THE STATUS OF IMPLEMENTATION OF THE ATMOSPHERIC COMPOSITION RELATED GMES MISSIONS SENTINEL-4, SENTINEL-5 AND SENTINEL-5P

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Abstract

The space component of GMES (Global Monitoring for Environment and Security) is procured by the European Space Agency (ESA) and comprises a series of space-borne missions called 'Sentinels'. While Sentinels-1,-2 and -3 are focusing on ocean, ice and land surface related topics, Sentinels-5 precursor, -4 and -5 (S-5p, S-4, S-5) address atmospheric composition, S-4 from a geostationary orbit (GEO), while S-5 and S-5p fly in a low earth orbit (LEO).

The objective of S-4 is to monitor key air quality trace gases and aerosols over Europe at high spatial resolution with a fast (hourly) revisit time in support of the GMES Atmosphere Service. The objective of the LEO missions, S-5 and S-5p, is to measure daily at global scale and high spatial resolution air quality and climate related trace gases and aerosols in the Earth's atmosphere. The target species including O_3, NO_2, SO_2, HCHO and aerosols shall be observed to support operational services covering air-quality near real-time applications, air-quality protocol monitoring and climate protocol monitoring. The S-4 system consists of an Ultra-violet Visible Near-infrared (UVN) imaging spectrometer embarked on EUMETSAT's geostationary MTG-S platforms and relies on the utilisation of subsets of data from EUMETSAT's IRS sounder on-board the same platforms and from EUMETSAT's FCI imager on-board the MTG-I platforms. S-5 UVN and SWIR (UVNS) is planned to be embarked on EUMETSAT's EPS-SG series of satellites, while S-5p will fly on a dedicated platform.

S-5p and S-4 have entered their implementation phase, i.e. Phase B2/C/D, while S-5 has advanced into feasibility study (Phase A/B1). For S-4 supporting studies focusing on retrieval algorithm prototyping and for S-5p on Level-2 product development are in preparation. For S-5 scientific activities are centred around requirements consolidation. Recently, a short study on the potential of the S-5 mission to monitor carbon dioxide was conducted (Chimot et al, 2011). The main result for the current S-5 baseline configuration is that random errors meet breakthrough user requirement, while systematic errors are only compliant with threshold requirements on a global to regional scale. Scattering effects are understood to be the main contributors to these systematic errors. An optimization of the mission for CO_2 monitoring to meet breakthrough requirements and to perform monitoring on a local scale would require substantial changes to the baseline such as improvements of the spectral sampling and/or an additional channel, which are incompatible with the S-5 UVNS instrument constraints for embarkation on EUMETSAT's post-EPS series of satellites.

The presentation at the upcoming conference will focus on the status of implementation of the atmospheric composition related Sentinels, in particular on the preparation of the missions at user level.

BACKGROUND

Atmospheric chemistry observations from space have been made for more than 30 years. They have been motivated by the concern about a number of environmental issues. However, most of the space instruments have been designed for scientific research, improving the understanding of processes that govern stratospheric ozone depletion, climate change and the transport of pollutants starting with the BUV instrument on Nimbus-4. Long-term continuous time series of atmospheric trace gas data have been limited to stratospheric ozone and a few related species. According to current planning, meteorological satellites will maintain some of these observations over the next decade. They will also add some measurements of tropospheric climate-relevant gases. As their measurements are motivated by meeting operational meteorology needs, they fall short in meeting requirements for atmospheric chemistry applications.

The general framework for use of 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-IGACO Theme Report (Barrie and Langen, 2004). That document includes also 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 GMES-GATO strategy report (2004), the EUMETSAT position paper on observation requirements for nowcasting and very short range forecasting in 2015-2025 (Golding et al., 2003), and a EUMETSAT commissioned study to identify requirements for geostationary platforms (GEO) in the context of Meteosat Third Generation (Lelieveld, 2003).

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). The study also assessed the contributions of existing missions to the fulfilment of these requirements, and prioritised observational techniques for future atmospheric composition missions. The study focused on Level-2, i.e. geophysical products. Tentative requirements at radiance level (Level-1) and other instrument and system related requirements were also identified. These requirements rely partly on the experience with the usage of existing similar instrumentation, and partly on retrieval simulations.

