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Sentinel 4 UVN: a geostationary imaging UVN spectrometer for air quality monitoring: performance, measurement modes and model philosophy

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Sentinel-4 UVN - A Geostationary Imaging UVN Spectrometer for Air Quality Monitoring - Performance, Measurement Modes and Model Philosophy

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ABSTRACT

Sentinel-4 is an imaging UVN (UV-VIS-NIR) spectrometer, developed by Airbus Defence and Space as prime contractor under ESA contract in the frame of the joint EU/ESA COPERNICUS program. The mission objective is the operational monitoring of trace gas concentrations for atmospheric chemistry and climate applications. This paper gives an overview of the Sentinel-4 system architecture, its design & development status.

Keywords: Sentinel 4, Copernicus, spectrometer, geostationary

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, OMI, GOME & GOME 2) 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 km²). Sentinel-4 will increase the frequency of cloud-free observations, which is necessary to assess troposphere variability.



Fig. 1: Left: artistic impression of Sentinel-4 embarked on Meteosat Third Generation-Sounder. Right: photo of the instrument e-EM (without MLI) currently under testing.

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Two identical Sentinel-4 instruments (PFM and FM-2) will be embarked, as Customer Furnished Item (CFI), fully verified, qualified and calibrated respectively onto two EUMETSAT satellites: Meteosat Third Generation-Sounder 1 & 2 (MTG-S1 and MTG-S2), whose Flight Acceptance Reviews are presently planned respectively in Q4 2021 and Q1 2030.

2. SENTINEL-4 REQUIREMENTS AND CONCEPT OVERVIEW

2.1 Sentinel-4 Requirements

The spatial coverage over Europe and adjacent regions will be achieved by continuous East/West scanning of the image by a push-broom mirror mechanism, which will cover a field-of-regard of about 11 degrees, while the North/South instantaneous field-of-view (IFOV) will be equal to 3.85 degrees.

Blue and red lines, shown in Fig. 2, indicate the borders of the specified Geo-Coverage area (GCA), which is the total area to be covered every day. The overall daily Earth observation pattern consists of a series of 1 hour-long East-to-West scans (“repeat cycles”) with a fast West-to-East retrace in-between.

The green border indicates the size of a 1-hour repeat cycle (Reference Coverage - RA). 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 starts at the eastern edge of the Geo Coverage area. The 1 hour 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.

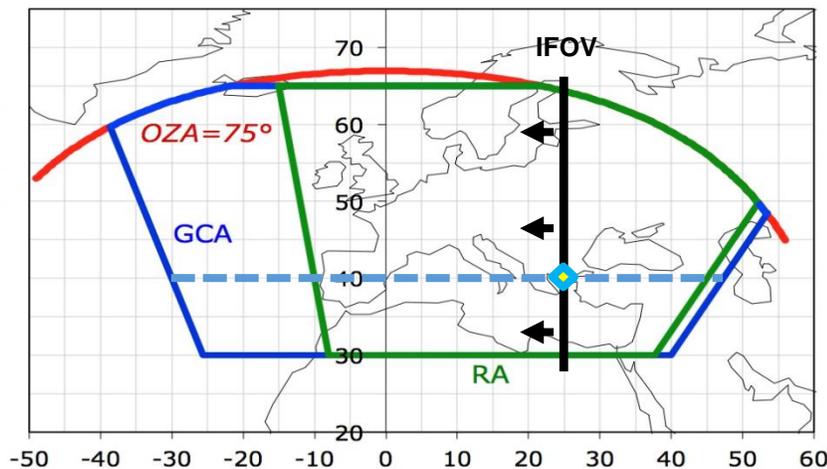


Fig. 2: Earth coverage from the geostationary Sentinel-4 perspective.

While observing Europe and its adjacent regions, the Sentinel-4 imaging spectrometer will acquire continuous spectra of Earth radiance using the Sun as a light source illuminating the Earth. It will cover the Ultra Violet (305-400 nm), the Visible (400-500 nm) and the Near Infrared (750-775 nm) wavelength bands, with spectral resolution of 0.5 nm in the first two bands and 0.12 nm in the third band (see Fig. 3 for the link between the acquired spectral bands and the Level-2 products).

