20

Operations, Challenges, and Prospects of Satellite-Based Surface Soil Moisture Data Services

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CONTENTS
20.1 Introduction ........................................................................................................................ 463
20.2 ASCAT Soil Moisture Service Operations ........................................................................ 465
  20.2.1 Near-Real-Time Swath Products of EUMETSAT ......................................................... 465
  20.2.2 Off-Line Time Series Product of TU Wien ................................................................. 467
20.3 Maturity of ASCAT Soil Moisture Products ..................................................................... 469
  20.3.1 Bates Maturity Model .................................................................................................. 469
  20.3.2 Maturity Analysis ....................................................................................................... 470
20.4 Challenges Faced by Providers and Users of Soil Moisture Services .............................. 475
  20.4.1 Instrument Calibration ............................................................................................... 475
  20.4.2 Product Validation .................................................................................................... 476
  20.4.3 Algorithmic Improvements ....................................................................................... 477
  20.4.4 Masking and Quality Flags ..................................................................................... 478
  20.4.5 Data Assimilation .................................................................................................... 479
  20.4.6 Application Development ....................................................................................... 480
20.5 Conclusions and Prospects ............................................................................................... 482
Acknowledgments ...................................................................................................................... 483
References .................................................................................................................................... 484

20.1 Introduction

Building upon the progress made in algorithmic research and improvements in sensor technologies, operational soil moisture products have increasingly become available over the past decade (Wagner et al. 2007b). The first global satellite-based soil moisture dataset that was freely shared with the user community was derived from backscatter measurements collected by the C-band scatterometer (ESCAT) on board the ERS-1 and ERS-2 satellites operated by the European Space Agency (ESA). It was first released in 2002 (Scipal et al. 2002) and after that it has been updated irregularly (Reimer et al. 2012). The ESCAT soil moisture dataset has been produced and distributed by the microwave remote sensing team of the Vienna University of Technology (TU Wien), and given that funding relied principally on research programs, it is a classical research product, that is, software development, dataset updating, and user support have all been done on a best effort basis, not yet having benefited from the more integrated and documented approach followed in
Remote Sensing of Energy Fluxes and Soil Moisture Content

operations. Despite the lack of formal operational user service support, over 350 scientific users worldwide have so far requested and received the ESCAT data. This has been the basis for numerous validation studies that verified the quality of the ESCAT soil moisture retrievals by comparing them to in situ and model data (Pellarin et al. 2006) and experiments testing the usability of these data in diverse application areas such as runoff forecasting (Brocca et al. 2009), numerical weather prediction (Zhao et al. 2006), yield modeling (de Wit and van Diepen 2007), greenhouse gas accounting (Verstraeten et al. 2010), climate studies (Künzer et al. 2009), and ground water modeling (Sutanudjaja 2012).

The free data policy adopted for the ESCAT soil moisture data was crucial for making the potential of active microwave scatterometry for soil moisture retrieval better known to a larger science community (Wagner et al. 2007a). This positive experience is likely to have spurred some other university teams to start distributing their satellite soil moisture dataset in a free and open manner as well. One of these was the microwave remote sensing team of the Vrije Universiteit Amsterdam (VUA), who started distributing soil moisture data derived from passive microwave radiometers in 2007. They use the Land Parameter Retrieval Model (LPRM) developed in cooperation with NASA to retrieve soil moisture from multifrequency microwave radiometers such as Advanced Microwave Scanning Radiometer–Earth Observing System (AMSR-E) (Owe et al. 2008) or Windsat (Parinussa et al. 2012). Like the ESCAT product of TU Wien, the LPRM soil moisture data of VUA is a classical research product that has found widespread use in the science community (Bolten and Crow 2012).

