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## *Sentinel 4: a geostationary imaging UVN spectrometer for air quality monitoring: status of design, performance and development*

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## SENTINEL 4: A GEOSTATIONARY IMAGING UVN SPECTROMETER FOR AIR QUALITY MONITORING – STATUS OF DESIGN, PERFORMANCE AND DEVELOPMENT

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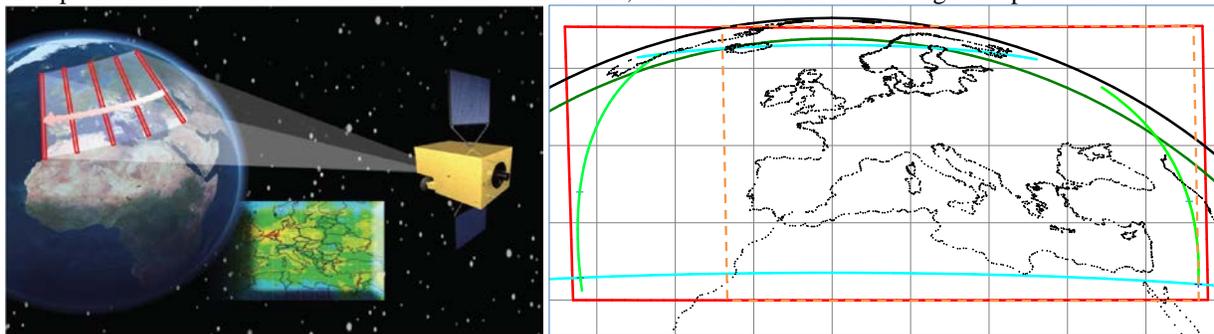
### I. INTRODUCTION

SENTINEL 4 is an imaging UVN (UV-VIS-NIR) spectrometer, developed by Airbus Defence and Space under ESA contract in the frame of the joint European Union (EU)/ESA COPERNICUS program. The mission objective is the operational monitoring of trace gas concentrations for atmospheric chemistry and climate applications. To this end SENTINEL 4 will provide accurate measurements of key atmospheric constituents such as ozone, nitrogen dioxide, sulfur dioxide, formaldehyde, as well as aerosol and cloud properties.

In the family of UVN spectrometers with space heritage (SCIAMACHY, OMI, GOME & GOME 2) and those currently under development (TROPOMI and SENTINEL 5), SENTINEL 4 is unique in being the first geostationary UVN mission. The SENTINEL 4 space segment will embark on EUMETSAT's Meteosat Third Generation Sounder satellite (MTG-S), sharing its platform with the MTG-S IRS instrument. For the period between 2021 and 2034 SENTINEL 4 will provide coverage of Europe and adjacent regions with a repeat cycle of 60 minutes and a spatial sampling of 8x8 km. This spatial coverage is achieved by push-broom continuous E/W-scanning of a N/S-oriented slit field-of-view (FOV) over an E/W field-of-regard of about 11°, see Fig. 1.

During Earth observation the SENTINEL 4 instrument will acquire continuous spectra of Earth radiance, using the sun as a light source illuminating the Earth, and covering the UV (305-400 nm), VIS (400-500 nm) and NIR (750-775 nm) spectral ranges. Additionally, SENTINEL 4 will provide a sun irradiance product with a sun measurement update frequency of 24 hours, which serves for calibration purposes and for determination of Earth reflectance. Furthermore, star measurements for geometric calibrations (absolute pointing & internal co-registration) of 15min to 2h duration will be performed in the early morning immediately before Earth observation, and in summer also immediately after Earth observation. Finally, the remaining night-period (4 to 6 hours) will be used for instrument-internal calibrations (dark-, White-Light-Source (WLS)-, LED light source- & detection-chain-calibrations, see also Table 2).

The main design and performance parameters of SENTINEL 4 are shown in Table 1. The key design-driving performances are Radiometric Accuracy (RA), chiefly Absolute RA & Relative Spectral RA, as well as Signal-to-Noise-Ratio (SNR). The specified RAs include straylight and polarization effects, as well as on-ground & in-flight radiometric calibration and algorithmic correction accuracies, and thereby drive all related subsystems and their performances. SNR is a driver for the instrument size, and for detection chain design and performances.



**Fig. 1.** Earth observation and scan concept of SENTINEL 4. The right hand picture shows Earth coverage from the geostationary SENTINEL 4 perspective. Green/turquoise lines indicate the borders of the specified Geo-Coverage area, which is the total area to be covered every day. The red rectangle represents the actual daily observation area covered by multiple E/W scans of the N/S-oriented slit FOV. The overall daily Earth observation pattern consists of a series of 1h-long East-to-West scans (“repeat cycles”) with a fast West-to-East retrace in-between. The orange dashed rectangle indicates the size of a 1h repeat cycle (Reference Coverage). Depending on the seasonally varying duration of Earth illumination by the sun, the daily Earth observation scan series consists of 16 (winter) to 20 (summer) 1h-scans. The first scan of a day starts at the eastern edge of the Geo-Coverage area. The 1h repeat cycle coverage is shifted westward in two steps during each day in order to follow the sun illumination and to achieve full Geo-Coverage.