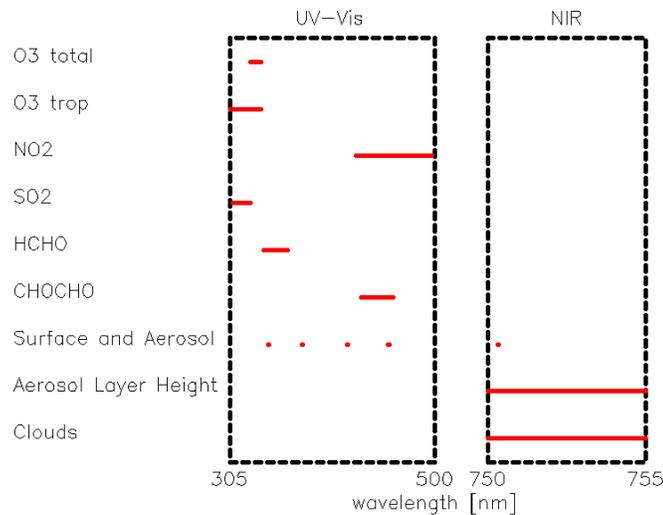


Fig 3: Spectral ranges exploited for each Sentinel-4 product during Level-2 processing

Besides scanning Earth, the instrument will also acquire the Sun, stars and internal light sources for calibration purposes. This leads to a round-the-clock measurement scheme of the Sentinel-4 instrument. Due to the yaw-flip performed by the satellite at each equinox, the Sun measurements will take place in the evening during winter and in the morning during summer. The Sun irradiance data product acquired every 24 hours will be used for instrument calibration purposes and for the determination of the Earth reflectance.

Furthermore, landmarks for image navigation observed in the early morning will be sparse and of low contrast as the measurement concept is based on the observation of backscattered solar light. As a consequence, it is expected that the INR processing will converge only after a few hours; for this reason, in order to speed up this convergence, star observation is foreseen right before Earth acquisition.

Table 1 below gives an overview of the Sentinel-4 instrument main design and performance requirements.

Table 1: Main design and performance parameters of Sentinel-4

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): <ul style="list-style-type: none"> • 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		

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

2.2 Sentinel-4 measurement Concept

The instrument measurement concept, illustrated in Fig. 4, can be described as follows:

- A scanning mirror (not shown in the figure), operating in push-broom mode, selects a strip of land whose “white light”, reflected by the Earth and transmitted through the Earth atmosphere, is collected by the telescope.

- The collected “white light” is split into two 2 wavelength ranges (i.e. the Ultraviolet & Visible-UVVIS and the Near-Infrared-NIR ranges) by a dichroic beam-splitter mirror and focused onto the two slits of the two separate spectrometers.
- Afterwards the light is first collimated onto the dispersing optical elements of the two spectrometer channels (either a grating or a grism) and dispersed in the spectral direction.
- The generated spectra are re-imaged onto two 2-dimensional charge coupled device (CCD) detector arrays. One dimension features the spectrum, the other dimension the spatial (North/South) direction corresponding to the selected strip on Earth (ground swath).
- At the end of this scanning process which lasts about 1 hour, spectra of multiple strips of land, which make up the complete field of view, are acquired and a complete spectral image of the Earth atmosphere over Europe is created. The process is repeated daily n-times so long as the relevant strip of land is illuminated by the Sun.

