# *MTG-S IRS Science Plan*

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# 1 INTRODUCTION

The following science plan describes in detail the MTG-S IRS mission concept and its scientific objectives. The document has been prepared collaboratively by the IRS Mission Advisory Group (MAG), which gathers experts from meteorological agencies and research entities under the coordination of EUMETSAT.

## 1.1 Scope

The document is aimed at providing a detailed overview of IRS capabilities and aeras of applications to the general public as well as future IRS data users.

## 1.2 Reference Documents

All websites and references are listed in section 7 of the document.

## 1.3 Terminology

### Acronyms and Abbreviations

| **Acronym/Abbr.** | **Explanation** |
|---|---|
| AC | Atmospheric Composition |
| AQ | Air Quality |
| AMV | Atmospheric Motion Vector |
| BB | Black Body |
| BT | Brightness Temperature |
| CAMS | Copernicus Atmospheric Monitoring Service |
| CDR | Climate Data Record |
| CMA | Chinese Meteorological Administration |
| CO2M | Copernicus Anthropogenic Carbon Dioxide Monitoring |
| CrIS | Cross-track Infrared Sounder |
| DS | Deep Space |
| ECV | Essential Climate Variable |
| EPS | EUMETSAT Polar System |
| EPS-SG | EPS Second Generation |
| EURD | End Users Requirements Document |
| EV | Earth View |
| FCI | Flexible Combined Imager |
| FDHSI | Full Disc High Spectral Imagery |
| FIM | Flip-In Mirror |
| FOV | Field Of View |
| GEO | GEostationary Orbit |
| GHG | GreenHouse Gas |
| GIIRS | Geostationary Interferometric InfraRed Sounder |
| HIRAS | Hyperspectral InfraRed Atmospheric Sounder |
| IASI | Infrared Atmospheric Sounder Interferometer |
| IASI-NG | IASI Nouvelle Génération |
| iFTS | imaging Fourier Transform Spectrometer |
| IR | InfraRed |
| IRIS | IR Interferometer Spectrometer |

| Acronym/Abbr. | Explanation |
|---|---|
| AC | Atmospheric Composition |
| IRS | IR Sounder |
| LAC | Local Area Coverage |
| LEO | Low-Earth Orbit |
| LI | Lightning Imager |
| LWIR | LongWave IR |
| MFG | Meteosat First Generation |
| MSG | Meteosat Second Generation |
| MTG-I | Meteosat Third Generation-Imaging |
| MTG-S | Meteosat Third Generation-Sounding |
| MWIR | MediumWave IR |
| NIR | Near-IR |
| NOAA | National Oceanic and Atmospheric Administration |
| NWC | Nowcasting |
| NWP | Numerical Weather Prediction |
| OPD | Optical Path Difference |
| PC | Principal Component |
| PCA | PC Analysis |
| PCS | PC Score |
| PCC | PC Compression |
| RSS | Rapid Scan Service |
| RTM | Radiative Transfer Model |
| SAF | Satellite Application Facility |
| SEVIRI | Spinning Enhanced Visible and IR Imager |
| SRF | Spectral Response Function |
| SWIR | ShortWave IR |
| TB | TeraByte |
| TIR | Thermal IR |
| UVN | UltraViolet and Near-infrared |
| VIS | VISible |
| VOCs | Volatile Organic Compounds |
| VSRF | Very Short-Range Forecasting |
| 3MI | Multi-viewing Multi-channel Multi-polarisation imager |

# 2 RATIONALE FOR IRS AND SYSTEM DESCRIPTION

EUMETSAT currently contributes to the Global Observing System of the World Meteorological Organisation with the series of Metop satellites forming the EUMETSAT Polar System (EPS). Each of these platforms has been embarking the IASI instrument, a Fourier transform spectrometer providing hyperspectral InfraRed (IR) soundings of the atmosphere from the polar orbit. The continuity in time of such observations will be ensured by IASI-NG ("Nouvelle Génération") aboard EPS-SG ("Second Generation"), doubling the spectral resolution of the measurements while dividing radiometric noise by two with respect to IASI (Crevoisier et al., 2014).

In addition, EUMETSAT will introduce by 2026 a novel viewpoint with acquisitions of hyperspectral IR soundings analogous to IASI and IASI-NG but from the Geostationary Orbit (GEO). Indeed, the Meteosat third generation sounding satellite (MTG-S) will embark an imaging Fourier Transform Spectrometer (iFTS), namely the IR Sounder (IRS). The IRS instrument will be the first European Fourier transform spectrometer on the GEO orbit and will provide atmospheric spectra in the Thermal IR (TIR) at an unprecedented spatial and temporal resolution.

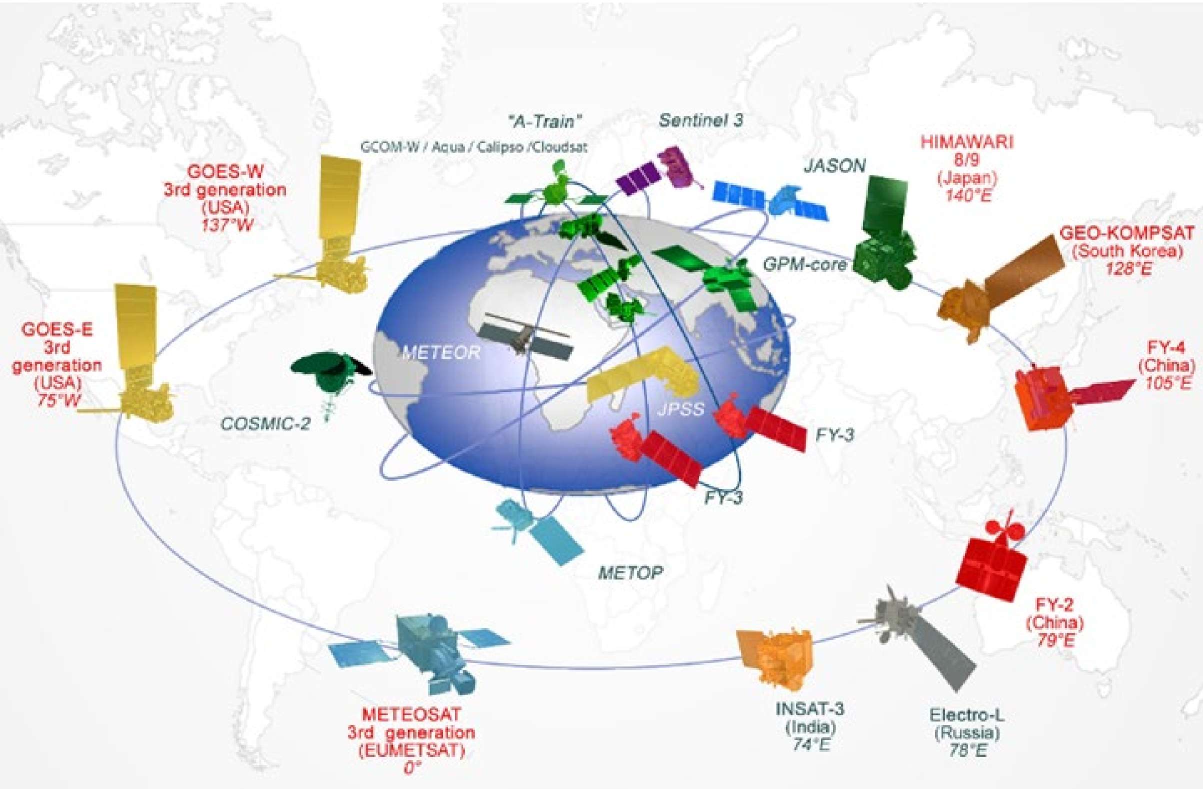


***Figure 1: Space-based meteorological observations of the World Meteorological Organisation Global Observing System***

### 2.1 Background on infrared hyperspectral sounding from space

Hyperspectral measurement of the Earth's IR radiation from space is a powerful mean to remotely sense the atmosphere composition and thermodynamic state. Continuous spectral measurements in the IR with high spectral resolution theoretically allow extraction of valuable information on the atmosphere and possibly the underlying surface without stringent a-priori hypotheses. This has thus triggered a long-standing interest in the scientific community and the first attempts to launch IR spectrometers date back to 1970, namely the IR Interferometer Spectrometer IRIS on-board the US satellites Nimbus 3 and 4 (Conrath et al., 1970) or the "Spektrometer Interferometer" SI-1 which flew on-board the Soviet platforms Meteor (Kempe et al., 1980). Routine IR hyperspectral measurements are however only possible since the beginning of the 21$^{st}$ century so that several such sensors are operating today on polar-orbiting Earth observation satellites, in particular the Infrared Atmospheric Sounding Interferometer IASI on Metop (Figure 2).

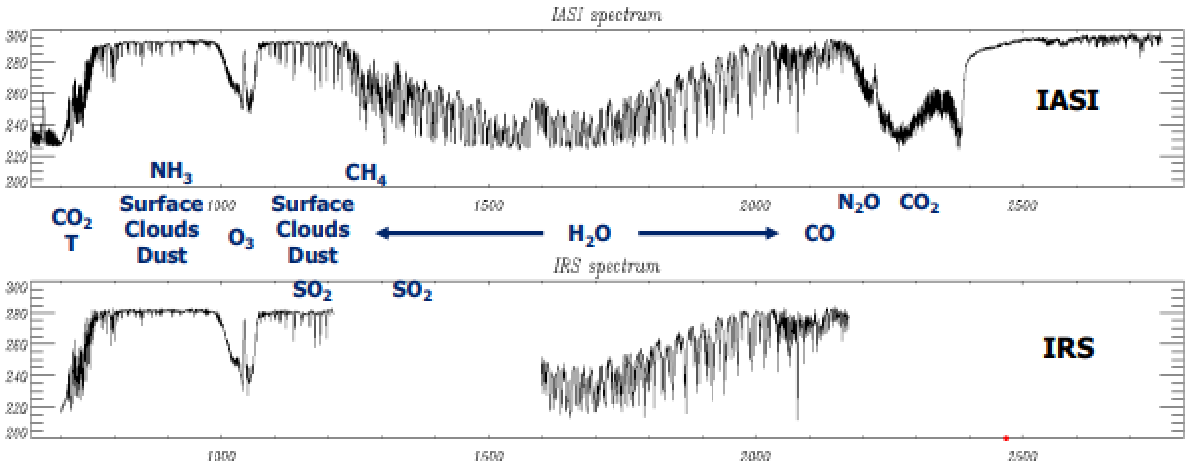


***Figure 2: IR spectral regions used for sounding of the atmosphere by Metop-IASI (up) and the two bands used by MTG-S IRS (down). Brightness temperature in Kelvin as function of wavenumbers in cm$^{-1}$ highlighting the impact of different trace gases on the measured radiances.***

When launched in October 2006 on board Metop-A for EUMETSAT, IASI was the first fully operational polar-orbiting Fourier transform spectrometer on a weather satellite. It is designed around a Michelson interferometer to provide measurements in 8461 spectral channels between 3.6 and 15.6 µm (645 – 2760 cm$^{-1}$) with a 0.25 cm$^{-1}$ sampling. 120 spectra are acquired in the cross-track direction (30 steps of 4 pixels) with a horizontal resolution of 12 km at nadir from an 815 km sun-synchronous orbit. A second and third IASI instruments were subsequently launched aboard Metop-B and Metop-C in September 2012 and November 2018. The first satellite, Metop-A, was however decommissioned in November 2021.

The series of European IASI instruments was followed by the US Cross-track Infrared Sounder CrIS that was first launched in October 2011 aboard the Suomi-NPP satellite for the National Oceanic and Atmospheric Administration (NOAA). Similarly to IASI, CrIS is a Fourier transform spectrometer on a polar orbit, scanning across track (30 steps of 9 pixels over 2200 km) with a spatial resolution of 14 km at nadir. It has 1305 spectral channels over 3 non-contiguous bands: LWIR (650 – 1095 cm$^{-1}$), MWIR (1210 – 1750 cm$^{-1}$) and SWIR

(2155 – 2550 $cm^{-1}$) with originally a spectral sampling (un-apodised) of 0.625, 1.25 and 2.5 $cm^{-1}$ respectively; the processing has recently been adapted so that the spectral sampling is harmonized to 0.625 $cm^{-1}$ over the three bands. Two subsequent CrIS instruments have been launched in November 2017 and 2022 aboard the NOAA-20 and 21 satellites.

The success encountered by the IASI and CrIS programs and the huge impact of IR hyperspectral observations from the polar orbit on Numerical Weather Prediction (NWP) led the Chinese Meteorological Administration (CMA) to develop its own operational program, namely the Hyperspectral Infrared Atmospheric Sounder HIRAS on board the platforms FY-3, the first of which, FY-3D has been launched in November 2017. The first HIRAS flight model had similar characteristics to CrIS. The two follow-up HIRAS-2 instruments possess slightly improved characteristics, in particular a continuous spectral coverage from 650 to 2550 $cm^{-1}$, and were launched aboard FY-3E and F in July 2021 and August 2023.

