1.07 The EUMETSAT Polar System

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Acronyms

ADA Antarctic Data Acquisition
ADCS Advanced Data Collection System
AIRS Atmospheric Infrared Radiation Sounder
AMSU Advanced Microwave Sounding Unit
AMV Atmospheric Motion Vector
ASCAT Advanced scatterometer
ATOVS Advanced TIROS (Television and Infrared Operational Satellite) Operational Vertical Sounder
AVHRR Advanced Very High Resolution Radiometer
BUFR Binary Universal Form for the Representation of meteorological data
CDA Command and Data Acquisition
CGS Core ground Segment
DCS Data Collection System
EARS EUMETSAT Advanced Retransmission Service
EFOV Elementary Field of View
ENVISAT Environmental Satellite
EPS EUMETSAT Polar System
EPS-SG EPS Second Generation
ESA European Space Agency
EUMETSAT European Organization for the Exploitation of Meteorological Satellites
FTS Fourier transform spectrometer
FWHM Full width, half maximum

GAC Global Area Coverage
GO Geometric Optics
GOME Global Ozone Monitoring Experiment
GPS Global Positioning System
GRAS GNSS (Global Navigation Satellite System) Radio-Occultation Atmospheric Sounder
GTS Global Telecommunication System
HIRS High-Resolution Infrared Radiation Sounder
HRPT High-Resolution Picture Transmission
IASI Infrared atmospheric sounding interferometer
IFOV Instantaneous field of view
IGDDS Integrated global data dissemination service
IJPS Initial Joint Polar System
JPS Joint Polar System
JPSS Joint Polar Satellite System
JTA Joint Transition Agreement
LRPT Low-Resolution Picture Transmission
LST Local solar time
Metop Meteorological Operational Satellite
MHS Microwave Humidity Sounder
NASA National Air and Space Agency
NOAA National Oceanic and Atmospheric Administration
NRT Near real time
NWP Numerical Weather Prediction
OBT On Board Time
PMD Polarization Measurement Device
POD Precise Orbit Determination
PPF Product Processing Facility
PRN Pseudo Random Noise
PRT Platinum Resistance Thermometer
SAF Satellite Application Facility
SAR Search and Rescue
SARP SAR Signal Processor
SARR SAR Signal Repeater
SCIAMACHY Scanning imaging absorption spectrometer for atmospheric chartography
SEM Space Environment Monitor
SLS Spectral Light Source
SSPA Solid-State Power Amplifier
SSR Solid-State Recorder
TLE Two-Line Elements
USO Ultra Stable Oscillator Clock
UTC Universal Time Coordinated
WIS WMO Information Service
WLS White Light Source
WMO World Meteorological Organization
WO Wave Optics

1.07.1 Introduction

The EUMETSAT Polar System (EPS) is part of the Global Operational Satellite Observation System, which is under the auspices of the World Meteorological Organization (WMO) (WMO, 2016). The Global Operational Satellite Observation System makes use of dedicated operational satellites and also research satellites both in polar orbits and in geostationary orbits. These systems provide a wealth of information to a global user community for operational meteorology, oceanography, atmospheric composition and chemistry, and climate and environmental monitoring.

In addition, EPS is part of the Initial Joint Polar System (IJPS, NOAA, 2016a; EUMETSAT, 2016a) with EUMETSAT's partner NOAA (National Oceanic and Atmospheric Administration) in the United States. EUMETSAT has committed to serve the so-called mid-morning orbit with an equator crossing time of 9:30 local solar time (LST), descending node, whereas NOAA continues to serve the afternoon orbit at 14:00 LST equator crossing time (ascending node). This illustrates one key element of the IJPS, the coordination of orbits to achieve full coverage of the whole globe within a minimum time span. Other key elements are the exchange of instruments and the processing and sharing of data. The current IJPS was extended to at least until 2019 with the Joint Transition Agreement signed in 2003. Recently, an agreement for a future Joint Polar System was signed extending the cooperation far beyond 2040 with the follow on systems for EPS, the second generation of EPS (EPS-SG), and the U.S. Joint Polar Satellite System (JPSS, EUMETSAT, 2015).

1.07.2 The EUMETSAT Polar System (EPS)

With the EUMETSAT Polar System EUMETSAT has entered the polar satellite era, and Europe has established its first operational meteorological polar satellite system (Cohen et al., 2006; Klaes et al., 2007). EPS is a complex program involving many international partners. It consists of a ground component and a space component. The space component consists of three Metop satellites (Edwards et al., 2006). They were jointly developed by EUMETSAT and the European Space Agency ESA. The payload of the Metop satellites was developed in international cooperation. Besides the cooperation with the United States as mentioned earlier, involving the exchange of the payload instruments HIRS, AMSU-A, MHS, and AVHRR common with the NOAA satellites, the partnership with the French space agency CNES (Centre National des Etudes Spatiales) led to the development of the IASI instrument (infrared atmospheric sounding interferometer) (Phulpin et al., 2006; CNES, 2016, 1). CNES also developed the Advanced Data Collection System (ADCS). The cooperation with ESA led to the embarking of instruments in heritage to research missions. These are the advanced scatterometer (ASCAT) (Figa-Saldaña et al., 2002) in heritage to the ERS SCAT (Lecomte and Wagner, 1998) and the Global Ozone Monitoring Mission-2 (GOME-2) (Munro et al., 2006) in heritage to the ERS-2 GOME (Burrows et al., 1993) mission. A radio occultation mission for atmospheric soundings of temperature and moisture was embarked for the first time as an operational meteorological mission with the GNSS (Global Navigation Satellite System) Receiver for Atmospheric Sounding (GRAS) (Luntama et al., 2008), developed by ESA.

At present, two of the Metop satellites have been launched into sun-synchronous polar orbits with an inclination of about 98 degrees and an equator crossing time around 9:30 LST, descending node. Metop-A was launched in Oct. 2006 with a Soyuz rocket from the Baikonour Cosmodrome and is operational in orbit since (Spoto et al., 2006). Metop-B was following in Sep. 2012 and is currently the prime satellite. Both spacecraft are flying in the same orbital plane following each other at a time distance of 48.98 min, which corresponds to half an orbit (Klaes et al., 2013). The last of the three Metop satellite is planned to be launched in Oct. 2018, from the Guyana Space Center at Kourou, also with a Soyuz rocket, and is expected to extend the EPS service beyond the 2025 time frame, hence achieving the provision of about 20 years of operation.

The ground component includes the northern command and data acquisition (CDA) stations at Svalbard. (complemented by the McMurdo Antarctic station, used under cooperation with NASA/NOAA, and not part of EPS), the mission control Centre at Darmstadt, with data processing, dissemination and archiving as the central component, and the Satellite Application Facilities (SAF), which are centers of excellence spread over Europe and hosted at and coordinated by EUMETSAT Member states.

1.07.2.1 Space Segment

Each Metop satellite is composed of a payload and a service module, and the solar array. The payload module embarks 11 instruments, 8 of which are providing meteorological measurements. The satellites are flying at an altitude of about 820 km in a sun-synchronous polar orbit with a equator crossing time of 9:30 LST. The orbit repeat cycle is 29 days. The full globe of the Earth is observed roughly every 12 h, depending on the swath width of the instruments. Metop satellites have a design lifetime of 5 years; however Metop-A is in orbit since 2006 and continues to provide valuable operational service with all instruments. Metop-B was launched in 2012 to assure the continuity of services, after the nominal lifetime of Metop-A has been exceeded by already 1 year. Metop-B is currently the prime operational satellite.

As mentioned earlier there are eight meteorological instruments on the Metop payload module. There are three major components for atmospheric sounding. The infrared sounders are IASI (Infrared Atmospheric Sounding Interferometer) and the High-Resolution Infrared Radiation Sounder (HIRS/4), the latter common to the NOAA satellites and part of the ATOVS [Advanced TIROS (Television and Infrared Operational Satellite) Operational Sounder] instrument package. HIRS is embarked on Metop-A and Metop-B only under the assumption that IASI will have proven its value and will provide the full infrared sounding capability (fully confirmed to date). The second component is composed of the microwave sounders AMSU-A (Advanced Microwave Sounding Unit-A) for temperature and humidity sounding and the Microwave Humidity Sounder (MHS) for moisture soundings.

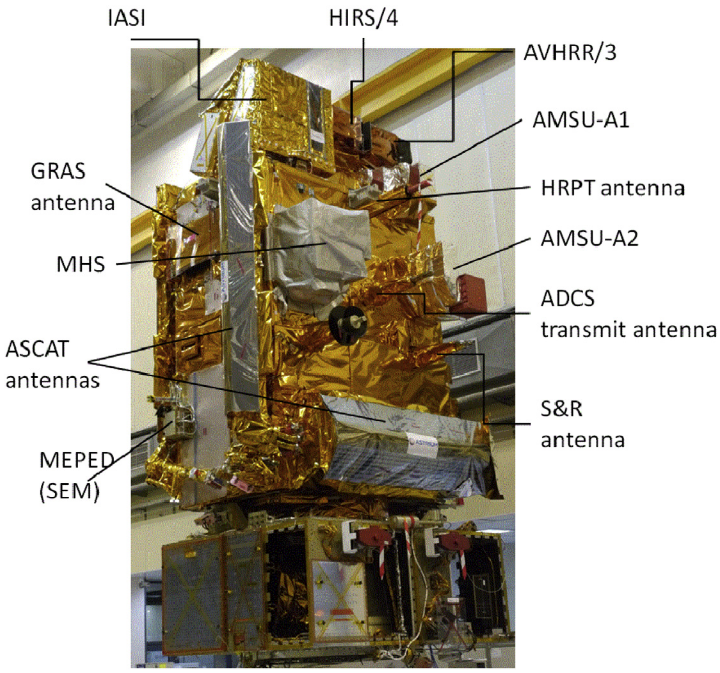

Fig. 1 Metop-B and the instruments embarked (pre-launch configuration in the clean room).

Both are part of the ATOVS package and fly on both the Metop and the NOAA satellites. AMSU and HIRS are provided by NOAA/NASA. MHS is an EUMETSAT development and was first flown on NOAA-18 (launch date: May 20, 2005). It was EUMETSAT's first instrument in polar orbit. The third component is the Radio-occultation instrument GRAS (GNSS Receiver for Atmospheric Sounding, GNSS stands for Global Navigation Satellite System) with two occultation antennas at the velocity and antivelocity sides of the satellites, and a third antenna on the top of Metop to provide precise satellite location information.

The Advanced Very High Resolution Radiometer (AVHRR/3) imager provides support to the sounding in the visible and infrared spectral regions (Cracknell, 1997) mainly through cloud and surface information. The IASI instrument has an integrated imager (IIS) observing in the infrared window region at 11 μm and supports the geolocation of the IASI instrument pixels through coregistration with AVHRR. The Global Ozone Monitoring Instrument (GOME-2) is mounted on the flight direction side of the payload module and supports the monitoring of total ozone, ozone vertical profiles, and other trace gases (Callies et al., 2000; Munro et al., 2006). The Advanced Scatterometer (ASCAT) is a C-band radar and supplies information about the ocean surface wind vectors and also soil moisture (Verspeek et al., 2013; Bartalis et al., 2007).

Fig. 1 provides an overview on the Metop satellites and their meteorological payload. Note that Metop-C, the third in the series of three satellites will not embark HIRS/4.

1.07.2.1.1 IASI

The Infrared Atmospheric Sounding Interferometer, known as IASI, was the most innovative on Metop at the time of the launch of Metop-A in 2006. IASI is a Fourier transform spectrometer (FTS). It is the largest and heaviest instrument on Metop and was developed by the French Space Agency CNES under a cooperation agreement with EUMETSAT. The Level 1 product processing software for the Core Ground Segment was as well developed and provided by CNES under the same agreement. CNES runs a Technical Expertise Centre (called IASI TEC) in Toulouse, in order to analyze instrument performance and investigate instrument anomalies and to maintain the Level 1 processing chain.

IASI measurements provide crucial input to derive vertical profiles of atmospheric temperature and humidity and also atmospheric species in the infrared spectral range from 3.63 to 15.5 μm (645–2760 cm^{-1}) at a spectral sampling of 0.25 cm^{-1}. After apodization the spectral resolution is 0.5 cm-1. There are 8461 spectral samples measured in three spectral bands specified in Table 1. They cover 645–1210 cm^{-1} (Band 1), 1210–2000 cm^{-1} (Band 2), and 2000–2760 cm^{-1} (Band 3).

An integrated imager (IIS, which stands for integrated imaging subsystem) uses the same focal plane as the sounding system and provides images in the broad band of 833–1000 cm^{-1} (12–10 μm). The IIS is used for the coregistration with the Advanced Very High Resolution radiometer (AVHRR) imager in order to provide the geolocation of the sounding pixels and together with the latter information on the scene within an individual field of view.

IASI is a cross track scanning instrument and covers a swath of $\pm$48.333 degrees from nadir giving a swath width of about 2200 km. The scan direction is from left to right in-flight direction. Across track 30 elementary fields of view (EFOVs) are sampled, each measuring interferogrammes at a matrix of 2 X 2 instantaneous fields of view (IFOVs) of 14.65 mrad, which is equivalent

Table 1 IASI bands

Band	*Wavenumbers (cm^{-1})*	*Wavelength (μm)*
1	645–1210	8.26–15.50
2	1210–2000	5.00–8.26
3	2000–2760	3.62–5.00

From IASI Level 1 Product Guide, EUMETSAT, 2016.

