THE STATUS OF IMPLEMENTATION OF ESA'S GAS[1] RELATED MISSIONS

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Abstract

Under the leadership of the European Commission (EC), GMES (Global Monitoring for Environment and Security), recently renamed Copernicus, relies largely on data from satellites observing the Earth. The EC, acting on behalf of the European Union (EU), is responsible for the overall initiative, setting requirements and managing the services. The space component of Copernicus is procured by the European Space Agency (ESA). It comprises a series of space-borne missions called 'Sentinels'. Sentinels-4, -5 and -5 precursor (S4, S5, S5p, respectively) address the Copernicus Atmospheric Services. S4 addresses the geostationary (GEO) component, while S5 and S5p will fly in a low earth orbit (LEO).

S5p embarks as single payload an Ultra-violet Visible Near infrared Short-wave infrared (UVNS) spectrometer. The instrument, the TROPOspheric Monitoring Instrument (TROPOMI), is jointly developed by The Netherlands and ESA and will measure key atmospheric constituents including ozone, NO_2, SO_2, CO, CH_4, HCHO as well as clouds and aerosol properties. The TROPOMI concept is based on heritage from both the Ozone Monitoring Instrument (OMI) and the SCanning Imaging Absorption spectroMeter for Atmospheric CartograpHY (SCIAMACHY). S5p will continue the existing high spatial resolution data record of OMI, as well as the short-wave infrared measurements of SCIAMACHY. The planned formation flying with the NPP satellite will enable important synergies, including the use of high spatial resolution imager data for enhanced cloud clearing of the observational data.

With a launch in late 2015, the satellite will be operated in an early afternoon sun-synchronous, polar orbit and will provide information and services on air quality, climate and the ozone layer over an expected lifetime of 7 years. The availability of MetOp, embarking GOME-2 and IASI will provide complementary information on diurnal variability.

The S4 baseline instrument is an Ultra-violet Visible Near infrared (UVN) spectrometer which will be embarked on the geostationary Meteosat Third Generation-Sounder (MTG-S) platforms. The instrument shall observe Europe with a revisit time of one hour. The expected launch date of the first MTG-S platform is 2019, and the expected lifetime is 15 years (two S4/UVN instruments in sequence on two MTG-S platforms).

The key parameters observed by the S4 mission are tropospheric densities of NO_2, O_3, HCHO, SO_2, and aerosols. ESA will develop Level-2 products based on the UVN measurements for these key parameters and for cloud and surface properties as intermediate products. Synergetic O_3 vertical profile product is foreseen based on observations from the UVN and the InfraRed Sounder (IRS) on-board the same platform. Synergetic aerosol and cloud products are foreseen based on observations from the UVN and from the Flexible Combined Imager (FCI) on-board the MTG-Imager (MTG-I) platform. Development activities resulting in the operational S4 Level-2 processor are in preparation.

The S5 baseline instrument is an Ultra-violet Visible Near infrared Short-wave infrared (UVNS) spectrometer which will be embarked on one of the two MetOp-Second Generation (SG) platforms. The key parameters observed by the S5 mission are O_3, SO_2, HCHO, BrO, NO_2, CH_4, CO and cloud and aerosol properties. Feasibility studies for the instrument are completed. It is planned to enter

[1] GAS = GMES (now Copernicus) Atmospheric Service

implementation phase beginning 2014. For S5 scientific activities are centred around requirements consolidation. Foci are at present the optimisation of the Near Infrared (NIR) and of the Short-wave InfraRed (SWIR) parts of the spectrum. In addition, it is planned to investigate the synergy offered by flying together with the infrared sounder (IAS), the multi-viewing/-channel/-polarisation imager (3MI) and MetImage, the baseline imager on-board the same Metop-SG platform.

BACKGROUND

Global Monitoring for Environment and Security (GMES), now renamed Copernicus, has been established to fulfil the growing need amongst European policy-makers to access accurate and timely information services to better manage the environment, understand and mitigate the effects of climate change and ensure civil security.

Under the leadership of the European Commission (EC), Copernicus largely relies on data from satellites observing the Earth. Hence, ESA – in accordance with the European Space Policy – is developing and managing the Space Component for the initiative. The EC, acting on behalf of the European Union (EU), is responsible for the overall initiative, setting user requirements and managing the services.

To ensure the operational provision of Earth-observation data, the Space Component includes a series of five space missions called 'Sentinels', which are being developed by ESA specifically for Copernicus.

In addition, data from satellites that are already in orbit, or are planned will also be used for the initiative. These so-called 'Contributing Missions' include both existing and new satellites, whether owned and operated at European level by the EU, ESA, EUMETSAT and their Member States, or on a national basis. They also include data acquired from non-European partners. The Space Component forms the European contribution to the worldwide Global Earth Observation System of Systems (GEOSS).