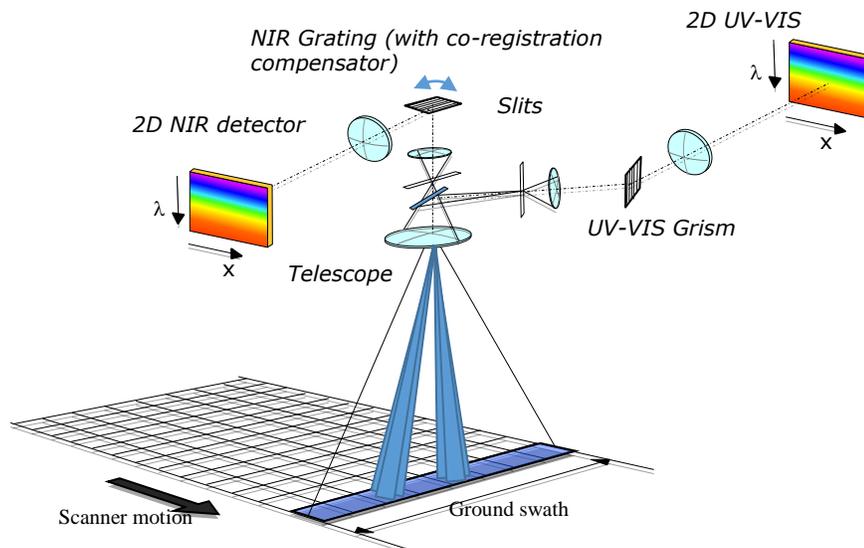


Fig. 4: Sentinel4 instrument measurement principle.

Observation from GEO orbit fulfilling the above mentioned requirements presents several challenges. *Optical coatings* have to fulfill simultaneously very challenging requirements related to polarization (incl. pol. spatial & spectral features), throughput, and straylight (ghost suppression) performances. *Grating structures* on the dispersers have also to fulfill simultaneously requirements related to polarization- and throughput-performances. To suppress straylight, very low *micro-roughness* on the order of 0.5 nm (rms) from essentially all surfaces in the nominal optical path is required. In addition the *lens mounts* have to meet very demanding tolerances & stability requirements in the 1 μ m range, and compensate for the different thermal expansion coefficients of the various materials. *Calibration OGSE* and *correction algorithms* have to be developed for the correction of straylight, and also the corresponding on-ground straylight characterization measurement concepts and OGSEs are very demanding, in particular the fine-tunable monochromatic light source needed to characterize the ISRF. Very demanding pointing and scan accuracies are required from the *scanner* leading to the development of a dedicated *encoder* for Sentinel 4. The *detector* requires a very large dynamic range and a very high *full well capacity* of about 1.5Me⁻.

3. SENTINEL-4 INSTRUMENT DESIGN

3.1 Instrument description

The Optical Instrument Module (OIM) unit is the core of the instrument and contains the main instrument subsystems including the structural parts, the optics, the focal plane detection & read-out, the calibration assembly, the scanner, the aperture cover and the thermal subsystems.

The OIM is mounted on the MTG-S Earth panel. Two other instrument electronic units, namely the Instrument Control Unit (ICU) and the Scanner Drive unit (SDE) are mounted inside the MTG platform. The location of the OIM, ICU and SDE units and of the Sun Reflector Shield (SRS, mounted on the MTG-S platform deck to prevent Reflection of the Sun into the instrument) on MTG-S is shown in Fig. 5.

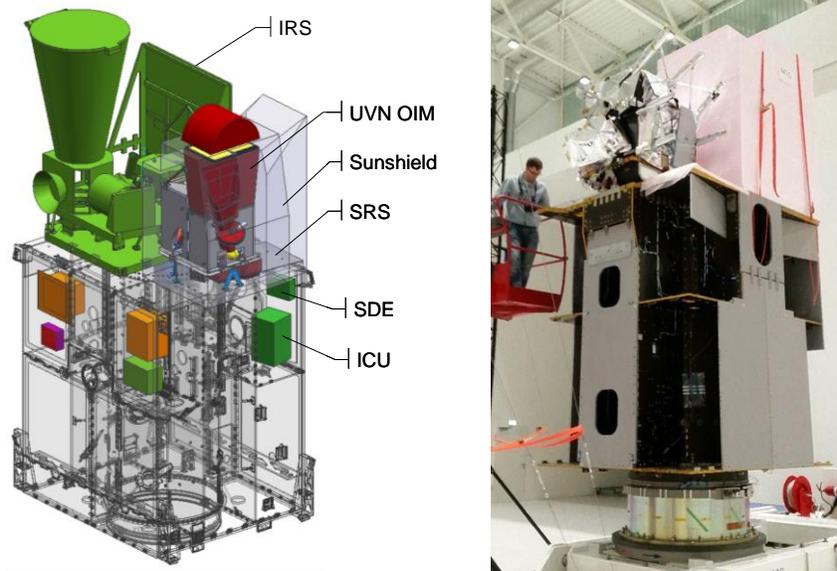


Fig. 5 Left: Sentinel-4 units location, configuration together with the IRS instrument on the MTG-S satellite. **Right:** Sentinel-4 STM mounted on MTG-S STM for the fit check (courtesy of OHB).

