EUMETSAT Satellite Application Facility on
Support to Operational Hydrology and Water Management

Algorithm Theoretical Baseline Document (ATBD) Surface Soil Moisture ASCAT NRT Orbit

H101, H102, H16, H103, H106, H107

Revision History

Revision	Date	Author(s)	Description
0.1	2015/08/04	S. Hahn	First draft.
0.2	2016/01/19	S. Hahn	Update annex, add product list table.

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1. Executive summary

The Algorithm Theoretical Baseline Document (ATBD) provides a detailed description of the algorithm used to retrieve surface soil moisture information. The concept of the Level 2 surface soil moisture retrieval method developed at the Vienna University of Technology (TU Wien) for use with C-band Scatterometers is a physically motivated change detection method. The first realisation of the concept was based on ERS 1/2 satellite data sets [3, 4, 5, 6] and later the approach was successfully transferred to Advanced Scatterometer (ASCAT) data onboard the METOP-A satellite [7, 8, 9]. The soil moisture retrieval algorithm is implemented within a software package called soil WAter Retrieval Package (WARP) and, for near real-time (NRT) applications, in a software package called WARP NRT. WARP is implemented in IDL, whereas WARP NRT is a software package written in C++. In contrast to WARP, which processes several years of METOP ASCAT Level 1b data and produces both a model parameter database and soil moisture time series, WARP NRT processes single orbits and produces soil moisture in the original Level 1b orbit geometry.

2. Introduction

2.1. Purpose of the document

The Algorithm Theoretical Baseline Document (ATBD) is intended to provide a detailed description of the scientific background and theoretical justification for the algorithms used to produce the METOP ASCAT soil moisture data sets.

2.2. Targeted audience

This document mainly targets:

1. Remote sensing experts interested in the retrieval and error characterization of soil moisture from active microwave data sets.
2. Users of the remotely sensed soil moisture data sets who want to obtain a more in-depth understanding of the algorithms and sources of error.

2.3. Addressed H-SAF soil moisture products

In the framework of the H-SAF project several soil moisture products, with different timeliness (e.g. NRT, offline, data records), spatial resolution, format (e.g. time series, swath orbit geometry, global image) or the representation of the water content in various soil layers (e.g. surface, root-zone), are generated on a regular basis and distributed to users. A list of all available soil moisture products, as well as other H-SAF products (such as precipitation or snow) can be looked up on the H-SAF website[1].

The following Table 2.1 gives an overview of the instances of soil moisture products, which are produced based on this ATBD.

Table 2.1: List of soil moisture products produced based on this ATBD.

ID	Product family	Product Name
H101	SSM ASCAT-A NRT O	Metop-A ASCAT soil moisture 12.5 km sampling NRT
H102	SSM ASCAT-A NRT O	Metop-A ASCAT soil moisture 25 km sampling NRT
H16	SSM ASCAT-B NRT O	Metop-B ASCAT soil moisture 12.5 km sampling NRT
H103	SSM ASCAT-B NRT O	Metop-B ASCAT soil moisture 25 km sampling NRT
H106	SSM ASCAT-A DR O	Metop-A AScAT soil moisture 12.5 km sampling DR1
H107	SSM ASCAT-A DR O	Metop-A AScAT soil moisture 25 km sampling DR1

3. ASCAT on-board METOP

3.1. Introduction

The European contribution within the framework of the Initial Joint Polar System (IJPS) is the EUMETSAT Polar System (EPS). The space segment of the EPS programme is envisaged to contain three sun-synchronous Meteorological Operational Platforms (METOP-A, METOP-B and METOP-C) jointly developed by ESA and EUMETSAT. Each satellite has a nominal lifetime in orbit of about 5 years, with a planned 6 month overlap between consecutive satellites. The first satellite METOP-A, was launched on 19 October 2006, Metop-B was launched on 17 September 2012. Metop-C is planned to be launched approximately in 2018. The Advanced SCATterometer (ASCAT) is one of the instruments carried on-board the series of METOP satellites.