The background including mission requirements related to the atmospheric composition and to S-4, -5 and -5p has been explained in earlier papers, e.g. Ingmann et al (2012a, 2012b), and will only briefly be touched on in this paper.

THE ATMOSPHERIC SENTINELS: SENTINEL-4, SENTINEL-5 AND SENTINEL-5P

The general framework for spaceborne atmospheric composition measurements in synergy with ground-based and airborne measurements and integration with atmospheric models and data assimilation schemes has been outlined in the IGOS Integrated Global Atmospheric Chemistry Observation (IGACO) Theme Report (Barry and Langen, 2004). That document included quantitative observation requirements, summarised for scientific and operational applications. Several other efforts have been made to identify the needs of long-term atmospheric composition data, such as the Eumetsat position paper on observation requirements for nowcasting and very short range forecasting in 2015-2025 (Golding et al., 2003), and the results of EUMETSAT requirements processes for operational atmospheric chemistry monitoring in the EPS second generation time frame (Kelder et al., 2006).

An ESA study on Operational Atmospheric Chemistry Monitoring Missions (CAPACITY) (Kelder et al., 2005) gathered all available inputs and generated comprehensive observational requirements by environmental theme, by user group, and by observational system (ground / satellite) primarily at product level, i.e. Level-2. This included an extensive assessment of the capabilities of spaceborne atmospheric chemistry instrumentation, either already existing or proposed for Sentinels-4, -5 and -5p, It also addresses observational requirements, a prioritisation of observational capabilities per application as well as further references justifying individual specifications for suggested space instruments.

Based on Kelder et al. (2005) the following implementation priorities had been recommended with respect to operational atmospheric composition monitoring:

- A satellite with UV-VIS-NIR (UVN), SWIR and TIR observational capabilities, also using auxiliary cloud and aerosol data, which serves air quality and climate protocol monitoring in LEO. This satellite complies with all temporal sampling / geographical coverage requirement scenarios and will provide continuity and improvement with respect to the OMI and Sciamachy missions. From the considered orbit scenarios, namely sun-synchronous or low inclination, the sun-synchronous option was chosen.

- An extension of this mission is to obtain regularly ≤ 1 hour revisit time as required for air quality applications. This extension would consist of a GEO platform carrying instrumentation with similar Level-1b performance specifications. It was decided to implement this mission, in addition to one LEO platform as specified under the first item.

Following recommendations expressed in and based on high level agreements, Sentinels-4 and -5 will get implemented as additional payloads on Eumetsat platforms, as follows.

- S-4 will be a realised as

  ➔ addition of a Ultra-violet Visible Near-infrared (UVN) spectrometer on the MTG-S platform series;

  ➔ plus utilisation of TIR data from the IR sounder (IRS) onboard the same platform series; and

  ➔ plus utilisation of Flexible Combined Imager (FCI) data from the MTG-I platform series.

- S-5 will consist of

  ➔ a UVN and SWIR (UVNS) spectrometer embarked on one of the MetOp-Second Generation (MOSG, space segment) or EPS-Second Generation (European Polar System, EPS-SG, full system) platforms;

  ➔ plus the implementation of the S-5 IR sounding requirements via the MOSG IR sounder (IAS);

  ➔ plus the utilisation of MOSG VIS/IR imager data (VII); and

  ➔ plus the utilisation of MOSG Multi-Viewing Multi-Channel Multi-Polarisation Imager (3MI).

The expected launch dates for MTG-S (2019) and MOSG (2020) imply a data gap following the end of life of the EOS-Aura mission (< 2014, including OMI and TES), affecting in particular short-wave measurements with sufficient quality for tropospheric applications. Hence, the need for an additional mission was identified, i.e. S5p.

The payload of S5p shall satisfy the requirements provided above for the S5 UVNS spectrometers with some exceptions including:

- the time frame - the precursor mission shall be operated from 2015 with a life-time of 7 years;

- the precursor shall include the UVN and one SWIR spectral band required for the S5 mission. Considering the transitional nature of the precursor and the availability of TIR data - albeit with reduced quality - from IASI, it is acceptable not to consider any S5 TIR instrument for the precursor.

S5p shall be flown on a sun-synchronous low Earth orbit (LEO) with an equator crossing mean local solar time of 13:35 h in loose formation with Suomi-NPP (S-NPP) allowing initial observations of the diurnal variation by exploiting the complementary GOME-2 early morning observations.

A thorough discussion of the S4, S5, and S5p mission requirements can be found in the S-4/S-5 mission requirements traceability document (ESA, 2012).