The ICU is the core of the instrument intelligence, and ensures that all the tasks of the instrument are performed correctly. It controls the timing for the execution of the measurement sequences, triggering the Front End Electronics / Front Support Electronics (FEE/FSE) measurements, the activation of the Calibration Assembly unit, the Aperture Cover mechanism and commanding the SDE that controls the scan mirror motion. The ICU manages also the instrument thermal control and all the needed ancillary services. All the Sentinel-4 control & telemetry data, the science data links and the power links are channeled to the MTG-S platform through the ICU, which is the only electrical interface with the platform.

The OIM cross-section is shown in Fig. 6. It has two main view ports to carry out its observation: an Earth view port (Nadir) and a Calibration view port. This configuration allows for four views settings. Three views are external: the Earth (radiance) observation view; the star viewing, both through the same nadir port and the Sun irradiance observation view, through the Calibration port. The last view is internal: the white light sources view through the Calibration port. The Earth port allows deep space measurement aimed at star viewing for instrument calibration and INR purposes. This function is enabled by the extension of the Nadir baffle clear FOV towards the East so that the entire spectrometer slit points beyond Earth to deep space to capture stars early in the morning or late in the evening.

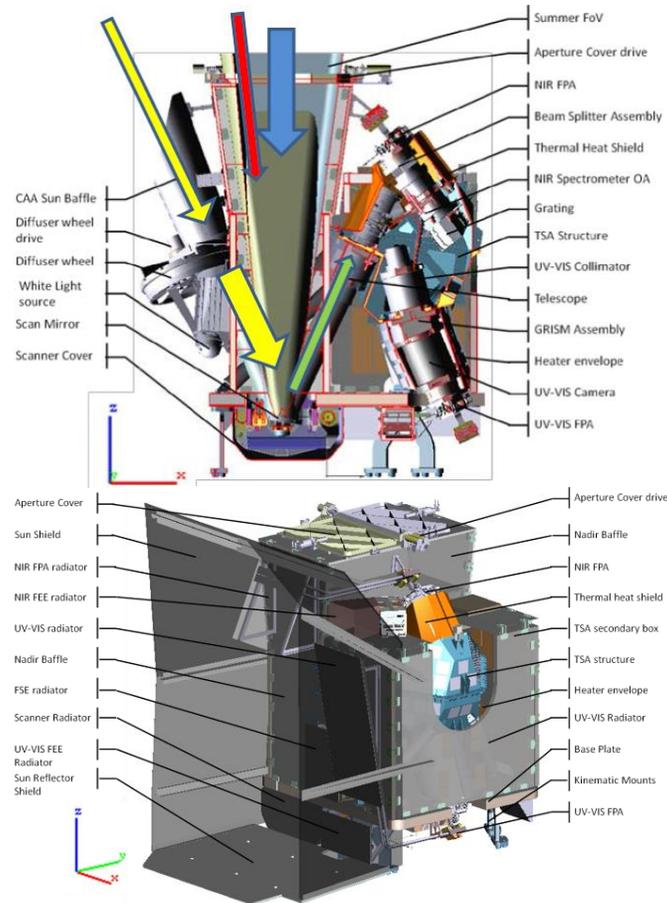


Fig. 6: OIM unit cross-section (The blue arrow indicates the Earth radiance path, the yellow arrows the Sun irradiance path, the red arrow the star viewing path. The green arrow indicates the observation path from scanner towards the telescope, which is common to all viewings (Earth, Sun, stars, white light sources and to all spectral bands (UV, VIS and NIR)).