3.2. Instrument description

ASCAT is a real aperture radar system operating in C-Band (VV polarisation) and provides day- and night-time measurement capability, which is unaffected by cloud cover. The instrument design and performance specification is based on the experience of the Scatterometer flown on the ERS-1 and ERS-2 satellite. It can basically work in two different modes: Measurement or Calibration. The Measurement Mode is the only mode that generates science data for users. The instrument

[1] http://hsaf.meteoam.it/

uses a pulse compression method called "chirp", at which long pulses with linear frequency modulation were generated at a carrier frequency of 5.255 GHz. After receiving and de-chirping of the ground echoes, a Fourier transform is applied in order to relate different frequencies in the signal to slant range distances. A pre-processing of the noise and echo measurements is done already on board to reduce the data rate to the ground stations, e.g. various averaging takes place reducing the raw data by a factor of approximately 25. Within each pulse repetition interval, after all pulse echoes have been decayed, the contribution of the thermal noise is monitored in order to perform a measurement noise subtraction during the ground processing. A side effect of on board processing is a degree of spatial correlation between different and within received echoes, but this is taken into account later on by the Level 1b processing. The radar pulse repetition frequency (PRF) is approximately 28.26 Hz, which yields to 4.71 Hz for the beam pulse repetition frequency in the sequence fore-, mid- and aft beam [10].

The Calibration Mode is used during external calibration campaigns (29 days every 13 months), when the platform passes over three different ground transponders located in central Turkey. The objective of such calibration campaigns is to verify that the backscatter measurements from a target is correct for the whole incidence angle range. In other words, the absolute and relative calibration will be monitored and checked. A stable radar cross section and an accurately known position on the Earth's surface are the basic and important requirements for each transponder. After receiving a pulse from ASCAT, the active transponder send a delayed pulse back, which in turn can be recorded by ASCAT. A comparison between the localised transponder position and the expected data allows to estimate three depointing angles and gain correction values for each antenna. An east-west distribution with a displacement of approximately 150 km, will allow to obtain transponder measurements from most of the incidence angles for each antenna beam. This high sampling is necessary in order to reconstruct the characteristics of each antenna gain pattern for the whole incidence angle range and achieve an appropriate relative calibration. Such a calibration set up allows to establish a reference system in order to evaluate and monitor the instrument performance on regular basis [11].

3.3. Geometry and coverage

The METOP satellites are flying in sun-synchronous 29 day repeat cycle orbit with an ascending node at 9:30 p.m. and a minimum orbit height of 822 km. This implies that the satellite will make a little more than 14 orbits per day. The advanced measurement geometry of ASCAT allows twice the coverage, compared to its predecessors flying on ERS-1 and ERS-2. Thus, the daily global coverage increased from 41% to 82%. The spatial resolution was also improved from 50 km to 25 km, still reaching the same radiometric accuracy compared to the ERS-1/2 scatterometer.

The advanced global coverage capability is accomplished by two sets of three fan-beam antennas, compared to only one set at the ERS satellites. The fan-beams are arranged broadside and ±45° of broadside, thus, allowing to observe three azimuthal directions in each of its two 550 km swaths. The swaths are separated from the satellite ground track by about 360 km for the minimum orbit height. Each point on the Earth's surface that falls within one of the two swaths, will be seen by all three antennas and a so-called σ° triplet can be observed. The incidence angles for those two antennas which are perpendicular to the flight direction intersect the surface between 25° and 53.3°, whereas the other four antennas have an incidence angle range from 33.7° to 64.5° [12].

3.4. Product processing

Global data products are often classified into different levels according to their processing progress. In case of ASCAT the different product levels can be summarised as follows:

- Level 0: Unprocessed raw instrument data from the spacecraft. These are transmitted to the ground stations in binary form.
- Level 1a: Reformatted raw data together with already computed supplementary information (radiometric and geometric calibration) for the subsequent processing.
- Level 1b: Calibrated, georeferenced and quality controlled backscatter coefficients in full resolution or spatially averaged. It includes also ancillary engineering and auxiliary data.
- Level 2: Geo-referenced measurements converted to geophysical parameters, at the same spatial and temporal resolution as the Level 1b data.
- Level 3: Geophysical products derived from Level 2 data, which are either re-sampled or gridded points.