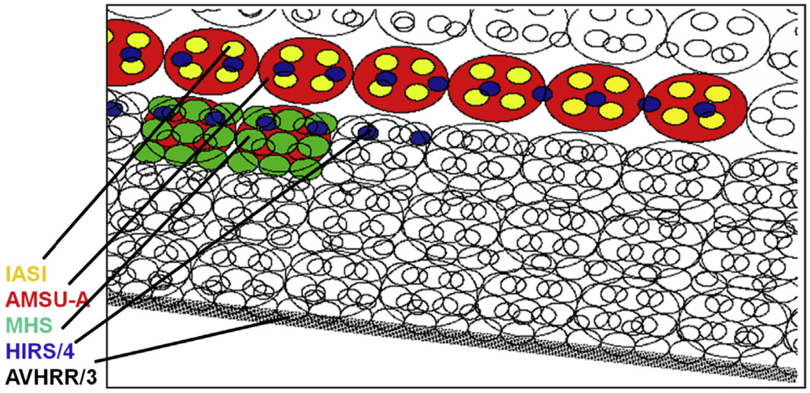

Fig. 2 Synergetic view of sounding and imaging instrument field of views on the Metop satellites (near Nadir). IASI, AMSU-A and MHS scans are synchronized.

to 12 km sampling at nadir at a satellite altitude of 819 km. The integrated imager covers the area of an EFOV at 59.63 X 59.63 mrad with 64 X 64 pixels.

The scan modus is stop and stare, and each measurement of the interferogrammes takes 151 msec. Compensation for the spacecraft motion is provided for the scan mirror. IASI measurements are taken at intervals of 8/37 s and include calibration measurements of cold space and of an internal black body. The IASI measurements are synchronized with the measurements of the AMSU-A instrument, the IASI scan rate being the same as for AMSU-A (8 s per scan line) (Fig. 2). Per orbit more than 1.2 million spectra are acquired. Table 2 summarizes the scanning characteristics of the IASI instrument including approximate on-ground footprint sizes.

Due to the on-board data rate of 1.5 Mbps allocated to the IASI instrument there is the need for a considerable amount of onboard processing implemented in order to reduce the large data rate of the interferogrammes (order of 40 Mbps). The on-board processing comprises the Fourier transform of the measured interferogrammes, the nonlinearity correction in band 1, the radiometric calibration, and the band merging to generate a valid compressed spectrum, which is then transmitted to ground. In addition, one reference interferogram per scan line is downlinked in order to allow checking the on-board processing.

Table 2 Scanning characteristics of IASI

Characteristics	*Value*	*Unit*
Scan type	Step and stare	
Scan rate	8	s
Stare interval	151	ms
Step interval	8/37	
EFOV/scan	30	
Swath	±48.333	°
Swath width	±1100	km
IFOV	14.65	mrad
IFOV shape	Circular	
IFOV size (nadir)	12	km
IFOV size (edge)—across track	39	km
IFOV size (edge)—along track	20	km
IFOV separation within EFOV—along-track at nadir	19	km

From IASI Level 1 Product Guide, EUMETSAT, 2016.

Hence, the resulting level 0 data are composed of calibrated spectra including quality information and the data of the integrated imager IIS. The subsequent product processing in the Core Ground Segment comprises several steps. At first, the data of the integrated imager are calibrated using the internal black body and the space view observations. Level 1 a data processing of the IASI spectra uses the IASI spectral data base to calculate the spectral calibration function and the apodization function based on the position of the interferometer axis in the detector plane which is also calculated in this processing step. Corrections are then applied using the spectral calibration function. Account is taken also of the scan mirror angle and temperature dependency and the black body emissivity. The final level 1a processing step constitutes the geolocation of the IASI IFOVs using the collocation of the IASI integrated imager calibrated data with the navigated AVHRR level 1b pixels and applying a maximum correlation method. The IASI level 1b processing is the interpolation of the IASI spectra on an equidistant spectral grid. In the final IASI level 1c processing step the apodization function is applied to the IASI spectra. A Gaussian function is used as the filter function. Moreover, a radiance cluster analysis is applied on the AVHRR pixels within each IASI IFOVs and the information on the clusters added to the data of each IFOV.

Level 1c spectra are disseminated to the user community in near real time (NRT) via EUMETSAT's EUMETCast dissemination system. IASI data are also archived in the EUMETSAT data Centre. In addition data are made available to the IASI level 2 product processing facility (PPF) (see below.)

1.07.2.1.2 ATOVS instruments

The ATOVS instruments are common to the Metop and the NOAA satellites (NOAA-18 and NOAA-19) and are in heritage of the NOAA-KLM satellite series (NOAA-15, -16, and -17). The ATOVS package is composed of the AMSU-A and HIRS/4 instruments, provided by NOAA, and the MHS instrument, provided by EUMETSAT.

1.07.2.1.2.1 AMSU-A

The Advanced Microwave Sounding Unit-A (AMSU-A) is a cross track scanning sounder in the microwave spectral domain and makes use of the oxygen lines and window regions in the microwave region between 23 and 89 GHz. Table 3 summarizes the radiometric channel characteristics of the AMSU-A1 and AMASU-A2 instruments. It provides a nearly all weather temperature sounding capability in complement to the infrared sounding measurements. The instrument was developed under the auspices of NASA and provided to EPS by NOAA in the frame of the IJPS and JTA (Joint Transition Agreement). The AMSU instrument collects 30 consecutive Earth view scenes in 15 individual channels in a stop and stare mode. The scan step is 3.3333 degrees with a sampling interval of 20 ms. A full scan cycle takes 8 s for one scan and is synchronized with IASI and the MHS instrument (see Fig. 2 which provides a synergistic view of the scan patterns). The scan swath is ± 48.33 degrees, which translates into ± 1037 km at a satellite altitude of 820 km. The antenna beam width at -3 dB is 3.3 degrees for each channel, which gives an IFOV size of about 48 km near nadir. Table 4 summarizes the scanning characteristics of the AMSU-A instruments.

In total, there are three antenna mounts for AMSU-A. AMSU-A1 has two antenna assemblies: the antenna in module AMSU-A1.1 measures in channels 6, 7 and channels 9–15, and module AMSU-A1.2 carries the antenna for measurements in channels 3, 4, 5, and 8. The AMSU-A2 module measures data in the channels 1 and 2 with one single antenna. Each module contains an internal black body with a distinct number of platinum resistance thermometers (PRT) (5 for module A1, 7 for module A2). In Table 5 calibration relevant parameters of the AMSU-A1 and AMSU-A2 instruments are summarized. The instrument temperatures are evaluated to provide an accurate estimate of the receiver nonlinearity.

Table 3 AMSU-A radiometric channel characteristics

Channel	*Channel frequency (GHz)*	*Passes per band*	*Nominal bandwidth (MHz)*	*Calibration accuracy (K)*
AMSU-A2				
1	23.8	1	270	<2.0
2	31.4	1	180	<2.0
AMSU-A1				
3	50.3	1	180	<1.5
4	52.8	1	400	<1.5
5	53.59 ± 0.115	2	170	<1.5
6	54.40	1	400	<1.5
7	54.94	1	400	<1.5
8	55.50	1	330	<1.5
9	$F_{LO} = 57.290344$	1	330	<1.5
10	$F_{LO} \pm 0.217$	2	78	<1.5
11	$F_{LO} \pm 0.3222 \pm 0.048$	4	36	<1.5
12	$F_{LO} \pm 0.3222 \pm 0.022$	4	16	<1.5
13	$F_{LO} \pm 0.3222 \pm 0.010$	4	8	<1.5
14	$F_{LO} \pm 0.3222 \pm 0.0045$	4	3	<1.5
15	89.0	1	<6000	<2.0

From ATOVS Level 1b Product Guide, EUMETSAT, 2016.

Table 4 AMSU-A scanning characteristics

Criteria	*Value*	*Unit*
Scan direction	West to east (northbound)	–
Scan type	Step	–
Scan rate	8	s
Sampling interval (duration)	200	ms
Sampling interval	3.3333	°
Pixels/scan	30	–
Swath	±48.33	°
Swath width	±1026.31	km
IFOV	3.3	°
IFOV type	Circular	–
IFOV size (nadir)	47.63	km
IFOV size (edge): across track	146.89	km
IFOV size (edge): along track	78.79	km
Scan separation (adjacent scan lines)	52.69	km

From ATOVS Level 1b Product Guide, EUMETSAT, 2016.

Table 5 Relevant AMSU-A antenna and calibration parameters

Instrument module	*AMSU-A1*		*Instrument module*
Antenna package	AMSU-A1-1	AMSU-A1-2	AMSU-A2
Channels	6, 7, 9–15	3,4,5,8	1.2
Number of warm target PRTs	5	5	7
Number of warm target views per scan line	2	2	2
Number of cold space views per scan line	2	2	2
Definition of instrument temperature	RF Shelf A1-1	RF Shelf A1-2	RF Shelf A2
Backup instrument temperature	RF Mux A1-1	RF Shelf A1-2	RF Mux A2
PLLO#1	All channels	All channels	All channels
PLLO#2	Channels 9–14	None	None

During each scan cycle, AMSU-A observes 30 Earth views, two times the internal black body (at approximately 300 K), and two times the deep space (at about 2.73 K).

1.07.2.1.2.2 Microwave Humidity Sounder MHS

The Microwave Humidity Sounder (MHS) is the successor instrument of the Advanced Microwave Sounding Unit-B, onboard the NOAA-KLM satellite series (NOAA-15, -16, and -17) (NOAA, 2016b). MHS was developed under the responsibility of EUMETSAT.

MHS complements the AMSU-A instrument and senses atmospheric water vapor using the absorption bands around 157 and 183 GHz. The MHS channels characteristics are summarized in **Table 6**. A channel at 89 GHz provides information in the window region for deriving surface properties and precipitation estimates. Technically the instrument is similar to the AMSU-B; however the side band at 176.31 GHz is missing on the MHS channel 5. (MHS channels are often referred to as microwave channels 16–20 in some publications, in heritage to the AMSU-A/AMSU-B channel denomination). In addition MHS has a better radiometric performance than its predecessor AMSU-B.

Table 6 Channel characteristics of MHS

Channel	*Central frequency (GHz)*	*Bandwidth (MHz)*	*Calibration accuracy (K)*
H1	89.0	±1400	1.0
H2	157.0	±1400	1.0
H3	183.311±1.00	±250	1.0
H4	183.311±3.00	±500	1.0
H5	190.311	±1100	1.0

From ATOVS Level 1b Product Guide, EUMETSAT, 2016.

Table 7 Scanning characteristics of MHS

Criteria	*Value*	*Unit*
Scan direction	West to east (northbound)	–
Scan type	Continuous	–
Scan rate	2.667	s
Sampling interval (duration)	18.52	ms
Sampling interval	1.1111	°
Pixels per scan	90	–
Swath	±49.44	°
Swath width	±1077.68	km
IFOV	1.1	°
IFOV type	Circular	–
IFOV size (nadir)	15.88	km
IFOV size (edge): across track	52.83	km
IFOV size (edge): along track	27.10	km
Scan separation (adjacent scan lines)	17.56	km

From ATOVS Level 1b Product Guide, EUMETSAT, 2016.

Table 8 Calibration characteristics of MHS in comparison to AMSU-B

Instrument/antenna package	*MHS*	*AMSU-B*
Channels	16-20 (H1-H5)	16-20
Number of warm target PRTs	5	7
Number of warm target views per scan line	4	4
Number of cold space views per scan line	4	4
Definition of instrument temperature	Mixer temperature of channels 18–20	
Backup instrument temperature	Mixer temperature of channel 16	

From MHS Level 1b Product Generation Specification, EUMETSAT, 2016.

MHS is a cross tracking instrument with a scan range of ±49.44 degrees around nadir resulting in a swath width of ±1078 km. The scan is continuous and provides 90 individual fields of view of 1.1 degrees, which provides circular IFOVs of about 15.9 km near nadir. The scan step is 1.1111 degrees (note that AMSU-B has a scan step of 1.1 degrees). Each scan cycle takes 2.667 s from left to right in-flight direction. Thus, MHS is synchronized with AMSU-A, and there are three scan lines within one AMSU-A scan line (Fig. 2). The scan characteristics of the MHS instrument are listed in Table 7.

For calibration the MHS instrument relies on internal black body target measurements and on cold space views. The internal black body has five PRTs with full redundancy. For each scan line, MHS observes 90 Earth views, four times the internal black body (at approximately 300 K), and four times deep space (at about 2.73 K). Table 8 summarizes the MHS calibration relevant parameters compared to those of AMSU-B.

1.07.2.1.2.3 High-Resolution Infrared Radiation Sounder HIRS/4

The HIRS/4 instrument (High-Resolution Infrared Radiation Sounder/4) is a cross track scanning instrument with a maximum scan angle of ±49.5 degrees around nadir providing an on-ground swath width of about ±1080 km for the Metop spacecraft altitude of 820 km. One scan line measures 56 Earth views in a step and stare mode at an IFOV of 0.69 degrees which yields a 10 km size circular pixel near nadir. One scan cycle takes 6.4 s to complete. The sampling time is 100 ms with a corresponding stepping angle of 1.8 degrees. The sampling distance between consecutive scan lines is around 42 km. The sampling characteristics of the HIRS/4 instrument are collected in Table 9.

The HIRS instrument measures radiances in 19 infrared channels both in the short-wave (3.7–4.6 microns) and long-wave (4.6–15 μm) infrared spectral domain. There is one channel in the visible (0.69 μm) spectral domain. The spectral channel information is generated using dichroic beam splitters and a rotating filter wheel. The characteristics of the HIRS/4 channels are summarized in Table 10.

Table 9 Scanning characteristics of HIRS/4

Characteristics	*Value*	*Unit*
Scan type	Step and dwell	
Scan direction	West to East (northbound)	
Scan rate	6.4	s
Sampling interval	100.0	ms
Sampling interval	1.8	°
Pixel s/scan	56	
Retrace steps	8	
Bits/pixel	13	bit
Swath	±49.5	°
Swath width	±1080.35	km
IFOV	0.69	
IFOV shape (nadir)	Circular	
IFOV size (nadir)	10	km
IFOV size (edge)—across track	33.27	km
IFOV size (edge)—along track	17.03	km
Scan separation	42.15	km

From ATOVS Level 1b Product Guide, EUMETSAT, 2016.