The increasing acceptance of these and other science products was the basis for making the first steps toward operational soil moisture data services. The first of these services was implemented for the AMSR-E instrument by NASA, starting the distribution of the data through the National Snow and Ice Data Center in 2003. Since then this dataset has been regularly processed with a polarization ratio algorithm as described by Njoku et al. (2003) with a short latency in the order of days. The online documentation of the dataset has been kept up to date, and open, straightforward data access has been provided. The quality and consistency of this data service ensured a wide popularity of the product. Yet, except over some test sites in the United States (Jackson et al. 2010), validation results for this product have, in general, not been as good as for the LPRM retrievals of VUA or the ESCAT data of TU Wien (Brocca et al. 2011; Rüdiger et al. 2009). NASA reacted to this situation by funding further research and development work to improve the polarization ratio algorithm and by implementing the LPRM algorithm in the Goddard Earth Sciences Data and Information Services Center (GES DISC). The LPRM soil moisture products from GES DISC included soil moisture retrievals and their associated errors (Parinussa et al. 2011b) from the Tropical Rainfall Measuring Mission (TRMM) observations and AMSR-E. Unfortunately, the implementation was realized only a few months before the failure of AMSR-E in October 2011. Therefore this operational service has not yet reached a broader user community. For completeness, it should also be noted that the Japan Aerospace Exploration Agency (JAXA) implemented several different retrieval algorithms for AMSR-E. Yet, this service never gained much popularity probably because too little information about the product characteristics and data access conditions was made available.

The next important step in the development toward operational soil moisture data services was undertaken by the European Organisation for the Exploitation of Meteorological Satellites (EUMETSAT). On the basis of the positive experiences made with ESCAT, EUMETSAT decided to implement a fully operational near-real-time (NRT) soil moisture processing chain for the successor instrument of ESCAT, the Advanced Scatterometer
Satellite-Based Surface Soil Moisture Data Services

ASCAT (Bartalis et al. 2007). ASCAT is flown on a series of three Meteorological Operational (METOP) satellites, which are planned to span the period from October 2006 to beyond 2020. The ASCAT soil moisture service was developed by EUMETSAT in cooperation with TU Wien, and operational NRT dissemination of ASCAT soil moisture data started in December 2008 (Wagner et al. 2010). METOP-B was launched in September 2012, while METOP-A is still in orbit and functional. ASCAT soil moisture data services will be available from both instruments, thereby significantly improving the spatiotemporal coverage (Wagner et al. 2013).

Finally, in November 2009, not long after the first operational ASCAT soil moisture data became available, ESA launched the Soil Moisture and Ocean Salinity (SMOS) satellite. SMOS is an experimental satellite that was designed for the purpose of soil moisture measurements over land (Kerr et al. 2010), and consequently, the release of the SMOS soil moisture data had been much awaited for by the soil moisture science community. The first SMOS soil moisture data were released in 2010, and since then many interesting studies comparing SMOS, ASCAT, and/or AMSR-E soil moisture data have been carried out (Albergel et al. 2012; Brocca et al. 2011; Wanders et al. 2012).

With SMOS, ASCAT, Windsat, and AMSR-2 (the successor of AMSR-E) in space and the launch of the next dedicated soil moisture satellite called Soil Moisture Active/Passive (SMAP) on the horizon (Entekhabi et al. 2010), operational soil moisture data services have become a reality. As discussed in Chapter 4, the measurement concepts and retrieval algorithms differ quite widely for these different satellite missions; yet, the basic challenges faced by the providers and users of the corresponding soil moisture data services are very similar. In this chapter we discuss these challenges based on the example of the 25-km ASCAT surface soil moisture products distributed by EUMETSAT and TU Wien. Even though many aspects are ASCAT-specific, the discussion is kept on a rather general level in order to ensure that it is also of relevance for the other satellite soil moisture monitoring services. This chapter will conclude with a discussion of the prospects of operational soil moisture services.