While the three programs IASI, CrIS and HIRAS pertain to the polar orbit, plans have been established very early to put an IR iFTS sounder on the geostationary orbit. The US developed the GIFTS concept (Smith et al., 2001), that was selected as a NASA's New Millennium Program (NMP) Earth Observing-3 (EO-3) mission to be launched between 2006 and 2008. Unfortunately, the mission was cancelled, and it was only in December 2016 that CMA launched the Geostationary Interferometric IR Sounder GIIRS on board the platform FY-4A that thus became the first hyperspectral sounder on the geostationary orbit (GEO). Spectra are obtained in two bands: LWIR (700-1130 $cm^{-1}$) and MWIR (1650-2250 $cm^{-1}$) with a spectral sampling of 0.625 $cm^{-1}$ and spatial resolution of 16 km. A follow-up GIIRS-2 instrument was launched aboard FY-4B in June 2021; it possesses the same spectral resolution but an enhanced spatial resolution of 12 km.

It is also worth mentioning that the Japan Meteorological Agency (JMA) will integrate an iFTS aboard the next Himawari platform to be launched in 2030.

## 2.2 The IRS mission rationale

### 2.2.1 Meteosat Third Generation

To build on the success of the Meteosat First Generation and Meteosat Second Generation (MSG) missions, EUMETSAT is developing the Meteosat Third Generation (MTG) satellites. After an elaborated user-consultation, the following needs have been identified:

- Continuation of the current imagery missions:
    - Full Disk High Spectral Imagery (FDHSI)
    - Rapid Scan Service (RSS).

- Development of new services:
    - Lightning Imagery
    - IR Sounding.

To cover these needs, the MTG space segment will consist of six satellites of two different types, namely four imaging satellites (MTG-I) and two sounding satellites (MTG-S). The MTG-I hosts the Flexible Combined Imager (FCI) and the Lightning Imager (LI) instruments, while the MTG-S hosts IRS and the Copernicus UltraViolet and Near-infrared sounder (UVN) instruments. Contrarily to the two first series which were spin stabilised platforms, MTG is a three-axis stabilised platform. OHB is, under ESA contract, in charge of the development of the MTG space segment.

The first MTG-I platform was successfully launched in December 2022 and is operational since December 2024. MTG-I1 has now been renamed Meteosat-12.

Moreover, the first MTG-S platform, which embarks the IRS instrument, was successfully launched on July 1st of 2025 and is currently in commissioning phase, with operational dissemination of IRS products expected in 2026.

### 2.2.2 IRS mission objectives and characteristics

The objectives of the IRS mission are to:

- provide high spatial and temporal information of atmospheric temperature and moisture structures
- monitor atmospheric dynamic variables with improved height information
- monitor atmospheric instability/forecast of convection
- support emerging operational air composition and air quality applications.

Operational meteorology is the primary target of the mission. Indeed, IRS data will meet the key needs of global/regional NWP through the provision of:

- more frequent information on small scale features (horizontal and vertical) of temperature and water vapour
- Atmospheric Motion Vectors (AMVs) with higher vertical resolution in clear air, to be extracted from the tracking of three-dimensional water vapour and ozone patterns.

To fulfil these objectives, IRS will acquire a very large number of spectral soundings simultaneously using two-dimensional detector arrays (160×160). The full Earth disk (as seen from the geostationary orbit at 0° longitude) will thus be covered by a succession of stares measuring the upwelling radiation at the top of atmosphere in two broad spectral intervals at moderate spectral sampling (cf. Table 1) with an impressive spatial sampling distance of 4 km at nadir in each band (increasing with the sounding zenith angle). These will allow deriving unprecedented four-dimensional information on atmospheric structures.

| Band | Wavenumber Range ($cm^{-1}$) | Spectral sampling ($cm^{-1}$) | Main Targets | Application |
|---|---|---|---|---|
| Long Wave IR (LWIR) | 679.5 – 1210.0 | ~0.6056 | $CO_2$, $O_3$, Surface | Temperature and Ozone profile, surface properties |
| Mid-Wave IR (MWIR) | 1600.0 – 2250.4 | ~0.6051 | $H_2O$ | Humidity profile |

***Table 1: High-level IRS spectral characteristics***

The IRS mission will greatly benefit from the experience acquired with IASI as well as the expertise gained on collaborative work on the CrIS, HIRAS and GIIRS instruments and on the past development of GIFTS.

## 2.3 IRS system description

### 2.3.1 Instrument design

The design of the IRS instrument is based on an infrared Michelson interferometer, which includes a detection chain composed of two imaging detectors operating in the medium and long-wave infrared (MWIR and LWIR) and located in a cooled cryostat along with the processing electronics. A moving scan mirror within the so-called front-telescope will allow imaging successive areas on Earth. The front telescope feeds the interferometer that includes a beam splitter, made of a separator and a compensator plate, and two corner cube reflectors. One of the corner cubes is fixed while the other can move along the optical axis with a range of ±4.5mm.

The optical path of IRS includes a moveable “flip-in” mirror (FIM) that can feed the interferometer with the radiance of either:

- the main viewing direction that allows viewing the Earth, referred to as “EV”, or the deep space beyond the Earth’s rim referred to as “DS2”, in which case the FIM does not intercept the beam
- the secondary deep space referred to as “DS1” pointing below the platform
- the blackbody view “BB”, pointing toward an on-board calibration target composed of a blackbody whose emissivity and temperature are carefully controlled.

The “DS2” views are used the derive the instrument offset, while the “BB” and “DS1” views allow computing the instrument gain. Both the offset and gain of the instrument are removed from the Earth’s views during the calibration process within the on-ground processing.

### 2.3.2 Measurements geometry and temporal sequencing

The field of view of IRS being 1.025 degrees, it is much less than the apparent diameter of the Earth as viewed from the geostationary orbit (about 17 degrees). The instrument is thus scanning the Earth in a “stop and stare” mode: IRS will image an area of the Earth covered by the field of view of the instrument, collecting in 9.7 seconds 160×160 interferograms and 4 broad-band high-resolution images for each spectral band (2 at the beginning, 2 at the end), then will move to the next adjacent area (Figure 3).

Furthermore, the Earth disc has been divided into 4 regions of interest called LACs (Local Area Coverage) numbered 1 to 4 from south to north (Figure 3). The LAC 4, the northernmost LAC covering Europe, will be scanned every 30 minutes; LACs 1, 2 and 3 will be imaged in-between successively. The nominal scan pattern, illustrated on Figure 4, has been defined to optimize the coverage and the need for calibration views, and to allow for the derivation of AMVs in the four LACs. However, it must be noted that the scanning law can be modified in flight if needed.

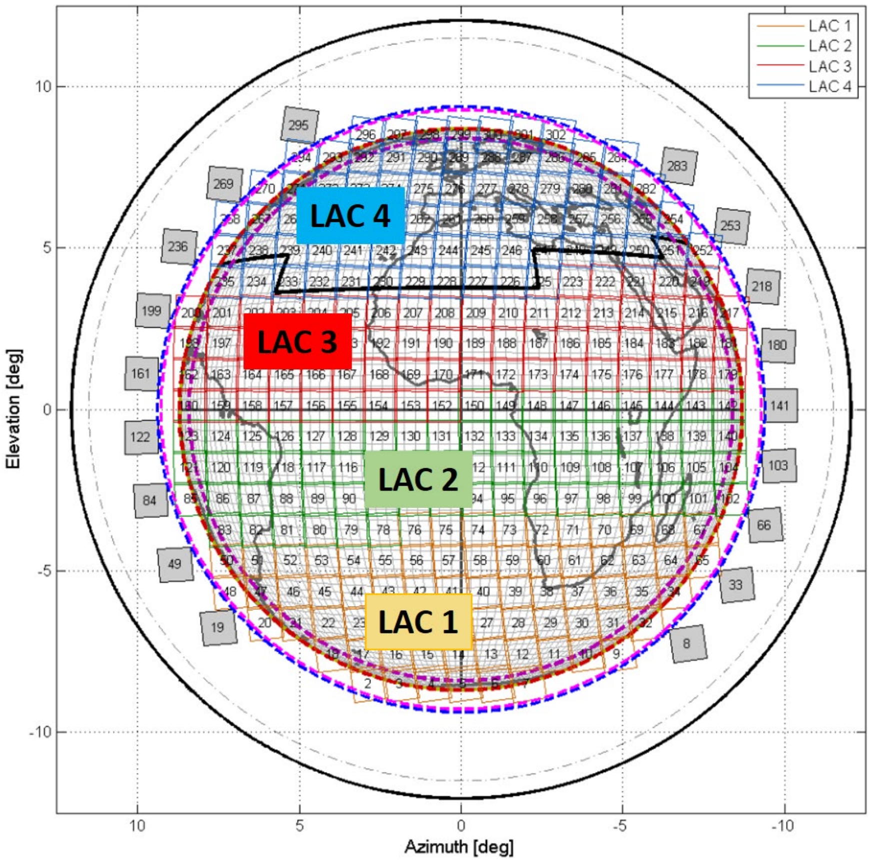


***Figure 3: Geographical distribution of the IRS dwells. Grey dwells outside the Earth disc are used for the calibration ("DS2"). The colour of the dwell outline is related to the Local Area Coverage (LAC) it belongs to. The thick black line denotes the southern limit of the LAC 4 area that is scanned every 30 minutes. The circles represent the boundaries of the limb, deep space and instrument baffle.***

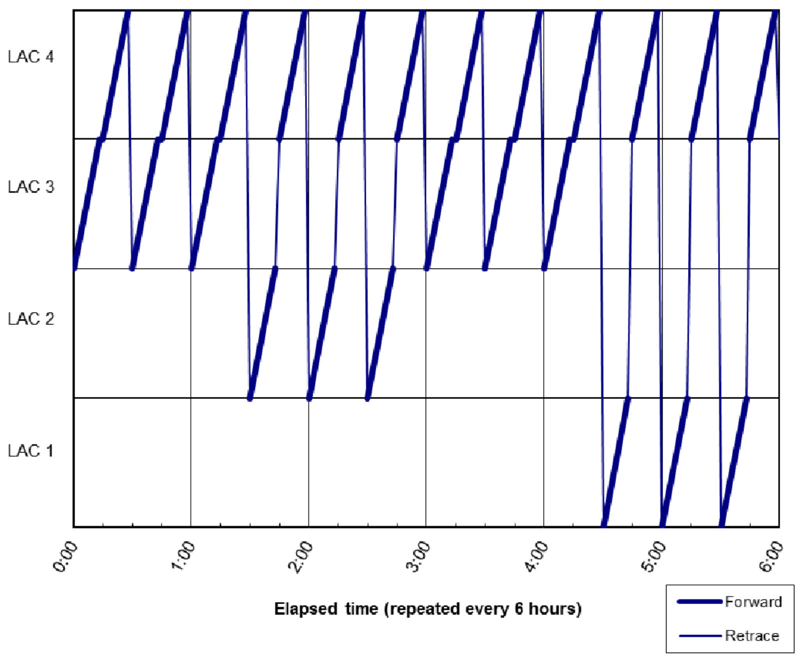


***Figure 4: LACs nominal time sequence over a 6h repeat sequence.***

### 2.3.3 On-board processing

Before transmission to the ground, the raw interferograms are corrected from various degradations and then compressed:

- Several corrections are required prior to any data reduction (in processing order):
  - Video-chain non-linearity correction
  - Metrology and interferogram spike detection and correction (generally caused by high-energy particles)
  - Compensation of contrast variation caused by the speed variations of the cube corner
  - Resampling of all interferograms on a fixed common Optical Path Distance (OPD) grid. This requires the actual OPD sampling grid of all raw interferograms to be known for each super-pixel of the detector. This is achieved using the three laser metrology signals. This 3D metrology system and the associated interferograms resampling on a fixed OPD grid will allow compensating for all parasitic corner cube movements.

- As the raw data rate is about 2 Gbits/s and the available board to ground transmission data rate is about 150 Mbits/s, the data size reduction factor shall be about 13.5. For that purpose, two processing steps are performed:
  - Filtering (keep only the useful modulation frequencies) and decimation (factor 19 in LWIR and 18 in MWIR)
  - Bit-trimming (storage bit adaptation as function of the OPD).

### 2.3.4 On-ground processing

The so-called "level-1" on-ground processing ensures that the interferograms are transformed into spectra, then that the spectra are properly calibrated, geolocated and finally compressed.

The interferograms received from the instrument are first numerically apodised (by "light-apodisation"). A Fourier transform then yields complex spectra that are then radiometrically and spectrally calibrated. Finally, the "uniformisation" processing harmonises the Spectral Response Function (SRF) of all pixels and wavenumber channels.

Geolocation is estimated from the satellite state vector, the broadband LWIR image acquired along the interferograms and the spectra themselves. The spectra are finally compressed by Principal Component Compression (PCC) as further discussed in section 3.1.2.

For detailed information on the "level-1" processing, the reader is invited to refer to the MTG-IRS Level 1 Algorithm Theoretical Basis Document [http://MTG-IRS_ATBD_L1] and the Product User Guide [http://MTG-IRS_PUG_L1].

Finally, the on-ground facility also derives atmospheric products, called "level-2" products, that are described in the MTG-IRS Level 2 Algorithm Theoretical Basis Document [http://MTG-IRS_ATBD_L2].

## 2.4 User requirements and main applications

MTG user requirements stem from the EUMETSAT mandate and are listed in the End User Requirements Document (EURD) [http://MTG_EURD]. The main applications pertain to operational meteorology and span from global to regional NWP and Nowcasting (NWC). They have however different needs:

- Global NWP need global input data, which typically polar missions provide, offering full Earth coverage including the polar regions twice a day from sun-synchronous orbit. The advent of geostationary IR hyperspectral sounding data is expected by NWP centres to provide a further forecast impact, in view of their higher frequency and also their higher spatial resolution.
- Regional NWP models require measurements with high temporal and spatial resolutions over a limited area. The use of radiative forward models in the data assimilation process represents a significant computational overhead in such models, which also have very tight constraints with respect to the overall timeliness of the forecasts. The assimilation of the level-2 products could be envisaged in such applications.
- NWC forecasters directly supporting application areas such as aviation or shipping forecasting need reliable and timely inputs to identify and monitor the development of severe weather events from the earliest stage in order to issue appropriate and precise warnings as early as possible. Products derived from IRS will thus provide crucial information (e.g. instability profiles, 3D-wind information etc.) in addition to the assimilation of these measurements in regional and local numerical models.