Table 10 Channel characteristics of HIRS/4

Channel Wave number (cm^{-1})	*Center frequency (μm)*	*Center bandwidth (cm^{-1})*	*Half*
1	668.5 ± 1.3	14.959	3.0 + 1/− .5
2	680.0 ± 1.8	14.706	10.0 + 4/− 1
3	690.0 ± 1.8	14.493	12.0 + 6/− 0
4	703.0 ± 1.8	14.225	16.0 + 4/− 2
5	716.0 ± 1.8	13.966	16.0 + 4/− 2
6	733.0 ± 1.8	13.643	16.0 + 4/− 2
7	749.0 ± 1.8	13.351	16.0 + 4/− 2
8	900.0 ± 2.7	11.111	35.0 ± 5.0
9	1030.0 ± 4.0	9.709	25.0 ± 3.0
10	802.0 ± 2.0	12.469	16.0 + 4/− 2
11	1365.0 ± 5.0	7.326	40.0 ± 5.0
12	1533.0 + 2/-6	6.523	55.0 ± 5.0
13	2188.0 ± 4.4	4.570	23.0 ± 3.0
14	2210.0 ± 4.4	4.525	23.0 ± 3.0
15	2235.0 ± 4.4	4.474	23.0 ± 3.0
16	2245.0 ± 4.4	4.454	23.0 ± 3.0
17	2420.0 ± 4.0	4.132	28.0 ± 3.0
18	2515.0 ± 5.0	3.976	35.0 ± 5.0
19	2660.0 ± 9.5	3.759	100.0 ± 15.0
20	14500 ± 220	0.690	1000 ± 150.0

From ATOVS Level 1b Product Guide, EUMETSAT, 2016.

For calibration HIRS makes use of internal black body views and deep space views. This takes place in calibration mode, which in nominal operations is entered every 256 s (i.e., a cycle of 40 scan lines). The scan mirror slews first at deep space, which takes the equivalent measurement time of eight IFOV views. In the measurement time of the remaining 48 views of a scan line cold space is sensed. Then a full scan line time is used to look at the internal warm target, that is, there are 56 measurements of the internal warm target temperature. After this calibration sequence, during which no Earth views are performed, 38 scan lines of 56 Earth views are taken.

Level 1 processing of ATOVS data consists essentially of the generation of level 1b products, that is, the calculation of calibrated and geolocated Earth view radiances at the original pixel resolution. There are several sequential steps involved: decommutation of the raw measurement data, geolocation, and the computation of the satellite and solar zenith and azimuth angles, and the computation of the calibration coefficients, which are applied to the measurement counts in the level 1b processing. These steps are common to all ATOVS instruments and are data driven.

Table 11 Scan characteristics of AVHRR/3.

Characteristics	*Value*	*Unit*
Scan type	continuous	
Scan rate	0.1667	s
Sampling interval	0.025	ms
Sampling interval	0.0541	°
Pixels/scan	2048	
Swath	±55.37	°
Swath width	±1446.58	km
IFOV	0.0745	°
IFOV size (nadir)	1.08	km
IFOV size (edge)—across track	6.15	km
IFOV size (edge)—along track	2.27	km
Scan separation	1.1	km

From AVHRR Level 1b Product Guide, EUMETSAT, 2016.

The geolocation step makes use of the default attitude information and an ephemeral model for the satellite. The zenith and azimuth values are estimated from the solar declination related to the time stamp and the location of the pixel under consideration. A coastline data base is used to determine the pixel surface type (land, sea, coast), and the terrain altitude is assigned using a digital elevation model.

In the follow-on processing step, the calibration coefficients of the instruments are computed from the instrument counts according to the calibration equations. For the microwave instruments AMSU-A and MHS they are based on the warm target views and the space views measured during each scan cycle. The internal mean warm target temperatures are calculated using the PRT measurements of the black body. Instrument prelaunch characterization data to correct the mean warm load temperatures and the fixed cold space temperature for biases are applied in order to account for temperature changes in the instrument and radiance contamination from the spacecraft and from the Earth's limb, respectively. Moon contamination of space views is also accounted for and flagged for questionable calibration information. A nonlinearity correction is applied before calculating the calibration coefficients, from parameters determined on-ground prelaunch and from the actual instrument temperature.

For the HIRS/4 instrument the two-point calibration of the 19 infrared channels is also based on the internal warm target and cold space as reference targets. However, the calibration measurements are only taken every 40th scan line. Calibration coefficients are calculated for the calibration scan lines and are linearly interpolated between those of subsequent calibration cycles for use in the Earth view scan lines in between. The warm target temperature is determined using the PRT measurements. Radiances are computed after a linear correction at the central wave number in order to take into account the effect of the spectral response function.

The visible channel is calibrated using coefficients of a linear equation which were determined prior to launch during instrument on-ground characterization.

A further step in the HIRS/4 preprocessing is the computation of the percentage of cloudy AVHRR/3 pixels in an HIRS IFOV from collocated AVHRR/3 level 1b data.

Level 1b processing transforms the instrument counts into radiances by applying the calibration coefficients derived through the aforementioned steps. For AMSU-A and MHS, a quadratic calibration equation is used. A quadratic equation is also used for the infrared HIRS channels, but with the quadratic coefficient set to zero, and the visible channel reflectivity is determined using a linear equation.

1.07.2.1.3 AVHRR/3

The Advanced Very High Resolution Radiometer (AVHRR/3) is a cross track imager which measures the Earth outgoing radiance in six channels, three in the visible and near-infrared, and three in the infrared spectral domain. The scan is continuous from right to the left in-flight direction with 2048 square pixels at about 1.08 km ground sampling at nadir (0.0745 degrees, equivalent to 1.3 mrad). The scanning angle is between ±55.37 degrees, which correspond to ±1464 km around nadir. There are six scan lines with equal time intervals per second resulting in an on-ground distance of about 1.1 km between two subsequent scan lines. Table 11 summarizes the scan characteristics of the AVHRR/3 instrument.

The spectral range is from 0.63 to 12 μm. Two channels in the visible, one in the near-infrared and three thermal infrared channels, consist the measurement data. Channel 3 is a split channel. Channel 3a measures radiances at 1.6 μm, whereas channel 3b measures at 3.7 μm. The data of only one of both of these channels can be transmitted to the ground together with the remaining four. The channel 3 transmitted is selected via telecommand. On the Metop satellites, channel 3a is selected for the day part of the orbit, and channel 3b is selected for the night part. On the NOAA-18 and NOAA-19 satellites, channel 3b is operated continuously because of its capability to support forest fire detection. Table 12 summarizes the channel characteristics of the AVHRR/3 channels.

Table 12 Channel characteristics of AVHRR/3.

			Channel noise specifications	
Channel	*Central wavelength (μm)*	*Half power points (μm)*	*Surface/noise @ 0.5% reflectance*	*NEdT @ 300 K*
1	0.630	0.580–0.680	9:1	–
2	0.865	0.725–1.000	9:1	–
3a	1.610	1.580–1.640	20:1	–
3b	3.740	3.550–3.930	-	$<$0.12 K, 0.0031 mW/(m^2 sr cm^{-1})
4	10.800	10.300–11.300	-	$<$0.12 K, 0.20 mW/(m^2 sr cm^{-1})
5	12.000	11.500–12.500	-	$<$0.12 K, 0.21 mW/(m^2 sr cm^{-1})

From AVHRR Level 1b Product Guide, EUMETSAT, 2016.

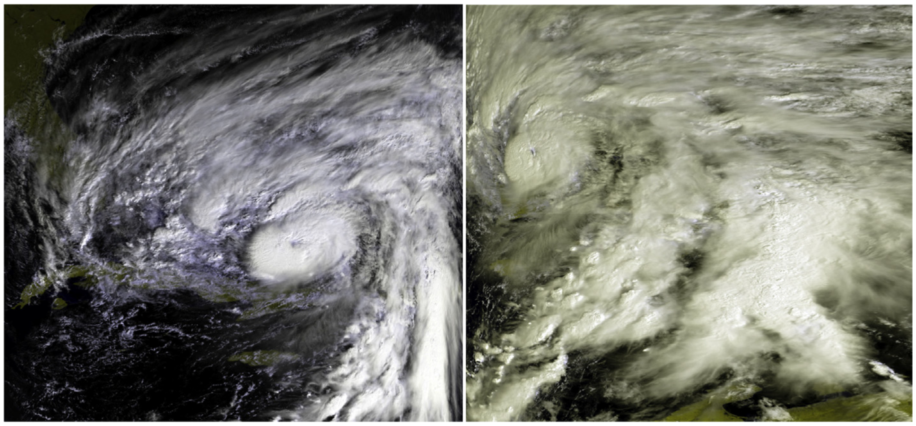

Fig. 3 Hurricane Sandy as seen by AVHRR on Metop-A (*left*) and Metop-B (*right*). RGB images composed of AVHRR channels 2/2/1.

On the Metop satellites global AVHRR data are provided for the first time at full spatial resolution of 1 km for the full orbit. An example of RGB images from AVHRR/3 is shown in Fig. 3 which displays Hurricane "Sandy" as seen by AVHRR/3 on both Metop-A and Metop-B. (On the NOAA satellites, reduced spatial resolution Global Area Coverage (GAC) were provided from AVHRR. The measured AVHRR data are processed on-board: Four out of every five samples along a scan line are used to compute one average value, and the data from only every third scan line are processed. Hence, the spatial resolution of the 409 GAC pixels per scan line near nadir is 1.1 km by 4.4 km with a gap of about 2.2 km between pixels across scan lines although generally treated as 4 km resolution. The full 10-bit precision of the AVHRR data is retained.)

Calibration of the Earth view measurement data is different for visible/near-infrared and thermal channels. The visible (channels 1 and 2) and the near-infrared channel 3a are calibrated preflight using a calibrated light source. A linear regression provides a linear calibration relation with gain and intercept. AVHRR/3 uses a dual/split gain/intercept in order to allow higher resolution at low radiance values. The visible and near-infrared channels are known to degrade during flight, and therefore, the calibration needs to be adapted. As there is no on-board calibration for these channels they are calibrated in-flight against stable known surface areas (e.g., White Sands) or by using other satellites imager data (e.g., MODIS onboard TERRA and AQUA), using established techniques also known as vicarious calibration. The calibration coefficients are updated regularly in about 2 months intervals.

The thermal infrared channels are characterized prelaunch but are also calibrated in-flight. For each scan line the AVHRR instrument looks at deep space and provides 10 measurements, before measuring the 2048 Earth views. At the end of a scan line AVHRR measures the internal black body target and provides 10 measurements. The deep space radiance is computed from prelaunch data, and the black body radiance is derived from the black body temperature, which is determined from four PRT measurements.

The AVHRR level 1 product processor follows similar steps as the sounders and performs as a first step the preprocessing, which includes geolocation, solar and satellite angle determination, and the calculation of the calibration functions. Initially, for the visible and near-infrared channels (1, 2, and 3a) the calibration coefficients originate from the instrument prelaunch characterization. In the further douse of the mission, updated characterization information from vicarious calibration is used. The counts measured for each pixel determine the gain regime and slope and intercept of the linear regression used. For the thermal infrared channels on-board calibration is performed with black body target temperatures determined from the PRT measurements and taking into account the spectral response function of the individual channel. Average black body radiances and counts as well as space radiances and counts yield the information required to determine the radiance of each Earth view pixel in the scan line. This is followed by a nonlinearity correction based on prelaunch characterization information. To reduce calculation uncertainties due to noise, a minimum of 55 subsequent AVHRR scan cycles is collected to obtain a complete set of calibration coefficients. In the geolocation step the pixel coordinates are determined for tie points along each scan line using satellite ephemeris information and solar declination information together with an instrument scanning model and the time tag of the scan line.

The second step is the generation of level 1b products applying the calibration coefficients to the counts of the individual pixels for each channel in order to determine the reflectivity values and radiances for both the visible and near-infrared and the infrared channels, respectively.

The geolocation information at the tie points is used to determine the geolocation of each individual pixel using a linear or Lagrangian interpolation. In the same way the satellite and solar zenith and azimuth angles are interpolated for each pixel. Using a high-resolution coast line data set the surface characteristics for each pixel (land, sea, or coast) is determined. For the full-resolution AVHRR data an automated landmark position correction is applied which allows to characterize the positioning accuracy and obtain accurate information on the platform attitude.

AVHRR information is used to support the sounder data processing of IASI and HIRS, and the aerosol detection algorithm of GOME-2 in particular to determine the amount of cloud contamination of the sounding pixels. Hence, for AVHRR, a scenes analysis step is performed as part of the level 1b processing with the main purpose to estimate whether an AVHRR pixel is cloudy or clear/snow-ice covered. The algorithm used is based on a threshold technique and is applied to each individual pixel. It compares brightness temperatures, brightness temperature differences, and channel reflectances of a pixel with threshold values marking the border between a pixel affected by clouds and a clear pixel. These threshold values are derived prelaunch from radiative transfer calculations or from actual forecast data. Different sequences of threshold tests are applied for land, coast, sea, twilight, and sun-glint conditions. Tests also include discrimination between optically thick and semitransparent clouds as well as tests on snow and ice cover for clear pixels. Moreover, for pixels determined as clear the surface temperature is determined, and for cloudy pixels the cloud top temperature is estimated. The test thresholds used depend basically on surface, location, satellite viewing geometry, and illumination condition. The result of the scenes analysis is cloud cover information which is added to the operational AVHRR level 1b product.

1.07.2.1.4 Advanced Scatterometer ASCAT

The Advanced Scatterometer (ASCAT) is a European Instrument developed by ESA and the only active instrument on the Metop satellites. It is a C-Band radar in heritage to the Active Microwave Instruments (AMI) flown on the ESA ERS satellites. The main mission of the ASCAT is to provide wind vectors over water surfaces and soil moisture.