20.2 ASCAT Soil Moisture Service Operations

Operational aspects of satellite soil moisture data services are hardly discussed in the scientific literature. Nonetheless, it is important to describe the implementation of these services as this has an impact on the characteristics and quality of the data. In this section we therefore discuss the implementation of the ASCAT surface soil moisture data services of EUMETSAT and TU Wien, which have been part of EUMETSAT’s Satellite Application Facility in Support to Operational Hydrology and Water Management (H-SAF) since 2012. Further value-added ASCAT soil moisture products such as the ASCAT Soil Water Index (SWI), assimilated profile soil moisture products, and a disaggregated 1-km product obtained by downscaling the ASCAT data using static scaling coefficients from synthetic aperture radar (SAR) data are also available (Wagner et al. 2013), but these are not discussed here.

20.2.1 Near-Real-Time Swath Products of EUMETSAT

The ASCAT surface soil moisture data services provide a suite of data products that all share the same physical basis (i.e., from a physical point of view all products should
be identical) but come in different flavors (spatiotemporal sampling, data latency, data format, and consistency) in order to meet the requirements of different user communities. The basic EUMETSAT products were designed to meet the needs of the Numerical Weather Prediction (NWP) user community. For that user group, one of the most important requirements was to receive the data in NRT with a maximum delay of 130 min after data acquisition (Wagner et al. 2010) and in a format commonly used by NWP centers, following World Meteorological Organization (WMO) standards. In NWP data assimilation, each individual measurement can be considered as an independent observation and it is furthermore favored to use data as close as possible to the original measurement, while because of the size of currently used NWP grids, spatial resolution is less of a concern. Consequently, the basic EUMETSAT ASCAT surface soil moisture data product is orbit swath-based, has a spatial resolution of approximately 50 km, and is sampled on a regular 25-km grid along and across orbit swaths. It should be noted that the resolution and sampling characteristics are directly inherited from the parent Level 1B Normalized Radar Cross Section (NRCS) ASCAT product so that no additional resampling errors are introduced. In order to achieve the latency requirements, products are sliced up in batches of data corresponding to 3 min of ASCAT sensed data and formatted in the Binary Universal Form for the Representation of meteorological data, which is a binary data format maintained by WMO. An example for such a 3-min data slice is shown in Figure 20.1. After processing the data within EUMETSAT’s Central Application Facility with software called Water Retrieval Package–Near-Real-Time (WARP-NRT) the data are distributed over the WMO Global Telecommunications System and via EUMETCast, a multicast dissemination system based on commercial telecommunication geostationary satellites and operated by EUMETSAT. In parallel to the 25-km sampled product a 12.5-km product with an approximate resolution of 25–30 km and a somewhat higher noise level is also produced operationally.

Both products are additionally archived and available in the EUMETSAT Data Center, where the original 3-min data patches are collated to form a complete orbit to reduce the

**FIGURE 20.1**
(See color insert.) (Left) Example of an NRT ASCAT surface soil moisture data product, representing a 3-min data take. This data slice was acquired on April 1, 2012, 0845:01 UTC over Africa. (Right) Example of a full orbit ASCAT surface soil moisture data product as available from EUMETSAT’s data archive is shown. The orbit was acquired between April 1, 2012, 0833:00 UTC and 1014:59 UTC.
number of small data files. EUMETSAT thus offers four distinct data products: 3-min NRT data file and full-orbit off-line data files at both 25- and 12.5-km sampling, respectively. The archived data are very useful to carry out off-line analysis and investigations, but because of occasional updates in the operational NRT products, they may be inhomogeneous. In support to climate research, EUMETSAT plans to carry out retrospective reprocessing campaigns for all the ASCAT missions in order to provide a consistently processed data record and up-to-date instrument calibration. This effort is already being initiated for METOP-A, where 6 years of scatterometer measurements are currently available. Therefore harmonized ASCAT swath-based soil moisture products will become available in the future.