Requirements at radiance level have been further investigated in the frame of ad-hoc expert meetings. Results of EUMETSAT requirement processes in the frame of MTG (EUMETSAT, 2007) and EPS-SG missions, i.e. Kelder et al., (2006), and EUMETSAT (2010), have also been taken into account.

Another ESA study, CAMELOT, has been performed in order to consolidate mission requirements for Sentinels-4, -5, and -5p (S-4, S-5 and S-5p, Levelt et al., 2009). The key objective of the CAMELOT study was to contribute to the definition of the air quality and climate protocol monitoring parts of future missions in the time frame 2012-2020. In particular, the user requirements derived in CAPACITY were assessed within the CAMELOT study relying on the user requirements for air quality protocol monitoring, air-quality near-real-time applications, and climate protocol monitoring.

The need for space based atmospheric composition monitoring will be addressed by a variety of instruments. A significant contribution will be provided by the GMES (Global Monitoring for Environment and Security) S-4 and -5 systems where S-4 provides a geosynchronous component with a European focus and S-5 a low Earth orbiting component with global coverage. S-5p will bridge the gap between existing missions, i.e. Sciamachy on Envisat and OMI on EOS-Aura, and S-5, and in conjunction with GOME-2 on MetOp will provide initial diurnal sampling bridging toward S-4.

Global Monitoring for Environment and Security (GMES) 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), GMES relies largely 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 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 GMES.

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(n) (inter-) national basis, which also includes 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 had been explained in earlier papers, i.e. Ingmann et al, (2008, 2009, 2010, 2012) and will only briefly be touched on in this paper.

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

Based on the preparatory work performed by Kelder et al., (2005) the following implementation elements have been recommended:

1. High temporal and spatial resolution space-based measurements of tropospheric composition, including the planetary boundary layer (PBL), for air quality applications,

2. High spatial resolution and high precision monitoring of tropospheric climate gases (CH_4, CO (precursor) and CO_2) and aerosols with sensitivity to PBL concentrations for climate protocol monitoring,

3. High vertical resolution measurements in the upper troposphere/lower stratosphere region for stratospheric ozone/surface UV and climate near-real time and assessment applications.

Following recommendations expressed in GAS (2009) and based on high level agreements, S-4 will and S-5 is expected to 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 platforms;
  - ➔ utilisation of TIR data from the IR sounder (IRS) onboard the same platforms; and
  - ➔ utilisation of Flexible Combined Imager (FCI) data from the MTG-I platforms.
- S-5 will consist of
  - ➔ a UVN and SWIR (UVNS) spectrometer embarked on the EPS Second Generation platforms;
  - ➔ the implementation of the S-5 IR sounding requirements within the EPS Second Generation IR sounder (IRS);

- ➔ utilisation of EPS Second Generation VIS/IR imager data (VII); and
- ➔ utilisation of EPS Second Generation Multi-Viewing Multi-Channel Multi-Polarisation Imager (3MI).

Concerning the third element, it has been concluded that it is premature to embark on an operational limb sounding mission at this stage.

The expected launch dates for MTG-S (2018) and EPS-SG (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. S-5p.

The payload of S-5p shall satisfy the requirements provided above for the S-5 UVNS spectrometers with the following exceptions:

- the time frame of the precursor mission being 2015-2020;
- the precursor shall include the UVN and the SWIR-3 spectral bands required for the S-5 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 the S-5 TIR instrument on the precursor;
- auxiliary data from the VII and 3MI will not be available.

S-5p shall be flown on a sun-synchronous low Earth orbit (LEO) with an equator crossing mean local solar time of 13:30h allowing initial observations of the diurnal variation by exploiting the complementary GOME-2 early morning observations.

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

STATUS OF THE ATMOSPHERIC SENTINELS

Sentinel-5p (S-5p)

Sentinel-5p (S-5p) will be implemented within ESA’s GMES programme with a major Dutch national contribution. The basic design is based on the TROPospheric Ozone Monitoring Instrument (TROPOMI), a 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 TROPOMI (=national) project is approaching the end of the detailed design phase and concluded with an instrument preliminary design review (IPDR) in spring 2011. The system level feasibility study was kicked-off in summer 2010 and has entered implementation phase. The tentative launch date is mid-2015. It is planned to fly S-5p in loose formation flying with Suomi-NPP where S-5p will follow NPP with a 5 minute delay in order to get the coincident imager data of VIIRS.