The ASCAT instrument is a real aperture radar at the C-Band frequency of 5.255 GHz. Six antennas are oriented at 45, 90, and 135 degrees relative to the satellite track, a feature inherited from the ERS instruments. They are polarized vertically (VV) for transmission and reception. These six fan-beam antennas cover two 550-km swaths which are separated from the satellite ground track by about 336 km for the minimum orbit height. Fig. 4 illustrates the ASCAT swath geometry for the six antennas. The incident angles of the beams are in the range of 25–65 degrees. Hence for each of the swaths, three antennas illuminate the sea surface at three different azimuth angles, measuring the backscattered signal. A so-called chirp, a linear frequency modulated long pulse, is transmitted from the antennas. The ground echoes are received and after dechirping are spectrally analyzed and detected. Data of the power spectrum are processed to map the frequency into slant range. Noise measurements are taken on board as well

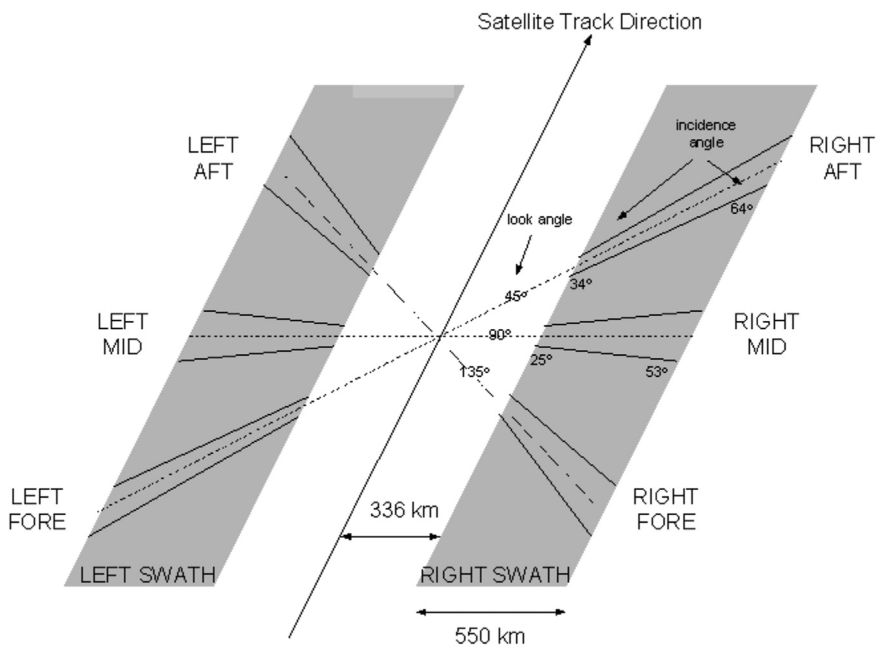

Fig. 4 ASCAT swath geometry for a Metop minimum orbit height (822 km). From ASCAT Level 1 Product Guide, EUMETSAT, 2016.

and are processed. The noise and echo processing through averaging is performed on board and reduces significantly the amount of data transmitted to the ground. The data transmitted to the ground are entering into the level 1 processing.

Calibration of the instrument is done during nominal measurement operations and is called internal calibration. A calibration phase and a noise estimation phase are part of each long pulse. The data obtained are transmitted to the ground and are used in the ground processing to correct for the instrument effects. In the frame of this processing instrument power and the receiver gain can be monitored against reference values, which are determined at the beginning of the mission lifetime.

In addition to the internal routine calibration the instrument can be set into external calibration mode. In this mode the pointing and the absolute gain of each antenna are determined in-flight. This External Calibration makes use of ground transponders which are active devices that receive a pulse from the ASCAT instrument and send back a defined pulse after a delay. This response delay and the radar cross section of the transponders are well known and stable. The accurate positions of the transponders are known as well. The measured transponder echoes and their earth location are compared to the expected values for the transponder. Through this comparison gain correction values and so-called de pointing angles can be determined. They constitute a reference calibration system which allows determining the system performance and also comparing the ASCAT performance on several Metop satellites.

The three transponders used are located in Turkey and are spaced in a way that allows the continuous and sufficiently dense acquisition of gain information over the whole range of incident angles. A series of transponder measurements takes about 6 min. and hence interrupts the measurements over a path of about 5000 km. The location of the transponders was also chosen in view to lose as few as possible of the nominal measurements over the oceans. Over a full orbit cycle of 29 days transponder measurements can be received for each of the antenna beams and the whole range of incident angles. The ground resolution of these measurements is about 10–20 km. Several transponder campaigns of 3 months each have already been conducted for both Metop-A and Metop-B (e.g., Anderson et al., 2012).

Once in an orbit cycle, the instrument Gain Compression needs to be monitored. The Gain Compression Monitoring mode is a special measurement mode. It analyzes the relation between the transmitted power and the RFU drive level setting. No science data are acquired during the gain compression monitoring which takes about 5 min. The gain compression monitoring is performed over land, and gain compression measurements are not used to retrieve science data.

Level 1 processing is performed in the central facility in Darmstadt. It processes the measurement data (echoes and noise) received in the instrument source data packets into normalized radar cross sections.

There are three processing steps involved in the level 1b processing. First, the power echoes undergo two correction processes, the gain correction (from the internal calibration) and the noise correction.

The next step is the normalization of the echoes into 256 sigma naught values, projected onto the earth surface for each antenna beam along each of the antennas. It includes the calculation of the Earth locations of each ground spot. The normalization factors are the coefficients needed to convert the raw data into sigma naughts. They are calculated by using the System Response Function of individual power samples along an antenna beam. Using orbital state vector predictions some hours in advance of the sensing time the normalization factors and the System Response Function are estimated in advance of the actual Metop pass.

In a third step, in order to obtain a sigma naught triplet (one from each of the three antenna beams on each side of the sub satellite track) on each grid node at the required radiometric resolution (K_p) spatial averaging is performed along- and across track. That means the sigma naught values are resampled onto a regular grid within the swaths to the right and left of the subsatellite track. Resampling reduces the noise and also collects the three sigma naught values from three antenna directions on one location, required for most applications. The currently generated regular gridded level 1b products are on a 12.5- and a 25- km grid. Currently a Hamming window is used for the averaging. **Fig. 5** shows the ASCAT resampling and averaging.

In addition EUMETSAT produces a full-resolution ASCAT level 1b product since May 2013, which contains all original individual sigma naught values of each beam, with their own geolocation attached. This product is as well disseminated in NRT and contains a regular 6.25 X 6.25 km grid to allow the user a customized resampling. One application making use of this product is the coastal wind product produced by the Ocean and Sea Ice SAF.

1.07.2.1.5 Global Ozone Monitoring Experiment 2 (GOME-2)

The Global Ozone Monitoring Instrument (GOME-2) is the second instrument in heritage from the GOME-1 instrument on the ESA ERS-2 satellite. It assures with its measurements on Metop the continuity of GOME-1 on ERS and also SCIAMACHY (scanning imaging absorption spectrometer for atmospheric chartography) on ENVISAT. A detailed view on instrument design, calibration, and level 1 data processing is provided in Munro et al. (2015). GOME-2 provides the operational capability to monitor the total ozone column, ozone profiles, and trace gases. **Fig. 6** illustrates the trace gases which can be retrieved by GOME. Additional products include as well water vapor and aerosols. Due to the need of calibrating the instrument with the actual solar spectrum, the instrument is located on the flight direction front side of the Metop satellite.

GOME-2 is a UV–VIS grating spectrometer that measures the back scattered ultraviolet and visible radiation from the Earth/ Atmosphere system. The data are acquired with a cross track scan mirror and illuminate four photodiode detector arrays with 1024 detector pixels each, thus providing 4096 spectral samples. The four detector arrays and their optical parts are often referred to as optical channels. Two Polarization Measurement Devices (PMD) are illuminated by the incoming radiation as well. They use the same type of detector arrays as the optical channels for the measurement of polarized radiation in two perpendicular directions. The optical channels are cooled actively to $-38°C$. The PMD are cooled to about $0°C$ in an open loop cooling configuration. The four main optical channels provide spectral information between 240 and 790 nm at a spectral resolution between 0.25 and 0.5 nm (FWHM). In **Table 13** the characteristics of the four GOME-2 channels (which are effectively spectral bands) are summarized.

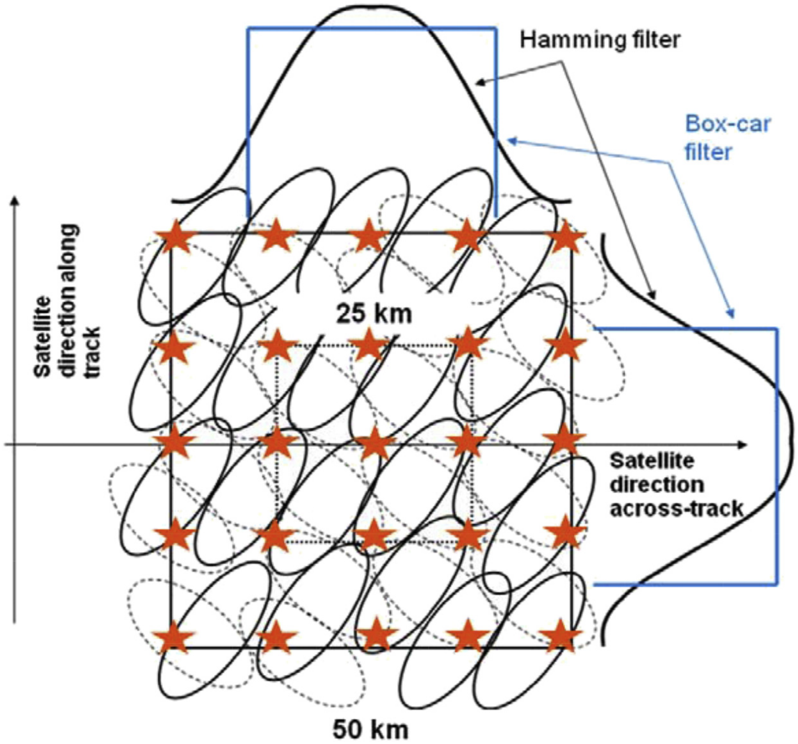

Fig. 5 ASCAT resampling and spatial averaging. From the ASCAT Level 1 User Guide, EUMETSAT, 2016.

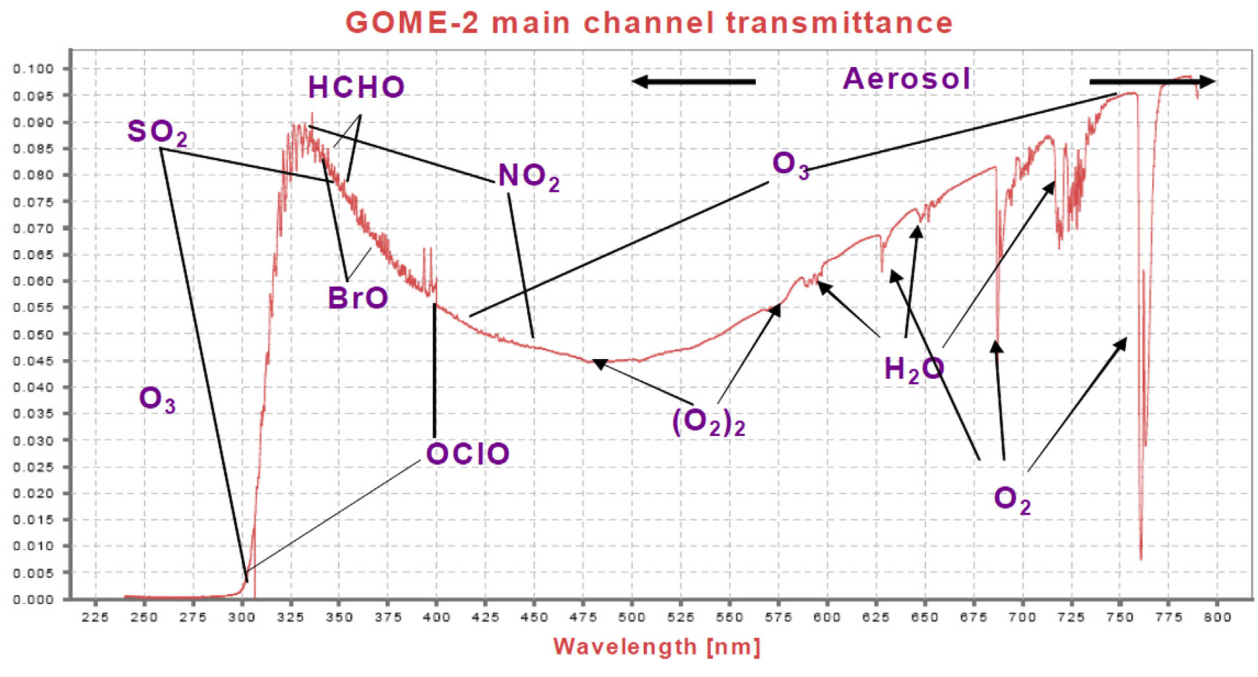

Fig. 6 GOME-2 channel transmittances and trace gases signatures. From the GOME-2 Fact Sheet, EUMETSAT, 2016.

The PMD measurements are at lower spectral resolution, but at higher spatial resolution. In Table 14 the characteristics of the PMD are listed.

GOME-2 measurements are acquired in "scans," where one scan corresponds to a 6-s time interval, subdivided into 16 "subsets" of 375 ms each. One "subset" is equivalent to one data packet. In Earth scanning mode the nominal scan performs a "forward" scan from east to west (i.e., from left to right in-flight direction) of 4.5 s, measuring subsets 0–11, and a "fly back" west to east of 1.5 s, to measure subsets 12–15. This scan pattern is illustrated in Fig. 7. Besides header and housekeeping information a 375 ms subset data

Table 13 Channel characteristics of GOME-2

Channel	*Spectral range (nm)*	*Detector Pixel size (nm)*	*FWHM (nm)*
1	240–314	0.12	0.26
2	310–403	0.12	0.27
3	397–604	0.21	0.51
4	593–790	0.21	0.48
PMD-P PMD-S	312–790	0.62 (312 nm)–8.8 (790 nm)	2.9 (312 nm)–37 (790 nm)

From GOME-2 Fact Sheet, EUMETSAT, 2016.

