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"KNOWING WHAT WE BREATHE": SENTINEL 4 – A GEOSTATIONARY IMAGING UVN SPECTROMETER FOR AIR QUALITY MONITORING

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I. INTRODUCTION

Sentinel-4 is an imaging UVN (UV-VIS-NIR) spectrometer, developed by Airbus DS 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 – hence the motto of Sentinel-4 "Knowing what we breathe". Sentinel-4 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).

In the family of already flown UVN spectrometers (SCIAMACHY, OMI, GOME & GOME 2) and of those spectrometers currently under development (TROPOMI, Sentinel-5p and Sentinel-5), Sentinel-4 is unique in being the first geostationary UVN mission. 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.

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.

This paper gives an overview of the Sentinel-4 system[1] architecture, its design & development status, current performances and the key technological challenges.

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

II. SENTINEL-4 REQUIREMENTS AND CONCEPT OVERVIEW

A. 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.

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[1] In this paper the term Sentinel-4 **system** refers to the instrument (flight) H/W & S/W, operations concepts, on-ground and in-flight calibration, L1b algorithms and processing.

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.

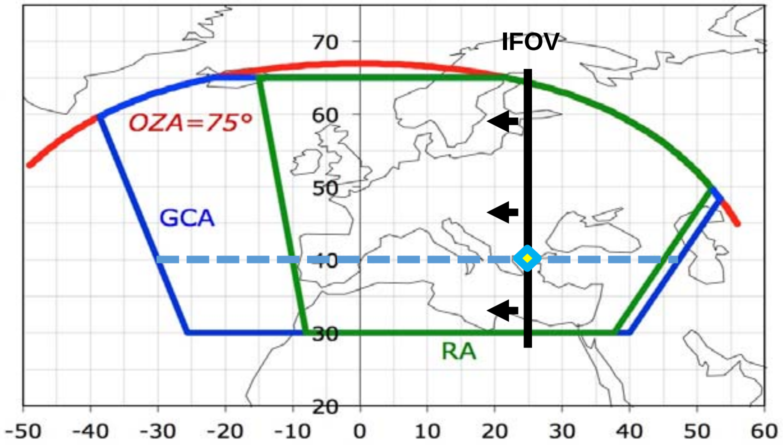

Fig. 2: Earth coverage from the geostationary Sentinel-4 perspective.

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).

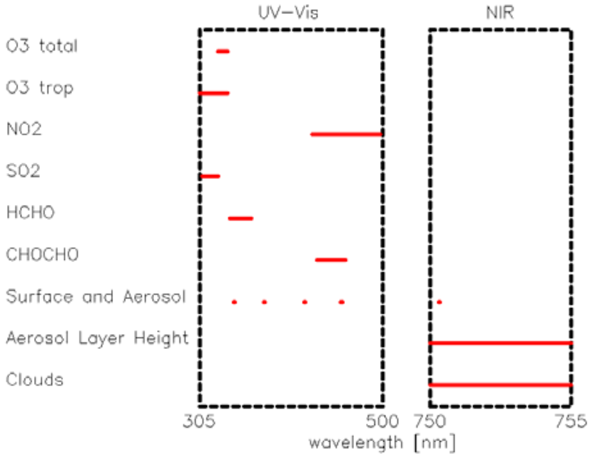

Fig 3: Spectral ranges exploited for each Sentinel-4 product during Level-2 processing

Additionally, Sentinel-4 will provide Sun irradiance data product every 24 hours, which will be used for instrument calibration purposes and for the determination of the Earth reflectance.

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	8 km x 8 km		On-ground-projected SSD at

(SSD)	(E/W) (N/S)		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	< 2%	< 2%	For sun irradiance
Polarization Sensitivity	< 1%	< 1%	
Polarization spectral features	< 0.015%	< 0.1%	
Sun diffuser spectral features	< 0.042%	< 0.076%	Caused by speckle effect
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		

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.

B. *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.
- The light is then first collimated onto the dispersing optical elements of the two spectrometers channels (either a grating or a grism) and then dispersed in the spectral direction
- The then generated spectra are re-imaged onto two 2-dimensional charge coupled device (CCD) detector array. 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 that Sentinel-4, 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.

