BAMS Article

The EUMETSAT Polar System

13+ Successful Years of Global Observations for Operational Weather Prediction and Climate Monitoring

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ABSTRACT: After successful launch in November 2018 and successful commissioning of *Metop-C*, all three satellites of the EUMETSAT Polar System (EPS) are in orbit together and operational. EPS is part of the Initial Joint Polar System (IJPS) with the United States (NOAA) and provides the service in the midmorning orbit. The Metop satellites carry a mission payload of sounding and imaging instruments, which allow provision of support to operational meteorology and climate monitoring, which are the main mission objectives for EPS. Applications include numerical weather prediction, atmospheric composition monitoring, and marine meteorology. Climate monitoring is supported through the generation of long time series through the program duration of 20+ years. The payload was developed and contributed by partners, including NOAA, CNES, and ESA. EUMETSAT and ESA developed the space segment in cooperation. The system has proven its value since the first satellite *Metop-A*, with enhanced products at high reliability for atmospheric sounding, delivered a very strong positive impact on NWP and results beyond expectations for atmospheric composition and chemistry applications. Having multiple satellites in orbit—now three—has enabled enhanced and additional products with increased impact, like atmospheric motion vector products at latitudes not accessible to geostationary observations or increased probability of radio occultations and hence atmospheric soundings with the Global Navigation Satellite System (GNSS) Radio-Occultation Atmospheric Sounder (GRAS) instruments. The paper gives an overview of the system and the embarked payload and discusses the benefits of generated products for applications and services. The conclusions point to the follow-on system, currently under development and assuring continuity for another 20+ years.

KEYWORDS: Remote sensing; Satellite observations; Instrumentation/sensors

https://doi.org/10.1175/BAMS-D-20-0082.1
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In final form 22 February 2021

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Three Metop satellites comprise the space component of the first European series of polar-orbiting meteorological satellites in the frame of the EPS (see the appendix). EPS is the European polar-orbiting component in sun-synchronous low Earth orbit of the space-based part of the WMO Global Observing System (GOS) (WMO 2020a). Several partner satellite operators have committed in the frame of the WMO vision (WMO 2020b), to serve a number of essential orbits (early morning, midmorning, and afternoon orbits) for the support of numerical weather prediction (NWP). EPS continues to work in the frame of the Initial Joint Polar System (IJPS), a joint U.S.–European operational polar system, where the European satellites provide the service from the midmorning orbit, whereas the U.S. contribution serves from the afternoon orbit. The EPS satellites continue the successful provision of the midmorning service from NOAA with the TIROS-N and advanced TIROS-N series (see, e.g., Schwalb 1978, 1982; Rao et al. 1990). The Metop satellites fly in sun-synchronous midmorning orbit (descending node at 0930 local solar time) at an inclination of 98.70° and an altitude of 817 km (nominal orbit parameters). The nominal lifetime of each of the Metop satellites is 5 years. EUMETSAT, ESA, and CNES developed them jointly under cooperation agreements. For the development of the satellites, please refer to (Edwards and Pawlak 2000; Edwards et al. 2006). Details on the development of the satellites and their payload can be found in Callies et al. (2000), Cohen et al. (2006), Edwards et al. (2006), Gelsthorpe et al. (2000), Figa-Saldaña et al. (2002), Loiselet et al. (2000), Luntama et al. (2006), and Klaes et al. (2007).

With the successful launch of *Metop-C* with Soyuz-ST-B/Fregat on 6 November 2018 (Kourou time) from the Guyana Space Center and successful commissioning, the third of the EPS Metop satellites is in orbit and operational. The first satellite *Metop-A* had been launched on 19 October 2006, the second one—*Metop-B*—on 17 September 2012, both with *Soyuz-2-1a/Fregat* from the Baikonur Cosmodrome in Kazakhstan. The system continues to provide key observations from the imaging and sounding instruments on the three satellites, which allows the suite of enhanced products to be increased through the synergetic use of the data from multiple spacecraft.

Already with the launch of *Metop-B*, EUMETSAT member states have authorized the use of the two satellites simultaneously (the program originally foresaw to have only one spacecraft at a time). The two satellites *Metop-A* and *Metop-B* were positioned in a configuration in the same orbital plane, phased 48.92 min (close to 180°) apart. The use of data from two spacecraft with the same payload allowed the development of new enhanced products. As soon as *Metop-C* became operational, three operational Metop satellites have been contributing to EUMETSAT's main mission objectives for about 3 years (2019–21). At the end of 2021, EUMETSAT intends to deorbit *Metop-A* and the EPS mission will continue with the remaining satellites. *Metop-B* end of life is expected around 2027, *Metop-C* is expected to last until around 2030.

NOAA satellites accompany the Metop satellites in the frame of the IJPS (NOAA 2013) and in the future of the Joint Polar System (JPS) (EUMETSAT 2015). The latest satellite launched on the 18 November 2017 is *NOAA-20* (formerly known as JPSS-1) and has been the NOAA primary operational satellite since 7 March 2018 (Zhou et al. 2019). EUMETSAT cross support

to *NOAA-20*, as part of the JPS, will start when EUMETSAT Polar System Second Generation (EPS-SG) enters operations. Launched on 28 October 2011, the *Suomi National Polar-Orbiting Partnership* (*Suomi NPP*) satellite has been the nominal IJPS satellite in the afternoon orbit from 1 May 2014 to 7 March 2018. EUMETSAT provides no direct support to operations of *Suomi NPP*, initially a NASA satellite. EUMETSAT is however supporting global and regional *Suomi NPP* data services within the scope of the IJPS. Launched on 6 February 2009, *NOAA-19* continues to be operated with the support of EUMETSAT as prime for Advanced Data Collection System (ADCS) and Search and Rescue Satellite Aided Tracking (SARSAT) mission services and with all other instrument data also being processed, within the IJPS framework. Satellite performance remains good.

The EPS mission objectives are primarily the support of operational meteorology and climate monitoring. In particular, temperature and humidity sounding information in support of NWP, supported by imaging information on clouds, have proven an increasing impact on the forecast quality (e.g., Lorenc and Marriot 2014). Measurements for atmospheric composition monitoring and chemistry could be achieved with EPS beyond expectations. Further applications include marine meteorology, cloud and aerosol detection and monitoring, and emerging applications for nowcasting.