Table 14 PMD Channel characteristics of GOME-2

Band-S No.	*Pix1*	*Pixw.*	*Wav1*	*Wav2*	*Band-p no.*	*Pix1*	*Pixw.*	*Wav1*	*Wav2*
0	22	5	311.709	314.207	0	20	5	311.537	313.960
1	30	4	316.762	318.720	1	29	4	317.068	318.983
2	37	12	321.389	329.139	2	36	12	321.603	329.267
3	50	6	330.622	334.443	3	49	6	330.744	334.560
4	57	6	336.037	340.161	4	56	6	336.157	340.302
5	84	17	360.703	377.873	5	83	17	361.054	378.204
6	102	4	380.186	383.753	6	101	4	380.502	384.049
7	117	19	399.581	428.585	7	116	19	399.921	429.239
8	138	27	434.083	492.066	8	137	27	434.779	492.569
9	165	18	494.780	548.756	9	164	18	495.272	549.237
10	183	2	552.474	556.262	10	182	2	552.967	556.769
11	187	11	568.070	612.869	11	186	11	568.628	613.680
12	198	9	617.867	661.893	12	197	9	618.711	662.990
13	218	4	744.112	768.269	13	217	4	745.379	769.553
14	224	2	794.080	803.072	14	223	2	795.364	804.351

From GOME-2 Fact Sheet, EUMETSAT, 2016.

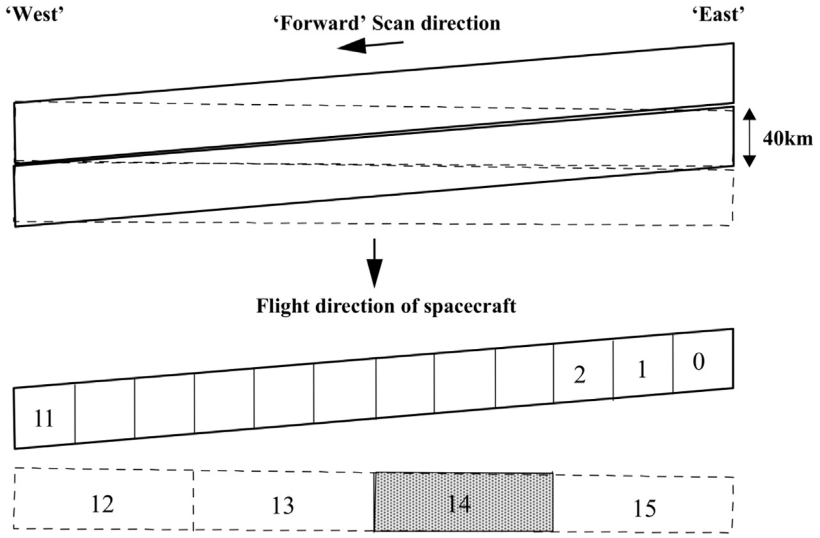

Fig. 7 GOME-2 scan pattern. Courtesy Rosemary Munro, from the GOME-2 Level 1 Product Guide, EUMETSAT, 2016.

packet contains science data from the focal plane arrays (FPA) and PMD information. A data packet can contain two main focal plane array readouts, corresponding to 187.5 ms of temporal resolution, or up to 16 PMD readouts, corresponding to 23.4 ms of temporal resolution. The default swath width covered by one scan is 1920 km; however, other swath widths can be adjusted via on-ground command. The default swath width provides full global coverage within 1.5 days.

Table 15 Scan characteristics of GOME-2.

Item	*Budget*
Spectral band (nm)	240–790 nm
Spectral resolution (nm)	0.26–0.51
Spatial resolution Metop-A (km^2) before 15 Jul. 2013	40 × 80 (main channels) 40 × 10 (PMD)
Spatial resolution Metop-A (km^2) after 15 Jul. 2013	40 × 40 (main channels) 40 × 5 (PMD) after 15 Jul. 2013
Spatial resolution Metop-B (km^2)	40 × 80 (main channels) 40 × 10 (PMD)
Swath width Metop-A (km) before 15 Jul. 2013	1920
Swath width Metop-A (km) after 15 Jul. 2013	960
Swath width Metop-B (km)	1920
Spectral channels	4096
Polarization channels	30
Calibration system	Spectral lamp, white lamp, solar diffuser

From GOME-2 Fact Sheet, EUMETSAT, 2016.

The along-track size of an Instantaneous field of view (IFOV) is about 40 km. The IFOV across-tack size is about 4 km. With the temporal resolution of 187.5 ms for a main FPA channel, the maximum pixel size for the nominal swath width is 80 X 40 km (across x along track). The PMD maximal pixel resolution is 10 x 40 km (across x along track) at the temporal resolution of 23.4 ms. The values are valid for the forward scan. The integration time (and thus the according pixel size) can be separately set for each channel.

The nominal mode of operation is the Earth view mode with a scan around nadir at the swath width of 1920 km. There are also possibilities to specially observe the North Pole region by scanning around 46.696 degrees viewing angle and the South Pole around a viewing angle of −46.172 degrees. Table 15 summarizes the scan characteristics of the GOME-2 instrument.

GOME-2 has a number of on-board calibration devices. There are internal and external calibration sources. Internal sources include several lamps. The white-light source (WLS) is used for etalon and pixel-to-pixel gain estimation. Pixel-to-pixel gain calibration can also be performed by using LED sources. The Spectral Light Source (SLS) can be used by pointing the mirror direct toward it. This mode is used to perform the wavelength calibration. The SLS can also be seen via a diffuser. The sun-diffuser reflectivity is monitored in orbit in this mode.

External calibration sources are the Sun and the Moon. Looking at the diffuser the sun is monitored once a day at the terminator over the Northern Hemisphere, where the sun is in view. The Moon can be monitored when the geometry allows it, which is possible only a few times per year. In this case, the moon moves across the slit view of the GOME IFOV in orbit. In addition, a dark current measurement is performed every orbit during eclipse.

The GOME-2 instrument is undergoing an extensive laboratory calibration campaign preflight. Calibration Key Data are determined during these campaigns, which also include long-term measurements. Prelaunch calibration activities comprise also the characterization of the instrument slit function and the measurements of trace gas absorption spectra.

In-flight calibration activities are part of routine operations. They include measurements with the internal and external calibration sources and are performed daily (Dark measurements every orbital eclipse, about 30 min per orbit, the result is the dark signal correction; the sun calibration looking at the sun over the diffuser, 30 s over the terminator, solar mean reference spectrum as result, wavelength calibration with the SLS, 2 min before the sun calibration, the results are calibration parameters for the PMDs, and the radiometric calibration with the WLS, 4 min after the sun calibration, the result here is the Etalon correction), monthly (10 min LED measurements to calculate the uniformity of pixel response for the pixel-to-pixel gain correction, the wavelength calibration with the SLS, about 3 time 4 min after the sun calibration, the results are calibration parameters for the main channels, diffuser monitoring about 15 min during eclipse, to monitor the stability of the sun diffuser), and at irregular intervals (moon calibration during eclipse in order to characterize the scan mirror reflectivity degradation). Every month after the monthly calibration static nadir measurements are performed to monitor potential degradation of the PMD. The resulting measurements are input to the Level 1 product processing.

GOME level 0 to Level 1b processing is performed in the EUMETSAT central facility. The first step is the level 1a processing which makes use of the calibration parameters measured on-board and the calibration key data to determine the calibration parameters needed for the transformation of the measurements into radiances/reflectivities. Another step performed if the geolocation of the pixels, using orbital state vectors. The calibration parameters determined are the following:

- Dark current correction
- Pixel-to-pixel gain correction
- Determination of spectral calibration parameters

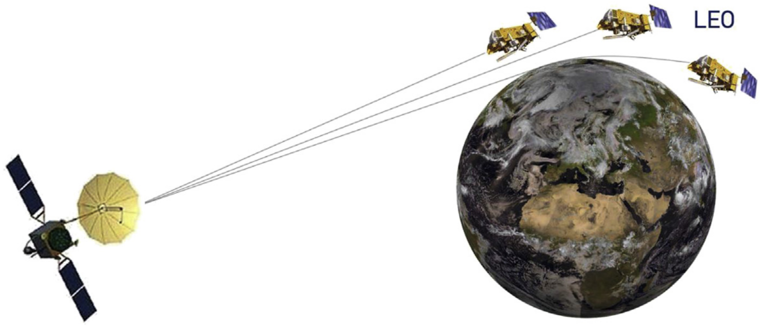

Fig. 8 Radio-occultation geometry with GRAS on Metop and GPS satellites. From the GRAS Level 1 product guide, EUMETSAT, 2016.

- Etalon correction
- Determination of stray light correction factors for the sun and polarization measurements
- Determination of the solar mean reference spectrum and atmospheric polarization state

In the Level 1b processing, the final geolocation is determined by using the actual pixel integration times. The calibration parameters determined in the previous step are applied to the measurement counts and calibrated radiances are generated. In a follow-on step, the cloud fraction and cloud top pressure are determined (Koelemeijer et al., 2001). Pixel quality information and calibration information are added to the level 1b product.

1.07.2.1.6 GNSS Receiver for Atmospheric Sounding GRAS

The Global Navigation Satellite System (GNSS) Receiver for Atmospheric Sounding (GRAS) instrument contributes to atmospheric profiling and is the first operational implementation of a radio-occultation mission making use of the Global Positioning System (GPS). The GRAS Instrument receives the signals from the GPS satellites as they pass through the atmosphere in limb view (occultations). Two antennas on the velocity and antivelocity side of the Metop satellite allow looking at rising and setting occultations. Each of these antennas can track two GPS satellites simultaneously. As the GPS signals pass through the atmosphere the signal rays are bent due to the change in density with height in the atmosphere. This in turn is a function of temperature and humidity. Fig. 8 shows the radio-occultation geometry for GRAS on Metop with GPS satellites. The observed quantity is the bending angle of the ray, which is related to the refractive index. High in the atmosphere, where low water vapor content is present, accurate temperature profiles can be obtained. In the lower troposphere, the bending angle is impacted by water vapor, too.

To determine bending angles with the required accuracy, the measurement geometry must be known at high precision. That means that there is a need to precisely determine the orbits and thus the positions of the satellites and instruments involved. For this purpose there is a third antenna on the zenith side of the Metop satellite in order to receive signals from GPS satellites for orbit determination purposes. Eight GPS satellites can be tracked with the zenith antenna. As several satellites are involved, each with a set of on-board clocks, time-based errors will contribute to errors in the measurements and need to be corrected. For this purpose, a set of ground-based reference stations has been established, which are able to see the satellites used for an occultation simultaneously. The clock errors of the satellite clocks involved can be eliminated through differencing. This network is the Ground support network (GSN) and is composed of about 24 stations worldwide. GSN information is also used to provide precise orbits for Metop and the GPS satellites.

The GPS carrier frequencies used are L1 at 1275.42 MHz and L2 at 1227.60 MHz. Pseudo random noise (PRN) is modulated on L1 as coarse acquisition code (C/A code) and on L1 and L2 a precise code (P(Y) code), which can be encrypted (using the Y code). Generally, the pseudo-noise code is tracked for navigation, while the carrier phase is tracked to allow for atmospheric demodulation. The main measurements provided by the GRAS instrument comprise:

- L1/L2 carrier phase
- L1/L2 code phase
- L1/L2 P code phase
- L1 C/A, L1/L2 P amplitude measurements

Ancillary data is provided for, for example, ephemeris, instrument monitoring.

GRAS operates in two tracking modes: closed-loop and open loop (also called raw sampling). In the closed-loop tracking, which is done at 50 Hz, the carrier phase is phase locked to the received GPS signal. The open loop tracking measures the carrier phase relative to an on-board Doppler model and is performed at 1 kHz. The GRAS instrument tracks from about 80 km down to the Earth surface. The switching from closed to open loop tracking occurs automatically based on the tracking of the P code; once it is lost, the open loop tracking will commence.

GRAS instrument data processing is performed in the EPS Core Ground Segment at the central facility in EUMETSAT headquarters at Darmstadt.

The very first processing step reconstructs the measurement data from the instrument source packets. In particular the relation between the GRAS instrument time (an Ultra Stable Oscillator Clock, USO) and UTC (Universal Time Coordinated) is established. The measurements are reconstructed from the level 0 data, and the resulting observations are provided with a time stamp. The observations include pseudo ranges, carrier phases, signal-to-noise ratios, and signal amplitudes. Auxiliary GPS clock data are added as well.

The essential product processing is composed of four steps, which are the Precise Orbit Determination (POD), the Level 1a processor, the Level 1b processor, and the extended product generation processor.

The POD makes use of the Navigation Package for Earth Orbiting Satellites (POSITIM, 2016). POD is implemented as a batch process and allows for the handling of data gaps and maneuvers.

Level 1a processing makes use of the reconstructed measurement data. It extracts the orbit and clock data for GPS satellites and Metop, applies antenna corrections to closed-loop and raw sampling measurements, and performs a preliminary geolocation. In addition the navigation bits are removed from the raw sampling measurements, and the total phase is calculated. A zero differencing is carried out in order to correct for the clock errors.

Level 1b processing generates the final level 1b bending angle product. Up to Oct. 2016 GRAS processing was done in the so-called Geometric Optics (GO) mode. It is performed on each single occultation. The modules for geometric optics include the calculation of the Doppler frequency shift, the computation of the bending angles, and the impact parameters based on the geometry of the satellites involved in the occultation. After some smoothing bending angles from L1 and L2 frequencies are combined to correct for ionospheric effects, and a neutral atmospheric bending angle profile is generated. A precise geolocation is performed. Finally the bending angle profiles are thinned to a fixed set of impact parameter heights.