IRS application areas in operational meteorology are further presented in chapter 4.

Atmospheric composition (AC) monitoring and air quality (AQ) forecasting are applications that benefit from IRS as well as, through the long programme duration and the resulting long data series, greenhouse gases (GHGs) and climate monitoring. Indeed, AC models used by services such as the Copernicus Atmosphere Monitoring Service (CAMS) require accurate knowledge of atmospheric temperature and humidity as well as accurate surface characterisation. Ideally, it would be an advantage to have these variables measured simultaneously to the AC: in that way, the errors and vertical sensitivity of the measurements could be characterised.

Resulting AC products are direct inputs of AQ monitoring systems, with practical applications in many critical areas of nowcasting and forecasting (civil aviation, pollution monitoring, etc.). Significant advances are expected from the improvement of existing algorithms and from new algorithms as well as from advanced sensors. The diurnal sampling capability of MTG-S IRS will be hugely beneficial to AQ monitoring and forecast applications and to the surveillance of extreme events (storms, fires, volcanoes).

The benefits of IRS measurements in support to AC monitoring and forecasting are further presented in chapter 5.

# 3 MTG-S IRS TECHNICAL CHALLENGES AND OPPORTUNITIES

IRS on-board the Meteosat third generation sounding satellite (MTG-S) represents a significant advancement in Europe's weather monitoring and forecasting capabilities. Capitalizing on its unprecedented spatial and temporal sampling, IRS is expected to improve many existing products, as well as enabling new ones. Such new concept comes with challenges but also new opportunities that are described in the following chapter.

The main challenge of IRS exploitation lies in its huge data rate production, 160×160 sounding every 10 s. But such unprecedented density comes with great benefits for nowcasting, AC and wind applications. Moreover, conversely to the previous generation of IR sounders, the IRS instrument is foreseen in GEO, that will create challenges in term of assimilation, particularly close to the Earth's rim but also many opportunities for synergies with other spaceborne instruments, such as the hyperspectral sounders in Low-Earth Orbits (LEO) and the GEO imagers. IRS will also acquire measurements up to the edge of the disk allowing emerging applications.

## 3.1 Challenges

### 3.1.1 Huge amount of data

The MTG mission is expected to generate a vast volume of IRS data owing to its unprecedented spatial and temporal sampling of the Earth's atmosphere (4 km at nadir and 30 min revisit over Europe). As an example, the IASI instrument aboard Metop is transmitting to ground at an average rate of 1.5 Mbits/s, while IRS will increase this rate up to 150 Mbits/s. The IRS instrument's capability to capture detailed atmospheric profiles and monitor various meteorological and environmental parameters translates into a substantial influx of data. This extensive dataset encompasses the level-1 product, aka. the calibrated radiances and the level-2 products, such as the temperature and humidity profiles, trace gas concentrations, and cloud properties, among other critical atmospheric variables. The sheer volume and richness of the IRS data offer novel opportunities for enhancing weather forecasting, climate monitoring, and environmental research. Effectively managing, processing, and analysing this vast volume of IRS data represents a significant challenge, but the potential benefits for improving our understanding of the Earth's atmosphere and its processes are substantial, positioning the MTG-S mission as a cornerstone in advancing our capabilities in meteorological and environmental observations.

### 3.1.2 Principal component compression

For the reason explained in the previous section, IRS radiances will be compressed before dissemination to the users. The disseminated products are called Principal Component Scores (PCSs) and are derived from the radiances using the Principal Component Analysis (PCA) technique. By analysing a representative dataset of radiances, the PCA methodology allows computing a new set of uncorrelated variables, called global Principal Components (PCs), that represent most of the variability of the original dataset. Thus, the PCA methodology preserves the most significant spectral features, which holds the bulk of the information, while rejecting mostly noise. In the case of IRS, 150 global PCs are retained per band which reduces the data dimension by a factor of 6.5. For information, IRS will still produce approximately 200GB of PCS products each day. Finally, upon reception of the PCSs, the radiances can be reconstructed by the users using the global PC set, received beforehand or available on EUMETSAT website.

Moreover, the PCA provides lots of advantages for the processing and the monitoring:

- It eases the visualisation of remaining instrument features (like micro-vibrations) and allow to highlight hidden patterns in the data that are not immediately obvious
- It can help in separating the signal from the noise by keeping only the components with significant variance (noise reduction)
- It is used in Machine Learning techniques as they perform better with reduced feature space, which PCA provides, thus potentially improving algorithm efficiency and performance.

Nonetheless, as the PCs are reducing the number of dimensions, there is an inevitable loss of some information. This can be critical if there are too many outliers that can't be captured in the global PCs. It has been shown that global PCs (i.e. derived from a representative set of global observations) guarantee a better noise reduction and preservation of the original signal with respect to PCs computed locally for each dwell (160×160 soundings). EUMETSAT has established an innovative approach to retain the spectral features associated with rare geophysical events which would not be sufficiently represented in the global training set. In this approach, referred to as hybrid PCs, the global PCs are complemented with a limited set of local PCs, when significant outliers are found within a dwell (Hultberg at. al., 2017b). The local PCs and associated PCSs are disseminated along with the global PCSs in the level-1 product. This ensures that the geophysical information can be well represented for dissemination without sacrificing the advantages of the global PCs.

Using a global PC basis with long-planned and limited updates was a requirement expressed by NWP users. Recent studies have shown however that reconstructed radiances could be assimilated, and the PCs updated seamlessly in an operational data assimilation environment tailored for radiances. Also, a recent study on the use of IASI reconstructed radiances in AC retrievals gave very good feedback on the potential of such hybrid method. The system did not need any retuning, while preserving the operational continuity and the forecast skills.

### 3.1.3 Slanted view and Earth's rim

The IRS instrument will provide soundings up to the Earth's rim, with acquisitions even reaching the deep space. The observations close to the edge of the disk will be made with extreme zenith sounding angles that are generally never achieved by the LEO instruments (remaining below 55°). The modelling of such highly slanted views is challenging for the Radiative Transfer Models (RTMs) and may limit the assimilations of IRS data above 70° of zenith angles, as shown by Figure 5 from the yellow line towards the limb views. Nonetheless, IRS could participate in the future development of the RTMs in these peculiar conditions. Moreover, by acquiring sounding at the very edge of the disk with a high revisit frequency, IRS will certainly enable emerging applications of AC analysis. Finally, acquisition into the deep space close to the Earth's rim will provide valuable information about the presence of straylight (spurious light reflections and scattering inside the instrument) and help designing efficient mitigations.

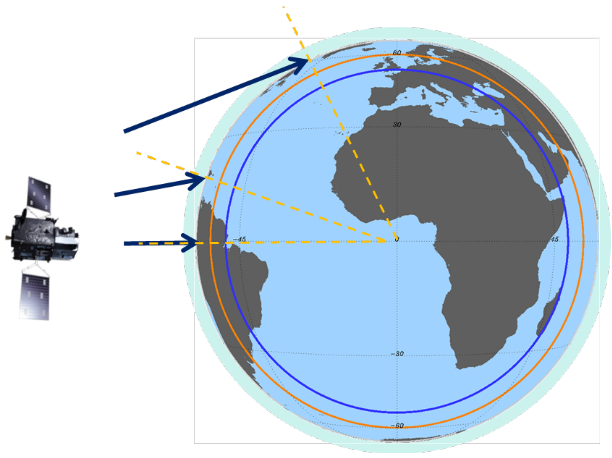

*Figure 5: MTG-S IRS observations at the edge of the disk. The yellow circle represents the zenith angles of 70°.*

## 3.2 Opportunities

### 3.2.1 Synergies with LEO instruments

The geostationary orbit of IRS offers a wide variety of synergy with the instruments onboard the LEO satellites, such as IASI, IASI-NG, CrIS and HIRAS. As IRS will provide a continuous and highly spatially resolved coverage of the Earth's disk, the LEO instruments will sweep through its field of view several times per day, producing many co-located acquisitions. Such co-locations will be used to cross-calibrate radiometrically the IRS radiances with respect to the LEO instruments. Moreover, IRS could be an intermediate to compare the LEO instruments between each other's, which is generally challenging as their orbits only cross at the poles. Then, the LEO instruments such as IASI and the future IASI-NG instruments display better spectral resolutions than IRS and therefore are expected to be more efficient for NWP and AC and AQ applications. Nonetheless as the LEO instruments cover every location on Earth only twice per day, IRS will be able to bridge the gap between the LEO acquisitions and provide unprecedented information about the temporal variabilities. The complementarity between high spectral resolution/low noise and high spatial resolution/high repetition is an asset for many applications.

### 3.2.2 Synergies with GEO instruments

IRS will share the same GEO viewpoint of other instruments of the MTG fleet, as UVN aboard MTG-S, on the same platform as IRS, and FCI aboard the imager satellite MTG-I. This first provides the opportunity for radiometric cross-calibration of IRS with the IR channels of FCI. Moreover, the FCI VISible (VIS) and NIR channels, as well as UVN ultraviolet imagery could bring spatially highly resolved foreground information to the IRS acquisitions. Using FCI and UVN to reveal the presence of clouds and aerosols within the IRS sounding could improve the reliability of the retrievals of temperature and humidity. Note that to this day, there is no plan at EUMETSAT for combined products of IRS, FCI or UVN that would share the same spatial gridding.

### 3.2.3 Synergies with in-situ instruments

Taking advantage of its GEO viewpoint and high spatial and temporal sampling, IRS will be able to make regular measurements pointing toward stations equipped with ground-based sensors and weather ballons. These daily colocations could help in improving the IRS products such as the temperature and humidity profiles (Bloch et al., 2019), especially close to the surface where IR sounders are limited by the lack of information content (Smith et al., 2021). This would be a great advantage for deriving more accurate instability indices for NWC activities (Gartzke et al., 2017, Maier and Knuteson, 2022).

### 3.2.4 Point source and super-sampling

With a 4 km sampling at nadir, IRS will potentially be able to detect point source emitting pollutants such as $NH_3$ and access their temporal evolutions. Moreover, by taking advantage of the slight variations of IRS orbit throughout the day, successive hyperspectral images may be used synergistically to increase the native spatial resolution of the acquisitions (Clarisse et al., 2019b).

# 4 SUPPORT TO OPERATIONAL METEOROLOGY

## 4.1 Application areas for IRS in operational meteorology

Satellite data contribute to two main areas of operational meteorology: Firstly, satellite radiance data are used within a range of data assimilation systems for NWP in global as well as regional models and over the lifetime of IRS not only limited area, but also global models will increasingly resolve convective-scale phenomena. Secondly, satellite data are a key input to NWC and Very Short-Range Forecasting (VSRF) activities that rely on current observations and retrievals together with algorithms forecasting their movement based on extrapolation or using observed wind fields. Additionally, VSRF is increasingly supported with rapid-update cycle NWP systems and new systems that merge NWC, high-resolution NWP and ensemble approaches to achieve a seamless prediction from observed structures into their numerical forecast. All these approaches need spatially and temporally dense observations characterizing the thermodynamic state, cloud parameters as well as surface conditions and IRS data will provide an important contribution along with other satellite data (e.g. Bojinski et al., 2023). Additionally, NWP models and assimilation methods are also being extended to coupled sea-land-atmosphere modelling and to simulate and analyse atmospheric chemistry components and aerosol, especially with the move to develop comprehensive earth system models. The potential of IRS to contribute to chemical analysis aspects is further discussed in chapter 5.

Data from hyperspectral IR sounders in polar orbit have contributed to NWP forecast performance for now about 20 years, especially through the assimilation of radiances in global and regional NWP systems (Chambon et al., 2023; Eyre et al., 2021; Hilton et al., 2009, 2012; Collard et al., 2009; Randriamampianina et al., 2021) and preparatory studies have been performed using simulated IR hyperspectral data from geostationary orbit (e.g. Wang et al., 2021). Their use for NWC has been much more limited due to the incomplete sampling in the time domain, so that frequently available information from satellite imagery and radar data have played a much more prominent role. Therefore, while an increasing number of IR hyperspectral sounders in polar orbit will also help to improve temporal coverage globally, geostationary hyperspectral sounders like IRS offer as essential benefit the continuous temporal sampling from the same instrument throughout the day combined with a high spatial resolution and continuous spatial coverage (see chapter 2). For IRS this is particularly true over Europe with the very high temporal sampling of 30 minutes for the LAC4 area. IRS will therefore open new opportunities in all areas of operational meteorology described above due to a much more detailed description of the time evolution and diurnal characteristics of temperature and humidity fields and atmospheric stability, as well as of wind fields and surface conditions.

