THE SENTINEL-4 MISSION, ITS COMPONENTS AND IMPLEMENTATION

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Abstract

The Sentinel-4 mission, as part of the Global Monitoring for Environment and Security (GMES), now called “Copernicus”, has the primary objective of observing the diurnal cycle of the tropospheric composition in support of the air quality applications of Copernicus Atmosphere Services. The paper addresses the Sentinel-4 mission, the respective space and ground segment implementation and its associated elements. The overall mission operations concept and principles are briefly outlined. The S4/UVN instrument will provide data products for continuous monitoring of the atmospheric composition above Europe and northern Africa with additional complementary value with respect to low Earth orbit predecessor missions, like GOME, SCIAMACHY, OMI, GOME-2 and future missions like Sentinel-5. The expected launch date of the first MTG-S satellite hosting the first Sentinel-4/UVN instrument is 2019; the expected mission duration is 15 years.

THE SENTINEL-4 MISSION

The Sentinel-4 mission is part of the Global Monitoring for Environment and Security (GMES) Initiative, whose overall objective is to support Europe’s goals regarding sustainable development and global governance of the environment by providing timely and quality data, information, services and knowledge. Within the Copernicus space component, Sentinel-4 covers the need for continuous monitoring of atmospheric composition. The mission will focus on air quality, with the main data products being O_3, NO_2, SO_2, HCHO and aerosol optical depth. The specific objective is to support air quality monitoring and forecast over Europe and Northern Africa [Fig. 1] with a high revisit time (~1 hour). =

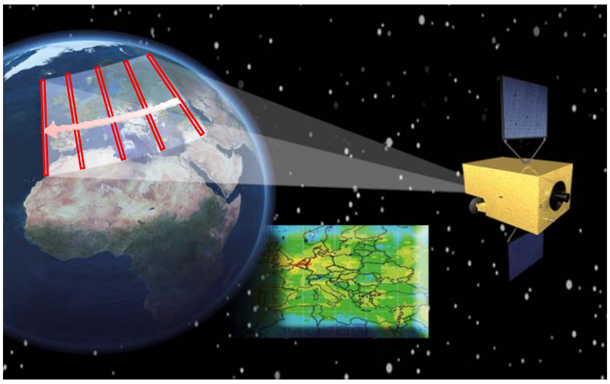

Figure 1: East-west scan for continuous monitoring above Europe and Northern Africa

The Sentinel-4 System consists of the Sentinel-4 space and ground segment elements, i.e.

- The Sentinel-4/UVN instrument (S4/UVN), hosted on-board the MTG Space Segment;
- The Sentinel-4 ground segment elements, hosted within the EUMETSAT MTG Ground Segment; composed essentially of the Sentinel-4 Level 1b and Level 2 Processors, including the interfaces to the Sentinel-4 User and mission performance functions, performance analysis for product monitoring, trending, algorithm maintenance and validation.

THE SENTINEL-4 INSTRUMENT

The Sentinel-4/UVN instruments are procured within the ESA Copernicus programme. They will be provided to the MTG programme for embarkation on the MTG-Sounder (MTG-S) satellite as Customer Furnished Item (CFI), fully verified and qualified together with its necessary GSE, test models and system deliverable inputs.

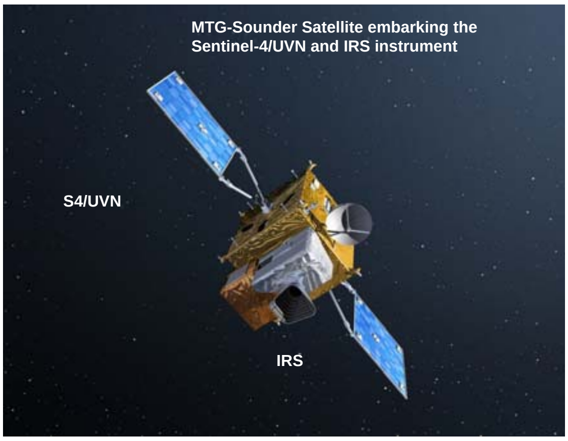

Figure 2: MTG-S with the Sentinel-4/UVN and Infra-Red Sounder (IRS)

The Sentinel-4/UVN instrument is a hyperspectral spectrometer operating with designated spectral bands in the solar reflectance spectrum [Fig. 3]. The key features are the spectral range from 305 nm to 500 nm with a spectral resolution of 0.5 nm, and from 750 nm to 775 nm with a spectral resolution of 0.12 nm, in combination with low polarization sensitivity and a high radiometric accuracy.