**Table 1:** Main design and performance parameters of SENTINEL 4

| <b>Spectral</b>                             |  |                                  |   |
|---|--|----------------------------------|---|
| <b>Parameter</b>                            | <b>UV-VIS values</b>   | <b>NIR values</b>                | <b>Comments</b>   |
| 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                        |   |
| <b>Geometric and Temporal Coverage</b>      |  |                                  |   |
| <b>Parameter</b>                            | <b>Value(s)</b>  |                                  | <b>Comments</b>   |
| 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 <sub>EW</sub> *1.13SSD <sub>NS</sub><br>90% over 1.72SSD <sub>EW</sub> *1.72SSD <sub>NS</sub> |                                  | Integrated energy is a measure for the spatial resolution of the instrument                         |
| N/S slit FOV (swath)                        | 4.0°   |                                  |   |
| E/W coverage & Repeat cycle                 | See Fig. 1   |                                  | See Fig. 1  |
| Daily Earth observation time                | Summer max: 01:40 – 21:40<br>Winter min: 03:40 – 19:40   |                                  | Adjusted to seasonally varying solar Earth illumination on monthly basis                            |
| Spatial co-registration                     | Intra-detector: 10% of SSD<br>Inter-detector: 20% of SSD   |                                  | 2-dimensional (E/W & N/S) absolute co-registration  |
| <b>Radiometric</b>                          |  |                                  |   |
| <b>Parameter</b>                            | <b>UV-VIS values</b>   | <b>NIR values</b>                | <b>Comments</b>   |
| Optical Throughput                          | ~50% (in UV)   | ~60%                             | End-to-end scanner-to-detector  |
| Radiometric Aperture                        | 70 mm  | 44 mm                            | Circular diameter   |
| Earth SNR                                   | UV: >160<br>VIS: >1600   | 759-770nm: >90<br>Rest NIR: >600 | For specified Earth radiance reference scene  |
| Earth Absolute RA                           | < 2%   | < 2%                             | For Earth radiance & reflectance  |
| Sun Absolute RA                             | < 2%   | < 2%                             | For sun irradiance  |
| Polarization Sensitivity                    | < 1%   | < 1%                             |   |
| Polarization spectral features              | < 0.042%   | < 0.076%                         |   |
| Sun diffuser spectral features              | < 0.015%   | < 0.1%                           | Caused by speckle effect  |

The term “spectral features” is used here synonymously for the so-called short range Relative Spectral RA, which again is defined as the peak-to-valley relative variation of the radiometric error (caused by a given effect, such as polarization sensitivity), over any spectral window of 3 nm (UVVIS), respectively 7.5 nm (NIR) width.

There are also many specific pointing and scan accuracy and stability requirements not explicitly listed in Table 1, which are main drivers for the scanner subsystem and for the instrument thermo-mechanical design.

This paper gives an overview of the SENTINEL 4 system<sup>1</sup> architecture, its design & development status, current performances and the key technological challenges.