## 4.2 General aspects for the use of IRS data for operational meteorology

*Hyperspectral radiative transfer*: Many important aspects that will help to successfully exploit IRS for operational meteorology are shared with hyperspectral sounders on polar orbiting platforms like IASI, IASI-NG, and CrIS as well as HIRAS, GIIRS and IKFS-2. These aspects comprise the need for accurate underlying spectroscopy, the corresponding data-bases, accurate line-by-line models and fast RTMs, the representation of properties of cloud particles and the (fast) modelling of cloud effects, the characterization of surface emission, surface and also vegetation radiation models. An overview of these shared aspects, of available databases and modelling approaches and their developments is described in the IASI-NG science plan (EUMETSAT, 2018) and not repeated here.

*Technical aspects:* A challenge for all operational meteorological applications, but particularly for high-resolution and rapid-update cycle NWP and NWC/VSRF applications, are the need for the timely processing of the high IRS data rates. This will likely require adaptations in the setup of technical data flows, e.g. the introduction of a continuous pre-processing of data following data reception instead of processing complete data batches within the applications themselves. Also, a careful evaluation of methods and algorithms in order to determine the most efficient data use is required. A key aspect relevant to NWP as well as NWC applications is the best way to exploit the full spectral information content. For this, PC based methods have received particular attention, both because IRS data will be transmitted in a compressed form based on PCs (Hultberg et al., 2017b), and because they allow to represent the atmospheric information without a significant loss of the signal while reducing instrument noise (Antonelli et al., 2004; Hultberg and August, 2017a). The data can be used either as PCs or in the form of so-called reconstructed radiances, i.e. a re-projection of the PCs into the spectral radiance space. However, applications need to take into account that the reconstructed spectra only contain a smaller number of independent pieces of information corresponding to the number of PCs used and that error correlations between the channels differ from those of the raw radiances. Different studies using IASI data represented as PCSs have addressed these aspects, both in the context of NWP and pure NWC applications (e.g. Matricardi et al., 2014; Zhang et al., 2023; Masiello et al., 2012).

*Horizontal coverage and resolution:* Due to the construction of the IRS instrument as a sensor array, the processing of the measurements prior to dissemination pays particular attention to eliminating resulting horizontal effects in the observed spectra covering one dwell (see section 2.3). Monitoring these new data will be supported by the monitoring services of the NWP Satellite Application Facility (SAF) that routinely compare the observed radiances to model equivalents based on short-range forecasts and RTTOV forward computations (see NWP SAF web service). Applications, especially those using the IRS data at full resolution, may need to take the effective resolution of IRS into account. Due to the characteristics of the point spread function of IRS footprints, the effective resolution will differ slightly from the nominal 4 km resolution (at nadir) and influence horizontal error correlation structures. Likewise, the spatial location of the longwave and mid-wave parts of the spectrum is not exactly identical. These effects may have to be taken into account depending on the application. One can refer the IRS L1 Product user Guide for more detail information to these matters [http://MTG-IRS_PUG_L1].

## 4.3 IRS data for numerical weather prediction

### 4.3.1 Use of temperature, humidity and cloud information

*Heritage of operational methods for hyperspectral instruments:* The key quantities from hyperspectral sounders used for present day NWP are the 3-dimensional temperature and humidity information contained in the spectra. Despite this information being limited to cloud-free areas and the profile parts above clouds, they are an important complement to the less cloud-sensitive microwave observations due to their high spectral resolution and sharper vertical weighting functions, thus representing the vertical structure in more detail. IRS will likewise be an important data source for the analysis of the 3-dimensional temperature and humidity fields with the key benefit of observing these quantities at very high time resolution and continuous spatial coverage, thus enhancing the importance of these data particularly for high-resolution limited area models. Current operational data assimilation systems use such radiance measurements predominantly as so-called 'raw radiances', typically implemented as an assimilation of brightness temperatures for a selected sub-set of about 100-200 channels from the long-wave $CO_2$ and the water vapour band (e.g. Collard and McNally, 2009), although some regional NWP systems may also use retrievals, mostly to ease computational load (see also IASI-NG science plan, EUMETSAT, 2018). For radiance assimilation, fast RTMs like RTTOV (Saunders et al., 2018) or CRTM (Johnson et al., 2023) are used as forward operators to evaluate the observation increments in observation space. Most current operational usage is limited to channels not affected by clouds, e.g. using cloud detection methods evaluating observed spectra in comparison to the model simulations (e.g. McNally and Watts, 2003), but development and operational implementation of the use of cloud affected radiances is progressing (see below). These tools and methods are available also for exploiting IRS data. Extensions of radiative transfer and its implementation in NWP are required, however, to make full use of the data up to the edge of the disc with observations at much larger satellite zenith angles for which the slanted path through the atmosphere needs to be taken into account. Especially in the context of high-resolution NWP and to exploit the full horizontal resolution and coverage of IRS, developments in the assimilation systems to account not only for spectral (inter-channel) observation error correlations, but also for horizontal and potentially temporal observation error correlations will be necessary. Approaches addressing these questions start being developed (Bedard and Behner., 2020).

*Use of PCs and the full spectral information:* Current operational assimilation of IR hyperspectral radiances in NWP is mostly based on using selected channels of the original radiances (e.g. Collard, 2007). For IRS, a subset of channels representative of the IRS spectrum has been suggested based on degrees of freedom for signal approach (Coopmann et al., 2022). A PC representation of the spectrum is the baseline for IRS data dissemination, and therefore assimilation approaches that are either using reconstructed radiances or PCs themselves are of particular interest for IRS. The use of reconstructed radiances based on a subset of channels selected from the spectrum has been studied using IASI data in the context of several different NWP systems. These studies have shown comparable forecast impact of reconstructed and raw radiances using the same channel selection and observation error covariance, even if the forward operator calculations are not adjusted and taken to be the same as for the raw radiances. Note that there could be difficulty estimating the error covariance if only reconstructed radiances are available (i.e. from the near real-time IRS feed). A more consistent approach can be achieved by performing the radiative transfer calculations in PC-space and several fast models have been developed, like the PC Radiative Transfer Model (PCRTM; Liu et al., 2006), the Havemann-Taylor Fast Radiative Transfer Code (HT-FRTC; Havemann et al., 2018) and PC-RTTOV (Matricardi, 2010), see also IASI-NG science plan (EUMETSAT 2018) for further details. Moving to a PC-based radiative transfer can be computationally advantageous, as the number of PCs that need to be considered in order to represent the full spectrum is much smaller than the number of original channels. Assimilation trials based on this method and using the maximally possible number of independent reconstructed channels to effectively use the full spectral information contained in the PCs have been conducted with promising results (e.g. Matricardi 2014, Zhang and Shao, 2023). However, the assimilation in these tests was restricted to clear FOVs. A different approach aimed at reducing the number of assimilated pieces of information, compared to hundreds of channels, is using so-called transformed or 'scaled projected state' retrievals (Migliorini, 2012). The assimilation of retrievals and of transformed retrievals are explored in a number of studies, either assimilating externally produced retrievals or using retrievals from a pre-1DVar-step of the full assimilation system (Levens and Migliorini, 2024). Both approaches require additional technical implementation solutions for forward operators, bias correction setup and the specification of observation errors.

*Exploitation of cloud-affected channels:* Due to its high temporal resolution and continuous horizontal coverage, a particular aim of IRS is to observe tropospheric temperature and humidity structures and their diurnal evolution with the potential to improve analyses also in the lower atmosphere. Therefore, the use of profile information from IRS in both clear-sky situations as well as down to the cloud top is important. Fast RTMs applicable also for cloudy atmospheres (e.g. Saunders et al., 2018) are the basis for assimilation approaches for cloud affected IR radiances from hyperspectral IR sounders (Prates et al., 2013) as well as geostationary imager radiances are being explored and implemented (see e.g. Geer et al., 2018, Geer et al., 2019; Okamoto et al., 2014, 2023). In order to extract maximum benefit from these observations, however, further improvements are needed. These include the accurate description of IR radiative transfer in clouds as well as a consistent treatment of cloud microphysics and its interaction with radiative transfer between the numerical model on one side and the used forward operators on the other side in order to minimize situation dependent biases (see e.g. discussion in Geer et al. 2018). Additionally, sub-grid scale inhomogeneities, their representation in fast forward models, and a consistent use of model simulations down to km or sub-km scale together with the coarser IRS observations at scales of several km need to be addressed. Here, the availability of information on sub-FOV heterogeneity, potentially from the additional IRS imaging channel, but especially from the MTG-I FCI imager offers additional opportunities for refinement of methods, especially due to its higher spatial resolution and the availability also of VIS channels information. A joint use of IRS and FCI would offer new potential to constrain atmospheric temperature and moisture profiles along with cloud parameters like cloud top, cloud condensate contents and phase (Mecikalski et al., 2011).

*Exploitation of surface affected channels:* Making full use of IRS data over ocean as well as land surfaces, especially also of the lower tropospheric temperature, humidity and stability information is of particular importance for high-resolution and short-range forecast models. For the exploitation of such low level as well as surface information, an accurate description of surface emission is required for the forward modelling. While different IR emissivity parameterizations and models are available over sea (Masuda et al., 1988; Wu and Smith 1997; Newman et al., 2005), modelling surface emissivity over land is much more complex and instead global climatological atlases of IR emissivity based on IR measurements of polar orbiters are derived and used for snow-free land surfaces, e.g. the CAMEL CLIM atlas (Saunders et al., 2020; Hook, 2017). Accurate emissivity spectra for snow and ice are more limited and difficult to apply due to the highly variable local conditions. Alternatively, the high spectral resolution of the observations also allows to retrieve the emissivity spectrum and the surface skin temperature together with the atmospheric profile information. Approaches using a description of the spectral dependence of the emissivity based on PCs have been successfully used for IASI data both in the context of data assimilation (e.g. Pavelin and Candy, 2014) and retrieval derivation (August et al., 2012; O'Caroll at el., 2012). IRS therefore has a high potential to not only contribute to characterizing the lower troposphere but also surface conditions (emissivity, vegetation) and ocean and land surface skin temperature and its diurnal variations. This will be an important contribution to model evaluation and improvement. In the context of earth system models, the hyperspectral IRS can contribute surface related observations in coupled assimilation approaches. First trials are taking place using the skin temperature information from geostationary imager channels or hyperspectral data from polar orbiting satellites over ocean and also over land (e.g. Sassi et al., 2023). In order to reliably exploit the low level and surface information, collocated FCI imager data can support IRS usage by more reliably detecting low level and sub-pixel clouds.

#### 4.3.2 Use of indirect wind information

The IRS scanning pattern provides observations at 30 min intervals in the northern part of the disc covering Europe and four to eight times a day with three consecutive scans at 30 min intervals for other parts of the disc (Figure 4). Such consecutive observations allow the tracking of the movement of atmospheric structures, e.g. from water vapour but also ozone at higher altitudes, which can in turn be used to infer information about the wind fields. This indirect wind information can be exploited for NWP either through using derived wind products, like the well-established AMVs based on geostationary imagery (e.g. Borde et al., 2014), or directly within data assimilation systems themselves.

The assimilation of radiances, e.g. from consecutive geostationary imager scans, in 4D-Var leads to meaningful wind increments through the so-called tracer effect which has been studied and demonstrated using MSG/SEVIRI water vapour radiances (e.g. Peubey and McNally, 2009). Ensemble based systems, like the Local Ensemble Transform Kalman Filter approach, with their multivariate and situation dependent background error covariances can also derive wind information from assimilating humidity retrievals (Liu et al., 2009) or directly the radiances. IRS will offer a much larger potential for extracting wind information compared to current geostationary imagers due to the description of water vapour and ozone (or other trace gas) structures, with especially a considerably higher vertical resolution of water vapour structures by the hyperspectral observations.

For the alternative approach of assimilating derived AMV products, observation errors associated with the vertical height assignment (e.g. Borde et al., 2014) constitute a major challenge. Especially winds derived from clear-sky water vapour structures represent broader vertical motion as compared to single level winds. In order to better exploit this clear-air motion information, an alternative AMV derivation using sequences of retrieved water vapour fields on fixed vertical levels based on the full spectrum of hyperspectral observations is being investigated. For the tracking either classical tracking algorithms or, more recently, 3-dimensional optical flow approaches (Heas and Mémin, 2008; Borde et al., 2019) are being explored. The use of derived AMVs can be an interesting alternative approach where a full radiance assimilation with a system allowing to extract wind information itself is too costly or too technically demanding. A successful assimilation of AMV products requires a thorough analysis of the error characteristics in terms of biases and random errors, but also their spatial and temporal error correlations, in order to properly take the observation error characteristics into account within the assimilation system.

### 4.4 Nowcasting and very short-range forecasting

A key task of NWC, covering the immediate forecast of about 1-6 hours, is the detection and warning of the development of extreme weather, especially heavy convection. The main focus for these events is on precipitation amounts, intensity, and phase (e.g. hail) and lightning activity as well as strong winds and with the aim to forecast the expected exact time and location of such events. Other important areas include the forecasting of visibility and wind regimes, cloud glaciation, and volcanic ash which are important for aviation, as well as local cloud and radiation conditions, which are increasingly also needed for renewable energy production. NWC methods rely predominantly on current and recent observations of the relevant phenomena and parameters. While conventional observations from radiosondes and SYNOP stations provide important direct measurements, only radar and satellite data can offer the necessary continuous horizontal coverage coupled also with a high temporal resolution and are the main input for most NWC approaches. Methods used to produce NWC forecasts often apply an extrapolation of current and recent observations of clouds and convective cells using observed wind fields, extracted from recent satellite imagery (e.g. Müller, et al., 2022; Borde et al. 2019). In these methods, satellite data have the important role to allow an early detection of instable regions with a potential to develop heavy convection over the day and to characterize the evolution of such pre-convective situations with time. Recently, Machine Learning/Artificial Intelligence-based approaches with very promising performance are employed using satellite imager multi-channel information, like from MSG/SEVIRI and in future MTG/FCI, to predict convective events (Li et al., 2024; Leinonen et al., 2023; Ionescu et al., 2021; Lagerquist et al., 2021). Such techniques offer a large potential for further extensions to also include sounder based information contributing more detailed stability and humidity information to an observation based very short-range prediction using Artificial Intelligence.