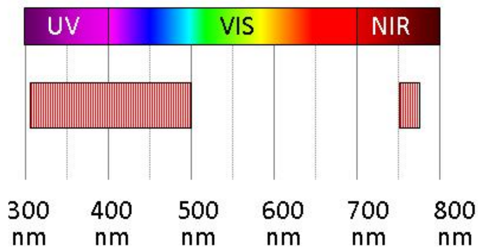

Figure 3: Instrument Spectral Coverage

The instrument design enables a short revisit time from east to west in one hour with sufficient east-west spatial dimension, covering most of Europe and North Africa. The reference area (RA) and the larger geographical coverage areas (GCA) are shown in Fig. 4.

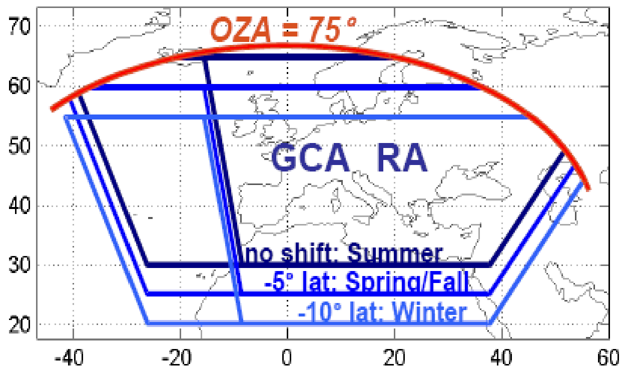

Figure 4: Sentinel-4/UVN geographical coverage area (GCA) and reference area (RA)

An example for a possible East-West scan in the Nominal Earth Observation (NEO) mode is given in Fig. 5. The east-west spatial dimension is accounted for by scanning the scan mirror from east to west in one hour. With about 570 spatial samples in the east-west spatial dimension this corresponds to about 6 seconds per 8 km spatial sample.

At sunrise in the east the instrument only scans the illuminated Earth, resulting in a total scan time of less than one hour. In the evening the same scenario is followed in the west. During autumn-winter the coverage area is shifted twice south by 5 degrees in order to optimise observation of illuminated areas, as shown in Fig. 4. During winter-spring this is reversed.

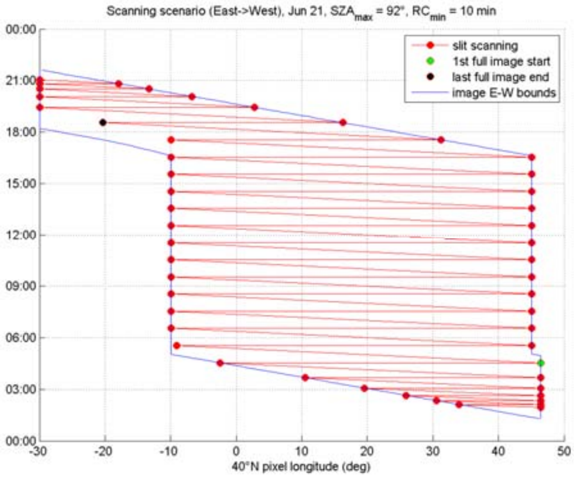

Figure 5: Example for a possible East-West scan pattern of the Nominal Earth Observation Mode

The MTG-Sounder satellite embarking the S4/UVN instrument is in geostationary orbit at a longitude of about 0 degrees. The accommodation of the instrument is optimised, allowing the Earth radiance, sun irradiance and thermal fields of view to be clear and unobstructed. Furthermore straylight from the sun or the Earth via other spacecraft components is minimized per design. This is particularly important for such class of space instrumentation for which the Level 1b and Level 2 data product accuracies are very sensitive to even small straylight contributions.

