the atmospheric constituents with the spectral response functions, that have been calibrated accurately prior to launch. The convolved spectra are then compared and fitted to the measured spectra in order to retrieve the atmospheric constituent concentrations. The instrument spectral response functions (ISRF) are thus essential for the accuracy of the level-1b to level-2 data processing and the accuracy of the level-2 data products. For accurate calibration of the spectral response functions a tuneable monochromatic light sources such as a wavelength-tuneable laser can be used.

The spectral calibration comprises the following measurements:

- The ISRF measurement is performed with a tuneable laser with sub S4/UVN spectral pixel step size. During this measurement, the slit is fully illuminated along its spatial direction by this monochromatic tuneable light.

Therefore, the ISRF is measured for all the N/S angles simultaneously. The minimum step size is less than one 30th of the S4-UVN spectral resolution. The ISRF will be measured for three geometries.

- Homogeneous ISRFs on the radiance port by tuning the wavelength over the full spectral range of S4 by steps with a 1/10th of a pixel
- Homogeneous ISRFs on the irradiance port at selected wavelengths to cross check the consistency with the radiance measurements.
- ISRFs for non-homogeneous scenes performed with a thin-slit OGSE.

Fig 8 present a first overview of the ISRF measurements for homogeneous scene and for the radiance port.

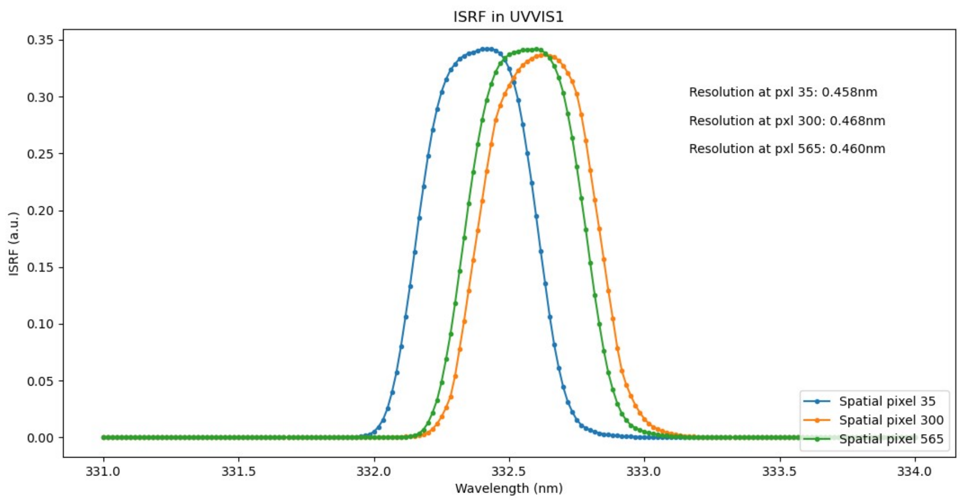


Fig. 8: ISRF in UVVIS1 band (preliminary results before post-processing)

- The Spectral calibration describes the derivation of the central wavelengths of each detector pixel. During the on ground campaign there are two options to perform this calibration.
  - One is relying on the same measurements as the ones for the ISRFs as the wavelength of the isolated (I)VLS is absolutely known with its internal wavemeter.
  - The other light source implemented in the OGSE is a PtCrNeAr lamp, which produces several atomic lines with accurately known wavelengths in the S4 instrument spectral bands.

2.3 Geometric calibration

The orientation of the instrument's 3-axis reference frame with respect to the spacecraft's 3-axis reference frame will be calibrated prior to launch, as this is required for the latitude/longitude geolocation of the observed scenes. This will allow calibrating the relevant instrument geometrical parameters (lines of sight, pixel fields of view, angles on the on-board diffusers) with respect to the instrument alignment cube. The translation to the spacecraft reference frame will then be made via the above relative orientation calibration between the spacecraft and instrument reference frames.