Crucial input for NWC applications are particularly high-resolution information on the humidity distribution in the lower atmosphere, the atmospheric stability and their temporal evolution. Additionally, wind field observation is important to accurately characterize advective as well as convergence processes. Whilst multi-channel imagers provide very high spatial and temporal resolution cloud, humidity and also derived wind observations, the information on these quantities with respect to resolving vertical profile structures is relatively limited. Here, level-2 retrievals of temperature and humidity and derived stability profiles from the hyperspectral IRS sounders offer essential additional input (August et al., 2012, EUMETSAT 2017) and preparatory studies on the use of retrievals based on hyperspectral IR data, e.g. from instrument IASI or AIRS, have investigated the potential to add information for NWC purposes (e.g. Liu and Li, 2010; Li et al., 2012; Vocino, 2019, Weisz et al., 2015). Other studies have combined such retrieval information on atmospheric stability based on hyperspectral data from polar orbiting satellites with forward trajectory computations to provide and early detection and prediction of unstable regions with a potential to develop heavy convection over the day (e.g. Kahn et al., 2023). The upcoming IRS data with its much increased time resolution will provide additional information on the evolution of such pre-convective situations as additional input. A basic consideration in the use and configuration of retrievals is whether they should be as realistic as possible also with respect to fine scale vertical structures, which implies the incorporation of additional background information, normally drawn from NWP models, or whether retrievals should be as independent from NWP as possible with the drawback of not representing all fine scale vertical structure, especially in the boundary layer and for atmospheric inversions.

In addition to temperature and humidity profiles, the hyperspectral sounders can provide 3-dimensional wind fields to complement AMVs derived from geostationary imagers, e.g. through optical flow methods (e.g. Heas and Memin, 2008; Borde et al., 2019; Heas et al., 2023) but a thorough evaluation of their application for NWC purposes, e.g. with respect to a sufficiently accurate representation of convergence lines, will be needed.

An alternative approach to using retrievals is the more direct exploitation of the measurements from the IR spectra. This has been suggested e.g for the characterization of low-level humidity patterns through the use of selected frequencies and their combinations (Sieglaff et al., 2009). For exploiting information on atmospheric stability, studies have also been done to directly use selected PCSs from the spectra in PC representation as a predictor for convective activity or to base the derivation of retrievals on PCSs instead of on a selection of channels from the original radiance spectra (Masiello et al., 2011). In the context of very short-range radiation forecasts, IRS has the potential to also contribute through the exploitation of aerosol signals and retrieved aerosol properties (see also chapter 5).

Increasingly, purely observation-based NWC methods are complemented by uncertainty information from ensemble-based modelling or combined with short-range forecasts from very high-resolution and rapid update NWP systems (like in Brousseau et al., 2016). New approaches also merge NWC and NWP forecasts to allow a smooth transition of NWC, with its high precision in location of clouds, convective cells and related precipitation and wind for the first hours, into the further dynamic evolution which can be better represented in physically based NWP systems.

# 5 SUPPORT TO ATMOSPHERIC COMPOSITION MONITORING AND FORECASTING

## 5.1 Heritage from polar orbiting infrared hyperspectral missions

In the last 15 years IR hyperspectral sounders have significantly contributed to the monitoring of AC, from the scale of point sources to that of the global atmosphere (see Clerbaux et al., 2009; Hilton et al., 2012 for a review). With more than 30 species measured (De Longueville et al., 2021) they have added a lot to UV-VIS systems, which were primarily used for AC applications prior to the year 2000. Until recently all IR hyperspectral sounders have operated from polar orbits; they include –see also section 2.1.– IMG/ADEOS, TES/AURA, AIRS/AQUA, CrIS/JPSS, IASI/Metop. Among these, IASI and TES have been exploited the most extensively to deliver integrated columns and in the best cases vertically resolved profiles of a suite of gaseous species (see e.g. Clarisse et al., 2014; Hurtmans et al., 2012; Ronsmans et al., 2016; Vandenbussche at al., 2022; Worden et al., 2013) as well as aerosol optical depth and other properties (see e.g. Capelle et al., 2018; Clarisse et al., 2013, 2019; Vandenbussche at al., 2013). The combination of high spectral resolution and low noise have been important for the detection of weak absorptions and/or of vertical profiles, while continuous spectral coverage of the TIR spectral domain by IASI has proved essential for aerosol type discrimination (Clarisse et al., 2013). Continuous spectral coverage is also beneficial for the detection of reactive gases with weak but broadband absorption features (De Longueville et al., 2021; Franco et al., 2020). As introduced in section 2.1, the first hyperspectral sounder was placed on geostationary orbit in 2016 by CMA. Despite calibration issues, the measurements of GIIRS are confirming the breakthrough of GEO measurements for monitoring the diurnal cycle of pollution (Clarisse et al., 2021).

Figure 6 shows the spectral signatures for most of the species that are optically active in the TIR range and that are present in the atmosphere in sufficiently large concentrations (at least near sources) to be measurable. From the monitoring of these species, which have atmospheric residence times from hours to decades, a range of applications have emerged. These are briefly reviewed next, in terms of achievements and limitations from polar orbiters, and in terms of expectations from IRS in section 5.2.

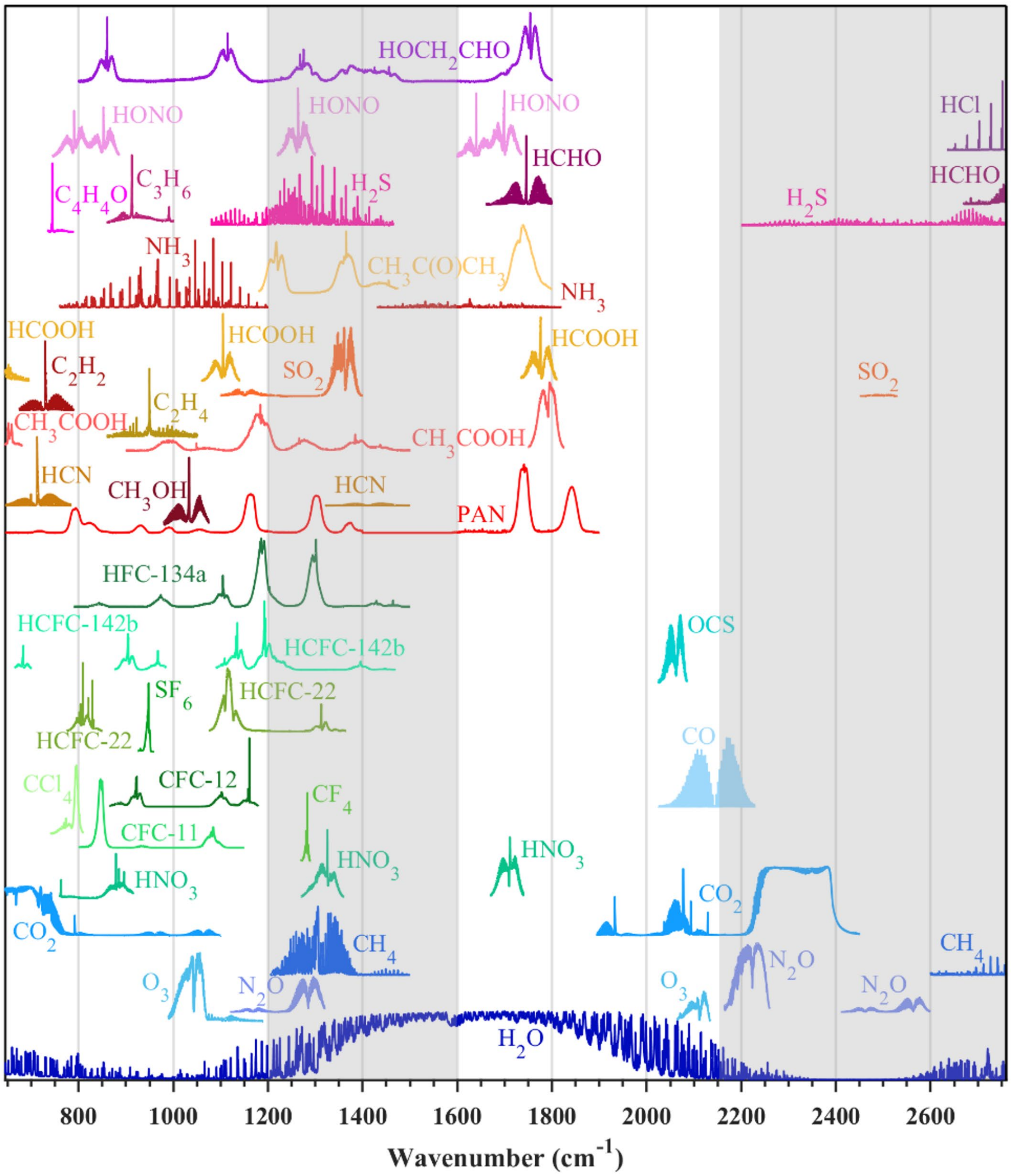


***Figure 6: Spectral signatures of trace gases detected by IASI over its entire spectral range. The white areas mark the two spectral bands covered also by MTG-S IRS over the domain. Note also that IRS spectral resolution will be coarser compared to IASI. Figure courtesy from H. De Longueville.***

### 5.1.1 Application areas and achievements from polar infrared hyperspectral sounders

Seven application areas for AC monitoring are identified and are reviewed next:

- *Air quality* is a major societal concern and a priority for current and future Earth observation programs. The contribution from IR sounders to AQ can be measurements-based only (e.g. elevated concentrations of CO or large aerosol optical depth) or enhanced with assimilation and forecast models. The key for AQ applications is the capability of the instrument to capture local enhancements in pollutant concentrations in the atmospheric boundary layer, over a sometimes large tropospheric background. The contribution of IR sounders essentially comes from the measurements of tropospheric $O_3$, CO, $NH_3$ (as aerosol precursor) and $SO_2$ (e.g. Bauduin et al., 2016, 2017; Boynard et al., 2014; Clerbaux et al., 2015; Viatte et al., 2021; Vohra et al., 2021, 2022).

- *Point source monitoring* is another important emerging application. It refers mainly to single industries or farms, or clusters thereof and is driven by the instrument on-ground pixel size and its revisit time, as well as its sensitivity to the near-surface. The contribution of IR sounders to the identification and surveillance of such permanent point emitters was recently made with IASI and CrIS with $NH_3$, by using large oversampled averages over several years of measurements (Clarisse et al., 2019; Dammers et al., 2019; Van Damme et al., 2018), after which the effective spatial resolution was brought down to a few kilometers (Clarisse et al., 2019). The occurrence of very large thermal contrast or temperature inversions have been shown to be important for quantifying the emission fluxes (Bauduin et al., 2016, 2017; Clarisse et al., 2010). Industrial point sources are starting to be detected by using signatures of short-lived organic species (Franco et al., 2022).

- *The monitoring of fires, volcanoes and other unpredictable events* stems from the measurement of plumes with enhanced concentrations of trace species emitted locally during extreme events. The species of interest have characteristic atmospheric residence times that varies from minutes, which can accordingly be used for source identification (e.g. $C_2H_4$, $NH_3$), to several seeks (e.g. CO, HCN, PAN), which are then good tracers of plume transport. Volcanic eruptions are very efficiently detected based on the signal of $SO_2$ in the $nu_3$ band around 1360 $cm^{-1}$, and of volcanic ash (e.g. Brenot et al., 2014; Theys, 2013). The $SO_2$ absorption is also used to infer plume altitude with an estimated accuracy of 1 km (Clarisse et al., 2014). The measurement of $SO_2$ and ash can frequently be tracked for several days to weeks and thereby contribute to a better understanding of tropospheric transport and troposphere-stratosphere exchanges (e.g. Boichu et al., 2014, 2015).

- *Global tropospheric chemistry* is supported by IR hyperspectral measurements mostly with the provision of the distribution and time evolution of reactive trace gases (lifetime on several weeks or shorter) and aerosols, and their subsequent use in chemistry-transport models. The products, ideally in the form of a vertical profile or a column, include $O_3$, CO, $NH_3$, $SO_2$, a suite of Volatile Organic Compounds (VOCs), and aerosols. The applications range from improved atmospheric budgets (in terms of emission and deposition) (e.g. Fortems-Cheney et al., 2009; Luo et al., 2022; Marais et al., 2021; Müller et al., 2018; Stavrakou et al., 2011) to the determination of medium-term trends, indirectly supporting climate (e.g. De Longueville et al., 2023; George et al., 2015; Ronsmans et al., 2018; Van Damme et al., 2021; Wespes et al., 2018; Worden et al., 2013).

- *Global stratospheric chemistry* is sustained by IR hyperspectral sounders with global measurements of stratospheric or total columns of $O_3$ and $HNO_3$ (to lesser extent chlorofluorocarbons and substitutes), during day and night, including at polar latitudes. Their time evolution, when monitored over a sufficient number of years, contributes to the determination of trends and hence the control of the Montreal protocol and its amendments (De Longueville et al., 2023; Wespes at al., 2019, 2022).

