EUMETSAT Satellite Application Facility on
Support to Operational Hydrology and Water Management
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Product User Manual (PUM)

Metop ASCAT Surface Soil Moisture
Climate Data Record v7 12.5 km (H119)
and Extension (H120)

Revision History

Revision	Date	Author(s)	Description
0.1	2021/05/28	TU Wien	First draft based on H115 PUM. Update graphics and product description.
0.2	2022/03/02	TU Wien	Fixed typos, updated sections 1, 2 and updated figures 4.1, 4.3.

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List of Acronyms

ASAR Advanced Synthetic Aperture Radar (on Envisat)

ASAR GM ASAR Global Monitoring

ASCAT Advanced Scatterometer

ATBD Algorithm Theoretical Baseline Document

BUFR Binary Universal Form for the Representation of meteorological data

DORIS Doppler Orbitography and Radiopositioning Integrated by Satellite (on Envisat)

ECMWF European Centre for Medium-range Weather Forecasts

Envisat Environmental Satellite

ERS European Remote-sensing Satellite (1 and 2)

ESA European Space Agency

EUM Short for EUMETSAT

EUMETCast EUMETSAT's Broadcast System for Environment Data

EUMETSAT European Organisation for the Exploitation of Meteorological Satellites

FTP File Transfer Protocol

H SAF SAF on Support to Operational Hydrology and Water Management

Météo France National Meteorological Service of France

Metop Meteorological Operational Platform

NRT Near Real-Time

NWP Near Weather Prediction

PRD Product Requirements Document

PUM Product User Manual

PVR Product Validation Report

SAF Satellite Application Facility

SAR Synthetic Aperture Radar

SRTM Shuttle Radar Topography Mission

SZF Sigma Zero Full resolution

SZO Sigma Zero Operational (25 km spatial sampling)

SZR Sigma Zero Research (12.5 km spatial sampling)

TU Wien Technische Universität Wien (Vienna University of Technology)

WARP Soil Water Retrieval Package

WARP H WARP Hydrology

WARP NRT WARP Near Real-Time

ZAMG Zentralanstalt für Meteorologie und Geodynamic (National Meteorological Service of Austria)

1. Executive summary

The Product User Manual (PUM) describes the Metop ASCAT Surface Soil Moisture (SSM) Climate Data Record (CDR) v7 12.5 km (H119) [2] and extension (H120) [3]. A general introduction of the purpose of this document and a section identifying related surface soil moisture products are described in section 2. The product categories (CDR and offline) and previously released CDR products are discussed in section 3.1, followed by a product description of the Metop ASCAT SSM CDR v7 in section 4. References to technical reports and journal articles are summarized at the end of the document.

The Metop ASCAT SSM CDR products are consistent data records based on the latest version of the EUMETSAT H SAF TU Wien soil moisture retrieval algorithm described in the Algorithm Theoretical Baseline Document (ATBD) [4]. In order to provide a consistent extension to the CDR, offline SSM products are generated until a new CDR supersedes the previous CDR. A validation of the present Metop ASCAT SSM CDR can be found in the Product Validation Report (PVR) [5].

2. Introduction

2.1. Purpose of the document

The Product User Manual (PUM) is intended to provide a description of the main product characteristics, parameters, format and availability. Although reasonably self-standing, the PUM's rely on other documents for further details. Specifically:

- Algorithm Theoretical Baseline Document (ATBD) [4], for extensive details on the algorithms, only highlighted here.
- Product Validation Report (PVR) [5], for a full recount of the validation activity, both the evolution and the latest results.

2.2. Targeted audience

This document mainly targets:

- Users of the remotely sensed soil moisture data sets.

2.3. Related products

Various soil moisture products with different timeliness (e.g. NRT, offline, data records), spatial resolution (1-50 km), format (e.g. time series, swath orbit geometry) and 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 by H SAF. A list of all available soil moisture products, as well as other H SAF products (such as precipitation or snow) can be found on the H SAF website http://h-saf.eumetsat.int/.

3. Climate Data Record and Extension

SAF products are categorized according to their availability and timeliness. Three main product categories exist: Near Real-Time (NRT), Data Record (DR) and Offline products. Each SAF product belongs to a certain category and is tagged with a product status. The status reflects the scientific maturity and operational readiness of the product. Each product will go through a pre-defined review-cycle depending on its product category.

3.1. Product category and status

The Metop ASCAT Surface Soil Moisture (SSM) Climate Data Record (CDR) products are consistent data sets and belong to the group of Thematic Climate Data Records (TCDR). A TCDR typically represents a geophysical variable associated with GCOS Essential Climate Variables based on a Fundamental Climate Data Record (FCDR). A FCDR is considered to be a single sensor type re-calibrated and inter-satellite calibrated Level 1 data set, such as the ASCAT Level 1b backscatter FCDR. The product stages of a CDR is given in the following listing:

- In development: product is under development and not available to users
- Demonstration: product is delivered to users without any commitment on the quality and availability
- Released: product that is made available to users, satisfying largely the applicable requirements, with documented characteristics, validations results and limitations

It is foreseen to process a new SSM CDR each year based on the latest version of the EUMETSAT H SAF TU Wien soil moisture retrieval algorithm. Hence, depending on the version of the algorithm and the version of the Metop ASCAT Level 1b backscatter data, the soil moisture values for each CDR can be different. In addition, each CDR is based on empirical model parameters computed as part of the soil moisture retrieval algorithm and therefore yet another reason why each SSM CDR is unique.

The Metop ASCAT Surface Soil Moisture (SSM) Climate Data Record (CDR) Extension products represent continuations of the Metop ASCAT SSM CDR products. A CDR is a self-contained data set, i.e. it cannot be manipulated retrospectively or updated. This is the reason why the SSM CDR Extension data sets are offline products, since they can be generated continuously without the previously mentioned limitations of a CDR. Technically, an offline product is the same as a NRT product, although not as timely. Offline products are typically updated on a weekly, monthly or yearly basis. In order to nominate an offline (or NRT) product an extension of a CDR, it is important to use the same version of algorithm, software and input data to be able to produce a compliant and consistent continuation. The processing of an offline product is maintained until a new CDR is released, which will supersede the previous CDR and its extension. The product stages of an offline product is given in the following listing:

- In development: product is under development and not available to users
- Demonstration: product is delivered to users without any commitment on the quality and availability

- Pre-operational: product with documented limitations that is able to satisfy the majority of applicable requirements
- Operational: product with documented limitations that largely satisfy the requirements and level of maturity to be distribution to users
- Superseded: product that has been (pre-)operationally provided to users, which is no longer the case because the information of the same or superior quality and/or coverage is provided with another product
- Discontinued: product that has been previously (pre-)operationally provided to users but is not (pre-)operational anymore

3.2. Released products

It is recommended to use the latest released Metop ASCAT SSM CDR, which is based on the most recent version of the EUMETSAT H SAF TU Wien soil moisture retrieval algorithm. Table 3.1 and 3.2 shows all released Metop ASCAT SSM CDR products and extensions to users.

Table 3.1: List of available Metop ASCAT SSM CDR products.

CDR	Satellite	ATBD	PVR	Temporal coverage
H25 [6]	Metop-A	[7]	[8]	2007-01-01 – 2014-12-31
H109 [9]	Metop-A,-B	[10]	[11]	2007-01-01 – 2015-12-31
H111 [12]	Metop-A,-B	[10]	[13]	2007-01-01 – 2016-12-31
H113 [14]	Metop-A,-B	[15]	[16]	2007-01-01 – 2017-12-31
H115 [17]	Metop-A,-B	[18]	[19]	2007-01-01 – 2018-12-31
H119 [2]	Metop-A,-B,-C	[4]	[5]	2007-01-01 – 2020-12-31

Table 3.2: List of available Metop ASCAT SSM CDR Extension products.