Mission payload and products

The payload of the three Metop satellites reflects the commonality with and continuity to NOAA satellites in the beginning of the IJPS on one hand through a common instrument contingent on both the NOAA and the Metop satellites. On the other hand, innovative payload components and successful research missions put into operations allowed a strong enhancement and continuous impact of these observations on a manifold of applications over the long duration of the program (at this point in time, more than 14 years in orbit, and more than 20 years expected). Consequently, each of the Metop satellites (Fig. 1) carry the same payload instruments (with the exception, that no HIRS is flown on *Metop-C*). The continuity component is essentially the Advanced TIROS Operational Vertical Sounder (ATOVS) instrument package (NOAA 2014a) and the Advanced Very High Resolution Radiometer (AVHRR) imager (EUMETSAT 2020a). ATOVS includes the High Resolution Infrared Radiation Sounder (HIRS/4) instrument, the Advanced Microwave Sounding Unit-A (AMSU-A), and the Microwave Humidity Sounder (MHS) (successor of AMSU-B on NOAA KLM/*NOAA-15*, *NOAA-16*, and *NOAA-17*; NOAA 2014b) (EUMETSAT 2020c). MHS is a EUMETSAT development and flew first on *NOAA-18* in 2005, and is actually the first EUMETSAT development in polar orbit (Bonsignori 2007). The AVHRR/3 is a six-channel imager to provide cloud and surface information for the sounding instruments [five channels can be transmitted to the ground at a time, channel 3a and 3b can be switched; on all three Metop satellites, channel 3a is switched on for the day side (descending node), and 3b for the night side (ascending node) of the actual orbit]. AVHRR/3 provided for the first time global full resolution data at about 1 km sampling at nadir from the Metop satellites (EUMETSAT 2020a). One can find the details of these instruments'

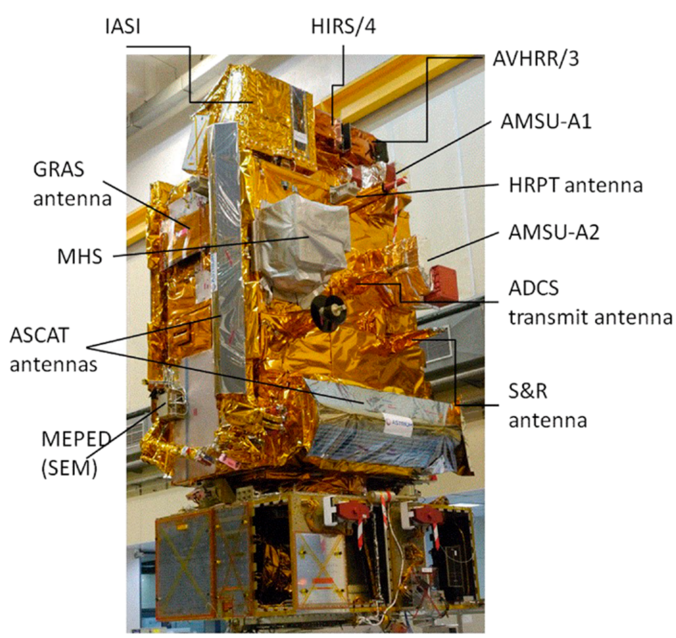

Fig. 1. Metop satellite and embarked instruments. *Metop-B* in the clean room 2012.

specification elsewhere (Klaes 2018). NOAA provided the AMSU-A, HIRS/4, and AVHRR instruments. The ATOVS and AVHRR instruments represent the common payload with the afternoon satellites in the frame of the IJPS, which were the satellites *NOAA-18* (NOAA-N) (launch in May 2005) and *NOAA-19* (NOAA-N′) (launched in February 2009). HIRS/4 on *Metop-A* and *Metop-B* assured continuity of an IR (Infrared) sounding capability. Assuming that by the time of the launch of *Metop-C*, Infrared Atmospheric Sounding Interferometer (IASI) would have proven its value, no HIRS/4 flies on *Metop-C*.

The IASI instrument was innovative technology and introduced hyperspectral high-resolution infrared sounding capabilities based on Fourier transform spectroscopy into operational meteorological service (Blumstein et al. 2004). Developed by Thalès Alenia Space under contract with CNES, the French space agency, it is still cutting-edge technology and makes Metop today still a state of the art satellite. CNES was also at the origin of the algorithm concept for the generation of the IASI calibrated radiances. The ESA developed the Global Ozone Monitoring Experiment (GOME-2) instrument (Callies et al. 2000) in heritage from the ERS GOME-1 instrument (Hahne 1997) providing ultraviolet visible (UVVIS) spectra in order to monitor the global ozone, and greenhouse gases (Burrows et al. 1999). The Advanced Scatterometer (ASCAT) instrument is a C-band radar, the only active instrument on board Metop, and brings Ocean surface wind measurements and soil moisture retrievals into operational service, in heritage of the Earth Resources Satellite Active Microwave Instrument (ERS AMI) research mission (Gelsthorpe et al. 2000).

In the past, research missions had demonstrated the use of radio-occultation measurements (Melbourne et al. 1994). The GRAS instrument, developed by ESA (Loiselet et al. 2000) and embarked on the Metop satellites has demonstrated its operational use, and the need to develop a system of ground support network and precise orbit determination with it. (Luntama 2006).

As three satellites are currently operational, two of them, *Metop-A* and *Metop-B*, have already exceeded their nominal lifetime of five years. However, they are still providing valuable data in fulfilment of their mission objectives. Some instruments have suffered from ageing effects and have shown some degradations. Table 1 summarizes the status of the instrument payload at the time of writing (more than 14 years of *Metop-A*, 8 years of *Metop-B*, and already 2 years of *Metop-C*).

Application areas and products

Operational meteorology—Numerical weather prediction. Data and products from EPS serve operational meteorology from EUMETSAT member states and all users over the whole globe. From the very beginning, data from the EPS have provided a major impact on the quality of numerical weather prediction. NWP is the basis of modern global and local weather forecasting, up to 10 days into the future. The technique to assimilate radiances into numerical weather prediction models started in the 1990s (Eyre et al. 2020) and led to the fact that today most (about 90%) of the input data ingested into the analyses of NWP stem from satellites. This includes all instruments of the Metop's payload. The sounding instruments in the microwave and infrared spectral range as well as the radio occultation soundings of the GRAS instrument provide the required three-dimensional temperature and humidity information in the troposphere as well as in the stratosphere. Visible and infrared imager data from AVHRR support these soundings. All major NWP centers are assimilating the data of these instruments. The main positive impact turned out to come from the microwave and infrared sounders, and in particular from the IASI sounding data, improving forecast quality on top of the data from Atmospheric Infrared Sounder (AIRS), which had paved the way for hyperspectral data before (Pagano et al. 2003; Chahine et al. 2006) and were routinely assimilated into NWP (McNally et al. 2006). IASI made it possible to provide temperature and humidity profiles at an unprecedented

Table 1. EPS/Metop instrument status as of time of writing (April 2020).