Sentinel-4 (S-4)

The Sentinel-4 (S-4) observation capability is defined as the S-4/UVN instrument(s) and utilization of a subset of data from the FCI instruments on MTG-I and the IRS instruments on MTG-S. The IRS and the FCI instruments are core EUMETSAT payloads designed primarily to provide meteorological information for the Nowcasting (priority one) and Numerical Weather Prediction (NWP) communities.

The S-4/UVN instruments are procured within the ESA GMES programme. They will be provided to the MTG programme for embarkation on the MTG-Sounder (MTG-S) satellite as a Customer

Furnished Item (CFI), fully verified and qualified together with its necessary ground support equipment, test models and system deliverable inputs.

The S-4/UVN project has started with the detailed design phase in the first quarter of 2011. The present target dates for the delivery of the instruments to the MTG programme are 2016 for the first flight model and 2018 for the second flight model.

Planned launch date of the first MTG-S satellite is 2018. The second satellite is expected to be launched in 2027.

The S-4/UVN instrument is an imaging spectrometer covering the ultraviolet (305-400 nm), visible (400-500 nm) and near-infrared (750-775 nm) bands. The spatial sampling is 8 km at 45 degrees North (0˚ longitude) with a spectral resolution between 0.12 nm and 0.5 nm depending on the spectral band. The S-4/UVN instrument is a push-broom imaging spectrometer that scans Europe in the East-West direction with a repeat cycle of 60 minutes with field-of-regard of ~6.8˚ in the East-West direction and ~3.6˚ in the North-South direction. Table 1 gives an overview of the characteristics of the S-4 UV to NIR bands.

<table>
<tr><th>Band ID</th><th>Bands
[nm]</th><th>Spectral Resolution
[nm]</th><th>Spectral Sampling Ratio</th><th>Spatial Sampling Distance at 45N, 0E
[km]</th></tr>
<tr><td>GEO-UV</td><td>305-400</td><td>0.5</td><td rowspan="3">3</td><td rowspan="3">8</td></tr>
<tr><td>GEO-VIS</td><td>400-500</td><td>0.5</td></tr>
<tr><td>GEO-NIR</td><td>750-775</td><td>0.12</td></tr>
</table>

Table 1: **S-4/UVN observation requirements**

Sentinel-5 (S-5)

The Sentinel-5 (S-5)/UVNS instruments are planned to be provided to a future operational programme in preparation by EUMETSAT for embarkation on the EPS-SG satellites as CFIs, similar to S-4/UVN. Preparatory activities have been approved. Feasibility studies for S-5/UVNS have started in 2011. Final approval and funding are expected in the 2012/13 time-frame by ESA and EUMETSAT. The tentative launch date of the first unit is 2020.

The S-5/UVNS instrument is a high resolution spectrometer covering the ultraviolet (305-370 nm), visible (370-500 nm), visible/near-infrared (685-710, 750-775 nm), and short-wave infrared bands (1590-1675 nm, 1940-2030 nm, 2305-2385 nm). The spatial sampling shall be 15 km threshold (T) and 5 km goal (G) for most of the bands and the spectral resolution between 0.4 nm and 1.0 nm (all T values) depending on the spectral band.

Table 2 gives an overview of the characteristics of the S-5/UVNS for the UV to SWIR bands (cf table 1).

<table>
<tr><th>Band ID</th><th>Spectral Range
[nm]</th><th>Spectral Resolution [nm]</th><th>Priority</th><th>Spectral Sampling Ratio</th><th>Spatial Sampling Distance at nadir
[km]</th></tr>
<tr><td>LEO-UV-1</td><td>270-300</td><td>1.0</td><td>1</td><td rowspan="8">3</td><td>50 km (T) / 15 km (G)</td></tr>
<tr><td>LEO-UV-2</td><td>300-370</td><td>0.5</td><td>1</td><td rowspan="7">15 km (T) / 5 km (G)</td></tr>
<tr><td>LEO-VIS</td><td>370-500</td><td>0.5</td><td>1</td></tr>
<tr><td>LEO-NIR-1</td><td>685–710</td><td>0.4 (T) / 0.2 (G)</td><td>1</td></tr>
<tr><td>LEO-NIR-2</td><td>750–775</td><td>0.4 (T) / 0.12 (G)</td><td>1</td></tr>
<tr><td>LEO-SWIR-1</td><td>1590–1675</td><td>0.25</td><td>1</td></tr>
<tr><td>LEO-SWIR-2</td><td>1940–2030</td><td>0.25</td><td>3</td></tr>
<tr><td>LEO-SWIR-3</td><td>2305–2385</td><td>0.25</td><td>1</td></tr>
</table>