The geometric calibration and characterization includes the derivation of the system's PSF. Furthermore, besides the intraband co-registration characterization for performance verification purposes (within UVVIS band and within NIR band) the optimized setting of the S4-UVN co-registration offset compensator will be determined and optimized for the UVVIS-NIR interband coregistration. The co-registration offset compensator is a thermally driven method to shift the image on the NIR detector in the N/S direction within one N/S pixel range in order to align its offset with respect to the

one of the image on the UVVIS detector. This is one of the first measurements during the on ground campaign in order to perform all other calibration and characterization measurements with this optimized setting.
Additionally, the relative Pixel Line Of Sight (PLOS) map will be measured. This is the angular distance both, the E/W and N/S center positions between two arbitrary detector pixels. These center position(s) (could be more than one, depending on the polarization scrambler performance) will additionally determine the relative line of sight (LOS) calibrations per detector pixel, as well as the co-registration between the various detector pixels, because the measurements will be performed with white light illumination in parallel beams. The width will also determine the spatial resolution and the width and the shape combined will be essential inputs to the integrated energy assessment. The measurement is similar to the star measurements. One or more point sources are scanned across the instrument's slit in E/W direction. This scanning is performed on ground in a step and stare fashion. A similar sequence is then performed with the point sources centered in the slit and scanned in N/S direction with sub-pixel steps. This measurement sequence will be performed with an unpolarized OGSE white light beam. Even though the polarization scrambler is expected to result in different PSF measurement parameters depending on the input polarization direction, it is assumed that this will not play an important role for the level 0 to 1b and 1-2 data processing or for the performance of the instrument.

3. CONCLUSION

This paper provides an overview of the requirements for the Sentinel-4/UVN instrument embarked on the geostationary Meteosat Third Generation Satellites, with special emphasis on the on-ground calibration requirements. The demanding instrument performance verification and calibration requirements and measurements, due to the high temporal and high spatial resolution, to continuously monitor the earth's atmosphere above Europe and northern Africa, are discussed.

Furthermore, this paper is presenting the key measurements objectives as well as implementation of the S4-UVN PFM Calibration and Characterization campaign.

At the time this paper is written the first block of measurements (debugging including the instrument polarization characterization) is completed and the spectral measurements (ISRF in uniform and non-uniform scene) are on-going.

REFERENCES

[1] Ahlers, B., Bazalgette Courrèges-Lacoste, G. Guldimann, B., Stark, H., Dobber, M., "GMES Sentinel-4/UVN instrument concept and calibration approach", 20th CALCON Technical Conference.
[2] Riedl, S., Harlande, M., Schlosser, C., Kolm, M., Maurer, R., Bazalgette Courrèges-Lacoste, G., Pachot, C., Ahlers, B., Grabarnik, S., Gambicorti, L., Sallusti. M., Bulsa, G., Bagnasco, G., M., "Sentinel-4 UVN - A Geostationary Imaging UVN Spectrometer for Air Quality Monitoring - Performance, Measurement Modes and Model Philosophy", Conference: International Conference on Space Optics - ICSO 2018.
[3] Ahlers, B. et al. "In-orbit detection of spectral features in SCIAMACHY", Proc. SPIE 5570, 401, 2004.
[4] Lichtenberg, G. et al. "SCIAMACHY Level 1 data: calibration concept and in-flight calibration", Atmos. Chem. Phys., 6, 5347-5367, 2006.
[5] Dobber, M.R. et al. "Ozone monitoring instrument calibration" IEEE Trans. Geo. Rem. Sens., Vol. 44, no. 5, 1209-1238, May 2006.
[6] Dobber, M.R. et al. "EOS-Aura Ozone Monitoring Instrument in-flight performance and calibration", SPIE Proceedings, Optics and Photonics (vol. 6296), 2006.
[7] Callies, J., Corpaccioli, E., Eisinger, M., Hahne, A.,Lefebvre, A. ," GOME-2 – Metop's Second-Generation Sensor for Operational Ozone Monitoring", ESA bulletin 102 — May 2000.
[8] Kim, Jhoon et al. "New Era of Air Quality Monitoring from Space: Geostationary Environment Monitoring Spectrometer (GEMS)", Bulletin of the American Meteorological Society volume 101, issue 1, https://doi.org/10.1175/BAMS-D-18-0013.1, 2020.
[9] http://tempo.si.edu/index.html.