STATUS OF THE ATMOSPHERIC SENTINELS

Sentinel-5p (S5p)

Sentinel-5p (S5p) is being implemented within ESA's Copernicus programme with a major Dutch national contribution. The basic design is based on the TROPospheric Ozone Monitoring Instrument (TROPOMI), an ultraviolet-visible-near-infrared-short-wave-infrared (UVNS) instrument, successor of OMI on NASA's EOS-Aura platform. With respect to OMI, TROPOMI will also provide near-infrared and short-wave infrared coverage. In addition, the higher spatial resolution will increase the proportion of cloud-free samples. The tentative launch date is second half 2015. S5p will be operated in loose formation with NASA's S-NPP spacecraft. S5p will follow S-NPP with a five minute along track separation allowing the use of co-located cloud imager data of VIIRS (on board S-NPP) in routine Level 2 processing tasks.

Besides the hardware development, algorithm development for Level-2 products is underway. The species listed in table 1 shall be considered in the context of the Sentinel-5p mission split into mandatory (or core) and optional products.

Table 1: Sentinel-5p Level-2 products

	Total Column	Tropospheric Column	Profile
Mandatory Products			
Ozone - O_3	Yes	Yes	Yes
Nitrogen dioxide - NO_2	Yes	Yes	No
Sulphur dioxide - SO_2	Yes	No	No
Formaldehyde - HCHO	Yes	No	No
Carbon monoxide - CO	Yes	No	No
Methane - CH_4	Yes	No	No
Aerosols *(aerosol index, layer height)*	Yes		
Clouds *(optical depth, layer height)*	Yes		
Optional Products			
Water vapour - H_2O	Yes	No	No
Glyoxal – CHOCHO	Yes	No	No
Bromine monoxide - BrO	Yes	No	No
Chlorine dioxide - OClO	Yes	No	No
Deuterated water/water ratio - HDO/H_2O	Yes	No	No
UV Index	Yes	No	No
Aerosol Optical Depth AOD	Yes		

Algorithm Theoretical Baseline Documents (ATBDs) have been tabled for the various products and undergone peer review earlier this year. The S5p satellite and ground system is expected to be ready for a launch in mid-2015.

Sentinel-4 (S4)

Within the Copernicus space component, S4 covers the need for continuous monitoring of atmospheric composition. The S4 ultraviolet-visible-near-infrared (UVN) instrument is entirely new. 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 with a high revisit time (~1 hour).

This list of Level 2 products comprises

- Core products for O_3 (total and tropospheric column), NO_2 (total and tropospheric column),SO_2 (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
- Optional products for the O_3 vertical profile exploiting the synergy between the S4/UVN and IRS, and for aerosol and cloud parameters exploiting the synergy between S4/UVN and FCI.

The following dependencies are foreseen between the S4 Level-2 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 (fall-back option);
- The trace gas products and the aerosol product depend on cloud data from the optional cloud product (preferred option) or from the Core cloud product (fall-back option);
- The trace gas products depend on aerosol data from the optional aerosol product (first choice), from the Core aerosol product (second choice), or from a climatology (fall-back option).

All Level-2 products depend on S4/UVN Level-1b 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.

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 (O_3 profile) and on FCI L1c data (aerosol and cloud parameters).

The data quality of the S4 trace gas products is assumed to be enhanced optimally when the innovative aerosol and cloud products can be used. However, the Sentinel-4 Core can also be generated ‘stand-alone’, i.e. without relying on any data from IRS or FCI.

For the generation of the S4 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 (fall-back option);
- A static digital elevation model (to be specified, TBS);
- NO_2 and O_3 data used as a-piori information for the NO_2 and O_3 products from chemical forecast model fields from ECMWF (preferred option) or from a climatology (fall-back option);
- Sea ice flags from (TBD) included in the S4 L1b radiance product.

During the development phase of the S4 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 S4 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 TBS) 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 TBS) 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 S4 Level 2 products.

Sentinel-5 (S5)

The Sentinel-5 (S5) UVNS instruments are planned to be provided to a future operational programme in preparation by EUMETSAT for embarkation on the MOSG satellites as CFIs, a concept similar to S4/UVN on MTG satellites. Preparatory activities have been approved. Feasibility studies for S5/UVNS finished in 2013. The tentative launch date of the first unit is 2020.

The S5/UVNS instrument is a high resolution spectrometer based on experience gained with instruments like SCIAMACHY, OMI and GOME. The S5 requirements for TIR will be met by making use of the IAS (infrared sounder) on-board MOSG. In addition, and in order to meet the service needs, S5 shall utilise MOSG VIS/IR imager (VII) and Multi-Viewing Multi-Channel Multi-Polarisation Imager (3MI) data.

S5 Supporting Studies

Table 2 summarises the expected Level-2 products from the S5 mission. They are tentative at present and need further consolidation. In particular, the species identified but also the uncertainty levels provided are a first guess and are planned to get consolidated via studies.