In the course of 2016 the development of the wave optics (WO)-based GRAS Level 1 b processing was finalized and became operational in Oct. 2016. This processing is able to handle radio-occultation measurements in the middle and lower troposphere, where, for example, due to strong vertical gradients of atmospheric humidity multiple rays can occur.

The level 1b processing is different from the geometric optics and needs a more sophisticated preprocessing of the measurements. The amplitude and total phase data from closed and open loop are used to construct the measurement signal. Data gaps which are not too long can be filled. The next step is to calculate the group delay of rays for defined Doppler frequencies using the Full Spectrum Inversion (FSI) algorithm. The results are converted to excess Doppler. In the following step the impact parameter and the bending angles are computed, taking into account the orbit geometry of the satellites involved. Smoothing and sorting steps as well as some quality control are performed next.

In this new configuration, the GRAS PPF uses Wave optics bending angles per default. Only if problems are occurring in the WO retrieval, the geometric optics will be used instead. Data will be flagged accordingly. It is possible to configure the GRASS PPF to employ a transition between wave optics retrieval in the troposphere and geometric optics in the upper atmosphere above.

The final processing steps, ionosphere correction, precise geolocation, and thinning remain the same for wave optics processing.

1.07.2.1.7 Nonmeteorological instruments on Metop

In addition to the meteorological payload there are three nonmeteorological instruments embarked on the Metop satellites. These are the Space Environment Monitor (SEM) which provides information on solar activity and space weather, which both may affect satellites and their operations, a Search and Rescue (SAR) transmitter and receiver, to receive and transmit emergency signals from specific beacons, and the ARGOS Advanced Data Collection System (A-DCS), which allows the reception and transmission of in-situ measurements from platforms and buoys.

1.07.2.1.7.1 Space Environment Monitor-2 (SEM-2)

The SEM-2 instrument (NOAA, 2016c) is one of the nonmeteorological instruments on Metop. It has been added to the set of American instruments in order to guarantee (NASA/NOAA) a continuity in the determination of auroral activity—intensities of charged particle radiation within the Earth's atmosphere that can degrade radio communications (occasionally making short-wave radio communication impossible in the polar regions); occasionally disrupt the proper operation of satellite systems; increase the radiation dose to astronauts in space (when intensities are high).

The Space Weather Prediction Center (SWPC), formerly the Space Environment Center (SEC) (NOAA.2016-4), processes the particle counts received from Metop and monitors solar activity and the state of the Earth's near space environment. Warnings are issued to advisories, and forecasts of conditions are relayed to customers whose systems are affected.

The SEM-2 instrument (NOAA, 2016d) is composed of several units which are the total energy detector (TED), the Medium energy proton and electron detector (MEPED), and a data processing unit. The Total Energy Detector measures the total energy flux carried into the atmosphere by charged particles. The medium energy proton and electron detector measures the flux of protons and electrons with a directional particle detector and omnidirectional proton detectors.

1.07.2.1.7.2 The SAR Terminal

A SAR Terminal is implemented by Sarsat instruments on the Metop Satellites. The COSPAS-SARSAT (e.g., NOAA, 2016e) Program coordinates the frequency management, satellite, and emergency beacons and maintains a register for 406 MHz emergency beacons. Different types of beacons (on aircraft, ships, or for individual usage) can transmit emergency signals during distress situations. The Sarsat instruments on the Metop satellites receive these emergency signals. They are transmitted to local user terminals (LUT), also known as distress terminals, which are distributed over the whole globe. Distress alerts can be generated from the processed data, and SAR activities can be initiated by the SAR Control Centers, to which the mission control center transfers the alerts.

The Sarsat instruments are comprised of a SAR Signal Repeater (SARR) and a SAR Signal Processor (SARP-3). The SARR receives the 406 MHz beacon burst signals and relays them to local User Terminals (LUT) on the dedicated 1544.5 MHz downlink. Beacon and Local User Terminals must be both in simultaneous view of the Metop satellite. Processing is done by the LUT, where after signal detection the Doppler information is computed and the beacon position is determined.

The emergency signals from the 406 MHz beacons are received by the SARP, which also processes the emergency signals. The processed data include identity, frequency, and time of the signal. They are immediately transmitted via the SARR and stored in memory for transfer to the Local User Terminals at a later stage, once in view. The beacons can be located at an accuracy of 5 km.

SARR is provided by NOAA and was developed in Canada under contract to the Canadian department of national defense. SARP-3 is provided by CNES.

1.07.2.1.7.3 Advanced Data Collection System (A-DCS)

The Advanced Data Collection System (EUMETSAT, 2016b) can receive and transmit signals from in situ measurement systems (ARGOS, 2016). Applications include

- Studying oceans and atmospheric conditions
- Preserving and monitoring wildlife
- Monitoring volcanoes
- Monitoring fishing fleets
- Monitoring shipments of dangerous goods
- Humanitarian applications
- Managing water resources
- Monitoring sea ice

The instrument is composed of two parts, the Receiver Processing Unit (RPU) and the Transmission Unit (TXU). An ARGOS beacon transmits a message to the RPU at 401.650 MHz. The RPU can process up to 12 messages simultaneously. It determines the location of the data collection platform (DCP) or small moving measurement platform by evaluating the Doppler Effect. A location accuracy between 150 and 1 km can be achieved.

Through the UHF transmitter (TXU) at 465.9875 MHz the A-DCS is able to transmit ARGOS messages which have been uplinked to the spacecraft via ARGOS master beacons (at Svalbard, Fairbanks, and Toulouse) to the user terminals. The downlink is continuous.

The data processing is performed at the ARGOS centers by CLS Argos, Toulouse, and Service Argos Inc., USA a subsidiary of CLS. The ARGOS program is implemented under a joint agreement between NOAA/NASA and CNES. The A-DCS instrument was provided by CNES under a cooperation agreement.

1.07.2.1.8 Direct readout AHRPT

The Advanced High-Resolution Picture Transmission (AHRPT) is the direct readout capability on Metop (EUMETSAT, 2016c). All instrument data are transmitted in real time to the ground in the L-band. The prime frequency used is at 1701.3 MHz, and the backup frequency is 1707.0 MHz. The data rate is at 3.5 Mbps. The data stream contains all instrument data from Metop. The transmission is continuous and provides full-resolution global data. Users can receive data as long as the satellite is in view of a local tracking station. The data received are Channel Access Data Units (CADUs) which contain multiplexed instrument data and housekeeping and telemetry information. The users have to demultiplex the data and perform the generation of level 0 data and also any higher-level data processing, in particular level 1b/c and level 2 processing. This includes the calibration and geolocation of the data. (Software for doing this can be obtained, for example, from the NWP SAF: the AAPP software (ATOVS and AVHRR Processing Package allows the processing of AVHRR, the ATOVS suite, and IASI) (NWP SAF, 2016).)

The user notification service (UNS) provides actual orbital information for the Metop and NOAA satellites in the frame of the Initial Joint Polar System (IJPS). The Multimission Administrative Message (MMAM) contains operational information relevant to users of the Metop AHRPT direct broadcast service. It contains administrative information for multiple satellites from multiple missions or programs. A wide range of information is contained for the satellite transmitting the MMAM via its AHRPT direct readout signal, including:

- Operational announcements
- Spacecraft and instrument status
- Navigation data, including orbital position, attitude, and events
- Processing data, including OBT/UTC time correlation information

To allow the geolocation of the data EUMETSAT distributes two-line elements (TLE) covering a period of 3 days before and after a maneuver. This is made available in addition to the orbit information provided via the admin message and is available via the UNS web page.

The direct readout service functions nominally over the whole globe, which is the case for Metop-B. On Metop-A there has been an anomaly where the Solid-State Power Amplifier (SSPA) of the HRPT receiver was sensitive to radiation and underwent an

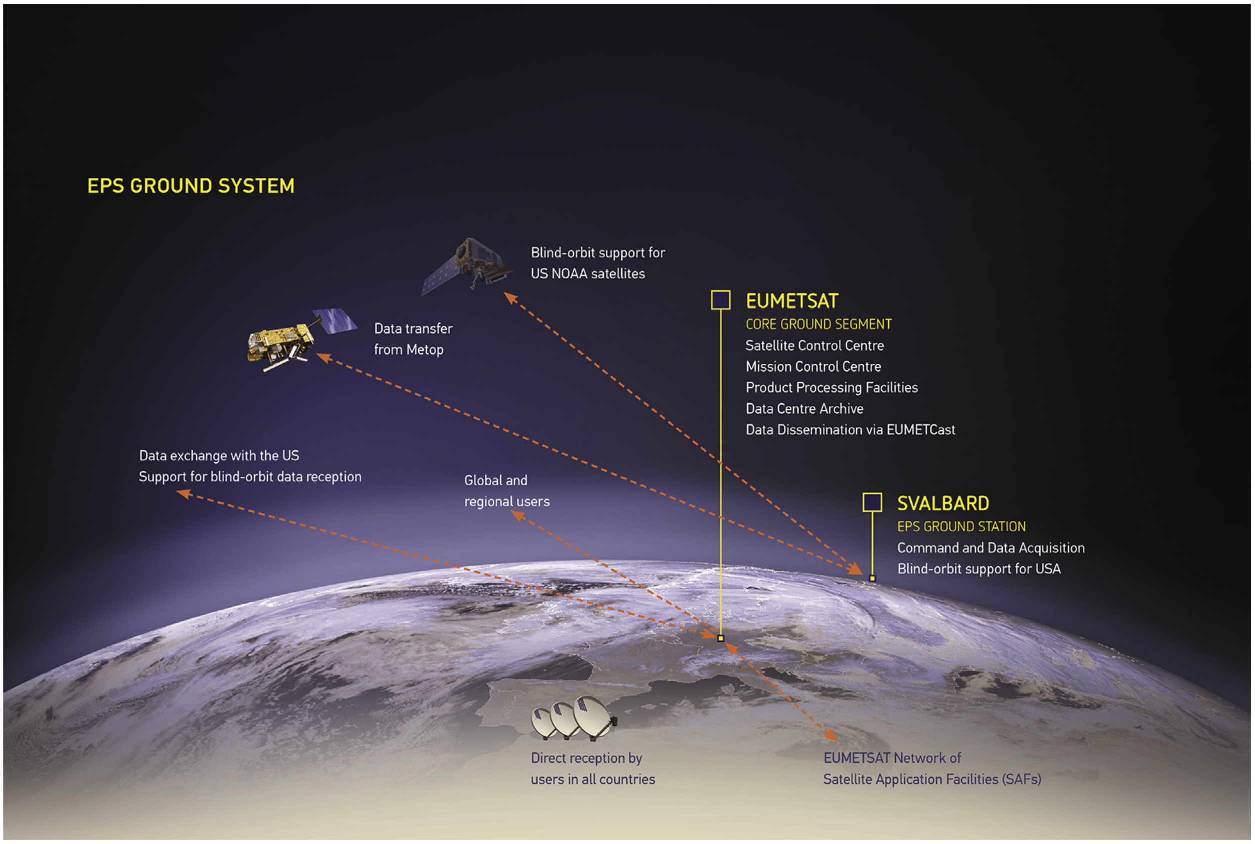

Fig. 9 The EPS ground system. From EUMETSAT, 2016-4.

anomaly. The AHRPT service on Metop-A is working with the redundant SSPA and is only switched on over nonradiative sensitive regions. It is running on the redundant component because of the above-mentioned anomaly.

1.07.2.2 Ground Segment

The EPS Ground Segment is composed of all elements which are required to receive the data from the satellites, transmit them to the processing site, process them, and distribute the resulting products to the User community. In addition, facilities are needed to control and operate the spacecraft and the subsystems of the ground segment and also to archive the received and processed data and products. A summary view of the EPS Ground System is depicted in Fig. 9.

1.07.2.2.1 Command and Data Acquisition Stations

The EPS Command and Data Acquisition Stations (CDA) are located on the Svalbard archipelago at about 78°N and 15°E (EUMETSAT, 2016d). There are two stations which provide the capability to receive telemetry and data from the satellites and transmit commands to the Metop satellites. The global data measured by the instruments embarked on Metop satellites are stored on board in a so-called Solid-State Recorder (SSR) over one orbit and sent via X-band transmission to the CDA stations, once the satellite is in line of sight of them. The stations are located sufficiently north so that they are able to receive the data from all about 14 orbits of a day. Commands are transmitted to the satellite in the same visibility period via S-band.

The stations also provide so-called blind orbit support to NOAA, that is, they can acquire data from the NOAA satellites in particular for those orbits which cannot be seen from the stations in Fairbanks, Alaska and Wallops Island, Virginia, both USA due to their location further south.

Through cooperation with NASA/NOAA, Metop data are downlinked to US acquisition stations at McMurdo Station in Antarctica near the South Pole (ADA=Antarctic Data Acquisition, ADA is not part of the EPS Program) (EUMETSAT, 2016f). ADA service is provided for the prime Metop satellite, which is currently (2016) the Metop-B satellite. The data transmitted to ground are from the first half of the descending node orbit track of the Metop satellites. The second ascending node path data of the orbit is downlinked at Svalbard and complements the McMurdo Data. This cuts in half the timeliness of the global data to about 60 min. Fig. 10 illustrates the concept of the Antarctic Data Coverage and the related data coverage.

As discussed earlier the data are continuously transmitted via the L-band AHRPT. An AHRPT reference station is located at Svalbard as well.