Extension	CDR	Temporal coverage
H108 [20]	H25	2015-01-01 – 2015-06-30
H110 [21]	H109	2016-01-01 – 2016-07-31
H112 [22]	H111	2017-01-01 – 2017-11-01
H114 [23]	H113	2018-01-01 – 2018-12-31
H116 [24]	H115	2019-01-01 – 2021-12-31
H120 [3]	H119	2021-01-01 – ongoing

4. Metop ASCAT Surface Soil Moisture CDR v7 12.5 km

4.1. Lineage

The Metop ASCAT Surface Soil Moisture (SSM) Climate Data Record (CDR) v7 12.5 km product (H119) is based on Metop-A, -B, -C Level 1b backscatter products with 12.5 km spatial sampling. For the time period 2007-01-01 until 2014-03-30 the Metop-A Level 1b Fundamental Climate Data Record (FCDR) [25] is used and combined with archived Metop-A Level 1b NRT product from 2014-04-01 until 2020-12-31 [26]. In case of Metop-B (2013-01-01 until 2020-12-31) and Metop-C (2019-04-01 until 2020-12-31), the Level 1b NRT product has been used [26]. The empirical model parameters generated during the retrieval of surface soil moisture have been derived from Metop-A, -B and -C together. Further input data sets used to generate the Metop ASCAT SSM CDR v7 are the Köppen Geiger Climate Classification [27] and land surface temperature from ERA5 [28].

The EUMETSAT H SAF TU Wien soil moisture retrieval algorithm [4], [29], [30] is used to derive relative surface soil moisture information and represents a physically based change detection method. Long-term backscatter measurements are used to model the incidence angle dependency of backscatter, which allows to normalize backscatter to a common reference incidence angle. The relative surface soil moisture estimates range between 0% (completely dry) and 100% (completely saturated and are derived by scaling the normalized backscatter between the lowest/highest backscatter values corresponding to the driest/wettest soil conditions. Soil moisture is represented in degree of saturation, but can be translated from relative (%) to absolute volumetric units (m^3m^{-3}) using porosity information (see Equation 1). Figure 4.1 shows mean surface soil moisture condition for 2007-2020 derived from Metop ASCAT SSM CDR v7 expressed in degree of saturation.

The retrieval algorithm is implemented in a Python software package called soil WAter Retrieval Package (WARP). In practice, the latest Metop ASCAT Level 1b Fundamental Climate Data Record (FCDR) and the latest operational Level 1b data are manually combined to a common Level 1 data set. Except for the surface temperature data (used for deriving the Surface State Flag (`SSF`)) and a static climate classification map (used for the determination of the wet correction), no external data is required for the soil moisture retrieval. A detailed description of the retrieval algorithm together with a description of the derivation of the model parameters can be found in the Algorithm Theoretical Baseline Document (ATBD) [4]. The ASCAT Product Guide [31] contains an overview of the ASCAT instrument and product configuration.

The following changes have been introduced with respect to the previous Metop ASCAT SSM CDR v6 (H115) [17].

- Derivation of new empirical model parameters
- Add Metop-C ASCAT Level 1b product
- Introducing spatially-variable cross-over angles [32]
- Increasing threshold of masking backscatter observations affected by water bodies during resampling

4.2. Parameters

The soil moisture CDR and offline products are composed of several parameters (geophysical parameters, flags, geo-location information, auxiliary parameters, etc.). The following subsections give an overview of all relevant parameters and flags.

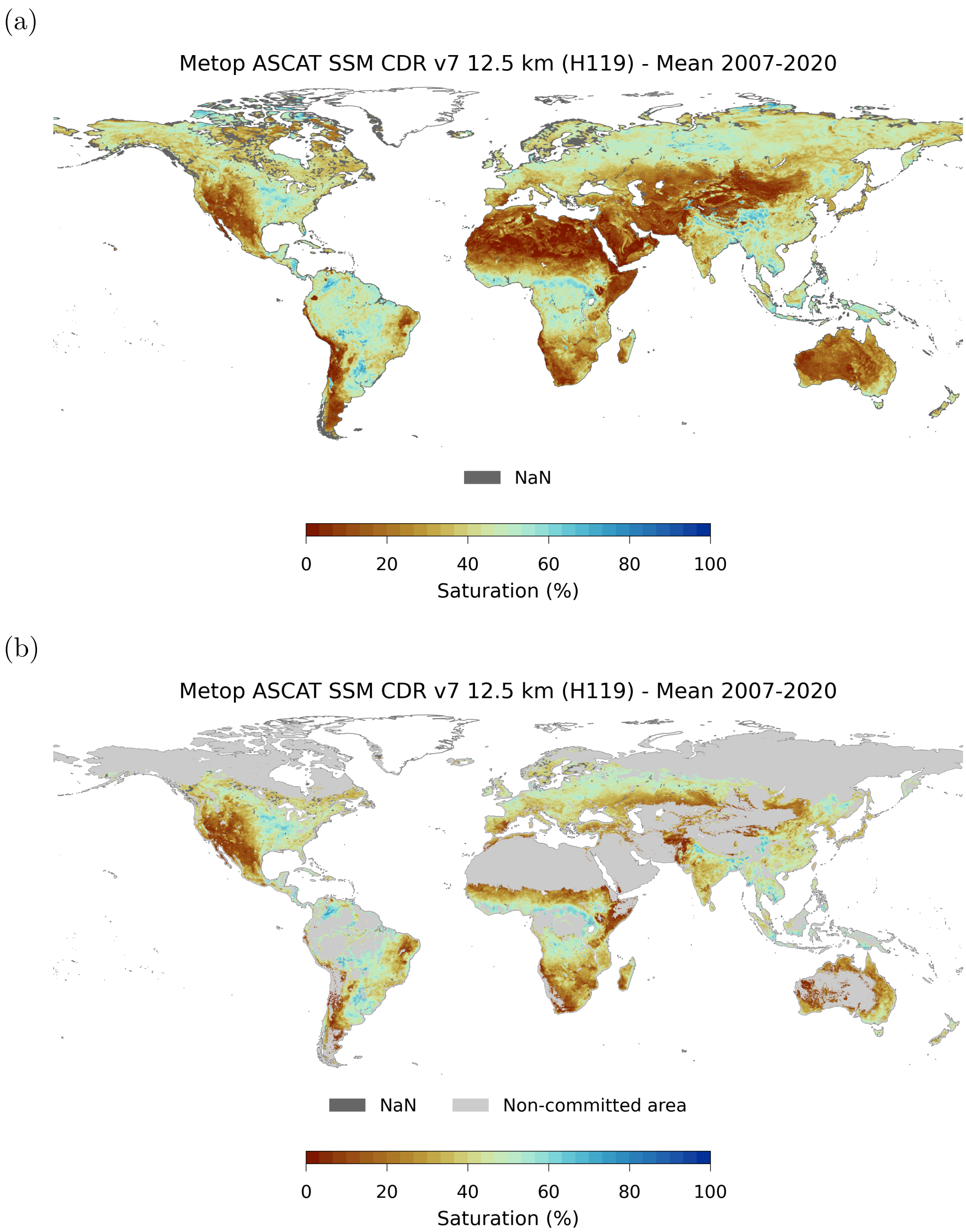


Figure 4.1: Mean surface soil moisture from Metop ASCAT SSM CDR v7 for the period 2007-2020 globally (a) and for the committed area only (b).