- *Climate monitoring* is made by measuring the tropospheric concentrations of long-lived GHGs ($CO_2$, $CH_4$, $N_2O$) with sufficient accuracy, over medium to long time periods to quantify interannual variability and trends (Crevoisier et al., 2009, 2013). The measurement of short-lived and/or indirect climate forcers (e.g. $O_3$, CO, and aerosols) has recently triggered interest and is supported by various programs (Gaudel et al., 2018); the computation from the radiances of the longwave $O_3$ radiative effect is another (Doniki et al., 2015).

- *Long-range transport, winds, convective events* can be followed by exploiting the dense coverage of IR hyperspectral measurements for species with short to medium lifetimes (e.g. Ikeda et al., 2021; Sodemann et al., 2011). This is helped further when the retrieval of profiles allows vertical structures in the atmosphere to be differentiated. Tracers of tropospheric pollution transport include CO, $O_3$, PAN and others. As mentioned $SO_2$ can be used to track volcanic plumes; CO and HCN for tracking fire plumes (e.g. Bègue et al., 2021; Benchérif et al., 2020; Parrington, 2012; Turquety et al., 2009). The use of the spatial and temporal distributions of water vapor and of chemical species allows retrieving winds, which is an important emerging application for the hyperspectral sounders (Héas et al., 2023). Lastly, the use of water isotopes was demonstrated useful to study the dynamics of air masses and trace the history of evaporation/condensation processes along transport (e.g. Lacour et al., 2018 and references therein).

### 5.1.2 Limitations

As introduced, the aforementioned applications from the hyperspectral sounders in polar orbit have been possible thanks to high spectral and radiometric instrument performances. At the same time, they are bound to the limitations of the polar orbit in terms of temporal sampling, and to the predetermined geographical scan patterns, often chosen as a compromise for reaching or approaching the different mission objectives. The maximum temporal sampling of polar sounders (IASI and in the future IASI-NG) is typically bi-daily and is achieved by scanning off-nadir along a broad swath. The general choice of a sun-synchronous orbit is such that the local overpass time is always similar (e.g. morning and evening for the European platforms and mid-afternoon and night for the US ones) and it follows that the diurnal cycle of concentrations and their related processes, when they are significant, cannot be captured. Important examples of such strong diurnal cycles include that of pollutants in cities and agricultural regions or fires (Figure 7). Note that the choice of the overpass time has also important consequences when it comes to the monitoring of the boundary layer composition, as the measurements under low thermal contrast situations have low sensitivity; in this respect the mid-afternoon sounders generally offer better performances.

The other limitation is that of spatial resolution and sampling, which is such that instruments usually don't resolve variations in composition on sufficiently small spatial scales for the target applications. This again puts limitation on what can be achieved for monitoring point sources (emissions at the scale of individual industries, agricultural fields, roads etc…) or AQ at the sub-city scale, which is turn prevents accurate impact assessment (for instance for calculating the exposure of people to air pollution (de Ridder et al., 2014). These limitations in terms of sampling are sometimes enhanced by the non-continuous spatial coverage, e.g. the gaps between pixels for IASI and IASI-NG.

Figure 8 illustrates the above limitations for the particular case of $NH_3$, which, as a short-lived species (residence time of hours at maximum), shows very large spatial variability and a strong diurnal cycle in its concentrations. The left panel of Figure 8 shows the average diurnal cycle of $NH_3$ for the Netherlands, on which the IASI overpass times are superposed. The right panel shows the distribution of $NH_3$ for the Netherlands, modelled at 1 $km^2$ resolution, and on top the IASI footprints for one overpass. It is obvious here that IASI cannot resolve spatial gradients at this scale and in particular that it cannot identify local sources; furthermore, it never catches the concentrations at their daily maximum. These limitations would be largely overcome with IRS.

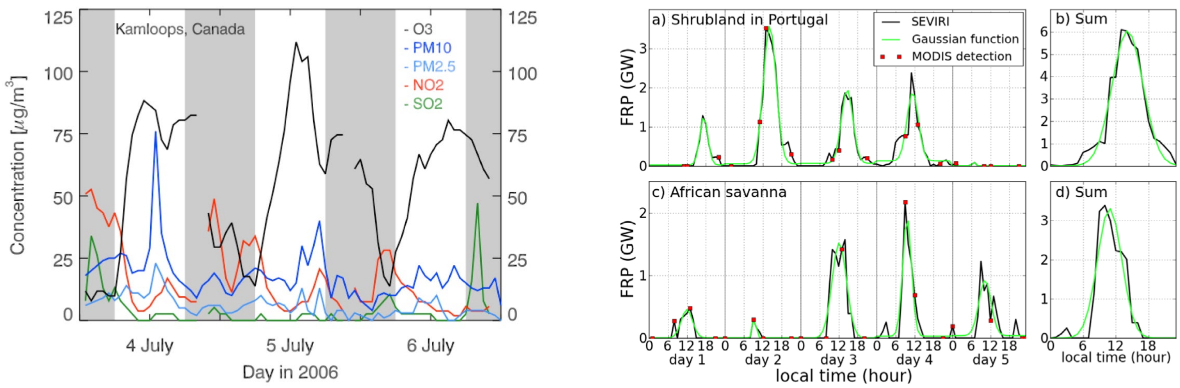


***Figure 7: Left: Daily variation in the surface concentrations of air pollutants in Kamloops, Canada (concentrations in $\mu g\ m^{-3}$; the shaded gray gives daytime). Figure extracted from OnTraq final report (ESA). Right: Diurnal variation of fire radiative power for 5 days, for fires in Portugal (top) and in Africa savannas (Andela et al., 2015).***

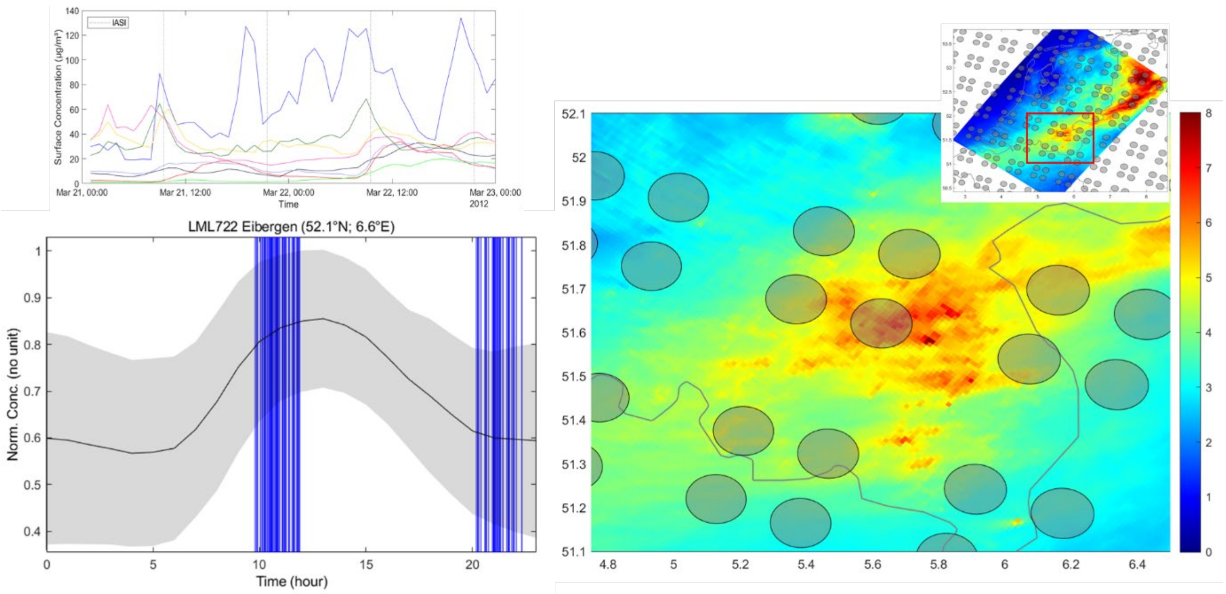


***Figure 8: Left: Hourly variation in surface $NH_3$ concentrations at several measurement sites from the LML network in the Netherlands; the IASI overpass times are shown by the vertical dotted lines. The bottom panel shows a monthly average (black line) and standard deviation (shaded grey) of the diurnal cycle for the station of Eibergen, with the corresponding IASI overpass times highlighted by blue lines. Right: Spatial distribution of $NH_3$ for the Netherlands (inset) and zoom for the South-East part around the city of Eindhoven; the colour scale shows concentrations in $\mu g m^{-3}$. The IASI pixels for one orbit are shown as grey circles. Figure from M. Van Damme (ULB).***

## 5.2 Contribution of MTG-S IRS for atmospheric composition monitoring

The major advantage of IRS over similar polar sounders for AC applications is related, as for most other applications, to its temporal and spatial sampling of the Europe-Africa disc. With a spatial resolution ranging from 4 to 7-8 km depending on latitude (increasing FOV at larger angles), a mapping of the Earth surface without gaps and hourly (half hourly) revisit time (see section 2.3 for detailed specifications) IRS will indeed allow diurnally resolved measurements of most (but not all) atmospheric species monitored by the polar IR sounders. This will benefit the AC monitoring system very significantly. However, the IRS spectral and radiometric performances will also be less in comparison to the sounders in polar orbit and this will reduce, as shown in several dedicated studies (i) the portfolio of products (in particular $CH_4$ and $N_2O$ will not be measured due to the smaller and non-continuous spectral range, see Figure 6) (ii) the vertical profiling capabilities and (iii) to lesser extent, the sensitivity to the boundary layer concentrations.

The contributions of IRS to the application areas identified in section 5.1 are driven by these advantages/disadvantages over the polar sounders. Another point deserving attention relates to the opportunities for synergies, as the IRS measurements will be made on top of the global monitoring backbone ensured by the polar orbiters, especially IASI-NG on EPS-SG that will fly in the same timeframe, and in parallel to the measurements of Sentinel 4 and other instruments on MTG. These synergies are likely to make an integral part of the mission success for AC and are briefly addressed in section 5.3.

The temporal/spatial sampling of IRS is expected to make a strong contribution in most aspects of *Air Quality* monitoring. These will indeed be helped by the smaller pixel size and mapping mode, that should better resolve the urban centres from the surrounding areas and increase the number of useful cloud free scenes, as well as by the measurements of the diurnal cycle of concentrations. In typical conditions, however, the sensitivity of IRS will peak higher in the troposphere than with IASI and IASI-NG and may prevent the observation of small boundary layer enhancements over otherwise large columns; this may be critical in particular for $O_3$, to lesser extent CO. For species absorbing radiation in the atmospheric window such as $NH_3$, VOCs and dust this should not be such an issue and the sensitivity to surface concentrations should even be significant during several hours of the day, when the thermal contrast reaches high values[1]. An example of simulation for $NH_3$ is provided in Figure 9. The contribution of IRS to AQ should benefit and be strengthened by the operational assimilation system put in place within CAMS (e.g. Iness et al., 2013).

Similarly to AQ, the *monitoring of point sources* would be improved dramatically with the IRS smaller on-ground footprint. If this is certainly true for species with short to medium lifetime ($NH_3$, CO and aerosols), it is not excluded to be the case also - after the development of suitable detection/retrieval approaches - for long-lived species, including $CO_2$ from strong emitters.

The surveillance *of fire, volcano and other events* would largely benefit from the diurnal sampling and continuous mapping of IRS (see Figure 7, right). The monitoring of volcanic plumes will not be possible with IRS using, as with IASI, the $SO_2$ signatures (the use of the weak $\nu_1$ could be used in case of large eruptions but the strong $\nu_3$ band is not covered; see above in Figure 6). But these volcanic plumes will be well captured with the calculation of an ash index and the retrieval of the ash optical depth (possibly the total mass load). IRS would

[1] The measurements of boundary layer $SO_2$ is not expected to be possible as IRS does not cover the strong $\nu_3$ band

then become a key element of an operational alert system for volcanic ash plumes, to the benefit of aviation safety (in the continuation of the current SACS system[2]). For fire, IRS would allow the determination of emission fluxes and emission ratios, and their relation to the temporal evolution of fire properties (combustion phase, type of vegetation etc.) at an unprecedented scale to support models. The development of a fast response system based on the early detection of several fire species (CO, $NH_3$, $C_2H_4$) could and should be envisaged in a similar way as it is currently done for active fires, based on temperature hotspots, or volcanoes. It is likely that similar types of operational applications for event detection and monitoring (e.g. for dust storms) will progressively develop with IRS.