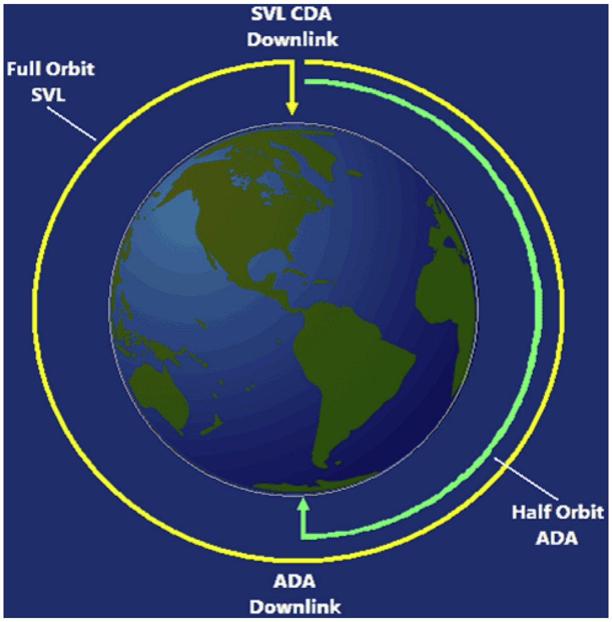

Fig. 10 The antarctic data coverage (ADA). From EUMETSAT, 2016-6.

From the Svalbard CDA stations and the ADA stations the global data from Metop and NOAA satellites acquired are transmitted to the EUMETSAT headquarters where they are processed in the EPS Core Ground Segment, disseminated to the user community, and archived in the EUMETSAT Data Centre. The data transmission via fiber link from Svalbard has been improved after the launch of Metop-B in 2013, from 101 min. to about 82 min. for the Metop-A data, and to about 72 min. for NOAA-19 data. For Metop-B data from McMurdo the timeliness is about 47 min.

1.07.2.2.2 Application ground segment and data processing

Data from the Metop satellites are processed from the global data stream, dumped to the CDA stations, and transmitted to the Central facility from there. In addition the regional and the local data processing make use of the AHRPT data.

The EPS Application Ground Segment has a centralized part and a decentralized part. One component of the centralized part is called the Core Ground Segment (CGS) and is complemented by the EUMETSAT Data Center which archives all mission data and products generated by EPS. The decentralized part consists of eight Satellite Application Facilities (SAFs) (EUMETSAT, 2016e), each hosted by EUMETSAT Member States Meteorological Services.

1.07.2.2.2.1 Core Ground Segment

In the EPS Core Ground Segment the global data transmitted from the CDA Stations are processed first to level 0 and then to level 1. Global data products are categorized according to instrument and product levels:

Level 0 Raw data after restoration of the chronological data sequence for each instrument, that is, after demultiplexing of the data by instrument, removal of any data overlap due to the data dump procedure, and relevant quality checks. Raw instrument data information (telemetry packets) is maintained during this process.

Level 1a Instrument data at full instrument pixel resolution with radiometric calibration and Earth location, both calibration and Earth location computed and appended but calibration was not applied.

Level 1b Calibrated, Earth located, and quality controlled measurements, at the original instrument pixel location, appended are needed ancillary, engineering, and auxiliary data.

Level 1c In the specific case of the IASI spectra, level 1b spectra after application of the apodization function.

Level 2 Earth-located measurements are converted to geophysical parameters, at the same spatial and temporal sampling as the level 1b and 1c data.

Level 1b/c products from all meteorological instruments on Metop are disseminated to the User community in NRT. Selected Level 2 products are also generated from the global level 1 products in the central Core Ground Segment. These are in particular ATOVS- and IASI-based vertical sounding products of temperature and humidity, surface temperatures and cloud information, and some trace gas information. The latter is processed with algorithms and software provided by the Ozone Monitoring SAF. Additional Level 2 products produced centrally comprise Polar and Global Atmospheric Motion Vectors (AMV) from the AVHRR instruments on the Metop satellites and a global polar multimission Aerosol (PMAp) product currently from GOME-2 and AVHRR (and in the future in addition from IASI). Products are disseminated via the EUMETSAT EUMETCast service. The dissemination can be in EPS native product format or as BUFR files.

All products are archived in the EUMETSAT data center. The products can be retrieved by the users directly from the archive via the EUMETSAT EO portal (EOP). A list of products is available via the EUMETSAT Product Navigator (EUMETSAT, 2016g).

1.07.2.2.2.2 Regional data processing

Regional data from Metop and NOAA satellites are provided to users via the EUMETSAT Advanced Retransmission Service (EARS) (EUMETSAT, 2016h). It makes use of a dedicated network of AHRPT reception stations which are located in the northern Hemisphere in the North Atlantic, Europe, and Indian Ocean Regions. The local data are processed by standard software on local processing nodes. Subsequently they are transmitted to EUMETSAT, where they are composed and retransmitted to the Users via EUMETCast (EUMETSAT, 2016i) or the Global Telecommunication System (GTS) (EUMETSAT, 2016j).

This service further reduces the timeliness of satellite products down to about 30 min. since the observation time and enables the timely provision of sounding, imaging, and scatterometer measurements to meteorological centers, in particular for regional and local models and also nowcasting applications. There are several among the EARS services for the different instruments on the Metop and NOAA satellites: EARS-ATOVS (providing HIRS, AMSU-A and AMSU-B, and MHS data), EARS-ASCAT, EARS-AVHRR, and EARS-IASI. (They are complemented by services for instruments of the Suomi-NPP satellite.)

EARS-ATOVS is making use of the AAPP (ATOVS and AVHRR processing package) software which processes the data of the ATOVS instrument suite received by AHRPT stations. AAPP was developed under EUMETSAT coordination and is now maintained and further developed by the NWP SAF. In the EARS-AVHRR service data segments of three minutes duration are transmitted to EUMETSAT, where they are located and one-minute segments are generated. It is automatically detected whether there are duplicated data segments due to overlapping station coverage. The best segment is retained and sent to the users via EUMETCast. The provided segments can be composed by users to a regional set. The retransmitted AVHRR data are not processed. In the EARS-IASI service locally received IASI spectra are processed to Level 1c by using the OPS-LRS software, which is provided by the NWP SAF. Principal component scores are processed using AAPP. A channel selection is performed to pick 366 channels out of the 8461 IASI channels. The product retransmitted is containing 300 principal component scores and 366 IASI channels along with cloud and scene analysis information. The product format is BUFR, and the dissemination is done via EUMETCast and GTS. The EARS-ASCAT service processes level 1b ASCAT products which are based on the ASCAT level 1 product-processing software in the Core Ground Segment, and from these level 2 Scatterometer winds processed by KNMI (Koninklijk Nederlands Meteorologisch Instituut) using software from the Ocean and Sea Ice Satellite Application Facility. The products are at the 25 and 50 km resolution and are transmitted in BUFR format.

Via a dedicated transatlantic link EPS data and products are transmitted to NOAA and NOAA data and products are transmitted to EUMETSAT. In the Core Ground Segment, the data from the NOAA satellite (NOAA-19) are processed as well and the products are disseminated to the users.

1.07.2.2.2.3 Local processing

Local processing is done from data received in direct readout at local AHRPT stations and is performed by the individual users running those stations. Some software to be used with local processing Software is provided by the NWP SAF (AAPP for AVHRR/ATOVS and OPS-LRS for IASI).

1.07.2.2.2.4 Satellite Application Facilities

The Satellite Application Facilities (SAF) (EUMETSAT, 2016k) are centers of expertise for processing data from both, polar orbiting and geostationary satellites and developing and distributing software and higher-level products. They are consortia which are hosted by EUMETSAT member states and are dedicated to specific application themes. The SAFs form the decentralized part of the Application Ground Segment and provide users with operational products and software packages for data and product processing (like AAPP which was mentioned earlier). The SAFs are also performing the research and development for new products in continuous development and operations phases (CDOP). Currently there are eight Satellite Application Facilities:

- Numerical Weather Prediction SAF, hosted by the MetOffice UK
- Ocean and sea ice SAF, hosted by Météo-France
- Nowcasting SAF, hosted by the Spanish Met Service AEMET
- Land surface application SAF, hosted by the Portuguese Met Service
- Climate SAF, hosted by Deutscher Wetterdienst (DWD)
- Ozone Monitoring SAF, hosted by the Finnish Met Institute (FMI)
- Radio-occultation Meteorology SAF, hosted by the Danish Met Institute (DMI)
- Support to Operational Hydrology and Water Management, hosted by the Ufficio Generale Spazio Aereo et Meteorologia (USAM)

SAF network activities are coordinated by EUMETSAT. Products generated by the SAF are archived at the SAF and partially provided to the EUMETSAT Data Centre for archiving. Users can order products centrally via the Data Center.

Table 16 Centrally produced near real-time products from EPS

- IASI global data service Level 1c Metop-A
- IASI global data service Level 1c Metop-B
- HIRS/4 global data service Level 1b Metop-A
- HIRS/4 global data service Level 1b Metop-B
- AMSU-A global data service Level 1b Metop-A
- AMSU-A global data service Level 1b Metop-B
- MHS global data service Level 1b Metop-A
- MHS global data service Level 1b Metop-B
- AVHRR/3 global data service Level 1b Metop-A
- AVHRR/3 global data service Level 1b Metop-B
- ASCAT global data service level 1 sigma 0 at full sensor resolution Metop-A
- ASCAT global data service level 1 sigma 0 at full sensor resolution Metop-B
- ASCAT global data service level 1 sigma 0 resampled at 12.5 km swath grid Metop-A
- ASCAT global data service level 1 sigma 0 resampled at 12.5 km swath grid Metop-B
- ASCAT global data service level 1 sigma 0 resampled at 25 km swath grid Metop-A
- ASCAT global data service level 1 sigma 0 resampled at 25 km swath grid Metop-B
- GOME-2 global data service Level 1b Metop-A
- GOME-2 global data service Level 1b Metop-B
- GRAS global data service Level 1b Metop-A
- GRAS global data service Level 1b Metop-B
- IASI Global data set Level 1 Principal components residuals Metop-A
- IASI Global data set Level 1 Principal components residuals Metop-B
- IASI Global data set Level 1 Principal components scores Metop-A
- IASI Global data set Level 1 Principal components scores Metop-B

1.07.2.3 Data Dissemination

The standard dissemination service for EUMETSAT products in NRT is the EUMETCast service. EUMETCast is a multiservice dissemination system based on standard Digital Video Broadcast (DVB) technology. It uses commercial geostationary satellites to multicast data and products to a wide user community. EUMETCast is the basis of EUMETSAT's contribution to the integrated global data dissemination service (IGDDS) which is a component of the World Meteorological Organization's (WMO) information service (WIS). The satellites currently involved are Eurobird-9 (EB-9) transmitting in the Ku-Band for EUMETCast Europe service, Atlantic Bird-3 (AB-3) transmitting in C-Band for EUMETCast Africa, and NSS-806 transmitting in C-Band for EUMETCast South America. Users can use off the shelf standard equipment, commercially available for DVB-S2 reception. There are more than 4000 users worldwide. Details can be found at the EUMETSAT webpage (EUMETSAT, 2016i).

1.07.2.4 EUMETSAT Data Centre

The EUMETSAT data and products and thus also those from EPS/Metop can be obtained offline from the EUMETSAT Data Center (EUMETSAT, 2016l). All processed data and products are archived there. The data center contains all mission data and products generated over the whole mission lifetime of a satellite and assures the long-term data preservation. Data are frequently reprocessed in order to assure that the latest state of the art algorithm is used for product generation. The Data Center contains all Metop-A and Metop-B data since mission begin in 2007, and this includes global and regional products of all instruments, i.e., AMSU-A, MHS, HIRS/4, AVHRR/3, GOME-2, ASCAT, and GRAS. The EUMETSAT product navigator provides information on all products available in the data center.

1.07.3 EPS Products and Applications

The missions embarked on the Metop satellites support operational meteorology and climate monitoring of EUMETSAT's member states and cooperating states, and all users around the globe, and in particular the World Meteorological Organization (WMO).

1.07.3.1 Level 1 products

All data measured by the instruments on the Metop satellites are processed to level 1 in the Core Ground Segment as indicated earlier. The following Table 16 summarizes the level 1 products provided by the two Metop satellites 24 h a day 7 days a week.

These data are complemented by the ATOVS and AVHRR products from the NOAA-19 satellite. More details can be found via the EUMETSAT product navigator.

One main application benefiting from EPS/Metop is Numerical Weather Prediction (NWP), which is at the origin of all modern weather forecasts. The global data generated by the instruments on Metop are assimilated into the NWP models of many national weather centers and contribute to forecasts up to 10 days.

The infrared and microwave sounding instruments provide essential input on the three-dimensional structure of the atmosphere. The temperature and humidity information which is inherent in the hyper spectral resolution data provided by the IASI instrument provides the high vertical resolution information of temperature and humidity required by global NWP in order to distinguish baroclinic development structures which may lead to the development of major storms with high damage and the potential risk of loss of lives and property. These IASI measurements are provided with unprecedented accuracy of 1 K in temperature and about 10% in humidity at a vertical resolution of about 1 km. The microwave measurements of AMSU-A and MHS complement the infrared measurements and provide the all weather capability required in the presence of clouds. HIRS/4 (Metop-A and Metop-B only) information is provided supplementary to IASI. Fig. 11 depicts a IASI spectrum, together with the HIRS/4 channels. The sounder information is supported by the observations of the AVHRR/3 imager, which gives information on the cloud contamination of the sounder pixels. AVHRR together with the ATOVS suite (AMSU-A, MHS, and HIRS/4 instruments) also ensure the continuity to the NOAA-TIROS-N era and also the commonality with the NOAA afternoon satellites NOAA-18 and NOAA-19 in the IJPS.

The GRAS level 1 product is composed of the bending angles in the atmosphere and contributes as well to NWP. More than 1200 precise vertical temperature profiles are provided from the two Metop satellites in orbit every day and are assimilated into NWP models. They provide valuable anchor points for the vertical thermal structure of the atmosphere and hence have a high impact to the quality of NWPs.