4.2.1. Soil moisture

Soil moisture The soil moisture information provided in the Metop ASCAT SSM CDR product represents relative surface soil moisture (SM) of the topmost soil layer (< 5 cm). The soil moisture values are given in degree of saturation ranging from 0% (completely dry) to 100% (fully saturated). Degree of saturation expresses the water volume present in the soil relative to the pore volume and can be converted into (absolute) volumetric units m^3m^{-3} with the help of soil porosity information. If the exact amount of residual water content is also known, it can be used to adjust the absolute soil moisture content.

$$\Theta = \Theta_r + p \cdot \mathtt{SM}/100 \tag{1}$$

where Θ is absolute soil moisture in m^3m^{-3}, p is porosity in m^3m^{-3} and Θ_r the residual water content in m^3m^{-3}. As it can be seen in Equation 1, the quality and representativness of soil porosity is important for the translation to absolute soil moisture content.

Soil moisture noise In addition to soil moisture, an estimation of the uncertainty is also provided in the SSM CDR and offline products. The soil moisture noise (`SM_NOISE`) is computed based on error propagation in the soil moisture retrieval algorithm. The uncertainty, i.e. `SM_NOISE`, is quantified in terms of the standard deviation and therefore also provided in degree of saturation (%). It is important to understand that not each error source is being described by the error model, e.g. the impact of frozen or snow covered soil are difficult to quantify. For these circumstance, additional information is needed on the soil state (see Product flags 4.2.3) in order to mask affected soil moisture measurements.

Table 4.1: Overview of soil moisture parameters.

Name	Scaling factor	Units	Type	Byte size	NaN value
`SM`	10^{-2}	%	uint16	2	65535
`SM_NOISE`	10^{-2}	%	uint16	2	65535

4.2.2. Geo-location and satellite parameters

Location ID The location id (`LOCATION_ID`) is a unique identifier for a single grid point (GP). It is also often referred to as Grid Point Index (GPI). The position of a grid point can be queried using the online DGG locator tool[1].

Row size The number of observations per grid point is indicated by the row size (`ROW_SIZE`) or, in other words, the length of the time series per grid point. This parameter is needed to extract the time series of a certain grid point.

Latitude The latitude (`LATITUDE`) position of the grid point in degrees north.

Longitude The longitude (`LONGITUDE`) position of the grid point in degrees east.

Time The time parameter (`TIME`) represents the time stamp for the measurements. It is defined as the fraction of days since 1900-01-01 00:00:00 UTC (e.g. 1900-01-01 00:00:00 UTC + 39081.2494791667 = 2007-01-01 05:59:15 UTC).

[1] https://dgg.geo.tuwien.ac.at/

Orbit direction The orbit direction (DIR) indicates the movement of the spacecraft through the plane of reference. The ascending direction (DIR=0) represents a movement north through the plane of reference, and the descending (DIR=1) south through the plane of reference. Metop satellites are flying in a sun-synchronous 29-day repeat cycle orbit with an equator crossing Local Solar Time (LST) of 09:30 a.m. and p.m. in descending and ascending nodes, respectively.

Satellite id The satellite id (SAT_ID) represents the sensor's platform identification (Metop-A=3, -B=4, -C=5).

Table 4.2: Overview of geo-location and satellite parameters.

Name	Scaling factor	Units	Type	Byte size	NaN value
LOCATION_ID	-	-	int64	8	-
ROW_SIZE	-	-	int64	8	-
LATITUDE	-	Degrees North	float32	4	-
LONGITUDE	-	Degrees East	float32	4	-
TIME	-	Fraction of days	float64	8	-
DIR	-	-	int8	1	127
SAT_ID	-	-	int8	1	127

4.2.3. Flags

The product flags indicate various conditions of interest advising the user on the quality and validity of the soil moisture observations. The flags provide an initial assistance on the usability and shall not prevent the usage of external data sets for masking soil moisture observations.

Table 4.3: Product flags.

Name	Scaling factor	Units	Type	Byte size	NaN value
SSF	-	-	int8	1	127
CONF_FLAG	-	-	uint8	1	255
CORR_FLAG	-	-	uint8	1	255
PROC_FLAG	-	-	uint8	1	255

Surface state flag The surface state flag (SSF) indicates the surface conditions: unknown, unfrozen, frozen, temporary (snow-)melting/water on the surface or permanent ice. The flag should be used to filter invalid soil moisture observations, since a screening has not been performed in advance. This way, users have full control of the masking and can decide on their own in a borderline case (e.g. during freeze/thaw transition periods). If land surface temperature data is available in the study area, it is recommended to combine this information with the SSF.

The retrieval of SSF is based on a logistic regression function and decision trees using temperature and backscatter data [33]. The SSF represents only the top soil layer and performs best during summer and winter periods. During transition periods and in areas with less frequent freezing the quality of the SSF deteriorates. In the latter case the relationship between negative temperature and backscatter can be no longer accurately modeled.

Table 4.4: Surface state flag meaning.

Flag value	Flag meaning
0	Unknown
1	Unfrozen
2	Frozen
3	Temporary (snow-)melting/water on the surface
4	Permanent ice
127	NaN

Confidence flag The confidence flag (CONF_FLAG) provides advise on the validity of the soil moisture observations. In case of problematic surface conditions (e.g. frozen soil, mountainous terrain, wetland) and/or high measurement uncertainty, the flag indicates unreliable soil moisture observations. The CONF_FLAG is provided as decimal number and needs to be converted into binary representation, in order to check which bit has been set. For example, CONF_FLAG=23 translates to 00010111 meaning that 1-3 bits and 5 bit are set.

The 1 bit is raised if SSF is set to 2, 3 or 4. The 2 bit is set in case of a high topographic complexity. The topographic complexity is computed as the normalized standard deviation of elevation using GTOPO30 data. The 3 bit indicates if fraction coverage of inundated and wetland areas derived from a combined analysis of the Global Lakes and Wetlands Database (GLWD) Level 3 product and the Global Self-consistent, Hierarchical, High-resolution Shoreline Database GSHHS (v1.5) is higher than 50%. The 4 bit is raised if soil moisture noise is higher than 50%. The 5 bit indicates if the sensitivity (i.e. the difference between wet and dry reference) is less than 1 dB. The 6 and 7 bit are reserved for future use. If all bits are set, the flag is invalid.

Table 4.5: Confidence flag meaning.

Bit	Meaning
1	Bad surface state flag
2	Topographic complexity > 50%
3	Wetland > 50%
4	Soil moisture noise > 50%
5	Sensitivity of soil moisture < 1 dB
6	Reserved for future use
7	Reserved for future use
1-8	NaN

Processing flag The processing flag (PROC_FLAG) explains the reason why a soil moisture value is set to Not a Number (NaN) in the product. The PROC_FLAG is provided as decimal number and needs to be converted into binary representation, in order to check which bit has been set.

For example, PROC_FLAG=4 translates to 00000100 meaning that the 3 bit is set. The 1 and 2 bit indicate that soil moisture was out of bounds and the 3 bit show that either backscatter or the dry and wet reference are not valid. If all bits are set, the flag is invalid.

Table 4.6: Processing flag meaning.

Bit	Meaning
1	Original soil moisture lower than -25%
2	Original soil moisture larger than 125%
3	Backscatter is out of limits or dry/wet reference is not valid
4	Reserved for future use
5	Reserved for future use
6	Reserved for future use
7	Reserved for future use
1-8	NaN

Correction flag The correction flag (CORR_FLAG) indicates that the soil moisture value has been modified. The CORR_FLAG is provided as decimal number and needs to be converted into binary representation, in order to check which bit has been set. For example, CORR_FLAG=1 translates to 00000001 meaning that the 1 bit is set. The 1 and 2 bit are raised if soil moisture was corrected to 0% or 100%, respectively. The 3 bit is raised when a wet correction was applied. In some regions truly saturated conditions are very rare due to the prevailing climate (e.g. deserts). Hence, a correction needs to be applied simulating wet conditions allowing to estimate a real or better wet reference. The application of the wet correction is based on an external climate data set [27], since scatterometer measurements alone are not sufficient to locate these regions. The wet correction is done in two steps: first the lowest level of the wet reference is set to -10 dB and subsequently, raised until a sensitivity (i.e. the minimum difference between the wet and dry backscatter reference) of at least 5 dB has been reached [34]. If all bits are set, the flag is invalid.