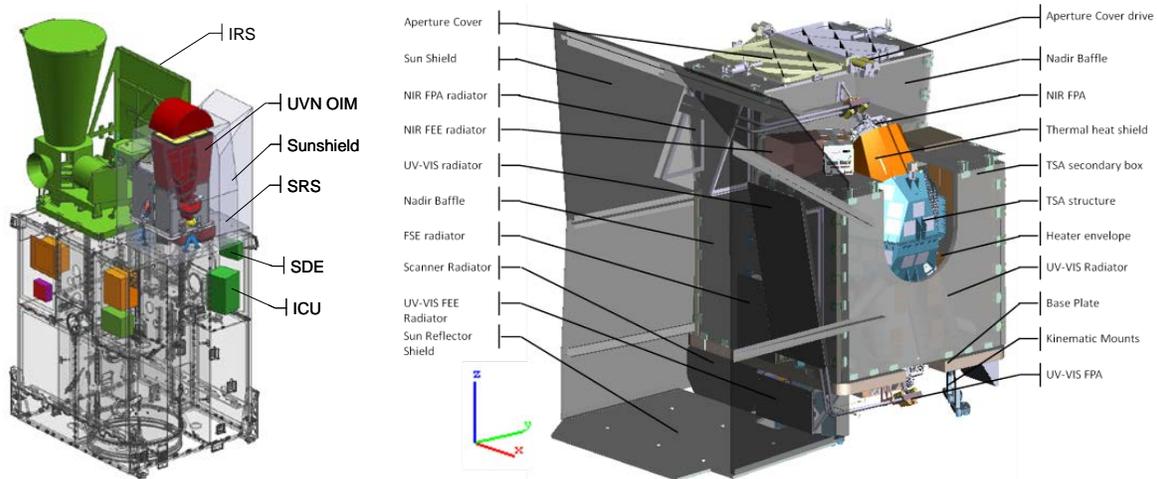
## II. INSTRUMENT DESIGN

### A. Overall Instrument Design

As shown in Fig. 2 the SENTINEL 4 flight H/W consists of an Optical Instrument Module (OIM) and a sunshield, placed on the Nadir panel of the MTG-S platform, as well as two pieces of electronic H/W, the Instrument Control Unit (ICU) and the Scanner Drive Electronics (SDE), which are placed inside the satellite and are connected to the instrument by a dedicated harness.

The OIM, with a cross-section as shown in Fig. 3 (Left), has two main view ports which can be selected with a scan mirror: an Earth observation view port and the Calibration Assembly (CAA) view port, the latter being used for both sun viewing and White-Light-Source (WLS) viewing. A single two-axis scan mirror is used for two purposes: 1) to switch between CAA port and Earth port, and 2) to scan the Earth in E/W direction in the Earth observation mode. The Earth view consists of two sub-ports, because due to the bi-annual yaw flip manoeuvre of the MTG-S satellite, pointing towards the target Earth coverage area around Europe requires opposite orientation of the scanner N/S axis in summer and winter. For this reason the aperture cover mechanism has two flaps, a summer and a winter opening flap, which are adjacent in N/S direction.

<sup>1</sup> In this paper the term SENTINEL 4 **system** refers to the overall system comprised of instrument (flight) H/W & S/W, operations concepts, on-ground and in-flight calibration, L1b algorithms and processing, etc..

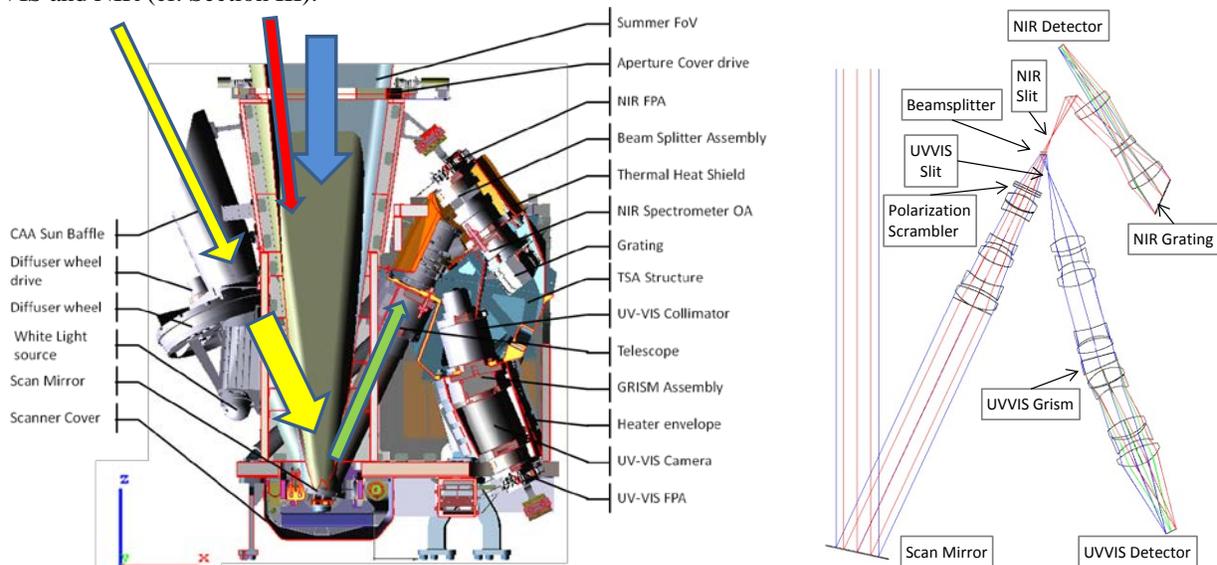


**Fig. 2. Left:** SENTINEL 4 configuration together with the IRS instrument on the MTG-S satellite. **Right:** SENTINEL 4 OIM from a radiator- and IRS-side perspective.