A single two-axis scan mirror fulfils two main functions: 1- it switches between the two view ports; 2- it scans the Earth in East/West direction, when set in the Earth observation mode. The scan mirror is mounted on a 2-axis flexible hinges, and it is driven by voice coils. The power to the voice coils is provided by the SDE, which performs also the control of the mirror angle. The Qualification Model of the scan mirror is shown in figure 7a

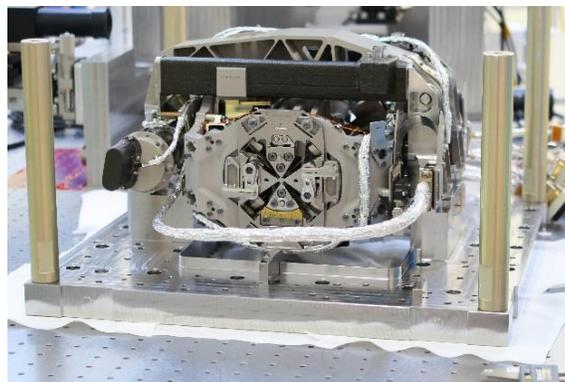


Fig.7a: Scanner Mechanism Qualification Model

The Earth port can be closed and opened through a motorized aperture cover (ACV) mounted on the top of the nadir baffle.

The calibration port can be closed or can switch between the internal and external view by rotating a wheel mechanism hosting diffusers and mirrors. In the first setting (external view) the Sun is observed through one of two selectable diffusers. In the other setting (internal view) the flat-field White Light Source (WLS) is observed for instrument transmission degradation and for pixel response diagnostic purposes.

The ACV and the CAA qualification Models are visible in Fig.7b, where the ACV is still assembled on its mounting frame.

The OIM structure provides the support for the accommodation of the other equipment, and it is basically constituted by a rigid CFRP baseplate mounted on MTG via 3 titanium kinematic mounts and by a nadir baffle. The scanner is mounted below the baseplate, on top of which is mounted the Telescope-Spectrometers Assemblies (TSA) structure, shown in Fig. 8. The TSA provides a rigid frame where the optics (the two spectrometers and the telescope) are integrated such that their relative position and alignment does not change.

The OIM is then completed by the nadir baffle and the TSA secondary box, shown in Fig.9, which provide additional structural stiffness and a protection against straylight.



Fig.7b: Left: Aperture Cover Qualification Models Right: Calibration assembly and ACV QM assembled on the Instrument EM