Table 4.7: Correction flag meaning.

Bit	Meaning
1	Original soil moisture between -25% and 0%, but set to 0%
2	Original soil moisture between 100% and 125%. but set to 100%
3	Wet correction applied
4	Reserved for future use
5	Reserved for future use
6	Reserved for future use
7	Reserved for future use
1-8	NaN

Table 4.8: Overview of auxiliary parameters.

Name	Scaling factor	Units	Type	Byte size	NaN value
SIGMA40	10^{-2}	dB	int16	2	32767
SIGMA40_NOISE	10^{-2}	dB	uint16	2	65535
SLOPE40	10^{-3}	dB/degree	int16	2	32767
SLOPE40_NOISE	10^{-5}	dB/degree	uint16	2	65535

4.2.4. Auxiliary information

Backscatter at 40 degree Backscatter normalized to an incidence angle of 40 degree (in dB) (`SIGMA40`). Backscatter at 40 degree is scaled between the dry and wet backscatter reference in order to compute surface soil moisture information [4].

Backscatter at 40 degree noise An estimation of uncertainty of backscatter at 40 degree incidence angle (in dB) (`SIGMA40_NOISE`) based on propagation of uncertainty.

Slope at 40 degree The first derivative of the relationship between incidence angle and backscatter at 40 degree (in dB/degree) (`SLOPE40`). The slope parameter is used for the incidence angle normalization of backscatter and for the computation of the dry and wet backscatter reference.

Slope at 40 degree noise An estimation of uncertainty of slope at 40 degree incidence angle (in dB/degree) (`SLOPE40_NOISE`) based on propagation of uncertainty.

4.3. Spatial resolution and sampling

The spatial resolution of the Metop ASCAT SSM CDR and extension products is 25-34 km × 25-34 km and defined by the spatial resolution of the Level 1b input product. A trade-off between spatial resolution and radiometric accuracy was necessary in the processing of the Level 1b product by applying a variable filter width. Thus, the spatial resolution of the Level 1b ranges from 25 km in the near swath to 34 km in the far swath. More information on the Level 1b averaging and processing can be found in the ASCAT product guide [31].

The spatial sampling is defined by the WARP 5 grid, which represents a Discrete Global Grid (DGG) with a fixed spacing of 12.5 km in longitudinal and latitudinal direction. The WARP 5 grid consists of 3264391 grid points, but only 839826 gird points are over land and can possibly contain data. The location of the grid points are stored in an auxiliary file available on the H SAF FTP (`TUW_WARP5_grid_info_<version>.nc`). An interactive tool, the so-called DGG Point Locator[2] can be used to search for specific grid points.

4.4. Temporal resolution and sampling

The temporal resolution of the Metop ASCAT SSM CDR and extension products represents instantaneous observations. No temporal filtering or averaging has been applied to the surface

[2] https://dgg.geo.tuwien.ac.at/

soil moisture estimates, i.e. the time stamp from the original Level 1 observation remains unchanged.

The temporal sampling is defined by the number of Metop satellites and latitude. The following Figure 4.2 shows exemplary the coverage of ASCAT for one, two and three Metop satellites within 24 hours.

4.5. Application, limitation and caveats

The soil moisture retrieval algorithm is most suited under following conditions: (i) low to moderate vegetation regimes, (ii) unfrozen and no snow, (iii) low to moderate topographic variations and (iv) no wetlands and coastal areas. Still, the Metop ASCAT SSM CDR product is globally available for all grid points over land. Therefore, users have to decide about masking inaccurate soil moisture values using the enclosed advisory and quality flags (see section 4.2.3), as well as their expert knowledge about the study area. Users are also advised to use the best and most accurate auxiliary data available improving the filtering and masking procedure. As soon as, dense forest, snow cover, frozen soil, open water or topographic complex area are dominating the instrument footprint, the retrieval of soil moisture becomes inaccurate or even impossible. Furthermore, it is important to understand that the error model is not able to describe all error sources, specifically frozen soil, snow and wetland. In such cases, the noise estimation is not reliable.

Depending on the application of the Metop ASCAT SSM CDR product users can decide themselves about the flags and thresholds used in the procedure of filtering and masking inaccurate soil moisture values, e.g. [35], [36]. More details and the influence of the different error sources are discussed in the Algorithm Theoretical Baseline Document (ATBD) [4].

4.6. Validation

The Metop ASCAT SSM CDR v7 has been validated using the Noah GLDAS data set [37] and the ESA CCI passive soil moisture data set (v4.5). As described in the Product Validation Report (PVR) [5], after quality checking and masking the SSM CDR, a temporal and spatial matching has been carried out. The following flags and thresholds have been used to mask inaccurate soil moisture: (i) soil temperature $< 4°$ Celsius, (ii) snow water equivalent (SWE) $<$ 0 kg m^{-2} and (iii) surface state flag (SSF) > 1. The Pearson Correlation Coefficient and the Signal-to-Noise Ratio (SNR) (using Triple Collocation) were computed as quality benchmarks between the collocated data sets.

The validation has been performed globally, but the evaluation mainly targets the so-called committed area. This area represents a restricted geographical region with high confidence in the successful retrieval of surface soil moisture and is limited to: (i) low and moderate vegetation regimes, (ii) unfrozen and no snow cover, (iii) low to moderate topographic variations, as well as (iv) no wetlands and coastal areas (see Figure 4.3). More information about the products requirements can be found in the Product Requirements Document (PRD) [38]).

The validation results indicate an acceptable performance for the committed product area (see Figure 4.4). On a global scale, a lower performance of the Metop ASCAT SSM CDR v7 can be found in areas with low soil moisture dynamics (e.g. deserts) or at higher latitudes. In the latter case, frozen soil and snow cover are the main reason why many measurements needs to be masked. Therefore, in these regions only summer months can be used for validation.

(a)

(b)

(c)