Studies by NWP centers place the IASI and AMSU instruments at the highest level with regard to the impact on the quality of the NWP, Radio Occultation, and ASCAT are close followers (e.g., English et al., 2013, available from ECMWF, 2016; Joo et al., 2012, available on Met Office, 2016).

Level 1 products from the scatterometer are the sigma naughts, which are the radar reflectivities of the six scatterometer antennas. Those are provided at different resolutions to the user community, which are meteorological services and also the satellite application facilities. They are processed into higher-level products which comprise typically ocean surface wind vectors and also soil moisture over land. These products are produced by the Satellite Application Facilities.

GOME-2 level 1 products are UV and VIS spectra and also Polarization measurements. Main users of the data are the Satellite Application Facilities (in particular Ozone Monitoring SAF). NWP also started to use GOME data.

1.07.3.2 Level 2 products

Level 2 products are geophysical quantities at an original satellite sensor grid. A number of Level 2 products are generated in the Core Ground Segment at EUMETSAT headquarters. The majority of the Level 2 (and higher level) products are processed at the Centers of expertise formed by the Satellite Application Facilities. The EUMETSAT product navigator provides an overview on all those products.

Vertical soundings of temperature and moisture are derived at the Central Facility. Most of the Metop payload is used in a synergistic way. The main products are global measurements of temperature and humidity profiles at high vertical resolution. These products are complemented by surface emissivity and surface temperature, related cloud information, and atmospheric composition parameters. More details can be found in (August et al., 2012, 2015). With the latest version of the IASI L2 PPF EUMETSAT is at the forefront of retrievals, as can be seen in the NOAA NPROVS validation. Fig. 12 shows this validation for the three latest versions of the IASI Level 2 PPF (NOAA, 2016f; Reale et al., 2010). The version 6 of the IASI Level 2 PPF offers improved sounding capabilities in terms of yield and precision at the IASI footprint resolution. This version uses AMSU-A- and MHS-based microwave information along with the infrared IASI soundings which enables nearly all-sky temperature and moisture retrievals. The piecewise linear regression (PWLR) (Hultberg and August, 2015) gives about 85% of useful yield. The quality of the temperature and humidity profiles has been significantly improved, particularly in the lower troposphere for clear and cloudy pixels. The precision of the temperature and moisture profiles is better than 1 K and better than 1.2 g/kg in specific humidity. With this the product is at the forefront of retrieval performance (see NPROVS validation at NOAA). In the product the full retrieval error estimate is provided, from which averaging kernels can be derived. The complete description of the processing is available in EUMETSAT (2015). ("IASI L2 v6 Validation Report" EUM/TSS/REP/14/776443, 290 pp). The product also includes new atmospheric composition products, in terms of CO profiles, which are provided with the algorithm provided by ULB/LATMOS (Hurtmans et al., 2012). Within the same framework the ULB/LATMOS-based SO2 and HNO3 products will follow in the coming years.

The IASI L2 Temperature and humidity profiles are used as inputs to a number of atmospheric composition retrieval algorithms, for example, in the ESA CCI aerosol project or for the generation of near-real-time AC products, which in turn are used for air quality and climate monitoring.

The IASI-based retrievals are complemented by a full ATOVS/AVHRR processing chain.

New centrally provided products include the Polar Multimission Aerosol Product (PMAp) which in its current version is supported by GOME-2 PMD data and AVHRR, and in future versions will also be based on IASI Data. It is operational for ocean coverage, and under test (demonstrational) for land coverage.

The orbit convergence and the resulting overlap areas near the poles of the AVHRR swaths are used for the derivation of Polar Cap Winds, which are providing an additional positive impact to NWP. This information is complementary to the geostationary Atmospheric Motion Vectors (AMV) derived from the geostationary satellites.

The majority of the higher-level products from the Metop satellites are generated by the satellite application facilities. The complete list can also be assessed in the EUMETSAT product navigator. Some examples follow.

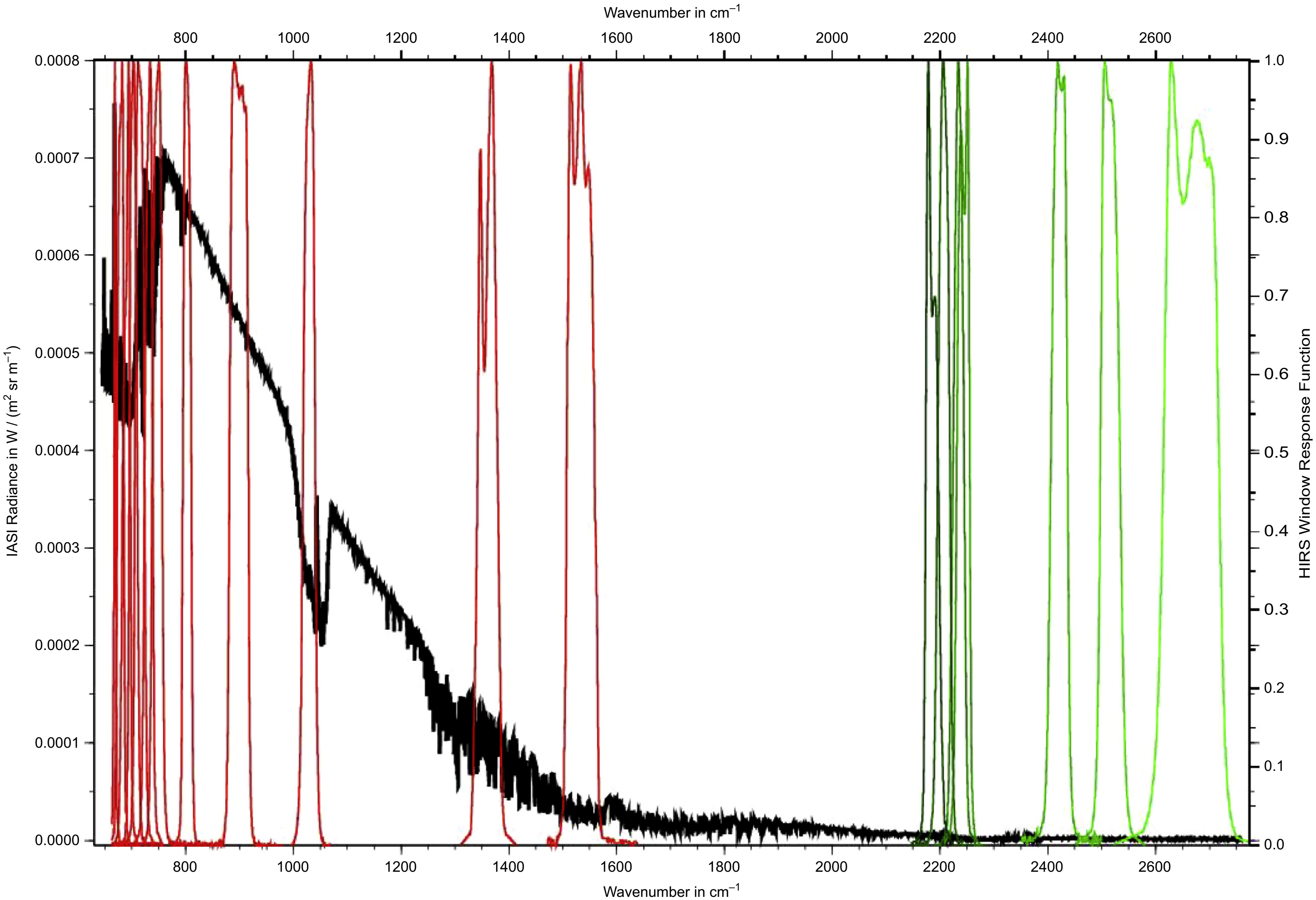

Fig. 11 Full IASI spectrum with overlaid HIRS/4 channel ISRF Long wave (*red*) and short wave (*green*). Courtesy J. Ackermann, 2016, personal communication.

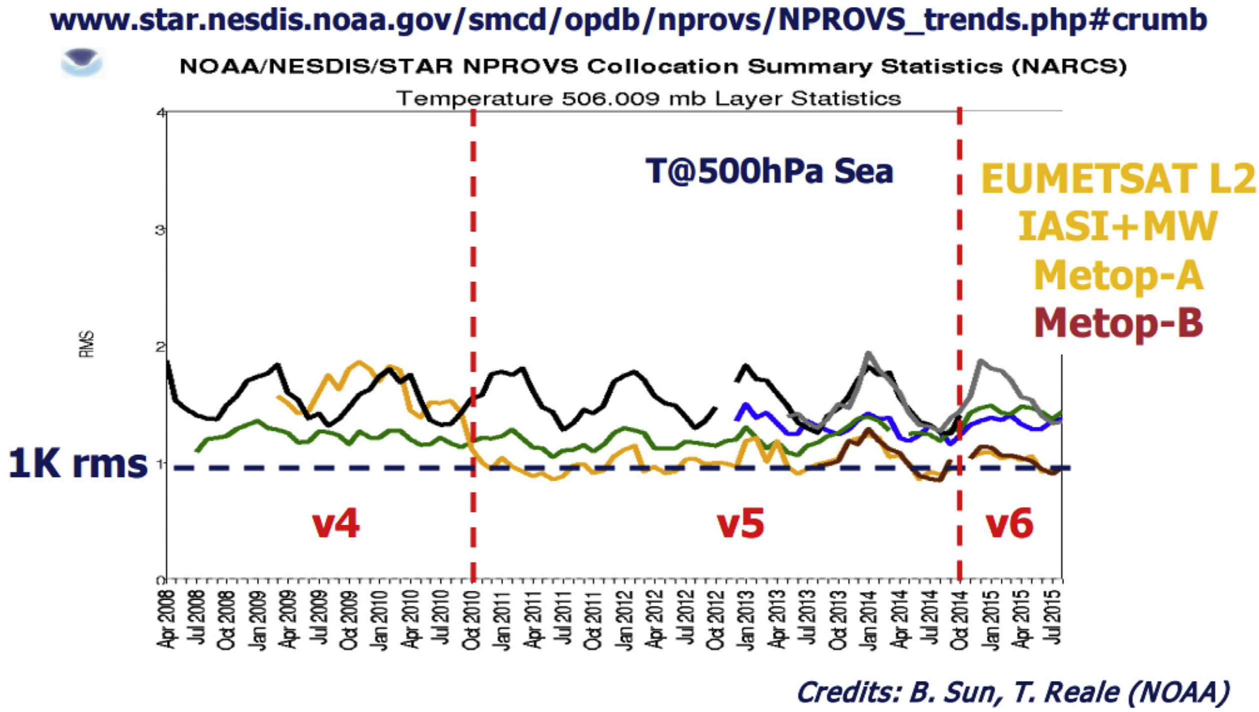

Fig. 12 IASI temperature retrieval quality, as assessed by NOAA/NPROVS. NOAA, 2016, credit NOAA/NESDIS Center for Satellite Applications and Research.

The observation of atmospheric trace gases and the monitoring of atmospheric composition is a major application area. The GOME instrument is a major contributor to this area. Total ozone column and ozone profile information are routinely derived by the ozone monitoring SAF and provide important monitoring information on the development and trend of the ozone content. Further trace gas products include brO, formaldehyde, and other products relevant to the ozone cycle. So2 is a major indicator for volcanic eruptions, and tracking its propagation can indicate the distribution of risk related to volcanic ash. GOME contributes to this monitoring.

The IASI instrument has performed far beyond expectations providing information on trace gases (Clerbaux et al., 2009). In the frame of the ozone SAF algorithms have been developed to track co, ozone, so2, and hno2. These are integrated in the central IASI level 2 PPF and will be disseminated via EumetCast. IASI contributes as well to volcanic ash monitoring. Many trace gas species have been derived from IASI to date. Some important examples were Clarisse et al., 2009, and Stavrakou et al. (2012). A summary of achievements with IASI was provided by Hilton et al. (2012).

The main ASCAT-derived products are the ocean surface winds, which is done by the ocean and sea ice SAF. Products include winds at resolutions of 25 and 12.5 km and high-resolution coastal winds. The hydrology SAF uses the ASCAT data of land and derives soil moisture products.

With the launch of Metop-B in 2012 two satellites are in the mid-morning 9:30 LST (desc. node) orbit. They are phased about 48 min apart which generates overlap zones between adjacent swaths of the instruments over the whole globe.

With the AVHRR imagers these overlap zones are used to derive atmospheric motion vectors over the whole globe (EUMETSAT, 2016o), complementing the polar cap winds derived already over the polar areas. In particular these AMV fill the gap between the geostationary winds and the polar cap winds and provide a positive impact on NWP when assimilated.

Another instrument which is used in tandem operations is GOME-2. As discussed earlier, GOME-2 can be commanded to cover different swath widths at different ground sampling. By combining GOME-2 on Metop-B in nominal mode (swath 1920 km) and Metop-A in higher-resolution mode (swath 960 km) the ozone product can be provided at higher resolution with more detail by combining the information of the two satellite instruments (EUMETSAT, 2016n).

EPS products contribute to climate monitoring. The estimated operational lifetime of about 20 years allows long series of observation data which extend existing data records (e.g., ATOVS or GOME/SCIAMACHY) and also provide new enhanced series (trace gases from IASI, etc.) EPS data are used in the EUMETSAT climate service (EUMETSAT, 2016m).

1.07.4 Concluding Remarks

The EUMETSAT polar system provides since 2006 key observations from space for operational meteorology and climate monitoring. It assures the continuity and also the innovative contribution to the global observation system in the mid morning orbit. With its three Metop satellites, of which two are currently in orbit, and are expected to exceed their design lifetime considerably, more than 20 years of operations can be expected. Metop-C is planned to be launched in Oct. 2018 and will extend the current data coverage beyond 2023, expectations are up to 2028. This will assure the long-term series needed for climate monitoring as well as the overlap with the follow on system EPS-SG, which is currently under development and will assure continuity and innovation to EPS beyond the 2040 timeframe.

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