The raw data arriving at the ground processing facility are passed into the Level 1 ground processor. This data driven processing chain generates radiometrically calibrated Level 1b backscatter coefficients. It also includes an external calibration processing chain in order to support the localization and normalisation process of the measurement power echoes. Before satellite launch, it is only possible to estimate parameters characterising the expected instrument performance, since some of them depend on in-flight conditions. But once the satellite is his orbit, these parameters can be assessed during a calibration campaign. The first intermediate product generated just before the swath node generation and spatial averaging steps, is called Level 1b full resolution product. The main geophysical parameter in this product is the normalized backscatter coefficient $\sigma°$. Along each antenna beam 256 $\sigma°$ values are projected on the Earth's surface. The footprint size is about 10×20 km of various shapes and orientations, depending on the Doppler pattern over the surface. The radiometric accuracy and the inter-beam radiometric stability is expected to be lass then 0.5 dB peak-to-peak, whereas the georeferencing accuracy is about 4 km. In addition a number of quality flags are computed associated with every individual $\sigma°$ sample along each antenna beam.

The other two products generated within the Level 1b processing are averaged $\sigma°$ values at two different spatial grids. A two-dimensional Hamming window function centered at every grid node is used in both cases for spatial filtering. This weighting function is based on a cosine function, which will basically attenuate the contribution of values with increasing distance. The window width is deciding the magnitude of spatial resolution and which values contribute to the weighted result. This means, values beyond the window width are disregarded. The spatial resolution is then defined as the distance when the window function reaches 50% of its peak intensity. This spatial averaging is used in the along- and across-track direction, with the objective to generate a set of $\sigma°$ triplets for each grid node of each swath at the desired radiometric resolution. The first product generated with this approach is called the nominal product and has a spatial resolution of 50 km for each grid point. The grid spacing is 25 km with 21 nodes at each swath per line. The higher resolution product has a spatial resolution ranging from 25 to 34 km. This variability is the result of a trade-off between spatial resolution and the desired radiometric accuracy, which lead to an alternating Hamming window width across the swath for the different beams. In this case the grid spacing is only 12.5 km, with 41 nodes at each swath per line.

4. TU Wien soil moisture retrieval algorithm

The soil moisture retrieval in near real-time (NRT) follows the same algorithm and underlying assumptions also used for the generation of soil moisture data records in time series format implemented in WARP [1]. The only difference concerns the NRT implementation, where precomputed model parameters are needed for the retrieval of soil moisture.

5. WARP NRT

The software package WARP NRT represents the NRT implementation of the TU Wien soil moisture retrieval algorithm. It is a rather small, batch-mode software system implemented in C++. The spatially averaged METOP ASCAT Level 1b backscatter products are used as input, together with precomputed model parameters. The main output of WARP NRT is surface soil moisture on the same orbit grid as the Level 1b input data set.

WARP NRT's processing architecture is very similar to WARP [1]. The main difference is that WARP re-samples (interpolates) the orbit data to a fixed spatial grid, where the model parameters are stored and also directly applicable, while, conversely, WARP NRT interpolates the parameters to the orbit grid, in order to obtain the soil moisture product in the orbit geometry. This way, the processing becomes quick and robust.

5.1. Processing steps

The following list shows the processing step sequence:

1. Read grid information.
2. Read static parameters.
3. Read Level 1b input file.
4. Check data quality and initialize error flags.
5. Read periodic parameters for the current processing date.
6. Apply azimuthal correction to backscatter measurements.
7. Interpolate model parameters to the orbit grid.
8. Calculate normalized backscatter at θ_{ref} and its noise, set processing and correction flags.
9. Calculate surface soil moisture and its noise, set correction flags.
10. Compute advisory flags related to the probability of snow and frozen soil, wetland percentage and topographic complexity.
11. If there are more Level 1b files to process, go back to step 3.

5.2. Input data

5.2.1. Scatterometer data

The input data used to retrieve surface soil moisture information are backscatter measurements from the Advanced Scatterometer (ASCAT) flown on the METOP series of satellites [12, 10]. ASCAT is a multi-incidence angle radar operating at 5.255 GHz (C-band) at VV polarization. As ASCAT orbits the Earth, it generates two swaths, each yielded by three antenna radar beams looking 45° forward, sideways, and 45° backwards with respect to the satellites' flight direction. These beams illuminate a 500 km-wide swath as the satellite moves along its orbit, and each provides measurements of radar backscatter on a 25 km grid (for nominal, 50 km resolution data) or a 12.5 km grid (for research, 25-34 km resolution data). The result in each swath is three independent backscatter measurements for each grid point, obtained using the three different viewing directions and separated by a short time delay.