Instrument	*Metop-A* (drifting since 2016)	*Metop-B*	*Metop-C*
IASI			IASI operated on B side
AMSU-A	Channels 7 and 8 lost, channel 3 out of specification (spec.)	Channel 15 lost, channel 3 out of spec.	Although useable, the AMSU-A1 channel 3 continues to exhibit noise fluctuating above its specification limit; additionally, the gain is continuing to decline, which will lead to further degradation Channel 3 out of spec., channel 3 gain decreasing
MHS	After a further degradation on the redundant oscillator, the MHS channel 2 was declared as failed on 26 Feb 2020		After 13 Dec 2019, MHS channels 3 and 4 went out of spec. again and the noise has remained erratic due to variances in gain, which causes products to show striping artifacts Channels 3 and 4 around spec., strong noise fluctuation causes striping
HIRS/4	HIRS noise on all longwave channels and most shortwave channels continued to be out of specifications; the instrument is believed to be close to end of life	Channels 5, 6, 10, and 14 out of spec.; filter wheel not stable	No HIRS embarked
AVHRR/3			
ASCAT			
GRAS			
GOME-2	Periods without GOME-2 solar view due to drifting satellite		

accuracy of 1 K and 10%, respectively, at a vertical resolution of 1–2 km in the troposphere. The positive impact was enhanced by the simultaneous assimilation of the nearly all-weather microwave temperature and humidity information from the microwave sounders AMSU-A and MHS (Fig. 2).

Importantly also, the radio occultation measurements from the GRAS instrument provided—due to their characteristics as frequency measurement, not requiring a calibration—unique anchor points for NWP in the stratosphere, where very little information is otherwise available to constrain the models, and proved immediately beneficial to forecast quality improvement (Healy 2008). The measurements GRAS provides was a novel related to numerical weather prediction. The measurement is the time delay of the radio signals continuously received from the global positioning system (GPS) satellites at the GRAS receiver instruments on the Metop satellites, which occurs when these GPS signals are refracted while they travel through the atmosphere in a limb sounding geometry. The obtained bending angle profile contains information on temperature and humidity information at high vertical resolution (<1 km) in particular in the upper troposphere and the stratosphere. One can obtain from one radio occultation instrument like GRAS about 600 atmospheric profiles per day. Most NWP models assimilate directly the bending angle profiles. In addition, the Radio Occultation Meteorology Satellite Application Facility (ROM SAF), hosted by the Danish Meteorological Institute (DMI) provides derived near real time products of temperature, humidity, refractivity, and pressure profiles. They contributed recently to confirm some dynamical features induced by a smoke bubble caused by Australian bush fires, which traveled up into the stratosphere over a rather long period (Khaykin et al. 2020).

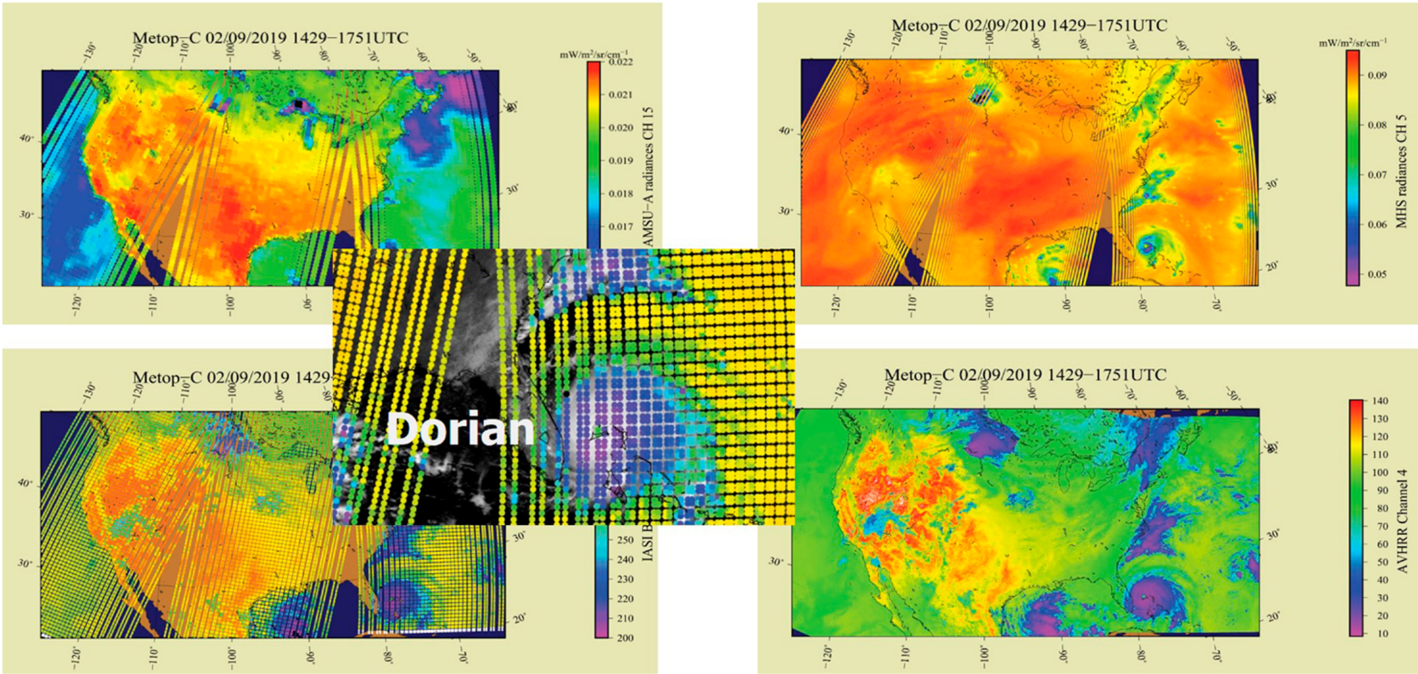

Fig. 2. Typical level 1b products from Metop assimilated into NWP: (top left) AMSU-A, (top right) MHS, (bottom left) IASI level 1C, and (bottom right) AVHRR/3 cloud information. The inset shows an enhanced composite of Hurricane Dorian 2 Sep 2019.