At the equinoxes the MTG-S spacecraft performs a yaw-flip manœuvre in order to keep the satellite and instrument thermal environment optimised. For the instrument this implies that the scan mirror has to adjust the north-south axis to keep the geographical coverage area in view and reverse the east-west scan axis in order to keep scanning from east to west. In addition, the sun observations are performed in the evening rather than in the morning, or vice versa, as a result of the spacecraft yaw-flip manœuvre.

The instrument is equipped with two frame-transfer Charge Coupled Device (CCD) detectors, one for the UV-VIS wavelength range and one for the NIR wavelength range. One dimension on the CCDs corresponds to the spectral dimension, while the other dimension corresponds to the north-south spatial dimension.

In the wavelength range covered by Sentinel-4/UVN the light from the Earth's atmosphere can be strongly linearly polarised, which is accounted for in the instrument design by minimising the overall instrument polarisation sensitivity in combination with the use of a weak polarisation scrambler. A refractive spectrometer design is the baseline with two separate spectrometers, one optimised for the Ultra-Violet (UV) and visible (VIS) wavelength range and the other for the 25 nm spectral band in the Near-Infra-Red (NIR).

The instrument's polarisation sensitivity has to be balanced with the optical quality properties on the Earth, which is especially critical for an instrument in a geostationary orbit. Using a too strong polarisation scrambler will result in too much blurring of the ground sampling distance on the Earth's surface. Another way of putting this is to say that the integrated energy within a ground pixel (spatial sample) will need to be contained within the required values. As such, the polarisation sensitivity, required to be less than 1%, and the integrated energy of a ground (spatial) sample are competing parameters.

The instrument is equipped with two solar diffusers that are designed to minimise the introduction of spectral and spatial features in the spectra that can interfere with the retrieval of the atmospheric trace gases. The first diffuser is used on a daily basis to provide the required solar irradiance measurement data to allow calculation of the Earth reflectance (Earth radiance divided by solar irradiance), the second one on a monthly basis in order to monitor the radiometric degradation of the first diffuser. The solar measurements are performed at sunrise or sunset when no useful Earth radiance measurements are performed.

The instrument is also equipped with a 5 Watts White Light Source (WLS) in its calibration assembly. Light Emitting Diodes (LED) are integrated close to the detectors to monitor potential radiometric degradation, detector and electronics properties like detector bad and dead pixels, detector Pixel Response Non-Uniformity (PRNU), system non-linearity, etc.

Instrument originating spectral features, e.g. from the on-board diffusers as observed in predecessors, as well as remaining polarisation spectral features may hamper the analysis of atmospheric trace gases. There are no dedicated calibration key parameters planned for correction of the spectral features, therefore these features have to be eliminated by the instrument design.

The relative spectral radiometric accuracy (peak-to-peak) are considering small spectral window widths of a couple of nm's, which for compliance of the requirement incorporate these spectral features next to other relevant errors for the instrument response in sun calibration, Earth observation modes and for Earth reflectance. As example, in the UVVIS between 315 and 500 nm, the maximum relative radiometric spectral accuracy error over a spectral window width of 3 nm is required to be smaller than 0.05%. The in-flight absolute radiometric accuracy of the Earth spectral radiance and of the Sun irradiance is required to be better than 3% with a goal of 2%. All values apply on a one sigma confidence level.

For sensitive hyperspectral spectrometers for Earth atmospheric observations such as Sentinel-4/UVN the performance at Level 1b (and subsequently at Level 2) is a challenging balance between instrument performance and design at Level 0 and calibration plus data processing to convert the Level 0 data into geophysically calibrated Level 1b data. Depending on the parameter under consideration the performance at Level 1b needs to be optimised by imposing more effort on any or more of the above three areas (instrument performance at Level 0, calibration and data processing) in order to obtain the best final results at Level 1b, that is compliant with the instrument Level 1b requirements at beginning of life and end of life.