5.2.2. Model parameter

In order to retrieve soil moisture from Scatterometer measurements, knowledge about the scattering characteristics of the land surface is required. Scattering parameters which describe these characteristics are derived from multi-annual backscatter time series and stored for each point of a predefined spatial grid in a model parameter database. Some of the parameters such as the slope are periodic (i.e., for each grid point, there is one value of the parameter for each day of the year), while others such as the Estimated Standard Deviation (ESD) are static (i.e., there is only one parameter per grid point). In addition, there are grid parameters determining the spatial structure of the parameters. A detailed description of the model parameters can be found in the soil moisture data record ATBD [1].

5.3. Level 2 output data

The following parameters are part of the Level 2 output data. A more detailed list with data type and data format can be found in the product user manual (PUM) [2].

5.3.1. Surface soil moisture and its noise

The surface soil moisture estimate represents the topmost soil layer (< 5 cm) and is given in degree of saturation, ranging from 0% (dry) to 100% (wet). Degree of saturation [%] can be converted into (absolute) volumetric units $[m^3 m^{-3}]$ with the help of soil porosity information.

$$\theta = p \cdot \frac{sm}{100} \tag{1}$$

where θ is absolute soil moisture $[m^3 m^{-3}]$, p is porosity $[m^3 m^{-3}]$ and sm is degree of saturation [%]. As it can be seen in Equation 1, the accuracy of soil porosity is as much as important as the relative soil moisture content.

An estimate of the uncertainty of soil moisture is given in the parameter soil moisture noise and its unit is degree of saturation [%].

5.3.2. Normalized backscatter coefficients and its noise

Backscatter is measured under various incidence angles. The normalized backscatter coefficient is equivalent to backscatter at a reference incidence angle of 40°. The normalized backscatter is complemented by its noise, derived by error propagation of the backscatter noise (covering instrument noise, speckle and azimuthal effects).

5.3.3. Seasonal variation of slope and its noise

The incidence angle dependency of the backscatter is largely determined by the amount of above ground biomass and by surface roughness. Mathematically, it can be defined with a second order polynomial determined by a slope and a curvature term. The slope term is especially sensitive to vegetation growth and senescence. The slope is complemented by the its noise, derived by error propagation of the backscatter noise (covering instrument noise, speckle and azimuthal effects). More scientific information on the slope parameter can be found in [3].

5.3.4. Sensitivity, dry and wet backscatter reference

The sensitivity of the TU Wien model to measure soil moisture is defined by the difference of the dry and wet backscatter reference values. The dry/wet reference represent the lowest/highest recorded backscatter in history of the data record. Generally, for a given point in time, the sensitivity depends on the amount of above ground biomass. High amounts of biomass result in a low sensitivities to soil moisture. The dry and wet backscatter reference values are complemented by their noise, derived by error propagation of the backscatter noise (covering instrument noise, speckle and azimuthal effects).

5.3.5. Processing, correction and advisory flags

These flags indicate several conditions of interest. Processing flags are set to flag the reason for a soil moisture value not being provided in the product and correction flags are set to flag a soil moisture value provided in the product, but that has been modified after the retrieval for different reasons, according to quality criteria based on the data itself.

In order to support users in judging the quality of the soil moisture products, advisory flags are provided as complementary information advising on the validity of the soil moisture values, according to quality criteria *not* based on the data itself, but on external data sources or predictions.

6. Reference documents

[1] "Algorithm Theoretical Baseline Document (ATBD) Soil Moisture Data Records, METOP ASCAT Soil Moisture Time Series," Tech. Rep. Doc. No: SAF/HSAF/CDOP2/ATBD-SM_ASCAT_DR, v0.1, 2015.

[2] "Product User Manual (PUM) Soil Moisture NRT, METOP ASCAT Soil Moisture Orbit," Tech. Rep. Doc. No: SAF/HSAF/CDOP2/PUM-SM_ASCAT_NRT, v0.1, 2015.