### 20.2.2 Off-Line Time Series Product of TU Wien

In addition to the four data products of EUMETSAT, TU Wien produces and distributes a 25-km ASCAT surface moisture data product stored as time series for a fixed global sinusoidal grid with a spacing of approximately 12.5 km. The data are available in a user-defined binary format. The motivation for this product is that many users are interested in having ASCAT surface soil moisture time series over relatively small study regions, sometimes even only over one particular location. In such a situation, the EUMETSAT products with their irregular spatiotemporal sampling (the exact orbit swath may vary from one orbit cycle to the next, causing a quasi-random shift of the latitude/longitude coordinates of the swath file) are impractical, requiring from the users major processing efforts to subset and resample the data to their areas of interest. An example of a time series product is shown in Figure 20.2.

The TU Wien time series product is not available in NRT, but it is generally of better quality than the EUMETSAT NRT swath products. This is because it is always based on the latest version of the retrieval algorithms due to the development and implementation cycle as adopted by TU Wien and EUMETSAT. As illustrated in Figure 20.3, the software development cycle starts with researchers—typically students pursuing their master or PhD degrees—investigating the ASCAT data and exploring new algorithms over selected test sites in order to improve one or more processing steps in the complete ASCAT retrieval scheme. Once an algorithm is found to perform well, it is tested globally to investigate its scientific quality and to check its computational performance. It may happen that even

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**FIGURE 20.2**

Example of an ASCAT surface soil moisture time series as produced and distributed by TU Wien. The ASCAT time series is compared with *in situ* measurements taken over the station Y7 from the Australian *in situ* network OZNET. For a description of the OZNET network, see Smith et al. (2012).
though an algorithm performs well from a scientific point of view, it is abandoned because processing of the historic time series would take too long (several weeks or months). Such computationally demanding algorithms may be reconsidered in the future when more powerful computers or distributed processing systems become available.

Once an algorithm is found to improve the quality of the soil moisture retrievals at reasonable processing costs, it is committed to the latest version of a software package called Water Retrieval Package (WARP). From then on it is being used in the reprocessing of the
ASCAT backscatter time series in order to derive consistent surface soil moisture time series and a set of optimally estimated model parameters. These model parameters are not only important for WARP itself, but also they are used by EUMETSAT as one of the inputs to the NRT processing software WARP-NRT (Figure 20.3). The use of these empirically derived model parameters ensures that the NRT retrieval is robust and computationally very fast. However, one caveat of this approach is that changes in the calibration of the ASCAT backscatter data may—if unaccounted for—lead to artifacts in the NRT products. This was the case at the start of the ASCAT NRT service of EUMETSAT (Hahn et al. 2012) but has significantly improved since then by putting procedures in place to ensure that changes in the backscatter calibration are accounted for in the soil moisture processor through the use of NRCS back-calibration tables (Section 20.4.1).

20.3 Maturity of ASCAT Soil Moisture Products

Given that the radiometric and measurement geometry characteristics of ESCAT and ASCAT are very similar, the development of an ASCAT soil moisture service could draw directly from the experiences with the ESCAT soil moisture product (Bartalis et al. 2007). The initial implementation of the ASCAT soil moisture data services was therefore reasonably fast, with EUMETSAT declaring the NRT ASCAT soil moisture service operational in December 2008, only about 2 years after the launch of METOP-A. Since then, various aspects of this service have been improved step by step. Nonetheless, the transition from a science to a fully operational Earth Observation product is more demanding than one might expect. Consequently, even though the ASCAT soil moisture products have now been available for several years, they still cannot be considered to be fully mature from a service point of view. In this section we illustrate this point by using a maturity model first proposed by Bates and Barkstrom (2006) and later refined by Bates and Privette (2012), herein after referred to as Bates maturity model.