Table 2: **S-5/UVNS observation requirements per spectral band**

S-5 CO_2 Capability

For S-5, a study was commissioned to investigate to what extent CO_2 related requirements could be met by either using S-5/UVNS as is or by adding observational capabilities (Chimot et al, , 2011). For this purpose three applications had been identified, namely

- **Application 1**: Monitoring total net CO_2 surface fluxes (natural and anthropogenic) at global to regional scale (~500-1000 km)
- **Application 2**: Monitoring anthropogenic city CO_2 surface emissions at city scale (~20-50 km)
- **Application 3**: Monitoring large anthropogenic CO_2 point sources (e.g. emissions by power plants) at local / point scale (~1km)

The corresponding user requirements are listed in table 3. Errors are expressed as errors relative to column averaged CO_2, usually referred to as XCO_2.

	Spatial resolution		**Random error ("precision")**		**Systematic error (*) ("accuracy")**	
	km		ppm		ppm	
	Threshold	**Goal**	**Threshold**	**Goal**	**Threshold**	**Goal**
Application 1	10	5	4	2	2	0.2
Application 2	10	5	2	1	2	0.2
Application 3	2	1	2	1	2	0.2

Table 3: **Requirements per application**

(*) threshold requirement may be acceptable if it is demonstrated that XCO_2 systematic error for a given space-borne does not present a regional spatial/temporal structure

For the baseline mission the results are listed in table 4 (YES = compatible, NO = not compliant with requirements)

<table>
<tr><th></th><th colspan="2">Spatial resolution</th><th colspan="2">Random error ("precision")</th><th colspan="2">Systematic error ("accuracy")</th></tr>
<tr><td></td><td colspan="2">km</td><td colspan="2">ppm</td><td colspan="2">ppm</td></tr>
<tr><td></td><td>Threshold</td><td>Goal</td><td>Threshold</td><td>Goal</td><td>Threshold</td><td>Goal</td></tr>
<tr><td>Application 1</td><td>YES</td><td>NO</td><td>OK</td><td>OK</td><td rowspan="3">marginally compliant</td><td>NO</td></tr>
<tr><td>Application 2</td><td>NO</td><td>NO</td><td>OK</td><td>NO</td><td>NO</td></tr>
<tr><td>Application 3</td><td>NO</td><td>NO</td><td>OK</td><td>NO</td><td>NO</td></tr>
</table>

Table 4: **Estimated S-5/UVNS performance per application**

The difficulties of the XCO_2 retrievals are mainly related to high XCO_2 systematic errors ("accuracy"). Derived from S-5 spectral measurements they are related to major scattering effects and are not well enough reduced by the retrieval due to lack of information from the NIR-2 and SWIR-2 channels. Corresponding recommendations, focused on enhancements of the S-5/UVNS instrument specifications, would be needed to mitigate this impact. This would imply the addition of the SWIR-2 channel (now priority 3) and a higher spectral resolution in NIR-2, i.e. goal, see table 2.

Technical assessment showed that the implementation of these additional capabilities will lead to an instrument concept not compatible with the Metop-SG constraints both in terms of resources and development risk. It has therefore been decided to discard any specific CO_2 related requirements for S-5/UVNS instruments.

S-5p and S-4 Products
The expected products from S-5p and S-4 are summarised in tables 5 and 6.

Driving applications for S-5p are air quality and climate.

Product	Application			Comment
	Air Quality	Climate	Surface UV	
O_3 total & trop. column	X		X	
O_3 profile	X		X	
NO_2 total & trop. column	X			
SO_2 total column	X			Also for volcanic eruptions
CH_2O total column	X			
CO total column	X	X		
CH_4 total column		X		
Aerosol extinction coeff. profile, column optical depth / type / index	X	X		Also auxiliary for other S-5p products Also for volcanic eruptions **Synergy with VIIRS on NPP**
Cloud optical thickness, fraction, altitude			X	Mainly auxiliary for other S-5p products **Synergy with VIIRS on NPP**

Table 5: **S-5p Level-2 baseline products (blue colour indicates driving application) – synergy with VIIRS on NPP is expected via a loose formation flying concept**

In addition to the species listed in table 5, there is a number of pre-operational products envisaged for S-5p including H_2O, CHOCHO, BrO, OClO and the HDO/H_2O ratio.