ASCAT is the only active instrument on board Metop. Its C-band radar provides ocean surface vector winds at 10 m over the global oceans derived from the backscattered radar cross section. Winds from ASCAT have proven essential for the prediction and monitoring of tropical storms (EUMETSAT 2020e) and for the measurement of the atmospheric circulation over the oceans as an important contribution for the atmosphere–ocean interaction. The ocean wind measurements are derived by the Ocean and Sea ice Satellite Application Facility (OSI SAF), hosted by Météo-France.

Marine meteorology

The EPS supports marine meteorology through the OSI SAF, which is one of the eight decentralized components of the EPS ground segment. Several sea surface temperature products are generated for regional and global use, based on the AVHRR imager and the IASI instrument. With the latter, the OSI SAF derives a global sea surface temperature product for Group for High Resolution Sea Surface Temperatures (GHRSST) using the SST product that is part of the Central Facility IASI level 2 product (O'Carroll et al. 2012) to back up the lost Advanced Along Track Scanning Radiometer (AATSR) based product. Important marine products are those monitoring sea ice. The product portfolio of the OSI SAF contains a wealth of sea ice products (OSI SAF 2020). Many of them are based on the microwave instruments on Metop (AMSU-A and MHS). In addition, the scatterometer ASCAT is an important source of generating ocean wind products.

Atmospheric composition and atmospheric chemistry

Besides providing essential observations for global NWP, the observed IASI spectra have provided considerable global observations of the atmospheric composition from the early days on. IASI spectra measure components of atmospheric composition over the whole globe two times a day. The covered spectral range, the spectral resolution and remarkable radiometric performance allow deriving and monitoring concentrations of a number of trace gases. Researchers at Université Libre de Bruxelles (ULB), Laboratoire Atmosphères,

Millieux, Observations Spatiales (LATMOS), and Laboratoire de Météorologie Dynamique (LMD) have obtained global-scale distributions of a number of trace gases, which included CO, CH_4, ozone, HNO_3, and NH_3, which have become integral of the operational IASI level 2 processing at EUMETSAT. During the forest fires in Greece in summer 2007 a number of organic species resulting from special atmospheric chemistry reactions in the course of fire events could be measured (Turquety et al. 2009; see also Clerbaux et al. 2015). The COVID-19 pandemic and related confinements have led to a significant drop of activities in many regions on Earth, which could also be observed from space through the CO measurements made by IASI (Clerbaux 2020a).

Ammonia concentrations have been observed over the whole globe in mid- and lower latitudes for 2008 already (Clarisse et al. 2009). IASI showed that the ammonia emissions during the COVID confinement continued (through agricultural fertilization) in particular in France. In another recent publication, a global monitoring ammonia capability has been demonstrated (Van Damme et al. 2018), which was the first time from space. It was also shown that the atmospheric pollution from fine particles continued in spite of the diminished traffic during the confinement (Clerbaux 2020b).

Furthermore, volcanic eruptions like those from 2010/11 could be followed with IASI measurements, retrieving volcanic ash information and also SO_2 measurements (Carboni et al. 2012). Volcanic SO_2 is also retrieved by the second instrument on Metop, capable to measure trace gases, the Global Ozone Monitoring Experiment 2 (GOME-2). This instrument monitors the global ozone total amount as well as the profile in continuity to the GOME-1 and Scanning Imaging Absorption Spectrometer for Atmospheric Cartography (SCIAMACHY) measurements, besides other trace gas measurements like, e.g., NO_2 and BrO (Fioletov 2013). All these products are processed in the Atmospheric Composition Satellite Application Facility (AC SAF) (https://acsaf.org/).

Concerning stratospheric ozone, a considerable decrease was observed over the North Pole at the beginning of the year 2020 (Clerbaux et al. 2020c). Later in the same year, IASI was able to observe the intense ozone hole over Antarctica due to a polar vortex of rare, sustained intensity, with ozone total columns dropping typically down to 100 Dobson units (DU) and even below.

Wind products

Atmospheric motion vectors (AMV) are derived operationally at EUMETSAT over polar regions since 2011 using data from AVHRR. The latest version of the algorithm allows the extraction of three different AVHRR AMV products, (Hautecoeur and Borde 2017; Borde et al. 2016; Horváth et al. 2017), using either a pair or a triplet of AVHRR images taken from one or two Metop satellites, with different coverage and temporal gaps between successive images. The main benefit of these products occurs in the 40°–60°N/S latitude bands, where few wind observations are usually available for assimilation. Since the launch of *Metop-C* in October 2018, the data from the three Metop satellites are processed at EUMETSAT to derive global wind products (Borde et al. 2019).

Surface characteristics and clouds

The AVHRR instrument is measuring solar energy and radiated thermal energy emitted mainly from land surfaces, ocean surfaces, and clouds. It is therefore used for a variety of applications, which includes cloud monitoring and analyses for sounding (IASI and ATOVS), the determination of surface properties (vegetation), snow coverage, land surface temperatures, and ocean surface temperatures. Furthermore, the Hydrology Satellite Application Facility (H SAF) uses the scatterometer data over land to derive soil moisture products (Brocca et al. 2017). Those have been recently used in synergy with microwave derived rain information to estimate precipitation products (Brocca et al. 2014).

Climate Data Records

Due to the long program lifetime, Climate Data Records (CDR) can be derived from the Metop instrument data. All mission data are regularly reprocessed and undergo thorough validations. A number of long time series have already been processed from the first two Metop satellites (which are still contributing) (EUMETSAT 2020d). Series of 20+ years of products are expected according to the actual Metop lifetime scenario.

The payload of the Metop satellites provides a number of opportunities for the synergistic use and cross validation which is particularly important for the generation of Climate Data Records: using IASI level 1 radiances as a reference, the radiometric accuracy of AVHRR channels 4 and 5, and the HIRS sounding channels can be assessed. Similarly, AVHRR channel 1 can be compared with collocated GOME-2 spectra. Another opportunity is the validation of AMSU brightness temperatures using radio occultation measurements from GRAS as reference. In addition, AVHRR level 1 products are used to process the geolocation of the IASI sounder pixels through collocation with the Integrated IASI Imager.