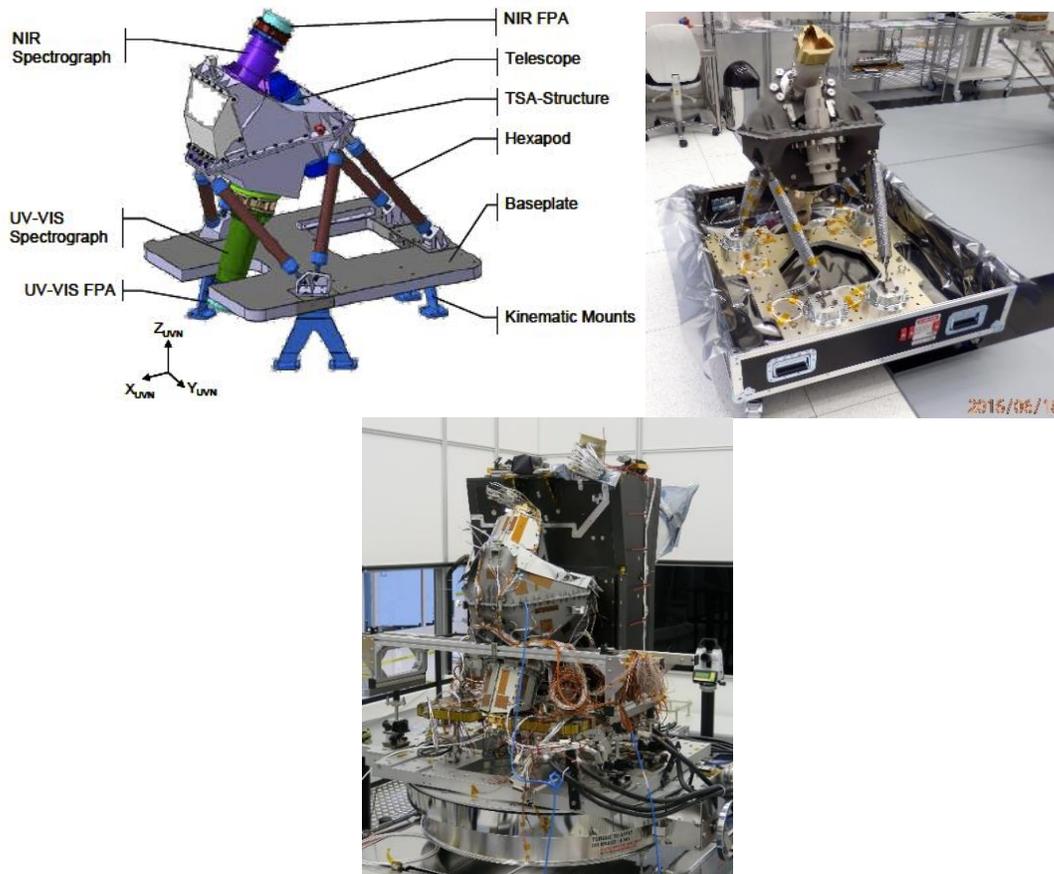


Fig.8 Left up: TSA mounted on the CFRP Baseplate with Titanium kinematic mounts. **Right up:** TSA Qualification Model. **Bottom:** Nadir Baffle, TSA and thermistors assembled on Instrument EM.

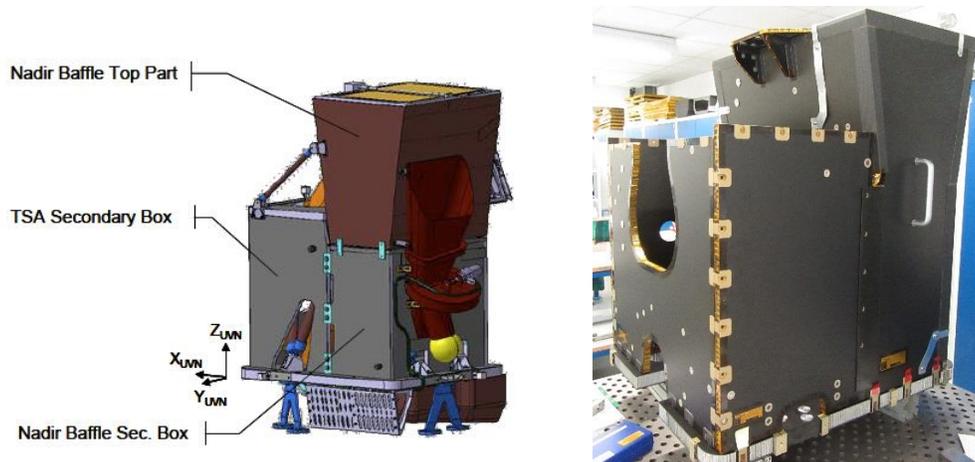


Fig.9 Left: OIM structure **Right:** OIM Structure Qualification Model

3.2 Optical Design

The Sentinel-4 core optical design is shown in Fig.10.