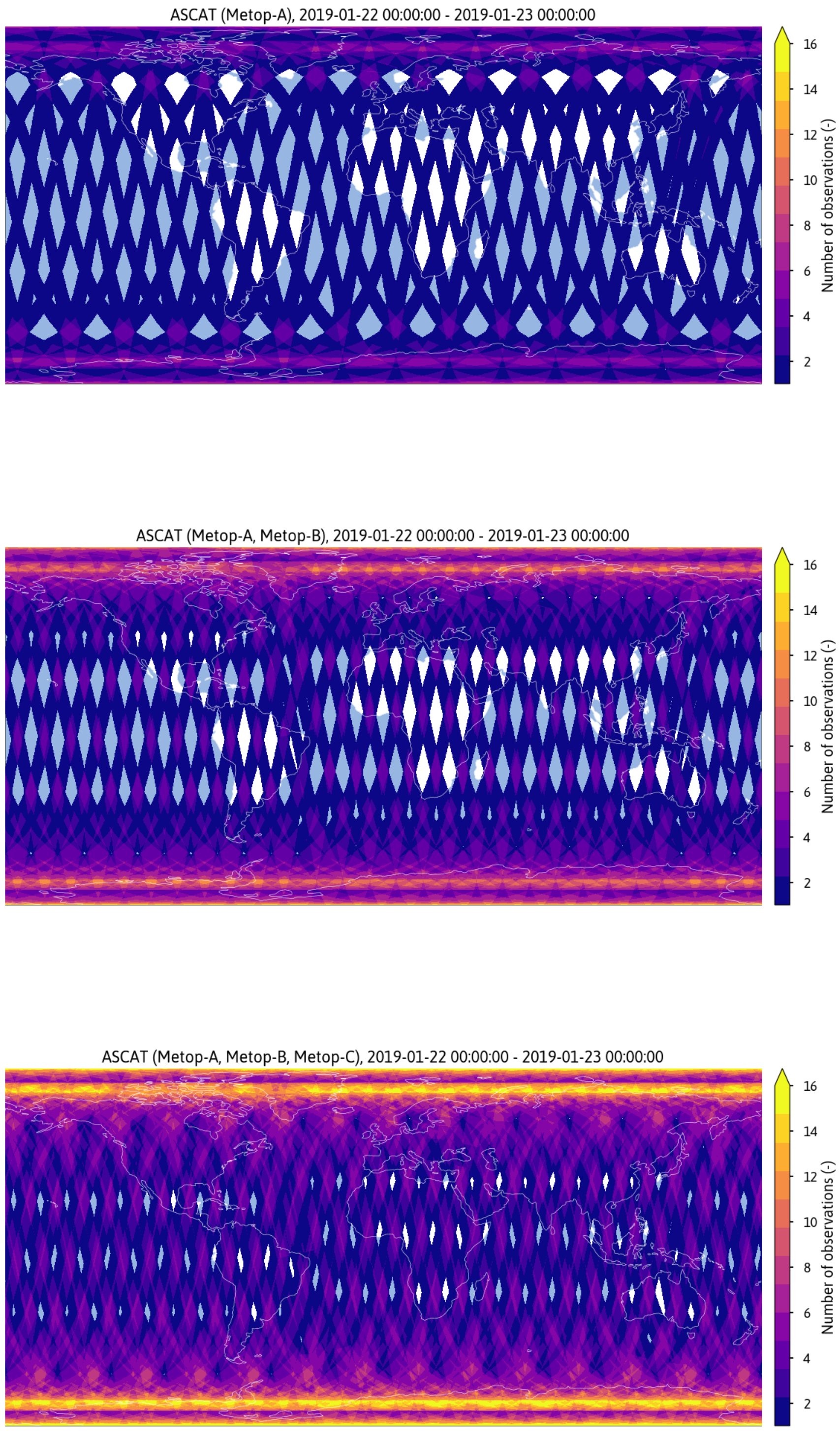


Figure 4.2: Number of ASCAT observations within 24 hours for one (a), two (b) and three (c) Metop satellites.

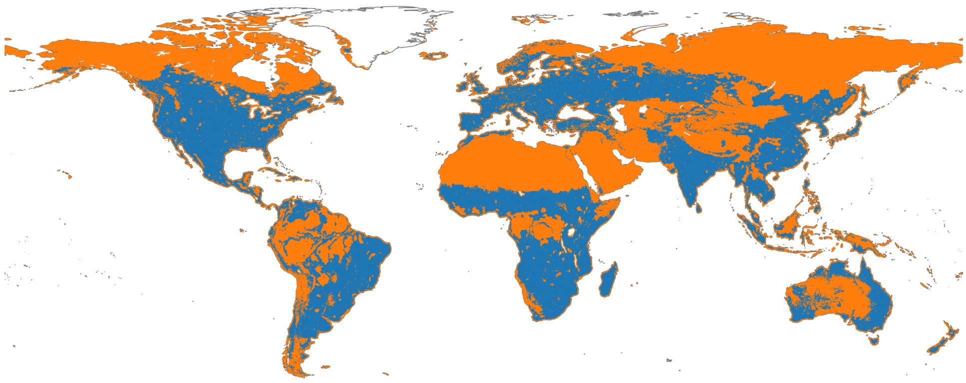


Figure 4.3: Map showing the committed product area.

More detailed information about the validation can be found in the Product Validation Report (PVR) [5].

4.7. File format

The CDR and offline products are provided in NetCDF and follow the Climate and Forecast (CF) Metadata Conventions v1.6 [39]. The time series representation of the CDR and offline products is organized in cells. A cell contains a number of grid points stored as NetCDF file (<hsaf_identifier>_<cell_nr>.nc). This way, the two extreme cases will be avoided: (i) one file per grid point and (ii) one file for all grid points. A cell is defined as $5° \times 5°$ and contains up to 2000 grid points. The cell number and the number of grid points per cell are shown in Figure 4.5. A look-up table between grid point index (GPI) and cell number, longitude and latitude is provided in an auxiliary file (TUW_WARP5_grid_info_<version>.nc) available on the H SAF FTP.

The time series are stored in the contiguous ragged array representation defined by the NetCDF Climate and Forecast (CF) Metadata Conventions [39]. The time series parameters (like `SM` and `SM_NOISE`) are associated with the coordinate values `time(obs)`, `lat(i)` and `lon(i)`, where `i` indicates the grid point time series. The time series `i` comprises the following data elements:

```
row_start(i) to row_start(i) + row_size(i)-1
```

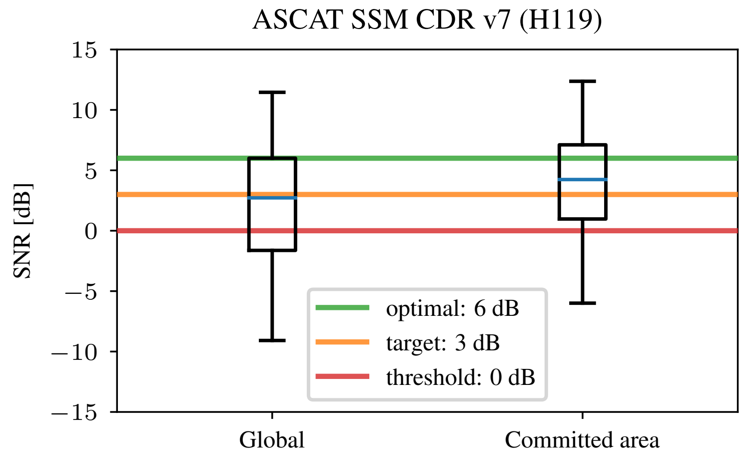
where

```
row_start(i) = 0 if i = 0
```

```
row_start(i) = row_start(i-1) + row_size(i-1) if i > 0
```

The variable `row_size` is the count variable containing the length of each time series feature along with an attribute named *sample_dimension* which holds the name of the sample dimension (*obs* in this case). The auxiliary location parameters `lat` and `lon` are GPI variables.

(a)



(b)

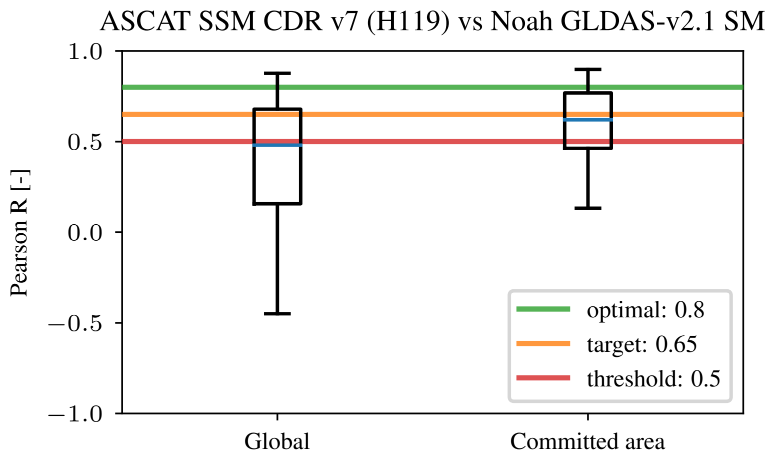


Figure 4.4: The boxplots indicate the distribution of the quality benchmarks globally and just for the committed area. A percentage of locations exceeding each of the three thresholds is indicated as well.