20.3.1 Bates Maturity Model

In Earth Observation (EO) science the concept of the maturity of data services has not yet been widely adopted. With the emergence of science-driven EO data services it becomes, however, increasingly important to introduce maturity indices that characterize the process of moving from a basic research dataset to a sustained and routinely generated product. The objectives of such maturity indices are to produce an easily understood way of characterizing the maturity of EO data services and to help identifying areas needing improvement. The first objective is mostly of importance for prospective new users of EO data services; the second for the service providers themselves. While many providers (such as EUMETSAT) develop and operate EO data services according to their own well-defined service requirements, there is so far only one science-driven maturity model that has gained more widespread acceptance in the international EO community, namely, the Bates maturity model.

The Bates maturity model has its origin in discussions between NASA and the National Oceanic and Atmospheric Administration (NOAA) on how to transition data services dealing with the generation of climate data records (CDRs) from NASA to NOAA for long-term sustained operations. As a result of this heritage, the Bates maturity model in some
respects may not be fully adequate for characterizing European data services designed for nonclimate applications. Nevertheless, the latest version of this maturity index (V4.0 from December 20, 2011) as used here has already benefited from several international assessments such as ones organized by the World Climate Research Programme or the Global Climate Observing System. These assessments have broadened the scope and usability of the Bates maturity model significantly, and we therefore apply it here also to the NRT ASCAT soil moisture data services, despite some remaining caveats for our specific purpose.

The latest version of the Bates maturity model considers six different thematic areas, namely, Software Readiness (stability of code), Metadata (amount and compliance with international standards), Documentation (description of the processing steps and algorithms), Product Validation (data quality in space and time), Public Access (availability of data and code), and Utility (uses by broader community). Each of these thematic areas is further split up into three to five subthemes that specify the best practices in these different domains. The maturity of each thematic area and each subtheme is rated with a number from one (basic) to six (mature). Advice is given that EO data products of the overall maturity levels 1 and 2 are used only for research purposes but not for decision making. Maturity levels 3 and 4 indicate initial operational capabilities, implying that the data products may tentatively be used in decision making. Full operational capabilities, allowing the use of the data products in decision making, are reached in maturity levels 5 and 6 (Bates and Privette 2012).

### 20.3.2 Maturity Analysis

The results of our maturity analysis are presented in Table 20.1 for the NRT swath products of EUMETSAT produced with the WARP-NRT software and in Table 20.2 for the off-line time series product of TU Wien produced with WARP. Our approach in this assessment was to select the appropriate ratings for each of the subthemes, then calculate the mean subtheme rating for each of the six thematic areas, and finally round the mean rating to the next lower or next higher number depending on how well the description of the maturity levels fitted to the actual situation. To make Tables 20.1 and 20.2 readable, they contain not only the rating for each thematic area and its subthemes but also the corresponding verbal description. For example, for the case of the EUMETSAT product shown in Table 20.1, Portability, which is a subtheme of Software Readiness, receives the rather high maturity level 5 as the software WARP-NRT is: “Operational: can be systematically and routinely run by 3rd party.” Tables 20.1 and 20.2 display the six thematic areas at the top row and their ratings at the last two bottom rows, the rest of the rows display the subcategories. Staying with the example Software Readiness of WARP-NRT, the average rating for all subthemes is 3.6, but as “Moderate code changes are still expected,” we selected the comparatively low overall maturity level of 3.

The outcome of this assessment of the maturity of the two ASCAT products groups provided some interesting insights. For EUMETSAT’s NRT products it turned out that, in terms of the categories Public Access and Utility, a maturity level of 5 has been reached; that is, in these two aspects the products can indeed be regarded fully operational. However, in the other categories it fares less well. While for the categories Software Readiness, Documentation, and Product Validation the scores are 3 and 4 (2 times), respectively, it only reaches the low maturity level 2 for Metadata. This demonstrates that still substantial efforts will be required to improve the overall system engineering (software, database management, and documentation) of the NRT ASCAT soil moisture service of
### TABLE 20.1

**Bates Maturity Matrix for ASCAT Surface Soil Moisture Orbit Product Produced by EUMETSAT Using the Software WARP-NRT 3.1.0**