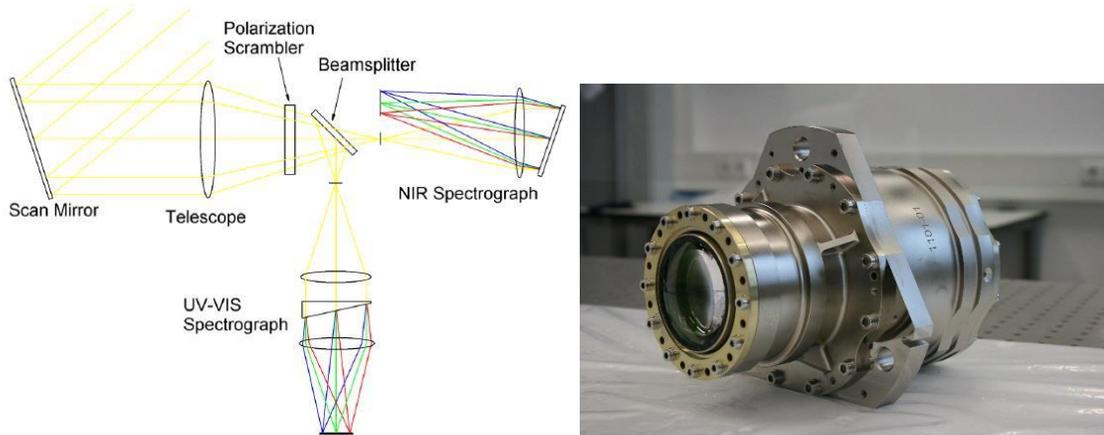


Fig.10 Left: Optical design sketch **Right:** Telescope Engineering Model

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 performances driving the optical design are the polarization (polarization sensitivity and its spectral & spatial features), the straylight and the 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 also enabling factors for the low optical distortion. Since some optical elements still inevitably are polarization sensitive and show spectral features (e.g. the grism) 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 optics, 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), can still meet 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 optimization of the optics design in all areas, e.g. spectrograph and disperser architectures, as well as by a sophisticated straylight baffling architecture; namely the beam splitter-slits-assembly and in the FPAs.

3.3 Detection Chain

The UV-VIS and NIR detectors are both frame-transfer CCDs featuring frame shift along the spectral direction. 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 so that 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. This synchronized UVVIS1-UVVIS2-NIR-sequencing avoids EMI signal distortions, which is mandatory in order to achieve the required radiometric performances. Figure 11 shows the detector integrated on its housing (FPA)

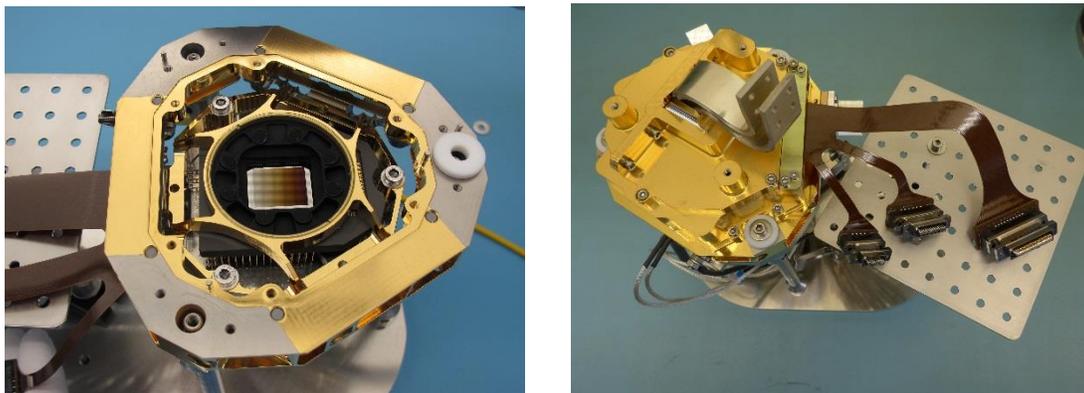


Fig. 11. Detector assembled in the FPA Qualification Model, top view (left) and bottom view (right)

4. INSTRUMENT DATA PROCESSING AND CALIBRATION

The L0 and L1b performance requirements will be verified on ground and partly in orbit, during the commissioning phase. The instrument characterisation and calibration will be carried out in an on-ground characterisation and calibration phase and an in-flight characterisation and calibration phase throughout the in-orbit commissioning period and with calibration key parameter updates during the routine operation period.

4.1 On-ground L0 performance verification and Calibration

The aim of the on-ground characterisation and calibration campaign is twofold, the verification of the performance related requirements and the measurements needed to derive the characterisation and calibration keydata. The latter ones are required by the L0 to L1b prototype processor (L1bPP) for the L0 to L1b processing.

The on-ground L0 performance verification will include instrument measurements in flight representative environmental conditions, carried out at a dedicated thermal vacuum chamber calibration facility, at the Rutherford Appleton Laboratories (RAL) in the UK.

Specific Ground Support Equipment (GSE) will be used for the on-ground testing phases. They will include, for example, dedicated turn-tilt tables to rotate the instrument within the thermal vacuum chamber in suitable orientations, as well as dedicated and well characterized Optical Ground Support Equipments (OGSEs). Those are composed of different light sources (Sun Beam Simulator, Integrating Sphere, absolutely calibrated light sources, spectral lines sources) used to simulate the different illumination conditions and to allow calibrating the instrument's behavior with the required accuracy.