The CAA port also has two principal sub-viewing options, which can be selected by the setting of the diffuser wheel mechanism of the CAA. In the first setting the sun is observed through one of two selectable diffusers (“nominal” and “reference” diffuser). In the other setting the flat-field WLS is observed for instrument transmission & pixel response diagnostic purposes. Deep space, and in particular star viewing is enabled by extensions of the Nadir baffle clear FOV towards the East. This allows pointing the slit sufficiently far to the east such that the entire slit points beyond Earth to deep space. In summary the instrument has 3 external views: Earth (radiance) observation, star viewing (both through the same port), and Sun (irradiance) observation.

Next in the light path after the scan mirror comes the Telescope-Spectrograph-Assembly (TSA), which features a common telescope for all spectral bands, followed by a dichroic beam splitter combined with the slit assembly, which separates the NIR from the UV-VIS band(s). The UV and VIS bands are covered by a single spectrometer all the way down to the detector, respectively Focal Plane Assembly (FPA). The relatively narrow NIR band (750-775 nm) is also covered by a single spectrometer and detector/FPA.

The light of the UVVIS band is dispersed by a transmissive grism (combination of a transmissive grating and a prism) in the UV-VIS spectrometer, and by a reflective grating in the NIR spectrometer. The NIR grating assembly includes a thermally activated co-registration compensation mechanism, which allows fine tuning of the NIR detector image position in spatial (N/S) direction and thereby optimum N/S co-alignment between UV-VIS and NIR (cf. Section III).



**Fig. 3. Left:** SENTINEL 4 OIM in a cross-section parallel to the main optical plane. The blue arrow indicates the Earth radiance path, the yellow arrows the sun irradiance path, the red arrow the star viewing path.

The green arrow indicates the observation path from scanner towards the telescope, which is common to all viewings (Earth, sun, stars, WLS) and to all spectral bands (UV, VIS and NIR). **Right:** Core optics layout from the same perspective. The UV-VIS path is in blue, the NIR path in red.

The two FPAs feature CCD detectors acquiring the spectral channels in one direction and the spatial sampling in the orthogonal direction. In addition, each FPA includes a dedicated LED light source, which is optimized for homogeneous in-band illumination of the respective detector. These LED light sources integrated in the FPAs are used for calibration purposes (cf. Section III). The detector is the core element of the FPA where the detected light is converted into an analogue electrical signal and subsequently processed by the Front End Electronics (FEE) where the analogue signal is converted into digital data and sent via a ChannelLink interface to the instrument control unit (ICU). The ICU adds dedicated ancillary telemetry to the image data such that they are self-contained, avoiding the need to re-assemble the observation and telemetry data on ground. In addition, the ICU is responsible for operating and controlling the instrument in its various modes.

The instrument thermal design utilizes a concept based upon a combination of passive cooling and active (closed-loop) heater control for temperature stabilization. While the core optics will be maintained and controlled at 293 K, the CCDs will be operated at about 215 K, via passive cooling. In-orbit temperature stabilities (short- and long-term) on the order of 0.1-0.2 K of the key optical elements and the detectors are necessary and achieved, in order to fulfill the requisite radiometric, geometric and spectral accuracy specifications. This presents a major challenge for the instrument thermal architecture and control, taking into account the geo-stationary orbit with continuously varying sun illumination.

### B. Optical Design

The SENTINEL 4 core optical design is shown in Fig. 3 (Right). It consists of the following optical modules, designed to be independently manufactured and aligned: Scanner, Telescope Module (including beamsplitter & slits), UVVIS and NIR Spectrograph Modules. The main end-to-end performance parameters driving the optical architecture are polarization (pol. sensitivity, pol. spectral & spatial features), straylight and co-registration.

Since the system level spatial co-registration requirements are defined on an absolute and not on a knowledge accuracy basis, very good co-registration has to be achieved by design. For the optics design this means ultra-low optical distortion and also extremely good matching of the effective focal lengths of the UV-VIS and the NIR optical path.

The planar symmetry of the core optics, the on-axis lenses, and a general optimization for low angles of incidence (e.g. on scanner) and low angles of dispersion, allow achieving almost neutral polarization behavior by design. These optical architecture features are in part also enabling factors for the low optical distortion. Certain optical elements still inevitably have increased polarization sensitivity and spectral features (e.g. the grism), and therefore a depolarizing element, the polarization scrambler, is introduced before these elements in the optical path. The pre-optimization of the optical architecture towards low polarization effects has two advantages regarding this polarization scrambler: 1) The front optics, including scan mirror and telescope, features sufficiently low polarization effects that the scrambler can be introduced *after* these elements. This leads to a significantly smaller scrambler, which has great advantages in terms of manufacturability; 2) A rather weakly depolarizing scrambler, which is directly associated with a very small degradation of the optical point-spread-function (i.e. image quality), is sufficient for achieving the system level polarization requirements.