<table>
<thead>
<tr>
<th>Category</th>
<th>Software Readiness</th>
<th>Metadata</th>
<th>Documentation</th>
<th>Product Validation</th>
<th>Public Access</th>
<th>Utility</th>
</tr>
</thead>
<tbody>
<tr>
<td>Subcategory</td>
<td>Documentation</td>
<td>File level</td>
<td>C-ATBD</td>
<td>Independent validation</td>
<td>Archive</td>
<td>Data usage if TCDR</td>
</tr>
<tr>
<td>Description</td>
<td>Overview and process descriptions complete; program headers and README complete</td>
<td>Complete pixel or grid-point level metadata; metadata sufficient to reproduce the data independent of external assistance</td>
<td>Updated and public</td>
<td>At least 5 comparisons to models, <em>in situ</em> data, or other independent products as available and appropriate to particular CDR; differences in results understood</td>
<td>Regular requests for data</td>
<td></td>
</tr>
<tr>
<td>Rating</td>
<td>3</td>
<td>5</td>
<td>5</td>
<td>5</td>
<td>3</td>
<td>6</td>
</tr>
<tr>
<td>Subcategory</td>
<td>Portability</td>
<td>Collection Level</td>
<td>OAD</td>
<td>Uncertainty (for TCDRs)</td>
<td>Updates to Record</td>
<td>Societal Sector Decision Support Systems</td>
</tr>
<tr>
<td>Description</td>
<td>Operational: can be systematically and routinely run by 3rd party</td>
<td>Limited</td>
<td>Not evaluated</td>
<td>Biases and errors identified and documented</td>
<td>Done systematically and operationally as dictated by availability of new input data</td>
<td>Potential benefits published</td>
</tr>
<tr>
<td>Rating</td>
<td>5</td>
<td>2</td>
<td>3</td>
<td>3</td>
<td>6</td>
<td>4</td>
</tr>
<tr>
<td>Subcategory</td>
<td>Numerical Reproducibility</td>
<td>Standards</td>
<td>Process Flow Chart</td>
<td>Quality Flag</td>
<td>Version</td>
<td>Citations in peer-reviewed literature</td>
</tr>
<tr>
<td>Description</td>
<td>3rd party output within machine rounding errors</td>
<td>Not evaluated</td>
<td>Public</td>
<td>Masks applied as appropriate (e.g., land masks, and cloud masks); algorithm failures identified</td>
<td>Under NCDC version control</td>
<td>Citations of product occurring</td>
</tr>
<tr>
<td>Rating</td>
<td>5</td>
<td>1</td>
<td>3</td>
<td>4</td>
<td>4</td>
<td>5</td>
</tr>
<tr>
<td>Subcategory</td>
<td>Meets coding standards</td>
<td>Peer Reviewed Docs Describing Algorithm and Product</td>
<td>Operational monitoring</td>
<td>Feedback to CDRP</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Description</td>
<td>Passes review against minimum CDRP coding standards</td>
<td>Paper on product published</td>
<td>Operational monitoring in place</td>
<td>Comments received</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Rating</td>
<td>3</td>
<td>5</td>
<td>5</td>
<td>5</td>
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</tr>
<tr>
<td>Subcategory</td>
<td>Security</td>
<td>Research grade</td>
<td>Public C-ATBD; Draft Operational Algorithm Description (OAD); Peer-reviewed publication on algorithm; paper on product submitted</td>
<td>Uncertainty estimated over widely distributed times/location by multiple investigators; Differences understood</td>
<td>Record is archived and publicly available with associated uncertainty estimate; Known issues public. Periodically updated</td>
<td>May be used in applications by other investigators; assessments demonstrating positive value</td>
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<tr>
<td>Description</td>
<td>PI knows of no security problems</td>
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<td></td>
<td></td>
<td></td>
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<tr>
<td>Rating</td>
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<tr>
<td>Overall Rating</td>
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<td>2</td>
<td>4</td>
<td>4</td>
<td>5</td>
<td>5</td>
</tr>
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*a* Source code is not available.