THE SENTINEL-4 GROUND SEGMENT

The Sentinel-4 Ground Segment elements are integrated and embedded within the EUMETSAT MTG ground segment.

They comprise the following elements:

1. The Sentinel-4 Level 1b and Level 2 processors;
2. The generic and multi-mission supporting functions of the EUMETSAT MTG Payload Data Ground Segment (PDGS) and Flight Operations Segment (FOS);
3. The Sentinel-4 ground segment system interfaces.

These ground segment interfaces are manifold at various levels:

a) Sentinel-4 Payload (S4/UVN) to Sentinel-4 L1b Processors. This interface is part of the MTG Space-to-Ground Interface;
b) MTG Ground Segment to S4/UVN Level 2 Processor interface for non-S4 data required for processing;
c) Sentinel-4 User Interface like to i) the Copernicus User Community, ii) the Sentinel-4 Expert Users, iii) the Copernicus Space Component Coordinated Data Access System (CCS CDS);

d) Sentinel-4 Level 2 Interface to ECMWF and other auxiliary providers (TBC);
e) Sentinel-4 L1bProcessor Interface to Sentinel-4 Image Quality Tool (IQT) which is part of the MTG-S IQT;
f) Interface with the ESA Sentinel-4 Mission Management. This interface is assumed to be a procedural interface.

Sentinel-4 Level 1 Data

The Sentinel-4 Level 1b data are generated by a dedicated L1b processor and based on the S4/UVN Level 0 data; the respective outputs are radiometrically and spectrally calibrated data at Level 1b and geometrically localised.

As shown in Fig. 5 the calibration keydata is an essential input. These data will be first determined during the on-ground calibration campaign of the instrument. In-orbit, the instrument calibration keydata will be continuously verified, monitored and modified, when necessary, in order to maintain the quality, completeness and accuracy of the Level 1b data.

During the instrument development phase the L1bPP will be executed using the Sentinel-4 UVN Instrument Quality Tool which is essentially a ground data processing system. The product perspective is illustrated in Fig. 5, which shows the data flow and the context of the L1bPP at a high level.

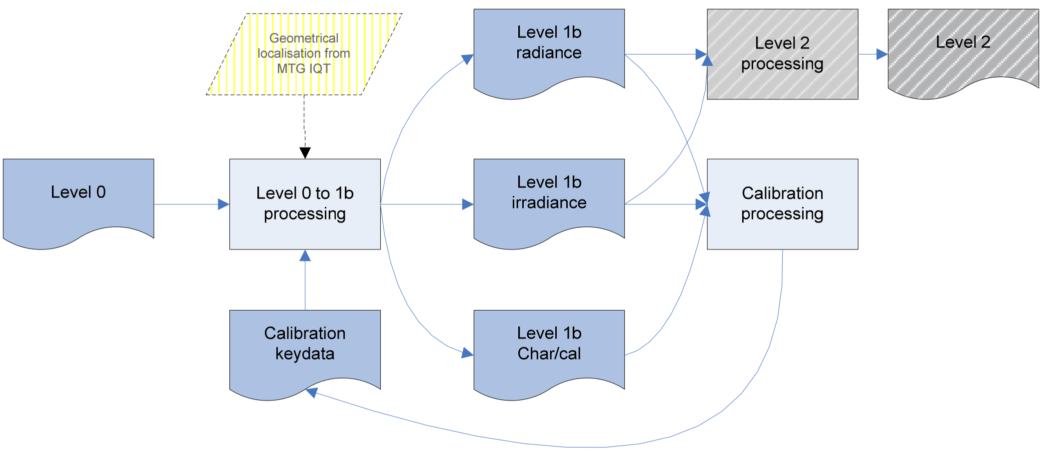

Figure 5: Level 0 to Level 1b product perspective

The shown dataflow in Fig. 5 is a logical data flow; the L1bPP does not actually interface directly with the Level 2 or calibration processing software components. Apart from the Level 2 processing, the generated Level 1b is used for calibration processing. The Level 1b data is used to recalculate and monitor calibration keydata for use in the Level 0 to Level 1b processing for subsequent measurements. This ensures that time dependent changes in the calibration keydata are accounted for, if necessary.