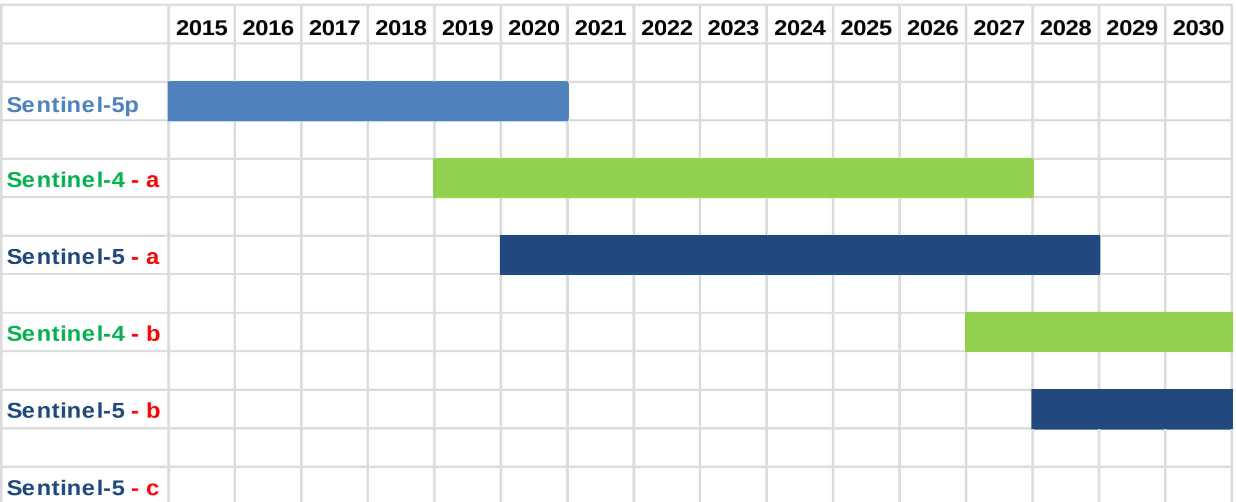
Driving application for S-4 is air quality.

Product	Application			Comment
	Air Quality	Climate	Surface UV	
O_3 total & trop. column	X		X	
O_3 profile	X		X	**Synergy with infrared data from IRS**
NO_2 total & trop. column	X			
SO_2 total column	X			Also for volcanic eruption monitoring
CHOCHO total column	X			By-product
CH_2O total column	X			
Aerosol extinction coeff. profile, column optical depth / type / index	X	X		Also for volcanic eruption monitoring Also auxiliary for other S4 products **Synergy with imager data from FCI**
Cloud optical thickness, fraction, altitude			X	Mainly auxiliary for other S4 products **Synergy with imager data from FCI**
Surface reflectance daily map			X	Mainly auxiliary for other S4 products

Table 6: **S-4 Level-2 Products targeted (blue colour indicates driving application) – synergy with IRS on MTG-S and FCI on MTG-I are expected via EUMETSAT**

SCHEDULE

The tentative overall launch schedule of the atmospheric sentinels is as follows:



Note: The third S-5/UVNS instrument is expected to be launched well beyond 2030.

CONCLUSIONS

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

The implementation of the atmospheric composition element of GMES Space Component, i.e. S-5p, S-4 and S-5, is well underway. Due to the nature of the programme and related to the programmatic frame, the missions are in different stages of development. S-4 is in a rather advanced status in line with the maturity of the MTG programme. The situation is rather similar for S-5p due to the preparatory work performed at national level in the Netherlands. For S-5, the situation is much more open as the mission complement is still in the payload selection phase and a corresponding budget needs to be allocated before entering the implementation phase.

The successive operational implementation of the various elements is expected in the period between 2015 and 2020 with S-5p first launched (2015), followed by S-4 (as of 2018) and then S-5 (as of 2020).

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