Another main optimization criterion of the optics design is the minimization of straylight: The main sources of straylight are scattering from surface roughness and particulate contamination, as well as ghosts. The term ghosts encompasses a variety of false light effects, such as multi-reflections from anti-reflection (AR)-coated surfaces, unwanted reflections from mechanical surfaces outside the nominal optical path (lens mounts, optical stops, baffles, etc.), and unwanted or multiple diffractions from the dispersers. All these straylight sources are mitigated by minimization of the number of optical elements. Furthermore, ghosts are suppressed by dedicated fine optimization of the optics design in all areas, e.g. spectrograph and disperser architectures, as well as by a sophisticated straylight baffling architecture, for example in the beamsplitter-slits-assembly and in the FPAs.

### C. Detection Chain

The UV-VIS and NIR detectors, which are developed by e2v (UK), are both frame-transfer CCDs featuring frame shift along the spectral direction (cf. Fig. 4). The NIR detector architecture is simpler, with a single frame, a single shift register and a single read-out port, while the UVVIS detector is divided into two spectral frames (effectively two individual CCDs), UVVIS1 and UVVIS2, with a frame split at about 340 nm. In addition, the UVVIS1 shift register has two read-out ports with different gain, the high gain being used for the low-signal spectral ranges below about 316 nm, and the low gain for wavelengths above. Furthermore, the UVVIS2 is divided into 4 individual shift registers and read-out ports. This architecture not only allows that the three main frames UVVIS1, UVVIS2 and NIR have individual gains, but also that their signal integration times can be individually adjusted. Thus optimum system SNR performance can be reached taking into account the particular spectral dynamics of the Earth radiance scenes. Furthermore, the frame periods of UVVIS1, UVVIS2 and NIR are set in multiples of the same time increment. This allows for a synchronized operation scheme (integration, frame transfer image-to-memory-zone, read-out) of the three main frames, which is used in all nominal SENTINEL 4 measurements.

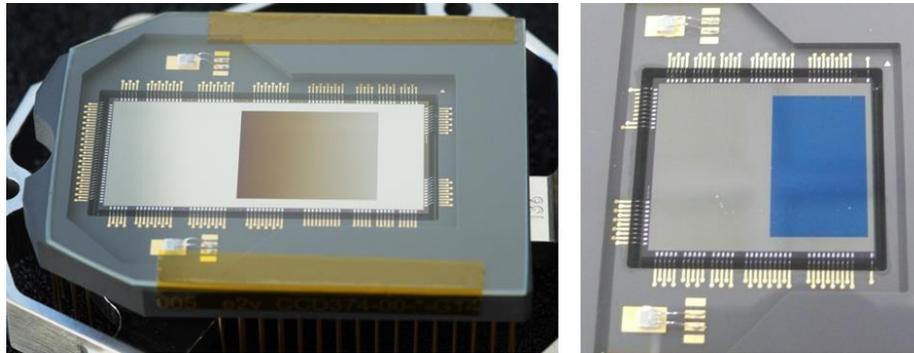


Fig. 4. Development models of the UV-VIS (left) and NIR (right) detectors

This synchronized UVVIS1-UVVIS2-NIR-sequencing avoids signal distortions by electro-magnetic-interference, which is mandatory in order to achieve the required radiometric performances, but this synchronization scheme is also a major challenge for the overall detection chain architecture and design.

### III. CALIBRATION CONCEPTS

The calibration of the SENTINEL 4 instrument is a key element to ensure that the specified performances are met and that high-quality processed data are provided to the users. In addition to the instrument H/W and its calibration, Airbus Defence and Space is developing under the SENTINEL 4 contract also the L1b processing algorithms and a L1b prototype processor, by which the calibration data are applied to the raw measurement data and the main L1b products (radiance, irradiance, spectral & geometric products) are established.

The main calibration sequences will take place in two different phases: on-ground and in-flight, during the instrument in-orbit commissioning and routine operation phases. The on-ground calibrations will be executed in a comprehensive characterization & calibration campaign at instrument level under representative thermal-vacuum conditions, which serves also for performance verification. The on-ground campaign will ensure that a fully calibrated instrument is provided at launch, whereas the in-flight activities will maintain the calibration of the instrument throughout lifetime, allowing to account for ageing effects, for example. The challenging instrument performance requirements also drive the design and performance of the Optical Ground Support Equipment (OGSE) to be used during the on-ground campaign.

Table 2 gives an overview of the calibration concepts of SENTINEL 4, whose two main aspects are: 1) "Calibration Measurement", which is the measurement used for the characterization of an effect, and 2) its associated "Correction Type" which refers to how the calibration measurement result is applied to scientific data (by the L1b algorithms) or to the instrument (for example, in case of co-registration compensation).