Application enhancements through multisatellite use

For the launch and commissioning, *Metop-C* was launched in an orbital position about 120° apart from *Metop-B* so that the three Metop satellites were in a quasi-tristar constellation between November 2018 and autumn 2019 (Fig. 3). In this constellation, the three ASCAT instruments provided an optimal global coverage for tracking storm systems in the tropics.

The impact of an additional satellite on the quality of numerical weather prediction was shown by many of the NWP centers already during commissioning (see, e.g., Healy et al. 2019).

The availability of two and then three satellites in the same orbit has introduced the opportunity to establish multisatellite products, which provide more and increased positive impact on forecast quality, as well as increased information on atmospheric state and composition.

The first application is related to the winds derived from the AVHRR data. Already with two Metop satellites 48.92 min apart, a global wind product could be generated making use of the overlap regions of the AVHRR swaths. In addition, the polar cap winds were enhanced by using multiple satellite overlaps over these regions, which made a better temporal resolution possible. Triplet winds were derived, making use of three images (Hautecoeur and Borde 2017) (Fig. 4). The impact on the global forecast quality was significant, in particular in the gap-of-coverage regions between the geostationary atmospheric motion vectors and the polar cap winds.

Another product that was improved through the multisatellite use is the global ozone product from the GOME instrument. Already since July 2013, GOME-2 products were derived using two satellites in tandem operations—*Metop-A* and *Metop-B*. Having the satellites in the same orbital plane allowed increasing the daily coverage and the spatial resolution of a

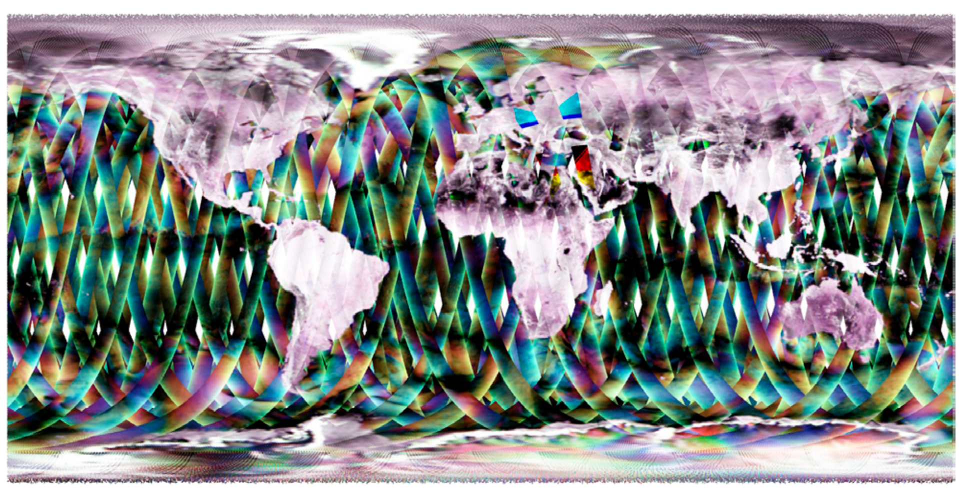

Fig. 3. Coverage of three ASCAT instruments on three Metop satellites in orbit (in tristar constellation during commissioning of *Metop-C* in 2018/19).

combined product made from observations from *Metop-A* at higher resolution of the 40 km × 40 km and a reduced 960 km swath, together with the coarser nominal resolution of 80 km × 40 km with a 1,920 km swath for GOME-2 on *Metop-B* (Hao et al. 2014).

The Polar Multimission Aerosol product (PMAp) algorithm is configured as a multi-instrument, but single-platform aerosol retrieval algorithm, using three instruments in a synergetic way. PMAp currently uses AVHRR/3, GOME, and IASI on all three Metop satellites. The PMAp algorithm uses the so-called Polarization Monitoring Devices (PMD) of the GOME-2 instrument which provides reflectance and Stokes fractions in 16 different spectral bands ranging from the UV to the red edge (311 to 805 nm). AVHRR/3 allows cloud correction and sun-glint detection. Three IASI thermal Infrared channels in the band 8.26 to 15.50 μm, for which collocations to the GOME PMD are calculated, provide an enhanced classification of volcanic ash aerosol. The PMAp product is produced as GOME-2 product with the spatial resolution of the GOME-2 PMD footprint. Using the combination of all the three Metop satellites allows to derive an aerosol optical depth (AOD) product with full daily global coverage (Fig. 5) (Vazquez-Navarro et al. 2019).

Further examples of multisatellite use emerged in the COVID-19 times in 2020, related to the shutdown in several countries over the globe in order to cut the infection chains in the countries. The GOME-2 derived content of NO_2 derived in the time frame of March–April 2019 is compared to the same NO_2 content of the same period in the following year 2020, where the lockdown occurred in many countries. NO_2 concentrations in 2020 are considerably reduced in those regions where there was a strong lockdown (see EUMETSAT 2020b).