Table 2: GMES-Sentinel-5 Expected Level-2 Data Products
Species have been ordered by wavelengths. Priority 1 is highest (FT = free troposphere).
Uncertainties apply to polluted conditions, detection only is required for background conditions

Level-2 data product	Wavelength range [nm]	Priority	Uncertainty (*)
Ozone vertical profile, O_3	270 – 330	1	10% PBL column, 25% tropospheric column
Sulphur dioxide, SO_2	308 – 325	1	20% PBL column
Albedo	310 – 775	2	0.1
Total ozone, O_3	325 – 337	1	3-5%
Aerosol	336 – 340, 400-430, 440-460	2	AOD: 0.05 or <10% mis-assignments
Formaldehyde, HCHO	337 – 360	1	20% PBL column
Bromine monoxide, BrO	345 – 360	2	30%
Rayleigh scattering (cloud), aerosol absorption	360 – 400	2	*Internal product; no explicit requirement*
Nitrogen dioxide, NO_2	405 – 500	1	10% PBL column
Glyoxal, CHOCHO	430 – 460	2	N/A
Cloud (O_2-O_2)	460 – 490	1	*Internal product, no explicit requirement*
Water vapour and cloud (effective scattering height)	685 - 710	2	10% for water vapour
Cloud (O_2-A band)	755 – 773	1	*Internal product, no explicit requirement.*
Aerosol profile (O_2-A band)	755 – 773	1	0.05 optical depth PBL column, FT column, and tropospheric column
Methane, CH_4	1590–1675	1	2%
Carbon dioxide, CO_2	1590–1675	2	0.5%
Aerosol profile	1940–2030	3	0.05 optical depth PBL column, FT column, and tropospheric column
Carbon Monoxide, CO	2305–2385	1	25% tropospheric column, 25% total

			column

(*) Expected uncertainty levels are based on study results, i.e. CAPACITY (Kelder et al, 2005) and CAMELOT(Levelt et al, 2009)

The Level-2 products identified require synergetic retrievals based on various bands with the UVNS instruments but also observations from other instruments on-board of MOSG:

- ozone from a combination of UV and TIR bands,
- CO from combination of the SWIR and the TIR bands,
- CH_4 from combination of the SWIR and the TIR bands,
- cloud information from NIR (i.e., O_2-A) band used in UV-VIS and SWIR retrievals,
- cloud information from VII used in UV-VIS, SWIR and TIR retrievals,
- refined cloud characterisation from the combination of all instruments,
- aerosol information from UVN and 3MI, also used in trace gas retrievals in UV-VIS
- aerosol information from UVN and TIR, also used in trace gas retrievals in UV-VIS

The study focussing on the NIR part addresses the optimisation of the mission requirements that allow an implementation of

- either a NIR-2 band covering a limited spectral range from 755–773 nm but with a high spectral resolution of 0.12 nm or better; in this case the implementation of the NIR-1 band is not mandatory;
- or both a NIR-1 and a NIR-2 band covering a broad spectral range from 685–773 nm; in this case the threshold spectral resolution of 0.4 nm is sufficient.

The implications of this trade-off between spectral coverage and spectral resolution in the NIR spectral domain on the L2 products is assessed.

The study focusing on the SWIR part aims at a consolidation of the requirements relevant to this band. The consolidation of the mission requirements is related to the primary (CH_4, CO) and secondary (H_2O and CO_2) SWIR products.

The performance of SWIR trace gas retrievals is assessed and covers retrievals of

- CH_4 and CO_2 using the SWIR-1 and the NIR-2 band,
- CO, CH_4, and H_2O using the SWIR-3 and the NIR band (lower resolution),
- CH_4 using the SWIR-3 and the NIR-2 band, and
- CH_4 using the SWIR-1, the SWIR-3 and the NIR-2 band.

CONCLUSIONS

The status of implementation of the dedicated space component for the atmospheric composition service of Copernicus has been outlined. The nature and origin of the requirements but also the programmatic background for implementing the Copernicus Atmospheric Services related missions have been explained.

The implementation of the atmospheric composition element of Copernicus Space Component, i.e. S5p, S4 and S5, is well underway. Due to the nature of the programme and related to the programmatic frame, the missions are in different stages of development. S5p, due to the preparatory work performed at national level in the Netherlands, is in a rather advanced status. The situation is rather similar for S4 in line with the maturity of the MTG programme. For S5 the situation is somewhat more open, as the mission complement is about to enter the implementation phase.

The successive operational implementation of the various elements is expected in the period between 2015 and 2020 with S5p first launched (2015), followed by S4 (as of 2019) and then S5 (as of 2020).

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