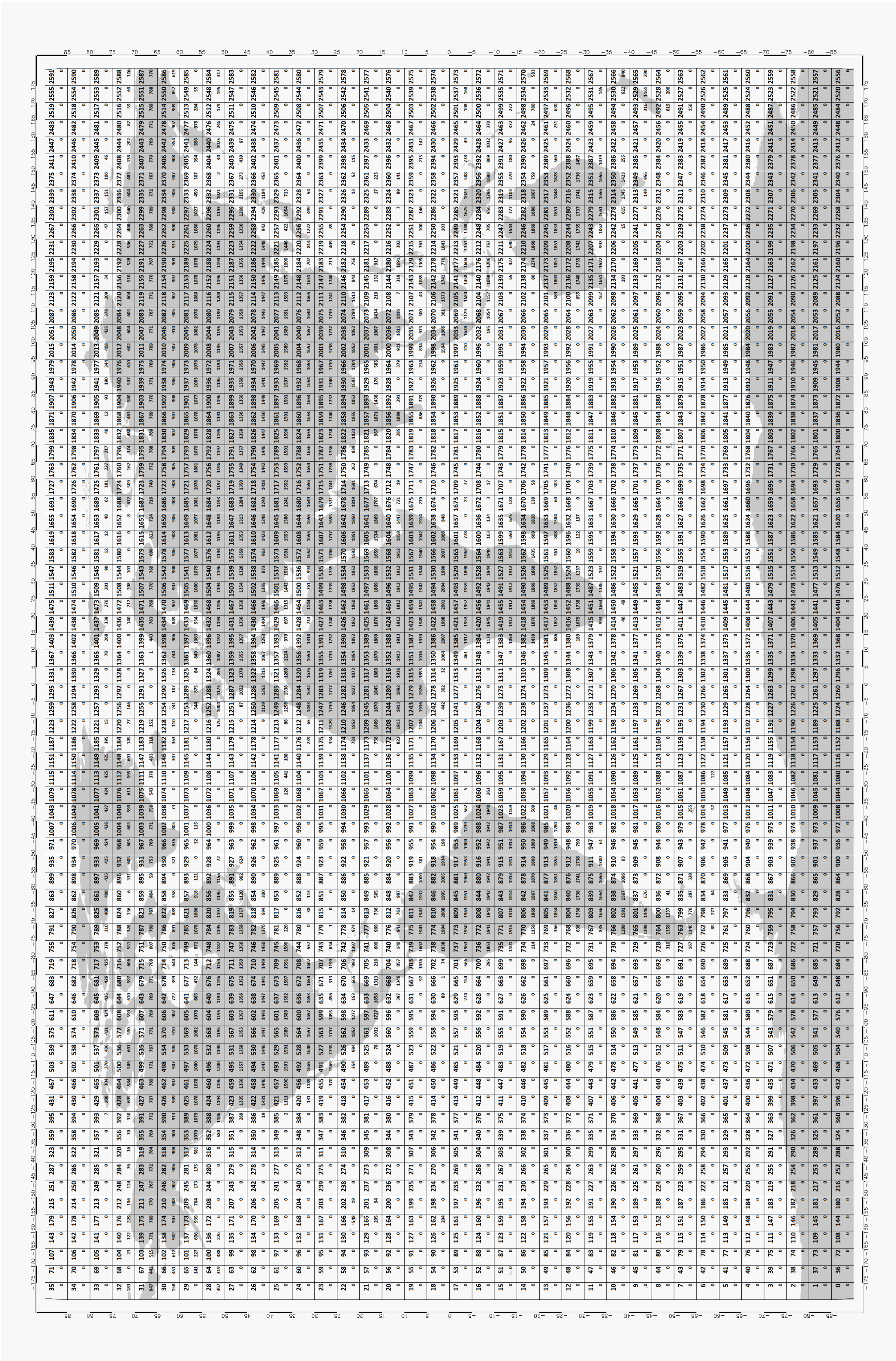


Figure 4.5: 5° × 5° cell partitioning of the grid points. The upper number in each cell represents the cell number and the lower number the number of grid points in this cell.

An example of the NetCDF variables is shown in Listing 1. The NetCDF can be read using the ascat[3] Python package or older versions of the pytesmo[4] Python package. The following Figure 4.6 shows a time series example.

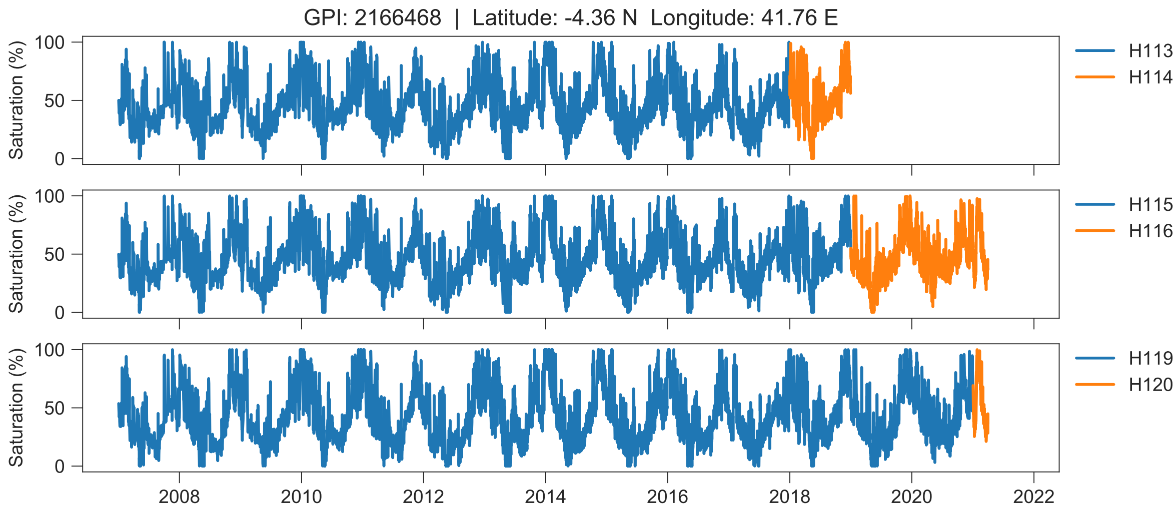


Figure 4.6: Example of surface soil moisture time series from various SSM CDR.