The L1bPP will generate data products like Earth Radiance, Solar Irradiance, Calibrations, Data Processing Parameters File and Star products.

Sentinel-4 Level 2 Data

In a second step the Level 1b products are further processed by the Level 2 processor facility to generate “Core” products and “Innovative” products/data.

This list of Level 2 products comprises

- **Core products** for O3 (total and tropospheric column), NO2 (total and tropospheric column), SO2 (total column), HCHO (total column), and aerosol parameters (vertical profile of the extinction coefficient and column parameters including optical thickness, type, and absorbing

index), cloud parameters (optical thickness, fraction, altitude) and surface reflectance (daily map) and CHOCHO; and
- **Innovative products** for the O3 vertical profile exploiting the synergy between the Sentinel-4/UVN and IRS, and for aerosol and cloud parameters exploiting the synergy between Sentinel-4/UVN and FCI.

The following dependencies are foreseen between the Sentinel-4 L2 products:
- The trace gas (O_3, NO_2, SO_2, HCHO, CHOCHO), aerosol, and cloud products depend on surface data from the daily UVN surface reflectance map (preferred option) or from a climatology (fallback option);
- The trace gas products and the aerosol product depend on cloud data from the Innovative cloud product (preferred option) or from the Core cloud product (fallback option);
- The trace gas products depend on aerosol data from the Innovative aerosol product (first choice), from the Core aerosol product (second choice), or from a climatology (fallback option).

All Level 2 products depend on Sentinel-4/UVN L1b radiance and irradiance data. The Flexible Combined Imager (FCI) Level 2 Cloud Mask (Scenes Analysis) and Cloud Analysis product (SCE/CLA) or the FCI Level 2 Optimal Cloud Analysis (OCA) product (TBC) is foreseen as **optional input** to the Core.

The usage of flags from the FCI SCE/CLA product has the potential of enhancing cloud and aerosol screening. The usage of the FCI OCA cloud product has the potential of enhancing the scattering correction in trace gas retrievals. With this optional input the synergy with FCI can be exploited to a certain extent, already before Innovative aerosol and cloud products are available. The Innovative products depend also on IRS L1b data (O3 profile) and on FCI L1c data (aerosol and cloud parameters).

The data quality of the Sentinel-4 trace gas products is assumed to be enhanced optimally when the Innovative aerosol and cloud products can be used. The Sentinel-4 Core can also be generated 'stand-alone' without relying on any data from IRS or FCI.

For the generation of the Sentinel-4 Level 2 products the following external auxiliary input is required:
- Pressure, temperature, humidity, and density fields from forecast data (in the case of forward processing) or from reanalysis data (in the case of reprocessing) from ECMWF (preferred option), or from a climatology (fallback option);
- A static digital elevation model (TBS);
- NO_2 and O_3 data used as a-piori information for the NO2 and O3 products from chemical forecast model fields from ECMWF (preferred option) or from a climatology (fallback option);
- Sea ice flags from (TBD) included in the Sentinel-4 L1b radiance product.

During the development phase of the Sentinel-4 ground segment the main emphasis will be placed on the Core products however considering the Innovative products in the development logic. Further MTG products are needed and required for the Sentinel-4 Level 2 processing such as
- FCI L1c (spectral sub-set)
- IRS L1b (spectral sub-set)
- FCI L2 Cloud Mask (Scenes Analysis) and Cloud Analysis product (SCE/CLA)
- FCI L2 Optimal Cloud Analysis (OCA)

The spectral sub-set (still to be specified) of FCI Level 1c data contains information on clouds and aerosols and shall be used in the Innovative cloud and aerosol products. The spectral sub-set (still to be specified) of the IRS Level 1b data contains information on the ozone profile and shall be used in the Innovative ozone profile product.