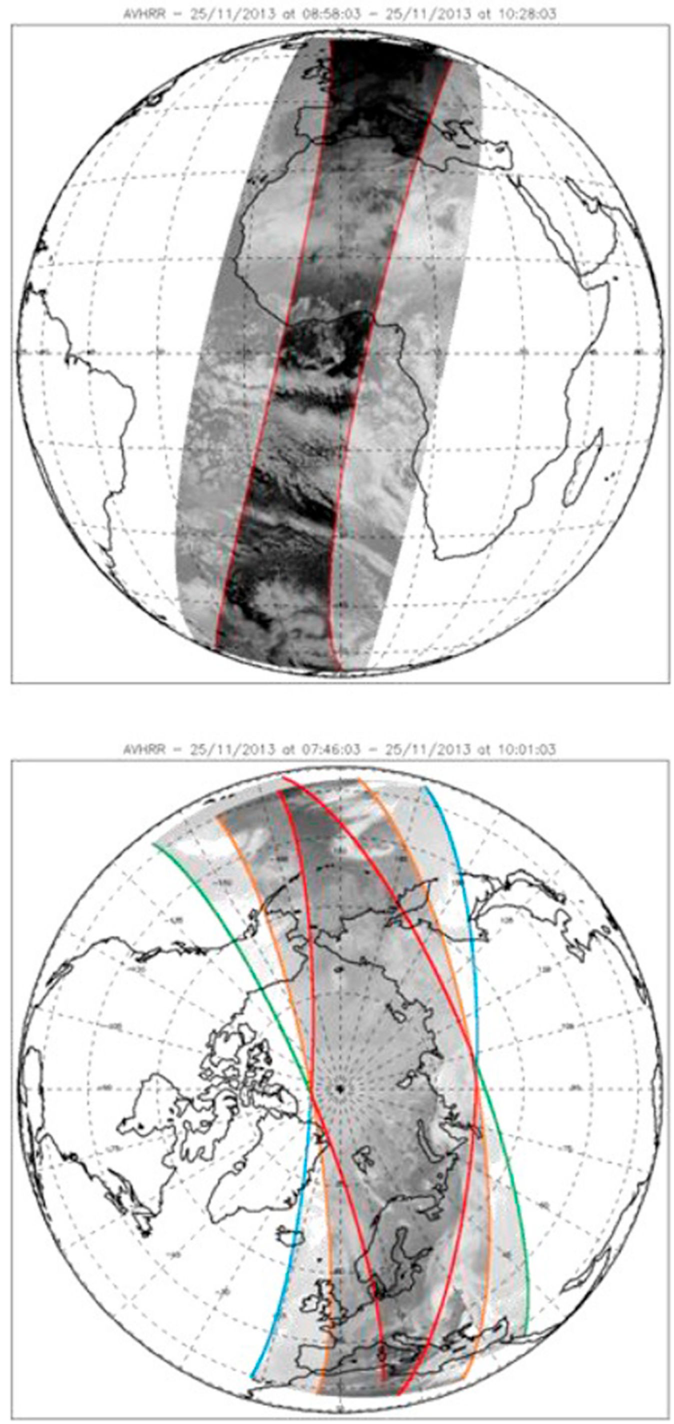

Fig. 4. Global wind products are created from dual Metop AVHRR global data. (top) Overlap area for global coverage and (bottom) overlapping orbits for polar winds.

Other examples shown before the COVID crisis were a new climatology of ammonia (Clerbeaux et al. 2015).

Ground system and dissemination

The ground segment of the EUMETSAT Polar System (Fig. 6) has a centralized part, the core ground segment, which is located at EUMETSAT Headquarters in Darmstadt, Germany. At this location, there is also the EUMETSAT Data Centre [formerly known as Unified Mission Data Archive and Retrieval Facility (UMARF)], where all mission data and reprocessed data

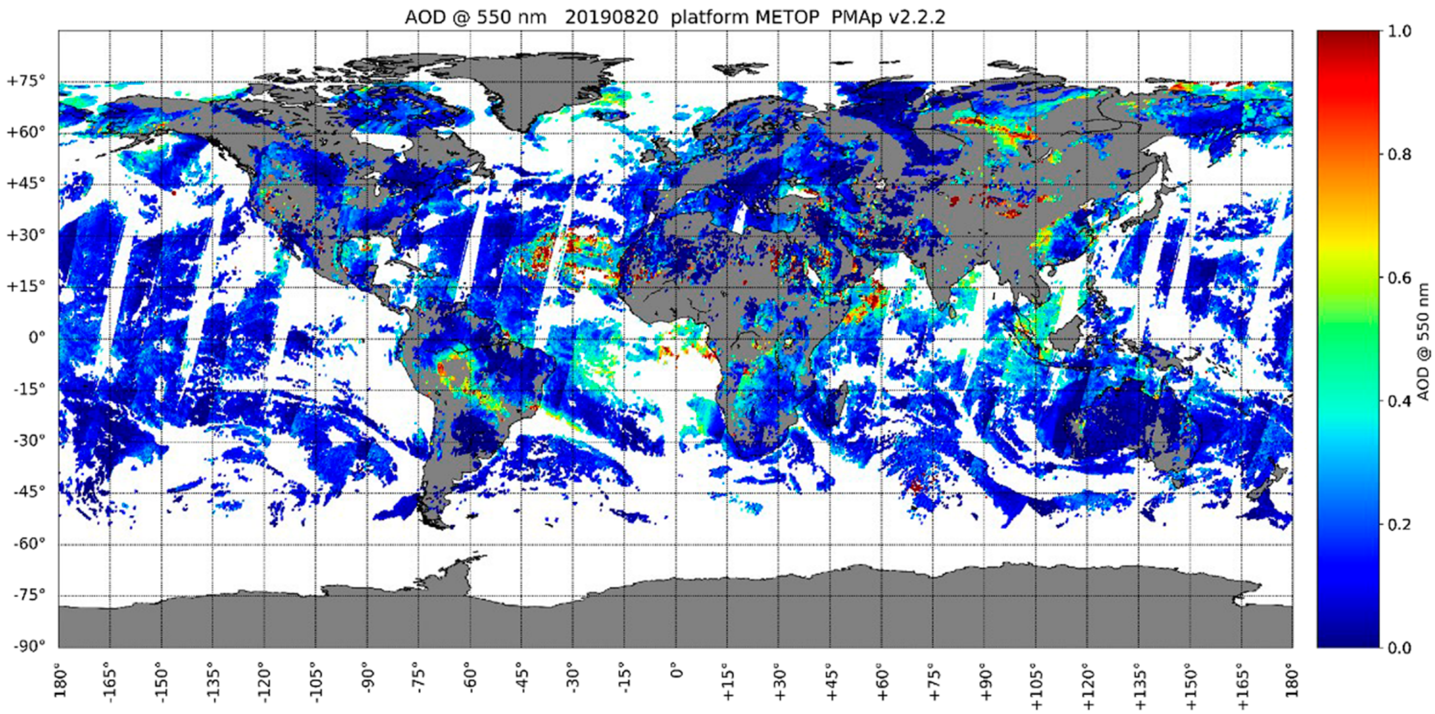

Fig. 5. Daily global aerosol optical depth product derived from Metop data from GOME-2, IASI, and AVHRR/3 in synergy [Polar Multi Mission Aerosol Product (PMAp)].

and products are archived. A second part of the ground segment is decentralized: the so-called Satellite Application Facilities (SAFs) are hosted by dedicated EUMETSAT member states' national meteorological services, and have consortia members from other member states' meteorological services or research institutes. They focus on specific meteorological application areas, e.g., ocean and sea ice or numerical weather prediction. There are eight SAFs (see EUMETSAT web page).