7. References

[3] W. Wagner, G. Lemoine, M. Borgeaud, and H. Rott, "A study of vegetation cover effects on ERS scatterometer data," *IEEE Transactions on Geoscience and Remote Sensing*, vol. 37, no. 2II, pp. 938–948, 1999.

[4] W. Wagner, G. Lemoine, and H. Rott, "A method for estimating soil moisture from ERS scatterometer and soil data," *Remote Sensing of Environment*, vol. 70, no. 2, pp. 191–207, 1999.

[5] W. Wagner, J. Noll, M. Borgeaud, and H. Rott, "Monitoring soil moisture over the canadian prairies with the ERS scatterometer," *IEEE Transactions on Geoscience and Remote Sensing*, vol. 37, pp. 206–216, 1999.

[6] K. Scipal, W. Wagner, M. Trommler, and K. Naumann, "The global soil moisture archive 1992-2000 from ERS scatterometer data: first results," vol. 3, IEEE, 2002, pp. 1399–1401, ISBN: 0-7803-7536-X. DOI: 10.1109/IGARSS.2002.1026129.

[7] Z. Bartalis, W. Wagner, V. Naeimi, S. Hasenauer, K. Scipal, H. Bonekamp, J. Figa, and C. Anderson, "Initial soil moisture retrievals from the METOP-a advanced scatterometer (ASCAT)," *Geophysical Research Letters*, vol. 34, L20401 2007. DOI: 10.1029/2007GL031088.

[8] V. Naeimi, "Model improvements and error characterization for global ERS and METOP scatterometer soil moisture data," PhD dissertation, PhD thesis, Vienna University of Technology, Austria, 2009.

[9] V. Naeimi, K. Scipal, Z. Bartalis, S. Hasenauer, and W. Wagner, "An improved soil moisture retrieval algorithm for ERS and METOP scatterometer observations," *IEEE Transactions on Geoscience and Remote Sensing*, vol. 47, no. 7, pp. 1999–2013, Jul. 2009. DOI: 10.1109/TGRS.2008.2011617.

[10] R. V. Gelsthorpe, E. Schied, and J. J. W. Wilson, "ASCAT – MetOp's Advanced Scatterometer," *ESA Bulletin (ISSN 0376-4265)*, vol. 102, pp. 19–27, 2000.

[11] J. J. W. Wilson, C. Anderson, M. A. Baker, H. Bonekamp, J. F. Saldaña, R. G. Dyer, J. A. Lerch, G. Kayal, R. V. Gelsthorpe, M. A. Brown, E. Schied, S. Schutz-Munz, F. Rostan, E. W. Pritchard, N. G. Wright, D. King, and U. Onel, "Radiometric Calibration of the Advanced Wind Scatterometer Radar ASCAT Carried Onboard the METOP-A Satellite," *IEEE Transactions on Geoscience and Remote Sensing*, vol. 48, pp. 3236–3255, Aug. 2010, ISSN: 0196-2892, 1558-0644. DOI: 10.1109/TGRS.2010.2045763.

[12] J. Figa-Saldana, J. J. W. Wilson, E. Attema, R. Gelsthorpe, M. R. Drinkwater, and A. Stoffelen, "The Advanced Scatterometer (ASCAT) on the Meteorological Operational (MetOp) Platform: A follow on for European Wind Scatterometers," *Canadian Journal of Remote Sensing*, vol. 28, no. 3, pp. 404–412, 2002.

Appendices

A. Introduction to H-SAF

H-SAF is part of the distributed application ground segment of the "European Organization for the Exploitation of Meteorological Satellites (EUMETSAT)". The application ground segment consists of a "Central Application Facilities" located at EUMETSAT Headquarters, and a network of eight "Satellite Application Facilities (SAFs)", located and managed by EUMETSAT Member States and dedicated to development and operational activities to provide satellite-derived data to support specific user communities (see Figure A.1):