The FCI Level 2 Cloud Mask (Scenes Analysis) and Cloud Analysis product (SCE/CLA) contains flags for cloud, dust storm, fire and volcanic ash detection and shall be used as optional input in Sentinel-4 Level 2 products.

The FCI Level 2 Optimal Cloud Analysis (OCA) product contains information on the cloud optical depth and cloud fraction as well as on drop size, phase, pressure and temperature at the cloud top, and can be used as optional input in Sentinel-4 Level 2 products.

THE SENTINEL-4 SYSTEM OPERATIONS

Sentinel-4 Instrument Operations

The S4/UVN operational baseline consists of a pre-defined sequence of instrument configurations, which are scheduled (repeatedly) in a pre-defined order. This pre-defined sequence of instrument measurement configurations is called “measurement sequence”.

The Sentinel-4 system allows to implement different measurement sequences (daily summer, daily winter, weekly summer, weekly winter, monthly summer, monthly winter and yearly) and a complete update of the measurement sequences nominally with a frequency of once per year.

During the Commissioning phase, the frequency of the measurement sequence updates can be increased up to once per day. Complementary to the nominal mode of operations the S4/UVN Instrument can support the sensing in diagnostic mode.

Sentinel-4 Mission Planning

The present working assumption is that the S4/UVN operations are pre-defined by ESA in close cooperation with EUMETSAT. The operations are defined at high level, e.g. coverage, scan pattern, rather than at telecommand level. After that, the satellite, the S4/UVN instrument and ground segment operations are conducted by EUMETSAT in line with an Operations ICD.

The S4/UVN operations are characterized by the Nominal Earth Observation (NEO) mode. Calibrations modes are foreseen for solar calibration, dark signal calibration, white light calibration, etc. The NEO mode will be pre-defined by the ESA mission management in collaboration with the EUMETSAT MTG operations management before exploitation. For the definition of the NEO mode several aspect need to be taken into account including amongst others satellite orbital position, yaw-flip of the platform, solar ephemeris, and (TBC) constraints imposed by solar calibration.

The NEO mode can be scheduled long time ahead (e.g., months before observation). Requests for modifications to the NEO mode by the ESA mission management will be communicated to the EUMETSAT MTG operations management. The nominal response time for implementation is on the order of a week.

In response to ESA high level mission plan, the S4/UVN mission planning and ground segment scheduling will be performed by EUMETSAT as part of MTG operations. ESA mission management will provide the S4/UVN utilisation plan to EUMETSAT as input to that process. The interface between ESA mission management and EUMETSAT will be procedural.

The MTG System will provide an interactive function to support the planning of all Sentinel-4 operations activities, including at least the capabilities for generation of a master plan, detailing all the satellite and related ground segment activities to be performed, and automatic identification of pre-configured operation constraint violations. The ground segment activities include all the activities performed by the system to support the operational services, including engineering maintenance of equipment that supports these services.

Based on system operations inputs (manual and/or pre-defined) as well as flight dynamic inputs (e.g. events predictions, instruments pointing data), the Mission Planning function will generate consistent and conflict free schedule(s) allowing the commanding operations for a period of one week of satellites and ground stations.

Agreed requests and resulting operations schedules will subsequently be implemented as part of the MTG mission planning system under consideration of constraint files and relevant other information, in particular related to flight dynamics.

CONCLUSIONS

This paper provides an overview of the Sentinel-4 mission, its elements and their implementation both at space and ground segment level. The Sentinel-4/UVN instrument, being embarked on the geo-stationary Meteosat Third Generation Sounder Satellite(s), will allow monitoring continuously the atmospheric composition. Compared to its low Earth orbit predecessor missions, like GOME, SCIAMACHY, OMI, GOME-2 and future missions like Sentinel-5, the Sentinel-4 mission will support and enrich continuously the air quality monitoring and forecast over Europe and Northern Africa with a high revisit time of 1 hour.

The Sentinel-4 ground segment elements are described with its processing modules at Level 1 and Level 2 including a description of the envisaged products. The overall mission operations concept and principles are outlined as they are baselined and defined today in cooperation with EUMETSAT.

ACKNOWLEDGEMENTS

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