Further decentralized parts of the ground segment are the northern latitude reception stations, which receive via X-band dumps the global data stored on board the Metop satellites during one orbit of 102 min, when the satellite is in view of the station. The stations provide also the telemetry and tele command links to and from the spacecraft for its operations and monitoring. The prime satellite (currently *Metop-B*) can make use of the Antarctic McMurdo Station in the frame of a cooperation with NOAA–NASA to dump a part of the global products there. This allowed the delivery delay of the global products to be shortened considerably down to about 60 min, instead of 135 min for level 1 products. The Antarctic Data Acquisition (ADA) service provided on average 13.8 *Metop-B* passes per day from McMurdo over a year, out of 14.1 possible. This corresponds to about one blind orbit (i.e., an orbit not supported by the ADA) in 3 days.

There is a large number of EPS services; they include global data and product services, local data and products, and archived data, as well as products from the SAFs and from the Data Centre. In addition, there are Search and Rescue Services on *Metop-A* and *Metop-B*.

In the Central Facility, the data from all instruments are received from Svalbard or from McMurdo and processed to level 1 and selected level 2 products. Delivery delay is nominally 135 min for level 1 and 3 h for level 2. The resulting products are disseminated to the community via EUMETCast via commercial telecom satellites. Further delivery for global users occurs through WMO Global Telecommunication System (GTS), and the Regional Meteorological Data Communication Network (RMDCN).

Most of the level 2 and higher products are generated by the decentralized SAFs. They receive the level 1 products from the Central Facility as input data. The SAF products are

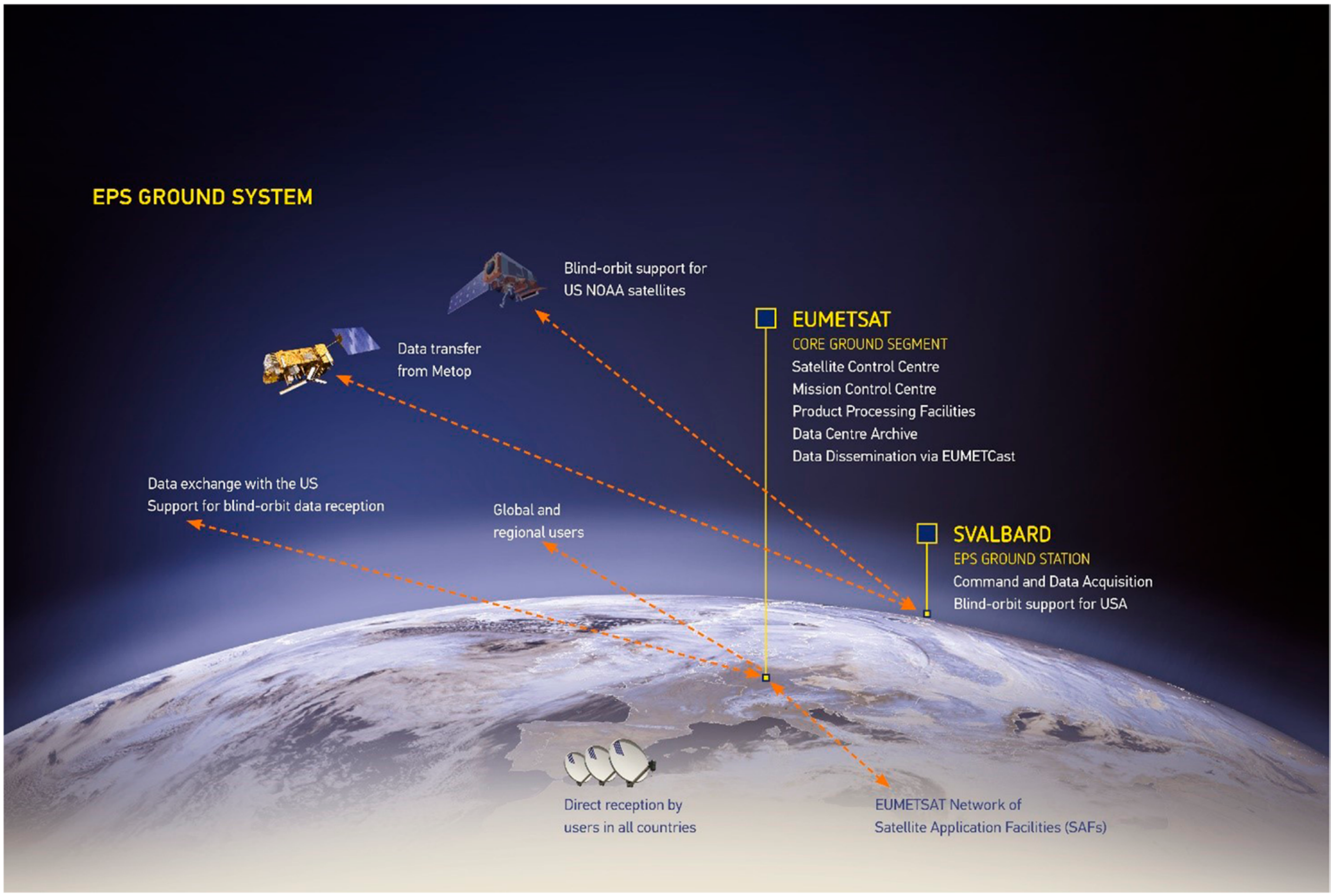

Fig. 6. The EUMETSAT ground system, which includes the elements of the EUMETSAT Polar System ground segment.

disseminated either through the SAFs or from the Central Facility in Darmstadt, Germany. All products are archived in the Data Centre or have a catalogue entry there if they are archived with the SAFs. A detailed list of products from EPS is available in the product navigator (EUMETSAT 2020f). The EUMETSAT web page contains a wealth of information on the products, including content and format information.

Among data quality, a constraint of satellite products for usage in NWP models is the difference between sensing time and the time when the data are disseminated to the users. To improve the timeliness over local areas, the Metop satellites have the capability of direct read out of all meteorological instruments data. A prominent example for the processing of local data are the EUMETSAT Advanced Retransmission Service (EARS), where stations distributed over the Northern Hemisphere collect the AHRPT raw data (e.g., from ATOVS/AVHRR and IASI) during local overpasses. AHRPT is the equivalent of HRPT of the NOAA satellites and includes the raw data of all instruments embarked on the platform. The raw data are processed to level 1 products using the ATOVS and AVHRR Preprocessing Package (AAPP) software. AAPP was developed under the coordination of EUMETSAT and today, is maintained and extended by the NWP Satellite Application Facility. Collocated and combined products are redistributed via EUMETCast and allow delay times of less than 30 min. In other regions of the world, direct broadcast (DB) networks provide similar regional services. In addition, ASCAT EARS level 1 products are directly processed with the same timeliness at EUMETSAT. The associated EARS level 2 surface wind products are provided by the OSI SAF. Besides EPS, EARS is also disseminating products from third-party missions.