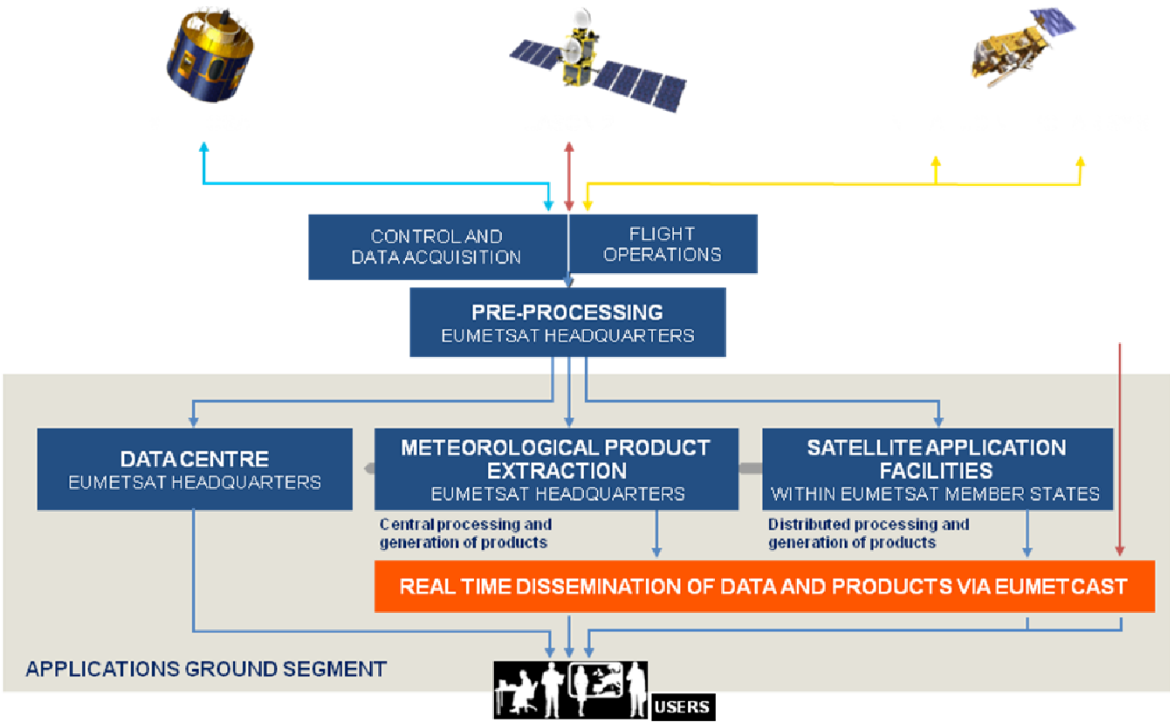

Figure A.1: Conceptual scheme of the EUMETSAT Application Ground Segment.

Figure A.2 here following depicts the composition of the EUMETSAT SAF network, with the indication of each SAF's specific theme and Leading Entity.