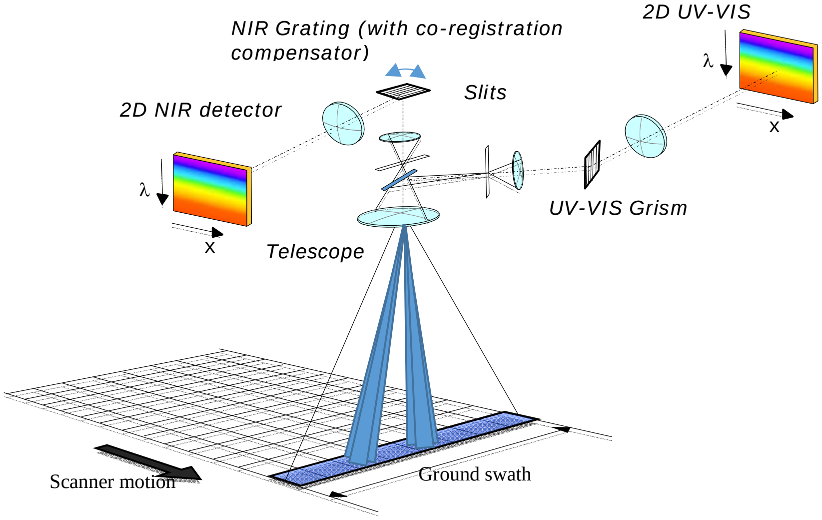

Fig. 4: Sentinel4 instrument measurement principle.

III. SENTINEL-4 INSTRUMENT DESIGN

A. Instrument Functional 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 ICU is the core of the instrument intelligence, and ensures that all the tasks of the instrument are performed correctly. It contains the instrument Basic Software and the Application Software which 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 the scan mirror motion.
All the Sentinel-4 control & telemetry data, the science data links and the power links are channelled to the MTG-S platform through the ICU.
It manages also the instrument thermal control and all the needed ancillary services. The survival heaters, needed to maintain the instrument at the required temperature when the instrument is off, are powered directly by the platform via control lines, which pass through the ICU. The ICU is therefore the only electrical interface with the platform.

B. Instrument Configuration and Main characteristics

The OIM cross-section is shown in Fig. 5. It has two main view ports to carry out its observation: an Earth view port (Nadir) and a Calibration view port which allow 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. One view is internal: the white light sources view through the Calibration port.

A single two-axis scan mirror, shown at the bottom of the OIM, 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 Earth port is used for nominal measurement but also for deep space measurement aimed at star viewing for instrument calibration. 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.
The Earth port can be closed and opened through a motorized aperture cover mounted on the top of the nadir baffle

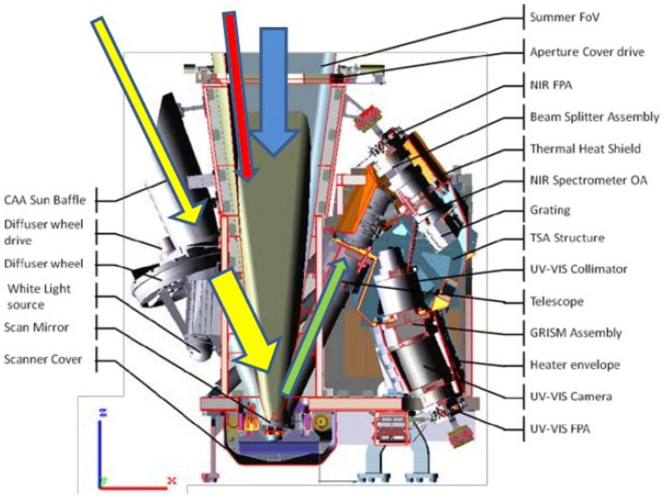

Fig. 5: OIM unit cross-section (The blue arrow indicates the Earth radiance path, the yellow arrows the Sun irradiance path, the red allow the star viewing path. The green arrow indicates the observation path from scanner towards the telescope, which is common to all viewings (Earth, Sun, stars, white light sources and to all spectral bands (UV, VIS and NIR)

The calibration port has two principal sub-viewing options, which can be selected by setting the diffuser wheel mechanism accordingly. In the first setting (external view) the Sun is observed through one of the 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 three main units, the OIM, the ICU and the SDE, are mounted onto MTG-S satellite platform deck together with their interconnecting harness.
In addition, a Sun Reflector Shield (SRS) is also mounted on the satellite platform deck to prevent Reflection of the Sun into the instrument.