To support the Radio Occultation Instrument, EUMETSAT had established a GRAS Support Network, which was since 2019 replaced by a more general radio occultation support network

(RSN), aiming to support future and third-party radio occultation missions by providing precise orbit and clock bias estimates for the satellites of multiple GNSS constellations.

Besides the user community in EUMETSAT member states and all over the world EPS is also supporting Copernicus activities. Products from both the Central Facility and the SAFs provide essential data to the Copernicus Atmospheric Monitoring Service (CAMS) and also the Copernicus Marine and Environmental Monitoring Service (CMEMS). The data and products range from IASI level 1 products to numerous atmospheric composition and trace gas monitoring products from IASI, GOME-2, and AVHRR instruments.

The Satellite Application Facilities also provide to users, in particular of local direct readout data from EPS, software packages to process data from level 0 to level 1 and level 2 and higher. In particular the NWP SAF, the Nowcasting SAF and the ROM SAF distribute such software packages (see https://nwp-saf.eumetsat.int/site/, www.nwcsaf.org/, and www.romsaf.org).

Summary and outlook

After more than 13 years of operations, the EUMETSAT Polar System is operating three satellites together, which provide a wealth of data and products for a global and regional wide spread user community, and for a large range of applications. The system, which was originally planned for 14 years of operations, has a perspective to be able to provide high-impact data and products to the user community until the end of the year 2030 time frame.

There is a follow-on system, EPS Second Generation (Schlüssel and Kayal 2017), currently under development with planned launch dates in the 2023/24 time frame and covering 20+ years of operations with extended and new capabilities, in particular multiangle, multipolarized measurements from the shortwave to near-infrared spectrum, and cloud, ice–cloud, and precipitation imaging from the microwave region. The space segment of EPS-SG is a dual satellite configuration and comprises six satellites: three identical satellites (Metop-SG A) will be operated for the hyperspectral and microwave sounding missions, supporting visible/infrared (VIS/IR) imaging missions, and for aerosol monitoring and trace gas missions. The other three identical satellites (Metop-SG B) are used for the microwave imaging, and the scatterometry missions. In addition, on all six satellites, the radio occultation mission will provide all-weather soundings. EPS-SG will continue coverage of polar-orbit data provision from midmorning orbit until the year 2040+ time frame. Hence, the social–economic benefit of polar satellite programs will be further assured (Hallegatte et al. 2014).

Acknowledgments. Many colleagues from EUMETSAT, ESA, CNES, and NOAA have contributed and are still contributing to the success of the program. The authors thank all of them for their contribution. Furthermore the authors thank the anonymous reviewers for valuable suggestions for the improvement of an earlier version of the paper.

Appendix: List of acronyms

AAPP	ATOVS and AVHRR Preprocessing Package
AATSR	Advanced Along Track Scanning Radiometer
AC SAF	Atmospheric Composition Satellite Application Facility
ADA	Antarctic Data Acquisition
ADCS	Advanced Data Collection System
AHRPT	Advanced High Resolution Picture Transmission
AIRS	Atmospheric Infrared Sounder
AMI	Active Microwave Instrument
AMV	Atmospheric motion vector
AMSU-A	Advanced Microwave Sounding Unit A
AOD	Aerosol optical depth

ASCAT	Advanced Scatterometer
ATOVS	Advanced TIROS Operational Vertical Sounder
AVHRR	Advanced Very High Resolution Radiometer
BrO	Bromine oxide
CDR	Climate Data Record
CAMS	Copernicus Atmosphere Monitoring Service
CH_4	Methane
CMEMS	Copernicus Marine Environment Monitoring Service
CNES	Centre National des Etudes Spatiales
CO	Carbon monoxide
COVID	Coronavirus disease
DMI	Danish Meteorological Institute
DMSP	Defense Meteorological Satellite System
DU	Dobson unit
EARS	EUMETSAT Advanced Retransmission Service
ECMWF	European Centre for Medium-Range Weather Forecasts
EPS	EUMETSAT Polar System
EPS-SG	EUMETSAT Polar System Second Generation
ESA	European Space Agency
ERS	Earth Resources Satellite
EUMETCast	EUMETSAT's data dissemination service
EUMETSAT	European Organisation for the Exploitation of Meteorological Satellites
GOME	Global Ozone Monitoring Experiment
GOS	Global Observing System
GPS	Global positioning system
GNSS	Global Navigation Satellite System
GRAS	GNSS Radio-Occultation Atmospheric Sounder
GRHSST	Group for High Resolution Sea Surface Temperatures
GTS	Global Telecommunication System
HIRS	High Resolution Infrared Radiation Sounder
HNO_3	Nitric acid
H SAF	Hydrology Satellite Application Facility
IASI	Infrared Atmospheric Sounding Interferometer
IJPS	Initial Joint Polar System
IR	Infrared
JPS	Joint Polar System
JPSS	Joint Polar Satellite System
LATMOS	Laboratoire Atmosphères, Milieux, Observations Spatiales
LMD	Laboratoire de Météorologie Dynamique
NASA	National Aeronautics and Space Administration
NH_3	Ammonia
MHS	Microwave Humidity Sounder
NOAA	National Oceanic and Atmospheric Administration
NO_2	Nitrogen dioxide
NWP	Numerical weather prediction
OSI SAF	Ocean and Sea Ice Satellite Application Facility
PMAp	Polar Multi Mission Aerosol product
PMD	Polarization Measurement Device
RMDCN	Regional Meteorological Data Communication Network
ROM SAF	Radio-Occultation Meteorology Satellite Application Facility

RSN	Radio-Occultation Support Network
SAF	Satellite Application Facility
SARSAT	Search and Rescue Satellite Aided Tracking
SCIAMACHY	Scanning Imaging Absorption Spectrometer for Atmospheric Cartography
SO_2	Sulfur dioxide
SST	Sea surface temperature
Suomi NPP	*Suomi National Polar-Orbiting Partnership*
TIROS	Television and Infrared Observation Satellite
ULB	Université Libre de Bruxelles
UMARF	Unified Mission Data Archive and Retrieval Facility
UV	Ultraviolet
VIS	Visible
WMO	World Meteorological Organization

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