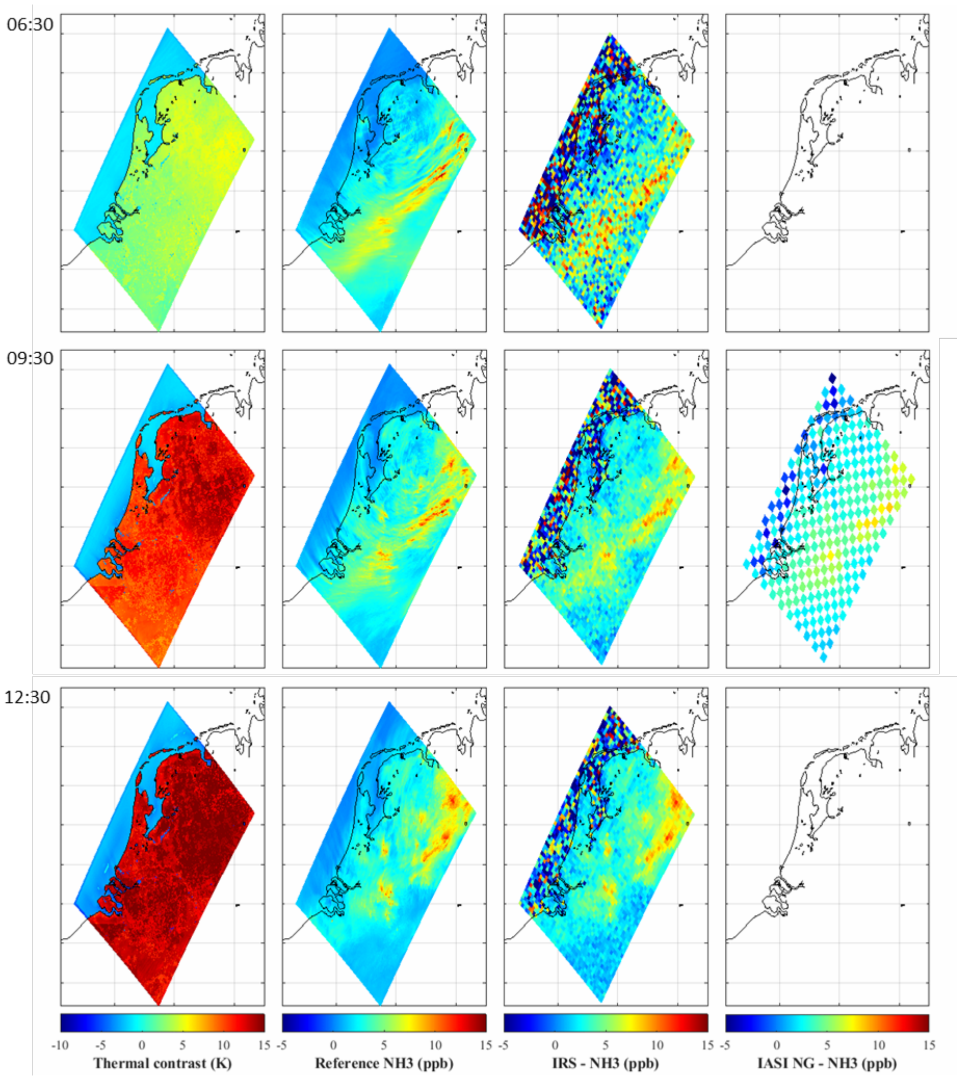


***Figure 9: Model distribution of thermal contrast (first panel) and $NH_3$ surface volume mixing ratio (second panel) at 1 km resolution, used as references in the retrieval experiment. The third and fourth panels show simulated observations of the $NH_3$ surface volume mixing ratio by IRS and IASI-NG, respectively. From top to bottom at three different times of the day: 06:30, 09:30 (IASI-NG) and 12:30. Note the impact of thermal contrast on the retrieval accuracy. Figure courtesy L. Clarisse (ULB). Model distributions courtesy from H. Eskes (KNMI)***

2 http://sacs.aeronomie.be/

By measuring the Europe-Africa Earth disc, IRS could only contribute partly to the *global monitoring of tropospheric chemistry*, for example by assessing atmospheric budgets on the continental and regional scales. There are a number of species that are relevant for this, all having short to medium lifetime ($O_3$, CO, $NH_3$, a suite of VOCs). However, if the measurement of these species by IRS will be useful for monitoring fast processes, it is not certain that they will bring more than the polar sounders for these specific applications, especially considering that the latter will provide global measurements with better tropospheric sensitivity and accuracy. The same arguments hold for *global stratospheric chemistry monitoring*, which, as explained above, is mainly supported with polar sounders by the measurements of stratospheric (or total) $O_3$ and $HNO_3$ columns. The sensitivity of IRS to these products is expected to be relatively good but as the stratospheric variability is weak and as IRS will not cover the sensitive polar regions, the potential added value for application in the stratosphere is to be consolidated. *Climate monitoring* may also benefit less from IRS. This is especially because $CH_4$ and $N_2O$ will not be measurable (see Figure 6) but also because the climate variations mostly relate to slow changes to the AC, which will be well captured from other types of instruments. This holds for the long-lived GHGs but also for more reactive ones ($O_3$, aerosols) or indirect climate forcers (CO, $NH_3$).

*The monitoring of long-range transport, winds, convective events* is, on the contrary, an area where IRS is expected to play an important role, despite restricting this to the Europe-Africa Earth disk. A key aspect would be, in the continuation of recent developments with the polar sounders, the measurement of winds from vertical profiles of water vapour and possibly $O_3$, at high spatial and temporal sampling. The monitoring of pollution export and long-range pollution transport could also be better exploited owing to the temporal sampling of IRS (target species would be pollution tracers such as CO, PAN, $C_2H_2$, as well as aerosols and $O_3$).

## 5.3 Opportunities from synergies

*Synergies with Sentinel 4 and other instruments on MTG*. If the AC applications of IRS are not the prime mission objective, we have underlined above that a lot is to be expected from its operations for local source monitoring, AQ surveillance or operational alerts. MTG-S will also carry the Sentinel-4 UV-VIS-NIR sounder, dedicated to AC. It will provide measurements at 8 km resolution of $O_3$, $NO_2$, $H_2CO$, $SO_2$ during daytime. The common exploitation of the two sounders will be unique in most applications but in particular those related to AQ, point sources and event monitoring. The contribution to AQ will be strengthened further by the Multi-viewing Multi-channel Multi-polarisation imager (3MI) instrument on EPS-SG, which will allow accurate mapping of atmospheric aerosols.

*Synergies with IASI-NG and other polar sounders*. IRS will make similar types of measurements as IASI and IASI-NG. With the exception of the GHGs $CH_4$ and $N_2O$, the most relevant species for AC monitoring will be accessible with IRS, although for some with less vertical sensitivity and less sensitivity to the lowest tropospheric layers. As apparent from the previous sections, IRS will be most useful for monitoring processes at the small scale (point sources) and that vary rapidly in space and time. The joint exploitation of IRS and IASI-NG products, after careful verification of their consistency, will provide an extensive view on the functioning of the tropospheric and to lesser extent stratospheric systems. Synergetic retrieval approaches (e.g. constrained profile retrievals from IRS using inputs from IASI-NG) could enhance the mission outputs. Synergies with the Copernicus Anthropogenic Carbon Dioxide Monitoring (CO2M) mission, under definition as high-priority Sentinel mission, are to be explored. The same holds for synergies for limb-sounding missions, such as ALTIUS, which could benefit the exploitation of IRS by providing accurate measurements of the stratospheric composition.

*Synergies with other IR hyperspectral sounders on GEO.* The common operation from GEO of hyperspectral IR sounders from different agencies, each measuring a specific disk on Earth, would of course provide a spatially extended view of the rapidly changing AC.

# 6 USE OF MTG-S IRS PRODUCTS FOR CLIMATE STUDIES

## 6.1 Introduction

It may seem paradoxical to say that MTG-S IRS is a hyperspectral mission with the goal of providing dedicated information on climate variables and climate change, since the IRS primary objective is NWC and NWP. Nevertheless as already demonstrated by its multispectral predecessor SEVIRI on the four MSG platforms (MSG-1 to MSG-4), many studies related to climate have been performed due to the geostationary (GEO) viewpoint, the good spatial resolution and the high time sampling frequency of this type of GEO sounders. It is then important in the present discussion to explain the added value of IRS for climate studies and its complementarity with other missions, including the sun-synchronous low Earth observing (LEO) meteorological sounders.

As mentioned, there will be a continuity in the services provided by EUMETSAT between the TIR channels of SEVIRI (on MSG) and IRS (on MTG-S) for which the LWIR and MWIR bands of IRS are relevant. In the same manner there will be a continuity between the VIS, Near-IR (NIR), IR and TIR channels of SEVIRI (on MSG) and FCI (on MTG-I), to acquire long time series of observations over the underlying observable disk in the various spectral channels. This complementarity between IRS and FCI on the two MTG-S and MTG-I platforms is always to be recalled when discussing climate issues.

For completeness, we mention here the notion of Essential Climate Variables (ECVs) for which an inventory is provided by the Committee on Earth Observation Satellites (CEOS) [https://CEOS] and the Coordination Group for Meteorological Satellites the (CGMS) [https://CGMS] member agencies. This inventory is housing information on 1251 Climate Data Records (CDRs) with a structured repository for the characteristics of two types of GCOS ECV CDRs: climate data records that exist and are accessible, including frequently updated interim CDRs and climate data records that are planned to be delivered.

The current list of the 1251 CDRs is accessible through the link [http://ECV] from which the Excel file *ECV_Inventory_v4.1.xlsx* can be recovered containing a huge amount of information on the status (existing or planned), the responsible organisation and all the details on each climate data record.

In this chapter we will concentrate on IRS only for its potential contributions to climate studies. One important aspect to keep in mind is that MTG-S IRS is a GEO satellite continuously viewing about one third of the planet, hence only observing a regional part of the global climate. The complete vision for climate change studies will only be available by combining the information collected by similar GEO sounders positioned at different longitudes for covering the full Earth. Finally, one has to remember that the long-term continuity of the MTG programme (more than 30 years) is a key feature for climate change studies (a period of 10 years is considered as a minimum for smoothing the interannual variability).

The following topics will be covered sequentially (focusing on IRS):

- TIR spectral coverage of IRS, SEVIRI and FCI
- Generation and archiving of level-1, 2 and 3 datasets
- Role of the different SAFs and essential climate variables

- Potential for GHGs and chemical species monitoring
- Potential for spectrally resolved surface TIR emissivity
- Potential for spectrally resolved aerosol TIR signatures
- Potential for improving land and sea surface models
- Specific short term priorities.

## 6.2 Thermal infrared spectral coverage of IRS, SEVIRI and FCI

One of the main differences (for covering the TIR domain) between the hyperspectral IRS and the preceding multispectral imager SEVIRI and its successor FCI is the much higher spectral resolution of IRS. This has a major impact on what could be one of the new contributions of IRS for climate. The following tables provide a comparison of the spectral coverage for the three instruments, using for convenience the two spectral units i.e. wavenumber *wn* (in $cm^{-1}$) and wavelength *wl* (in µm).

| IRS | $wn_1$ | $wn_0$ | $wn_2$ | $\Delta wn$ | $\delta wn$ | *npts* | $wl_1$ | $wl_0$ | $wl_2$ | $\Delta wl$ |
|---|---|---|---|---|---|---|---|---|---|---|
| LWIR | 679.5 | 944.8 | 1210.0 | 530.5 | 0.6056 | 877 | 8.26 | 10.58 | 14.72 | 6.46 |
| MWIR | 1560.0 | 1905.2 | 2250.4 | 690.4 | 0.6051 | 1076 | 4.44 | 5.25 | 6.41 | 1.97 |

***Table 2: Spectral coverage for IRS. Δwn and Δwl are the width of the domains in the two units, δwn is the sampling step and npts is the number of spectral samples at level-1b. Values computed from the information provided in [http://MTG-IRS_PUG_L1]***

| SEVIRI | $wn_1$ | $wn_0$ | $wn_2$ | $\Delta wn$ | *npts* | $wl_1$ | $wl_0$ | $wl_2$ | $\Delta wl$ |
|---|---|---|---|---|---|---|---|---|---|
| IR8.7 | 1123.5 | 1147.3 | 1171.1 | 47.6 | 79 | 8.54 | 8.72 | 8.90 | 0.36 |
| IR9.7 | 1021.0 | 1034.5 | 1048.1 | 27.0 | 45 | 9.54 | 9.67 | 9.79 | 0.25 |
| IR10.8 | 883.9 | 929.7 | 975.6 | 91.7 | 152 | 10.25 | 10.78 | 11.31 | 1.06 |
| IR12.0 | 804.1 | 838.2 | 872.3 | 68.2 | 113 | 11.46 | 11.95 | 12.44 | 0.98 |
| IR13.4 | 710.9 | 748.9 | 786.8 | 75.9 | 126 | 12.71 | 13.39 | 14.07 | 1.36 |

***Table 3: Spectral coverage for SEVIRI. Δwn and Δwl are the full width at half maximum (FWHM) of the domains in the two units and npts is the number of IRS level-1b spectral samples within Δwn. Values computed from the information provided in [http://SEVIRI]***

| FCI | $wn_1$ | $wn_0$ | $wn_2$ | $\Delta wn$ | *npts* | $wl_1$ | $wl_0$ | $wl_2$ | $\Delta wl$ |
|---|---|---|---|---|---|---|---|---|---|
| IR8.7 | 1176.5 | 1150.0 | 1123.6 | 52.9 | 88 | 8.90 | 8.70 | 8.50 | 0.40 |
| IR9.7 | 1047.1 | 1031.2 | 1015.2 | 31.9 | 53 | 9.85 | 9.70 | 9.55 | 0.30 |
| IR10.5 | 985.2 | 953.4 | 921.7 | 63.6 | 105 | 10.85 | 10.50 | 10.15 | 0.70 |
| IR12.3 | 829.9 | 813.3 | 796.8 | 33.1 | 55 | 12.55 | 12.30 | 12.05 | 0.50 |
| IR13.3 | 769.2 | 752.3 | 735.3 | 33.9 | 56 | 13.60 | 13.30 | 13.00 | 0.60 |

***Table 4: Spectral coverage for FCI. Δwn and Δwl are the full width at half maximum (FWHM) of the domains in the two units and npts is the number of IRS level-1b spectral samples within Δwn. Values computed from the information provided in [http://FCI]***

In the tables shown above we see that the spectral coverage of FCI and SEVIRI in the TIR region are comparable as expected from the mission continuity between these two multispectral imagers of MSG and MTG. But we also see (looking at the columns *npts*) that the spectral information available from IRS as contained in the SEVIRI and FCI bandpass will be much higher: between about 50 and 150 IRS samples in the corresponding imager channels. This means (in addition to the use of "clearer" level-1b samples in NC or NWP assimilation and level-2 retrievals a better determination of the underlying lower boundary limit properties (land and see surface for clear footprints or cloud top for cloudy ones) by better balancing the use of "troughs" between the lines and "peaks" (either in absorption or in emission) due to atmospheric molecules.