The absolute radiometric calibration of radiance (via the Earth port), irradiance (via the sun port) and reflectance (via relative measurements between the Earth and the sun port) that is performed on ground is the key element of radiometric calibration. To this end, several measurements are performed in a redundant way with various OGSE sources (traceable ANSI standard FEL lamps, Sun Beam Simulator, and a calibrated integrating sphere) and with dedicated Mechanical Ground Support Equipment, e.g. for the irradiance goniometry in which the dependence of the irradiance signal on the sun incidence angle is calibrated. The data obtained with all these measurements are combined in order to obtain calibration key data used to compute radiance and irradiance level 1b calibrated products. The Earth reflectance product is a combination of Earth radiance and sun irradiance measurement, and the on-ground radiometric calibrations are defined and combined in such a way that the Earth reflectance ratio can be computed with the best available accuracy.

The calibration and correction of straylight represent on one hand some of the most complex calibration measurements, and on the other the most complex correction algorithm of the SENTINEL 4 system. Despite the highly straylight-optimized optics design and optical components, the residual radiometric error caused by straylight still needs to be corrected to achieve the challenging required radiometric accuracies of the level 1b radiometric products. The level 0 straylight is extensively characterized on-ground with monochromatic, broadband and white light illumination of the full and partial slits. All these measurements are then combined to derive the straylight related calibration keydata used to correct simultaneously the spatial and the spectral straylight. A main challenge of this straylight calibration and correction is that the various straylight mechanisms, such as surface roughness-, particulate contamination- and ghost-straylight, which occur simultaneously and are physically very different, must all be properly characterized and corrected for.

In orbit SENTINEL 4 will make use of all external sources (sun, Earth and stars) to perform its calibration, but it will also strongly rely on its internal calibrations (WLS, LED, dark, offset, smear). The sun irradiance measurements with the nominal diffuser are used on a daily basis for radiometric calibration by monitoring the

throughput changes of the Earth radiance measurement path. Note that the same sun irradiance measurements also serve directly for the provision of a daily updated sun irradiance product, which allows the scientific user to translate Earth radiance data to Earth reflectance data. There are potential degradations of the nominal diffuser related to its daily use and the associated exposure to space radiation and molecular contamination in combination with UV light. In order to calibrate out such degradations, there is a second on-board diffuser, the reference diffuser, which is used less frequently and thereby less exposed to the radiation and contamination environment.

**Table 2:** Main calibrations and corrections of SENTINEL 4

| Calibration Measurement   | Correction Type  | Executed On-Ground or In-Flight? | For In-Flight Calibrations: Update Frequency |
|---|--|----------------------------------|--|
| Absolute radiometric calibration of radiance, irradiance, and reflectance (cf. main text)   | Level 1b processing algorithms for radiance, irradiance and reflectance  | O.-G.                            | -  |
| Straylight characterization   | Level 1b straylight correction algorithm   | O.-G.                            | -  |
| Instrument Spectral Response Function (ISRF) characterization   | N/A. This means the ISRF is directly a calibration product for the scientific user (L2 processing)   | O.-G.                            | -  |
| Spectral calibration on-ground based on OGSE (tunable laser & wavemeter, hollow cathode lamp).  | Attribution of a (center) wavelength to each spectral sample (pixel)   | O.-G.                            | -  |
| Pointing calibration vs. instrument alignment references (e.g. cubes)   | On-ground alignment when mounting the OIM onto the MTG-S platform  | O.-G.                            | -  |
| White-Light-Source (WLS)  | - Monitoring of Earth radiance path throughput<br>- Detector pixel response non-uniformity<br>- Flagging of degraded detector pixels   | O.-G. & I.-F.                    | weekly                                       |
| LED light sources   | - Correction of detection chain gain (non-linearity) curve<br>- Flagging of degraded detector pixels.  | O.-G. & I.-F.                    | daily  |
| Detector offset calibration. Offset pixels & lines are contained in every detector read-out (R/O)   | Level 1b processing algorithms: Subtraction of offset.   | O.-G. & I.-F.                    | continuously during every detector R/O       |
| Various types of dark measurements for background calibration and detector diagnostics  | Level 1b processing algorithms:<br>- Subtraction of dark.<br>- Flagging of degraded detector pixels.   | O.-G. & I.-F.                    | daily  |
| Detector smear calibration. Smear lines are contained in every detector R/O   | Level 1b smear correction algorithm  | O.-G. & I.-F.                    | continuously during every detector R/O       |
| Sun irradiance measurements via nominal diffuser  | Level 1b processing algorithms:<br>- Correction for instrument throughput changes (degradation).<br>- Spectral calibration (attribution of a wavelength to each spectral sample)<br>- ISRF monitoring (under investigation)    | I.-F.                            | daily  |
| Sun irradiance measurements via reference diffuser  | Same as for nominal diffuser (see one line above)  | I.-F.                            | monthly                                      |
| Star measurements<br>Two calibration parameters are extracted from star measurements:<br>1) co-reg. offset between UVVIS and NIR (morning and evening)<br>2) absolute pointing (morning only) | - Co-reg. offsets are fed back to the co-reg. compensators (cf. main text)<br>- Morning star measurements are processed into L1b star orientation and star brightness products which can be used to support the INR processing | I.-F.                            | daily  |
| Vicarious spectral calibration in-flight based on nominal Earth observation (radiance spectra) measurements.  | Level 1b spectral calibration algorithm, i.e. attribution of a (center) wavelength to each spectral sample (pixel)   | I.-F.                            | continuously during Earth observation        |