[3] https://github.com/TUW-GEO/ascat
[4] https://github.com/TUW-GEO/pytesmo

Listing 1: Example of NetCDF variables and dimension for cell 28.

```
dimensions:
        locations = 436 ;
        obs = UNLIMITED ; // (6207877 currently)
variables:
        int64 row_size(locations) ;
                row_size:long_name = "number of observations at this location" ;
                row_size:sample_dimension = "obs" ;
        float lon(locations) ;
                lon:standard_name = "longitude" ;
                lon:long_name = "location longitude" ;
                lon:units = "degrees_east" ;
                lon:valid_range = -180., 180. ;
        float lat(locations) ;
                lat:standard_name = "latitude" ;
                lat:long_name = "location latitude" ;
                lat:units = "degrees_north" ;
                lat:valid_range = -90., 90. ;
        float alt(locations) ;
                alt:standard_name = "height" ;
                alt:long_name = "vertical distance above the surface" ;
                alt:units = "m" ;
                alt:positive = "up" ;
                alt:axis = "Z" ;
        int64 location_id(locations) ;
        string location_description(locations) ;
        double time(obs) ;
                time:standard_name = "time" ;
                time:long_name = "time of measurement" ;
                time:units = "days since 1900-01-01 00:00:00" ;
        float sm(obs) ;
                sm:name = "sm" ;
                sm:coordinates = "time lat lon" ;
                sm:long_name = "soil moisture" ;
                sm:units = "percentage" ;
                sm:scale_factor = 0.01f ;
                sm:valid_range = 0US, 10000US ;
                sm:missing_value = 65535US ;
        float sm_noise(obs) ;
                sm_noise:name = "sm_noise" ;
                sm_noise:coordinates = "time lat lon" ;
                sm_noise:long_name = "soil moisture noise" ;
                sm_noise:units = "percentage" ;
                sm_noise:scale_factor = 0.01f ;
                sm_noise:valid_range = 0US, 10000US ;
                sm_noise:missing_value = 65535US ;
        byte dir(obs) ;
                dir:name = "dir" ;
                dir:coordinates = "time lat lon" ;
                dir:long_name = "orbit direction" ;
                dir:flag_values = 0b, 1b ;
                dir:flag_meanings = "ascending descending" ;
                dir:valid_range = 0b, 1b ;
                dir:missing_value = 127b ;
        byte ssf(obs) ;
                ssf:name = "ssf" ;
```

```
        ssf:coordinates = "time lat lon" ;
        ssf:long_name = "surface state flag" ;
        ssf:flag_values = 0b, 1b, 2b, 3b, 4b ;
        ssf:flag_meanings = "unknown unfrozen frozen_temporary
            melting_water_on_the_surface permanent_ice" ;
        ssf:valid_range = 0b, 4b ;
        ssf:missing_value = 127b ;
byte sat_id(obs) ;
        sat_id:name = "sat_id" ;
        sat_id:coordinates = "time lat lon" ;
        sat_id:long_name = "satellite id" ;
        sat_id:flag_values = 1b, 2b, 3b, 4b, 5b ;
        sat_id:flag_meanings = "ers-1, ers-2, metop-a, metop-b, metop-c"
             ;
        sat_id:valid_range = 1b, 5b ;
        sat_id:missing_value = 127b ;
byte proc_flag(obs) ;
        proc_flag:name = "proc_flag" ;
        proc_flag:coordinates = "time lat lon" ;
        proc_flag:long_name = "processing flag" ;
        proc_flag:flag_masks = 1b, 2b, 4b, 8b, 16b, 32b, 64b ;
        proc_flag:flag_meanings = "
            soil_moisture_set_to_nan_it_was_below_-25
            soil_moisture_set_to_nan_it_was_above_125
            soil_moisture_set_to_nan_backscatter_not_usable
            soil_moisture_set_to_nan_model_parameter_not_usable
            reserved_for_future_use reserved_for_future_use
            reserved_for_future_use" ;
        proc_flag:valid_range = 0b, 127b ;
byte corr_flag(obs) ;
        corr_flag:name = "corr_flag" ;
        corr_flag:coordinates = "time lat lon" ;
        corr_flag:long_name = "correction flag" ;
        corr_flag:flag_masks = 1b, 2b, 4b, 8b, 16b, 32b, 64b ;
        corr_flag:flag_meanings = "
            soil_moisture_set_to_0_it_was_between_0_and_-25
            soil_moisture_set_to_100_it_was_between_100_and_125
            wet_correction_applied
            subsurface_scattering_correction_applied
            reserved_for_future_use reserved_for_future_use
            reserved_for_future_use" ;
        corr_flag:valid_range = 0b, 127b ;
byte conf_flag(obs) ;
        conf_flag:name = "conf_flag" ;
        conf_flag:coordinates = "time lat lon" ;
        conf_flag:long_name = "confidence flag" ;
        conf_flag:flag_masks = 1b, 2b, 4b, 8b, 16b, 32b, 64b ;
        conf_flag:flag_meanings = "bad_surface_state_flag
            topographic_complexity_above_50perc wetland_above_50perc
            soil_moisture_noise_above_50perc
            sensitivity_to_soil_moisture_below_1dB
            reserved_for_future_use reserved_for_future_use" ;
        conf_flag:valid_range = 0b, 127b ;
short slope40(obs) ;
        slope40:name = "slope40" ;
        slope40:coordinates = "time lat lon" ;
        slope40:long_name = "slope at 40 degree" ;
```

```
                slope40:units = "dB/degree" ;
                slope40:scale_factor = 0.001f ;
                slope40:valid_range = -10000s, 10000s ;
                slope40:missing_value = 32767LL ;
        ushort slope40_noise(obs) ;
                slope40_noise:name = "slope40_noise" ;
                slope40_noise:coordinates = "time lat lon" ;
                slope40_noise:long_name = "slope at 40 degree noise" ;
                slope40_noise:units = "dB/degree" ;
                slope40_noise:scale_factor = 1.e-05f ;
                slope40_noise:valid_range = 0US, 10000US ;
                slope40_noise:missing_value = 65535US ;
        short sigma40(obs) ;
                sigma40:name = "sigma40" ;
                sigma40:coordinates = "time lat lon" ;
                sigma40:long_name = "backscatter at 40 degree" ;
                sigma40:units = "dB" ;
                sigma40:scale_factor = 0.01f ;
                sigma40:valid_range = -10000s, 10000s ;
                sigma40:missing_value = 32767LL ;
        ushort sigma40_noise(obs) ;
                sigma40_noise:name = "sigma40_noise" ;
                sigma40_noise:coordinates = "time lat lon" ;
                sigma40_noise:long_name = "backscatter at 40 degree noise" ;
                sigma40_noise:units = "dB" ;
                sigma40_noise:scale_factor = 0.01f ;
                sigma40_noise:valid_range = 0US, 10000US ;
                sigma40_noise:missing_value = 65535US ;

// global attributes:
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                :date_created = "2021-01-19 11:00:19" ;
                :featureType = "timeSeries" ;
                :platform = "Metop-A, Metop-B, Metop-C" ;
                :product_name = "Metop ASCAT Surface Soil Moisture Data Record
                   v7 12.5 km sampling" ;
                :software = "WARP v5.10.1" ;
                :source = "ASCAT Level 1b SZR" ;
                :project = "H SAF" ;
                :contact = "us_hsaf@meteoam.it" ;
                :geospatial_lon_resolution = "25-34 km" ;
                :geospatial_lon_sampling = "12.5 km" ;
                :geospatial_lat_resolution = "25-34 km" ;
                :geospatial_lat_sampling = "12.5 km" ;
                :created_with_software = "Python 3.6.10 and NetCDF 4.7.3" ;
                :uuid = "undefined" ;
                :institution = "TU Wien (Vienna University of Technology)" ;
                :creater_name = "TU Wien, Department of Geodesy and
                   Geoinformation (GEO)" ;
                :creater_url = "http://mrs.geo.tuwien.ac.at" ;
                :creater_email = "remote.sensing@geo.tuwien.ac.at" ;
                :cdm_data_type = "Time Series" ;
```

5. Product download, terms and condition

The soil moisture products are available via FTP. Download details are available after registering at the H SAF website http://h-saf.eumetsat.int/. If you need help, please contact the H SAF user helpdesk us_hsaf@meteoam.it.

All H SAF products are owned by EUMETSAT and the EUMETSAT SAF Data Policy applies[5]. The products are available for all users free of charge and users should recognize the respective roles of EUMETSAT, the H SAF Leading Entity and the H SAF Consortium when publishing results that are based on H SAF products. EUMETSAT's ownership and intellectual property rights into the SAF data and products is best safeguarded by simply displaying the words "© EUMETSAT" under each of the SAF data and products shown in a publication or website.