The spatial and time resolutions of IRS are not comparable to those of SEVIRI and FCI, but the real improvement is on the spectral resolution (as well as radiometric noise and accuracy). This argument is used in the next sections to underline the potential of IRS for climate studies.

### 6.3 Generation and archiving of level-1, 2 and 3 datasets

As a standard process (after the commissioning phase of IRS) the level-1b radiances will be monitored at EUMETSAT to ensure both their spectral and radiometric stability, meeting the requirements specified in the EURD. The traceability of the radiometric calibration will be a major aspect of this quality check process, and this is important for NWC and NWP applications. But this is even more important for climate studies for which the long-term stability is the major issue. A strong asset of the IRS instrument is its onboard calibration blackbody and thermal control as compared to SEVIRI that had to be radiometrically calibrated with less direct methods. Without going into the details of potential studies for checking the radiometric stability of IRS for climate studies the inter-comparison of TIR sounders for nearly coincident observations (in space, time and viewing geometry) will be needed. This task should be the responsibility of EUMETSAT within the well-established GSICS activities [http://GSICS] and has already been performed for the comparison of SEVIRI and IASI radiometric performances [http://SEVIRI-IASI]. A similar activity shall be performed for the comparison of IRS and IASI-NG radiances (for the same time and footprint location and for day and night conditions) after the proper "convolution" in the spectral domain for going from IASI-NG to IRS and spatial "convolution" for resampling/averaging the IRS footprints within the IASI-NG instantaneous FOVs. The same should also performed and is already planned between IRS and FCI. This must be done anyway for the NWC and NWP applications but should be planned for the mid-term and long-term operations of IRS in order to ensure its possible contributions to climate change studies.

Since the level-2 products from IRS [http://MTG-IRS_ATBD_L2] will be based on the level-1 products, the time stability of the latter will be essential for former, but not sufficient. The stability of the level-1 to level-2 processing algorithms will be key for using at best long time series for climate applications. No further discussion on this point is needed here, except to say that mid-term and long-term comparison with correlative measurements (ground based, airborne…) of similar or possible better quality should be the normal process for calibration/validations (Cal/Val) activities. Bias correction is always a possibility, but is always risky for long term analysis, since biases can be space and time dependent, but such ad hoc corrections have already been applied in the past. The big progress with the MTG programme is the insurance for a long lifetime for the IRS instruments and a required common period of operation during the transition from MTG-S1 to MTG-S2.

As far as the level-3 products from IRS for climates studies are concerned, they will be the responsibility of the different satellite application facilities (SAFs). The objective here is to define what would be the appropriate time averaging and space gridding. The latter could be based on the definition of the IRS "dwells", but could be also in latitude/longitude for a full coverage of the Earth by equivalent products from other equivalent GEO instruments. The combination/merging of diverse remote sensing datasets has been and will stay a standard strategy in this respect. For the time averaging periods the minimum is a monthly climatology, but yearly averaging (for interannual variability) and decennial averaging (for trends) are well established way of proceeding, each product having its own specificities.

Two aspects are to be quoted here:

- climatological records are needed for evaluating climate models providing "real" but "past" data to optimise their parameterisations and check their ability to generate "reconstructed" datasets as in the IPCC comparisons [https://IPCC] before making prediction for the "future" evolution of climatic variables (with given assumptions for the external forcings) as given in the IPCC scenarios [https://IPCC].
- international agreements on which climate parameters are emerging leading among the large variety of climate data records (CDR) to the definition of essential climate variables (ECVs). Their list is defined and controlled by committees like the Committee on Earth Observation Satellites (CEOS) [https://CEOS], the Coordination Group for Meteorological Satellites (CGMS) [https://CGMS] and the common efforts of these two bodies are merged within the joint CEOS/CGMS Working Group on Climate called WGClimate [https://WGClimate] under the umbrella of the United Nations Framework Convention on Climate Change (UNFCCC) [https://UNFCCC].

Finally, the question of archiving and reprocessing the climate datasets is a major logistical problem due to the volume and processing involved. Generally the initial "original" satellite data provider will manage the generation and storage of the level-1 and level-2 products, whereas higher level datasets (level-3 and derived level-4 products) will be disseminated in dedicated climate data centres, with questions of findable, accessible, interoperable, reusable datasets (FAIR) as promoted in Europe [https://FAIR].

### 6.4 Role of the different satellite application facilities and essential climate variables

EUMETSAT, with its SAF network, is providing a significant portion (~23%) of the CDRs, addressing 19 ECVs across the atmospheric, oceanic, terrestrial and cryosphere domains. MTG-S IRS will be an important contributor for feeding the corresponding data records. The list of EUMETSAT SAFs that could use/process IRS products together with the general "name" (identification) of the ECVs covered by each SAF is given below.

- Climate Monitoring SAF [https://CM-SAF]
  *Cloud properties, Radiative fluxes, Earth radiation budget*

  A validation report generated by the CM-SAF for assessing the quality of the SEVIRI cloud products with a discussion of the Brightness Temperature (BT) differences

BT(6.2 µm) - BT(10.8 µm) and BT(12.0 µm) - BT(10.8 µm) with considerations on their radiometric stability for climate studies is given in [Validation Report SEVIRI CLAAS, Edition 3]. The much higher spectral resolution and radiometric accuracy of MTG-S IRS will allow continuity and better performances for the time series of cloud product (including fractional cloud cover, cloud top level, cloud phase, liquid water path and ice water path).

- Land Surface Analysis SAF [https://LSA-SAF]
  *Land-surface temperature, Surface radiation budget*
  A study describing the methodology for deriving land surface temperature climate data records is given (A. Duguay-Tetzlaff et al., 2015) and one more recent example (among many others) of climate studies is the monitoring of heat extremes using LWIR channels of SEVIRI (Gouveia et al., 2022) (which will be much better covered by IRS).

- Atmospheric Composition monitoring SAF [https://AC-SAF]
  *Ozone, Precursors supporting ozone and aerosols ECVs, Aerosol properties, Carbon dioxide, methane and other GHGs*
  [See chapter 5. Support to atmospheric composition monitoring and forecasting]

- Ocean and Sea Ice SAF [https://OSI-SAF]
  *Sea-surface temperature*
  A recent use of LWIR measurements for assessing theimpact of climate change on the mediterranean sea surface temperature is discussed in (Guinaldo et al., 2023).

## 6.5 Potential for long-term monitoring of greenhouse gases and chemical species with IRS

Except for ozone, which is a level-2 product of IRS for Day-1, the IRS level-2 data on AC is not yet firmly decided. The chapter 5 on “Support for AC monitoring and forecasting” is covering good candidates for near-future products as $NH_3$, $SO_2$ and aerosols (possibly CO, better done by LEO sounders). But these constituents are more pertaining to process studies (because of their large variability in space and time) than to climate studies. However, these species discussed in chapter 5 are also relevant for their long-term impact on climate if the proper time series can be generated, analysed for trends and used for benchmarking existing (and future) chemical composition climate models in particular for AQ. A special comment can be made concerning $NH_3$: in addition to the emissions of this species by agricultural practices, this species is also emitted by fires. A contribution of IRS (through a $NH_3$ product) to the (increasing) trends in the frequency and spatial extension of fires is clearly of interest for monitoring climate change (as a complement to other instruments especially dedicated to fires).

The only GHG amenable to the IRS spectral coverage is $CO_2$ and indeed carbon dioxide is the in-situ thermometer, the spectral signatures of which are used to constrain the temperature distribution by assimilation of level-1b radiances in NWP as well as to retrieve the temperature profile in the level-1 to level-2 processing. The inversion of the $CO_2$ vertical profile (simultaneously with the temperature and humidity profiles) is mentioned in chapter 5 and as an option in the level-2 processing [http://MTG-IRS_ATBD_L2], but new dedicated studies are needed to demonstrate that one can decorrelate the temperature from the concentration of $CO_2$. The fact that IRS has a high revisit frequency allows potential enhancement of the signal to noise through time averaging or the detection of intense localized plumes (higher contrast for power plants or major cities) with respect to the $CO_2$ background (assuming then the ECMWF analysis or forecast temperature profile). Candidate spectral domains for the separate retrieval of $CO_2$ enhancements would be the "windows" where the "surface" is seen in intervals between 940 to 980 $cm^{-1}$ and 2050 to 2075 $cm^{-1}$ (with the possibility to perform a retrieval combining these two domains). If such retrievals are possible and produce results enabling the retrieval of fluxes (from the power plant or city plumes), IRS data could contribute to climate monitoring. Focused studies on this topic (including the statistical examination of conditions of favourable thermal contrast) could enhance the impact of IRS, especially by its day and night capability and its good spatial resolution (CO2M will only quantify $CO_2$ in clear sky and day time).

## 6.6 Potential for long-term monitoring of spectrally resolved surface thermal infrared emissivity

As mentioned above one of the gap filling capabilities of IRS would be to improve the retrieval of surface emissivity and its spectral dependence $\varepsilon(wn)$ as compared to the multispectral imagers (SEVIRI, FCI) or non-imaging sounders (with disjoint footprints like IASI or IASI-NG). Such a capability should be demonstrated by preparatory studies based on the currently proposed level-1 to level-2 algorithm for Day-1 [http://MTG-IRS_ATBD_L2] where the land surface emissivity is modelled in selected channels (of the order of 10), from which the entire spectrum can be reconstructed by application of PC transformations. Other approaches could be proposed and tested to benefit from the larger number of the potential "surface" channels as compared to the LEO sounders of GEO imagers. The high revisit frequency will allow to generate improved spectral emissivity data $\varepsilon(wn)$ (at a spatial and temporal scale to be defined for filtering cloud contaminated footprints) usable to generate monthly, annual, pluriannual or decadal time series for climate trend analyses and for better constraining climate model parameterizations. The variation of emissivity as a function of precipitation is a secondary effect that would have to be considered. This topic is related to the longwave surface radiation budget and to the overall Earth radiation budget, in combination with the shortwave information provided by other sounders or imagers.

## 6.7 Potential for long term monitoring of spectrally resolved aerosol thermal infrared signatures

The aerosol product (for coarse particles) that could be derived from IRS spectra in the TIR has already been discussed in chapter 5. The same argument as for the spectral dependence of the emissivity is applicable to aerosol signatures (and both effects have to be decorrelated). These signatures are varying slowly spectrally (as compared to the individual contribution of the $H_2O$ or $CO_2$ lines) but are clearly distinguishable (mostly when aerosol of the desert type is present in abundance) in the atmospheric windows on both sides of the ozone band at 9.6 µm or 1042 $cm^{-1}$. Other types of aerosols generated by wildfires could also be detected/identified in the spectral domain covered by IRS. Once retrieved with a 15 min repeat period diurnal, monthly, seasonal and annual time series could be derived from IRS level-2 aerosol products (thanks to the progress still to be made in retrieving aerosol properties through possibly joint retrievals of IRS spectra and FCI data). Midterm to long term trends in the aerosol amount are clearly of importance for climate studies (and IRS could contribute at least to the long-term monitoring of large particle aerosols and potentially fire aerosols).

## 6.8 Potential for improving land and sea surface models

The coupling between surface (or skin) temperature with surface emissivity and soil type (and humidity) is clearly taken into account in land surface models that are themselves key for future climate change modelling. IRS will contribute to simultaneous TIR measurements (at high spatial and time resolution) of $T_{surf}$ and $\varepsilon(wn)$. The elaboration of proper datasets for these two surface parameters (with the appropriate time and spatial sampling) will be an important contribution from IRS to climate model benchmarking if the appropriate studies are supported to generate the corresponding time series.

The same approach could also be examined for sea surface temperature and emissivity, a domain in which the high spatial and time resolution of IRS measurements could distinguish spectral signatures due to phytoplankton (or zooplankton) blooms that should be monitored over long time series to better understand the interaction between the various components of the Earth system in a rapidly changing state of the climate.

## 6.9 Specific short-term priorities

Finally, we detail several short-term priorities:

- Potential for long term monitoring of $CO_2$ (trends in emission) and $NH_3$ (trends in the frequency and extent of fires)
- Initiate studies long term monitoring of spectrally resolved surface TIR emissivity
- Initiate studies for long term monitoring of spectrally resolved (coarse) aerosol TIR signatures
- Examine the need for land models to better use the simultaneous information obtained by IRS on $T_{surf}$ and $\varepsilon(wn)$ to improve their capabilities of the coupled Earth models for climate predictions
- Potential to process statistically (PCA methods) the information contained in the 160×160 spectra of a given dwell (for all usable dwells of the disk seen by IRS) and to generate aggregate *mean*, *stdv*… spectra (possibly by category clear/overcast, sea/land, day/night) on a daily, monthly, annual and pluriannual basis. The "dwell" pattern being the fixed spatial grid for climatological variables.

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