The location of the OIM, ICU and SDE units and of the SRS on MTG-S is shown in Fig. 6.

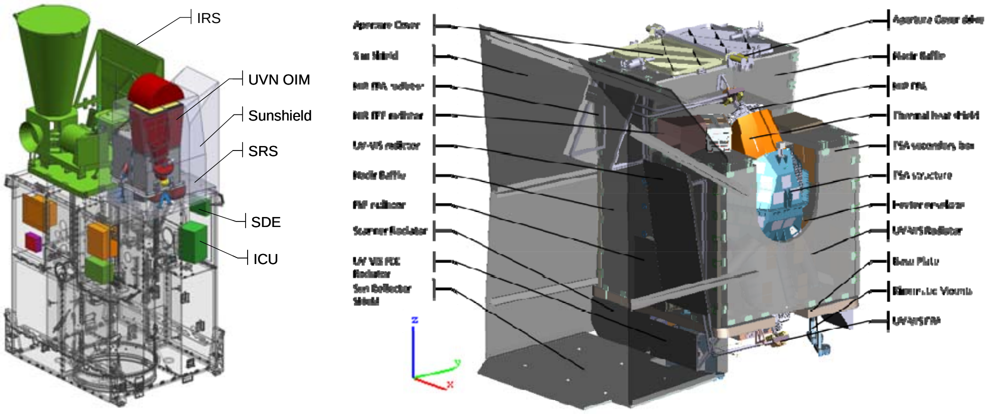

Fig. 6 Left: Sentinel-4 units location, configuration together with the IRS instrument on the MTG-S satellite.
Right: Sentinel-4 OIM from a radiator- and IRS-side perspective.

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 a common baseplate, on top of which is mounted the Telescope-Spectrometers Assemblies (TSA) structure, shown in Fig. 7 left. 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 instrument is then completed by the nadir baffle and the TSA secondary box, shown in Fig.7 right, which provide additional structural stiffness and a protection against straylight. On the nadir baffle the CAA is also mounted

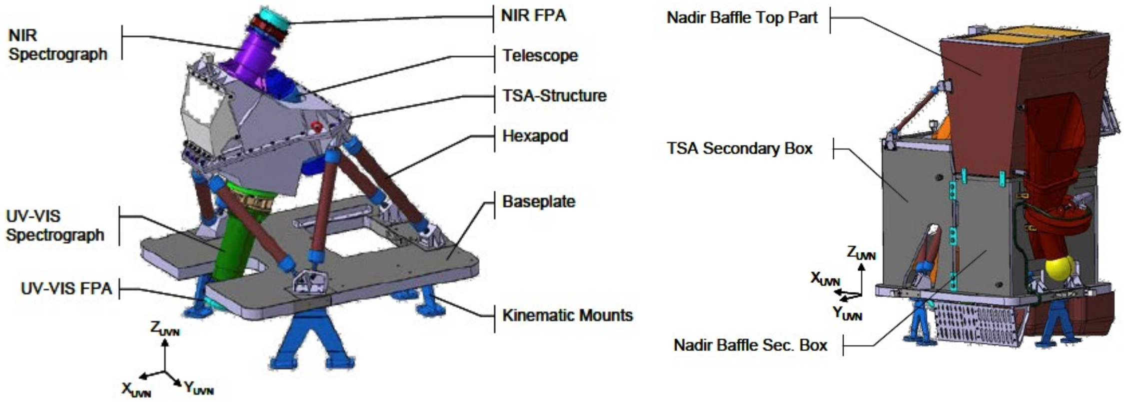

Fig.7 Left: TSA mounted on the CFRP Baseplatewith Titanium kinematic mounts. **Right**: Nadir Baffle and TSA Secondary box assembled

C. Optical Design

The Sentinel-4 core optical design is shown in Fig. 5. 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 beamsplitter-slits-assembly and in the FPAs.