5.1. Acknowledgment and citation

The SSM CDR and Extension product should be cited (depending on the bibliography style) as follows:

> H SAF (2021): ASCAT Surface Soil Moisture Climate Data Record v7 12.5 km sampling - Metop, EUMETSAT SAF on Support to Operational Hydrology and Water Management, DOI: 10.15770/EUM_SAF_H_0007. http://dx.doi.org/10.15770/EUM_SAF_H_0007

> H SAF (2021): ASCAT Surface Soil Moisture Climate Data Record v7 Extension 12.5 km sampling - Metop, EUMETSAT SAF on Support to Operational Hydrology and Water Management. https://navigator.eumetsat.int/product/EO:EUM:DAT:METOP:H120

```
@misc{H119-SSM-CDR,
  author = {{H SAF}},
  title = {{Metop ASCAT Surface Soil Moisture
            Climate Data Record v7 12.5 km sampling (H119)}},
  year = 2021,
  note = {{EUMETSAT SAF on Support to Operational Hydrology
           and Water Management}},
  doi = {10.15770/EUM_SAF_H_0007},
  howpublished= {\url{http://dx.doi.org/10.15770/EUM_SAF_H_0007}}
}

@misc{H120-SSM-CDR,
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  title = {{Metop ASCAT Surface Soil Moisture
            Climate Data Record v7 Extension 12.5 km sampling (H120)}},
  year = 2021,
  note = {{EUMETSAT SAF on Support to Operational Hydrology
           and Water Management}}
  howpublished= {\url{https://navigator.eumetsat.int/product/
```

[5] https://www.eumetsat.int/website/home/AboutUs/WhoWeAre/LegalFramework/DataPolicy/index.html

```
            EO:EUM:DAT:METOP:H120}}
}
```

5.2. User feedback and support

User feedback is warmly welcomed and encouraged. All questions and remarks concerning the product can be addressed to the H SAF user helpdesk us_hsaf@meteoam.it

5.3. Downstream services

The Metop ASCAT SSM CDR represents a base product for downstream services such as the Copernicus Global Land Service (CGLS)[6] or the ESA Climate Change Initiative (CCI)[7]. In case of CGLS, Metop ASCAT SSM observations are translated into the Soil Water Index (SWI), which quantifies the soil moisture profile from surface conditions. It is based on an exponential filter and the assumption that over a large footprint only the relative dynamic range of the soil water content can be represented accurately, since the variability of soil characteristics can be very high [40]. In case of ESA CCI, Metop ASCAT SSM CDR is part of the ESA CCI active soil moisture data set, which represents a combination of soil moisture products based on active microwave instruments. The active product is further merged with a passive soil moisture product creating a combined long-term soil moisture data record [41]. The downstream services CGLS and ESA CCI provide their products at a different spatial and temporal sampling compared to the original Metop ASCAT SSM CDR product.

6. References

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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):

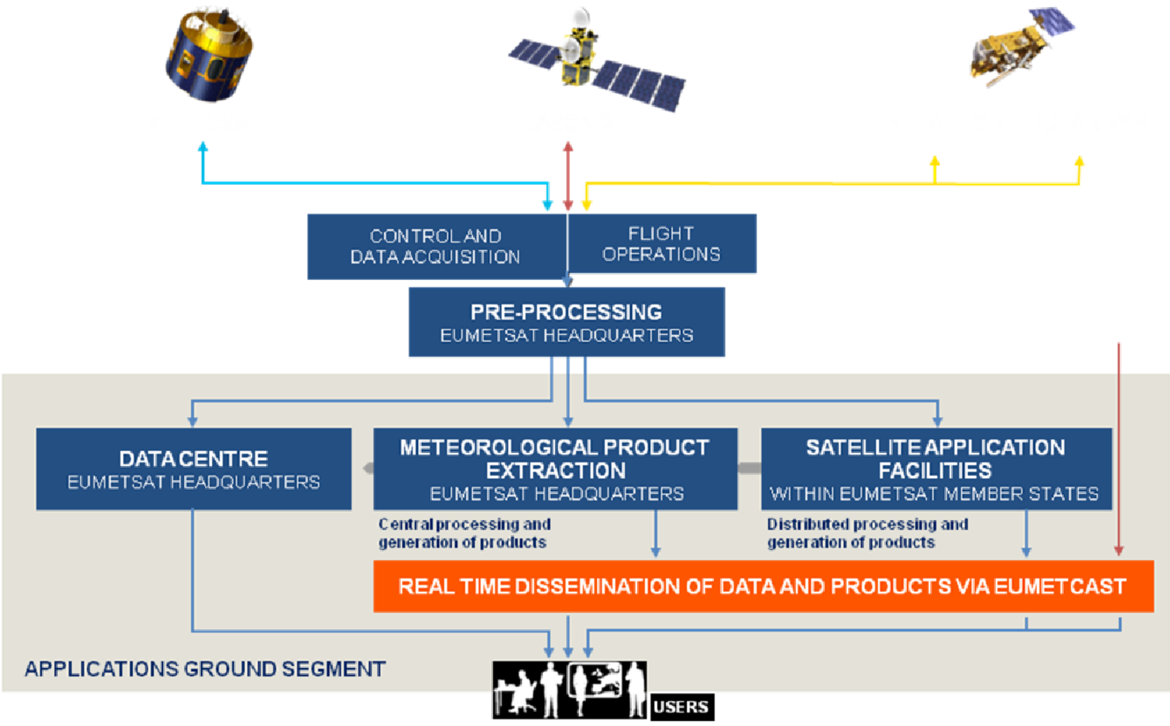

Figure A.1: Conceptual scheme of the EUMETSAT Application Ground Segment.

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.

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);

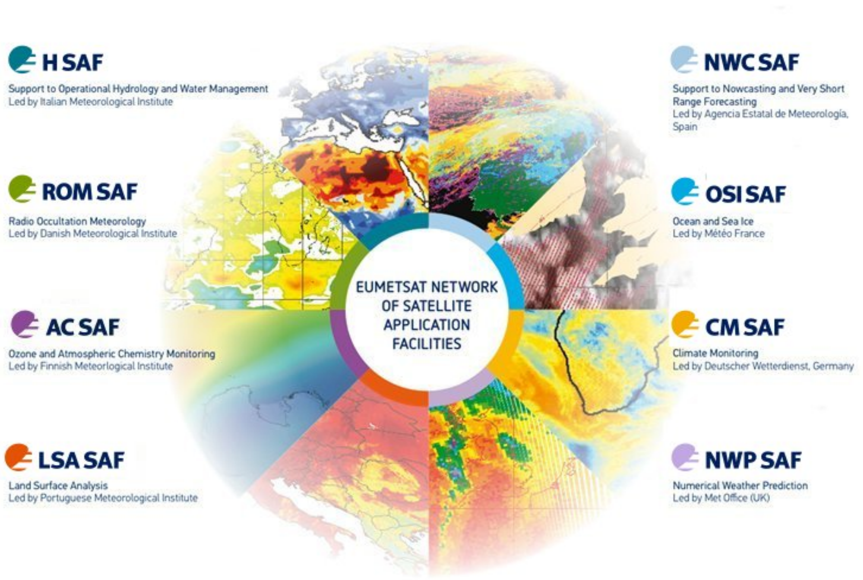

Figure A.2: Current composition of the EUMETSAT SAF Network.

- 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 http://h-saf.eumetsat.int. All products are available via EUMETSAT data delivery service (EUMETCast[8]), or via ftp download; they are also published in the H SAF website[9].

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.

[8] http://www.eumetsat.int/website/home/Data/DataDelivery/EUMETCast/index.html
[9] http://h-saf.eumetsat.int/

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: http://h-saf.eumetsat.int/ 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 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.