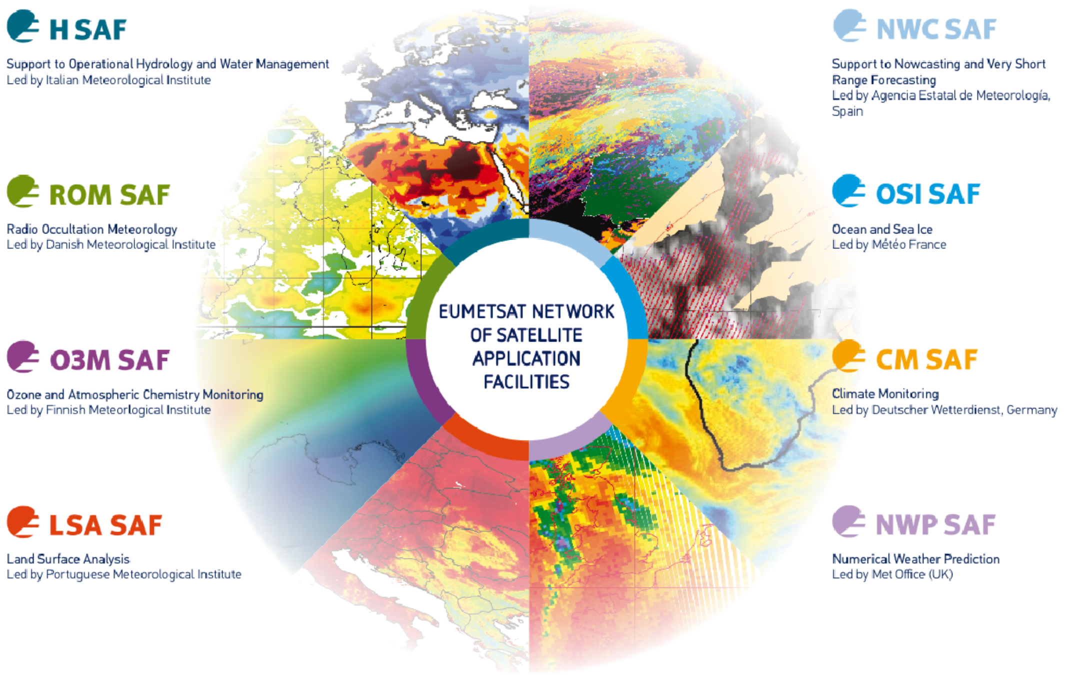

Figure A.2: Current composition of the EUMETSAT SAF Network.

B. Purpose of the H-SAF

The main objectives of H-SAF are:

a) to provide new satellite-derived products from existing and future satellites with sufficient time and space resolution to satisfy the needs of operational hydrology, by generating, centralizing, archiving and disseminating the identified products:

- precipitation (liquid, solid, rate, accumulated);
- soil moisture (at large-scale, at local-scale, at surface, in the roots region);
- snow parameters (detection, cover, melting conditions, water equivalent);

b) to perform independent validation of the usefulness of the products for fighting against floods, landslides, avalanches, and evaluating water resources; the activity includes:

- downscaling/upscaling modelling from observed/predicted fields to basin level;
- fusion of satellite-derived measurements with data from radar and raingauge networks;
- assimilation of satellite-derived products in hydrological models;
- assessment of the impact of the new satellite-derived products on hydrological applications.

C. Products / Deliveries of the H-SAF

For the full list of the Operational products delivered by H-SAF, and for details on their characteristics, please see H-SAF website hsaf.meteoam.it. All products are available via EUMETSAT data delivery service (EUMETCast[2]), or via ftp download; they are also published in the H-SAF website[3].

All intellectual property rights of the H-SAF products belong to EUMETSAT. The use of these products is granted to every interested user, free of charge. If you wish to use these products, EUMETSAT's copyright credit must be shown by displaying the words "copyright (year) EUMETSAT" on each of the products used.

D. System Overview

H-SAF is lead by the Italian Air Force Meteorological Service (ITAF MET) and carried on by a consortium of 21 members from 11 countries (see website: hsaf.meteoam.it for details)

Following major areas can be distinguished within the H-SAF system context:

- Product generation area
- Central Services area (for data archiving, dissemination, catalogue and any other centralized services)
- Validation services area which includes Quality Monitoring/Assessment and Hydrological Impact Validation.

Products generation area is composed of 5 processing centres physically deployed in 5 different countries; these are:

- for precipitation products: ITAF CNMCA (Italy)
- for soil moisture products: ZAMG (Austria), ECMWF (UK)
- for snow products: TSMS (Turkey), FMI (Finland)

Central area provides systems for archiving and dissemination; located at ITAF CNMCA (Italy), it is interfaced with the production area through a front-end, in charge of product collecting. A central archive is aimed to the maintenance of the H-SAF products; it is also located at ITAF CNMCA.

Validation services provided by H-SAF consists of:

- Hydrovalidation of the products using models (hydrological impact assessment);
- Product validation (Quality Assessment and Monitoring).

Both services are based on country-specific activities such as impact studies (for hydrological study) or product validation and value assessment. Hydrovalidation service is coordinated by

[2] http://www.eumetsat.int/website/home/Data/DataDelivery/EUMETCast/index.html
[3] http://hsaf.meteoam.it

IMWM (Poland), whilst Quality Assessment and Monitoring service is coordinated by DPC (Italy): The Services activities are performed by experts from the national meteorological and hydrological Institutes of Austria, Belgium, Bulgaria, Finland, France, Germany, Hungary, Italy, Poland, Slovakia, Turkey, and from ECMWF.