D. Detection Chain

The UV-VIS and NIR detectors are both frame-transfer CCDs featuring frame shift along the spectral direction (see Fig. 8). 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.

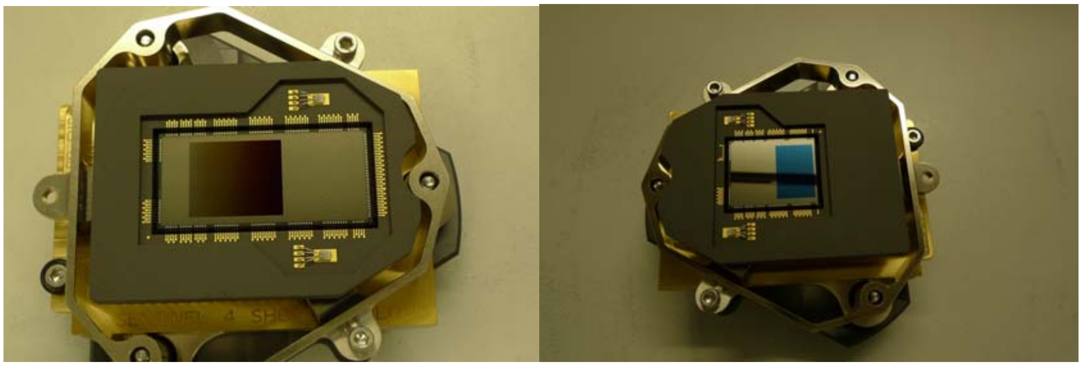

Fig. 6. Flight models of the UV-VIS (left) and NIR (right) detectors

IV. INSTRUMENT DATA PROCESSING AND CALIBRATION

The L0 and L1b performance requirements will be verified partly on ground and partly in orbit, during the commissioning phase. For this reasons, the instrument characterisation and calibration will be carried out in two different phases: 1- the on-ground characterisation and calibration phase; 2- the in-flight characterisation and calibration phase throughout the in-orbit commissioning period and with daily calibration key parameter updates during the routine operation period.

A. On-ground L0 performance verification and Calibration

The on-ground measurement activities of the flight instrument are divided into two phases: a Level-0 (L0) data performance verification programme phase followed by a calibration programme phase. During the L0 performance verification programme phase the applicable instrument performance requirements are verified to ensure that the instrument is fully performant; in other words the L0 programme objective is to verify if the instrument is built as designed.

Once compliance to all L0 performance requirements has been demonstrated, the instrument is calibrated in a comprehensive on-ground calibration programme phase during which all the instrument calibration key parameters that are required for the L0 to L1b data processing are obtained.

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 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 optical ground support equipment (OGSEs) to mimic different light sources, which will be used to simulate different in-orbit illumination conditions.

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

B. Ground processing & algorithms

The calibration key parameters and related accuracies that are required for L0 to L1b data processing are specified in the Algorithm Theoretical Baseline Document (ATBD), which defines the interface between the calibration and the L0 to L1b data processing software.

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.

C. in-flight Calibration

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

The in-flight activities will verify 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).

V. SPECIAL CHALLENGES

This subsection presents a non-exhaustive list of particular challenges faced in the Sentinel-4 subsystem development:

1) Development of *optical coatings* (Scan mirror reflective coating; AR coatings on lenses, pol. scrambler, back surfaces of grism & beamsplitter; Beamsplitter coating separating UV-VIS and NIR; NIR spectrograph folding mirror, which also has a spectral filter function). These coating have to fulfill simultaneously very challenging requirements related to polarization (incl. pol. 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 1µm 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_2, 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 $1.5Me^-$, 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).

VI. STATUS AND SUMMARY

Sentinel-4 has passed its system Preliminary Design Review (PDR) in 2013. The "bottom-up" subsystems CDRs cycle is almost completed. The System Critical Design Review will be kicked-off in November 2016. The results available from unit level breadboards and engineering models confirm so far compliance to all major performance requirements (cf. Table 1). The environmental testing of the instrument Structural Thermal Model (STM) and the electrical integration of the enhanced Engineering Model (e-EM) have started. The delivery of the first flight model in scheduled in 2019.

VII. ACKNOWLEDGEMENTS

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