The present baseline is to use the reference diffuser once per month. This frequency could be adjusted based on the observed relative degradation between reference and nominal diffuser in orbit. The nominal and reference diffuser are identical in terms of design.

One result of the star measurements is the spatial co-registration offset between UVVIS and NIR in N/S- and in E/W-direction. These calibrated offsets are fed back to the co-registration compensation mechanism (N/S offset), and to the temporal sample co-addition pattern in the on-board processing (E/W offset), respectively.

The flagging of “degraded” detector pixels appears in Table 2 under several calibration measurements (dark, WLS, LED). This is because the term “degraded” refers to several types of pixel parameter degradations, namely to the individual identification of “dead”, “bad” and “RTS-affected” pixels. Dead and bad pixels are defined in such a way that several different pixel parameters, namely Quantum Efficiency, dark current and read-out noise, can, if degraded, lead to a classification of a pixel as being bad or dead. The Random-Telegraph-Signal (RTS) effect is a permanent degradation effect as a result of in-orbit proton irradiation, which shows up as a dark current which switches randomly between two or more states. In addition to the flagging of degraded pixels, the L1b processing algorithms also provide further quality flags attached to the (radiometric) products and indicating, for example, unusually high or low measured calibration parameters, as well as an SNR-estimator product for each individual radiometric sample, which is derived from several in-flight calibration measurements as listed in Table 2.

#### IV. SPECIAL CHALLENGES

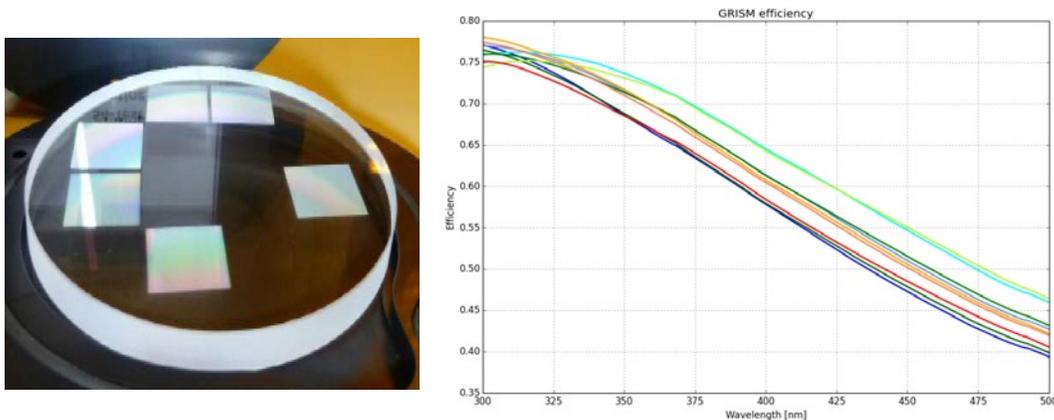
##### A. Overview

This subsection presents a non-exhaustive list of particular challenges faced in the SENTINEL 4 subsystem development, out of which one example, namely the UV-VIS grism (cf. bullet 2 of the following list), has been selected as an example for more detailed discussion in subsection B:

- 1) Development of *optical coatings* (Scan mirror reflective coating; AR coatings on lenses, pol. scrambler and back surfaces of grism & beamsplitter; Beamsplitter coating to separate UV-VIS and NIR; NIR spectrograph folding mirror, which also has a spectral filter function). These coatings have to fulfill simultaneously very challenging requirements related to polarization- (incl. polarization spatial & spectral features), throughput-, and straylight- (ghost suppression-) performances.
- 2) Development of the *grating structures* on the dispersers. These grating structures have to fulfill simultaneously very challenging requirements related to polarization- and throughput-performances. Dedicated developments are undertaken for both the UV-VIS grism and the NIR grating.
- 3) Very low *micro-roughness* on the order of 0.5 nm (rms) is requested for straylight suppression from essentially all surfaces in the nominal optical path.
- 4) The *lens mounts* have to meet very demanding tolerances & stability requirements in the 1 $\mu$ m range, and compensate for the different thermal expansion coefficients of the various materials involved (lens glasses and metal structure parts). A special challenge lies in the brittleness of CaF<sub>2</sub>, which is used for the convex lenses in the UV-VIS light path. In addition the lens mounts include also a lever mechanism, which is needed for athermalization of the optics. This lever mechanism produces a temperature dependent along-axis shift of the lens, which effectively acts like a passive re-focus mechanism.
- 5) *Calibration OGSE and correction algorithms*: Complex algorithms are being developed for the correction of straylight, and also the corresponding on-ground straylight characterization measurement concepts and OGSEs are very challenging. Another example for challenging on-ground calibration equipment is the fine-tunable monochromatic light source needed to characterize the ISRF.
- 6) *Particulate contamination* (for straylight suppression) and *molecular contamination* (for radiometric accuracy and throughput/SNR performances) *minimization* are considered not only in the processes, but also in the designs (mechanisms, material choices, etc.) on subsystem and system level.
- 7) Very demanding pointing and scan accuracies are required from the scanner. These are considered in the design of the *scanner mechanism* including a dedicated *encoder* development for SENTINEL 4.
- 8) Challenges of the *detector* development are, for example, a high *full well capacity* of about 1.5Me<sup>e</sup>, as well as the *AR coating* of the UV-VIS detector, which is graded to account for the large spectral range.
- 9) A main challenge of the FEE is the development of the required *16bit ADC* with low noise performance at high sampling frequency (pixel clock 1.42 MHz).

##### B. Example: Grism Structure

While the groove density of the grism is fixed (to about 500 lines/mm) by the optical design of the UV-VIS spectrograph, the actual fine design of the periodic grating structure of the grism is a (multi-dimensional) design degree of freedom with significant influence on the optical performances of the grism itself. The main performances are throughput (i.e. efficiency of the employed grism diffraction order) and polarization.



**Fig. 5. Left:** Etching test samples by ZEISS for the selected grism structure design. **Right:** Simulated grism efficiency (throughput) spectra for several example grism structure implementations, including the manufactured test samples. Photograph and simulation data are courtesy of ZEISS.

A particular constraint for the throughput is that it has to be on one hand as high as possible in the lower UV spectral range (305-320 nm) in order to achieve the system level SNR requirements, and on the other hand below certain limits at higher wavelengths in order to avoid detector saturation, especially in the VIS spectral range where the Earth radiance scenes feature very high signal levels. Regarding polarization there are several relevant performance parameters, chiefly polarization sensitivity and polarization spectral features.

The actual grism is manufactured by Carl Zeiss Microscopy GmbH (ZEISS) as a sub-contractor of the grism assembly supplier Jena-Optronik GmbH (JOP). In an iterative process, the optical performances of many possible grating structures have been simulated by ZEISS (cf. Fig. 5), subsequently integrated by Airbus Defence and Space in system level performance analyses, and evaluated in order to provide feedback to JOP/ZEISS for further structure optimization. The main challenge in this context is to fulfil simultaneously the needs for high throughput in the UV and for low polarization spectral features, because these two parameters tend to be anti-correlated, meaning that structures with high throughput tend to also have increased polarization spectral features. Out of these iterations, an optimum grism structure design has been selected.

For the selected design, etching tests have been performed by ZEISS (cf. Fig. 5) and the obtained grism structures have been mechanically characterized. These tests confirmed the manufacturability of the selected design, and also show that sufficiently low manufacturing tolerances are achieved. The selected grism design achieves impressively high efficiency on the order of 77% in the low UV, and allows to achieve on system level very good polarization spectral features performance of about 0.040% (at worst-case wavelength). At the time of writing of this paper, preliminary optical measurements of efficiency and polarization performances are available for the manufactured test samples, confirming the predictions of the simulations, and the manufacturing and characterization of full-size grism structure breadboards is on-going.

## V. STATUS AND SUMMARY

Regarding its status of development SENTINEL 4 has passed its system Preliminary Design Review (PDR) in 2013. The lower-level PDR cycle is planned to be completed in 2014. The lower-level Critical Design Review (CDR) cycle has also started, with first equipment CDRs successfully completed in the first half of 2014. Hence, SENTINEL 4 is currently in its unit level detailed design and implementation phase, which includes H/W manufacturing and S/W development. Results are available from unit level breadboards and first engineering models. Based on the current status of subsystem designs and unit level measurements, compliance to all major performance requirements (cf. Table 1) is expected to be achieved. The SENTINEL 4 system CDR is planned in 2016, and the delivery of the first flight model is scheduled in April 2018.

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