Electrical ground support equipment will also be used to command the instrument, OGSE and MGSE and receive all the necessary data (raw and housekeeping data) for the ground processing.

4.2 Ground processing & algorithms

The L0 to L1b data processing is specified in the Algorithm Theoretical Baseline Document (ATBD). Based on the ATBD specifications, the algorithms necessary to transfer L0 digital counts data, with the help of calibration key parameters, allow the L1b data to be generated in physical units.

The different modes in which the L0 to L1b prototype processor (L1bPP) will be used require a specific level of flexibility of the data processor software. For example, depending on the type of processing, it will be possible to change

the processing flow by adding, removing or changing the order of algorithms, thus allowing the optimization of the L1bPP to its specific usage.

4.3 In-flight Calibration

The Sentinel-4 in-flight calibration concept hinges on two main activities: 1) the “calibration measurements”, which will be used for characterization of the instrument; 2) the “application of correction” which will be applied either to the scientific data or to the instrument in order to correct / mitigate for changes.

The in-flight activities will check if the calibration of the instrument is maintained throughout its lifetime and which ageing effect, due for example to the very severe external radiation environment, will need to be taken into account.

External in-orbit geometric calibration of the absolute pointing by means of star observation will be performed each day for typically 15 minutes in the early morning immediately before the start of Earth observation and in summer also immediately after the end of Earth observation.

The remaining night-period (4 to 6 hours) will be used for internal in-orbit calibrations (darks, White-Light-Source (WLS), LED light source- & detection-chain-calibrations).

5. ENHANCED ENGINEERING MODEL (E-EM) – ASSEMBLY INTEGRATION AND TEST CAMPAIGN

The Sentinel-4 UVN instrument model philosophy consists of the following models: STM, Flat EM, e-EM, PFM and FM2. Amongst those, the enhanced Engineering Model (e-EM) is fully representative for the two flight models from Structural, Thermal and Electrical perspective except for what concerns redundancy – see Fig. 1 Right. From the optical and performance point of view, the e-EM has a simplified built standard with respect to the PFM/FM2, having in the optical path no spectrometers (neither UVVIS, nor NIR) but a QM telescope as well as the two focal plane assemblies, containing the two detectors and front-end-electronics. However only the NIR detector is in the nominal light path. With such built standard, the e-EM is optically speaking an imager that is using the NIR detector..

After its assembly and integration, completed since April 2018, the e-EM has encompassed a complete test programme consisting of microvibration and EMC tests at IABG (GER). After completion of this first test campaign by end of spring 2018, the instrument has been brought to the new test facility at RAL (UK), where the instrument will be further tested in thermo-vacuum conditions in fall 2018. Specifically the e-EM will experience a thermal balance test and a performance risk mitigation test. The whole campaign should be completed by end of 2018.

Due to its built standard limitation, the e-EM does not allow to perform a check of the performance of the instrument prior to the PFM campaign. However, aspects as critical interfaces between the instrument and the vacuum facility or between instrument and its EGSE, MGSE and OGSE (including the evaluation of the straylight generated by the OGSE), the run of test procedures, etc. will be checked with the e-EM. For all these aspects the e-EM is considered as a unique tool to de-risk the PFM test campaign.

6. DEVELOPMENT STATUS AND SUMMARY

Sentinel-4 has passed its system Critical Design Review (CDR) in 2017. The results available from unit level breadboards and engineering/qualification models have allowed consolidation of compliance to major performance requirements (cf. Table 1).

All the S/S, excluding the Optics for which a protoflight approach is baselined, have completed their Qualification Testing, and the Qualification Models were delivered to the Prime Contractor for their integration onto the Instrument EM, shown in Fig 1. The Instrument e-EM integration was completed in early 2018 and the testing has started. Mechanical Qualification was already achieved with the OIM structure Qualification Model (see Fig 12) prior to the CDR after successful vibration, shock and acoustic tests.



Fig. 12: OIM structure STM mounted on the vibration bench at IABG

7. ACKNOWLEDGEMENTS

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