*b* Under control of EUMETSAT (instead of NCDC).
<table>
<thead>
<tr>
<th>Subcategory</th>
<th>Description</th>
<th>Rating</th>
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<td>Metadata</td>
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<td>Standards</td>
<td>Documentation</td>
<td>2</td>
</tr>
<tr>
<td>Process Flow Chart</td>
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</tr>
<tr>
<td>Quality Flag</td>
<td>Uncertainty (for TCDRs)</td>
<td>4</td>
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<tr>
<td>Version</td>
<td>Updates to Record</td>
<td>5</td>
</tr>
<tr>
<td>Citations in peer-reviewed literature</td>
<td>Potential Benefits</td>
<td>6</td>
</tr>
<tr>
<td>Societal Sector Support</td>
<td>Product Validation</td>
<td>Public Access</td>
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**TABLE 20.2 Bates Maturity Matrix for ASCAT Surface Soil Moisture Time Series Product Produced by TU Wien Using the Software WARP 5.5**

<table>
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<th>Subcategory</th>
<th>Description</th>
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</tr>
<tr>
<td>Metadata</td>
<td>Documentation</td>
<td>2</td>
</tr>
<tr>
<td>Product Validation</td>
<td>Archive</td>
<td>3</td>
</tr>
<tr>
<td>Public Access</td>
<td>Data usage</td>
<td>4</td>
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</tbody>
</table>

**TABLE 20.2 Bates Maturity Matrix for ASCAT Surface Soil Moisture Time Series Product Produced by TU Wien Using the Software WARP 5.5**

<table>
<thead>
<tr>
<th>Subcategory</th>
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<td>Standards</td>
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<tr>
<td>Process Flow Chart</td>
<td>OAD</td>
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</tr>
<tr>
<td>Quality Flag</td>
<td>Uncertainty (for TCDRs)</td>
<td>3</td>
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<tr>
<td>Version</td>
<td>Updates to Record</td>
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<tr>
<td>Citations in peer-reviewed literature</td>
<td>Potential Benefits</td>
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<td>Societal Sector Support</td>
<td>Product Validation</td>
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</table>

**TABLE 20.2 Bates Maturity Matrix for ASCAT Surface Soil Moisture Time Series Product Produced by TU Wien Using the Software WARP 5.5**
<table>
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<tr>
<th>Subcategory</th>
<th>Meets Coding Standards</th>
<th>Peer-Reviewed Docs Describing Algorithm and Product</th>
<th>Operational monitoring</th>
<th>Feedback to CDRP</th>
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<tbody>
<tr>
<td>Description</td>
<td>Not evaluated</td>
<td>Paper on product published</td>
<td>Incomplete</td>
<td>Mostly positive comments received</td>
</tr>
<tr>
<td>Rating</td>
<td>1</td>
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<td></td>
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<td>Subcategory</td>
<td>Security</td>
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<td>Description</td>
<td>Not evaluated</td>
<td></td>
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<td>Rating</td>
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<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Description</td>
<td>Significant code changes expected</td>
<td>Public C-ATBD; Peer-reviewed publication on algorithm</td>
<td>Uncertainty estimated for some locations</td>
<td>Limited data availability to develop familiarity</td>
</tr>
<tr>
<td>Overall Rating</td>
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EUMETSAT, while from a scientific point of view the product can be considered to be relatively mature. This, however, does not mean that it can be recommended to scale back scientific research in favor of system engineering—far from that! The reason is that with increasing scientific maturity of an algorithm it becomes, in general, increasingly difficult and hence time consuming to further improving it (Figure 20.4). This is an expression of the fact that algorithms, even if unchanged in their core characteristics, tend to become more complex over time in order to capture the physical world more realistically. This is also the case for the ASCAT soil moisture retrieval algorithm, which has become increasingly complex over the years by adding, among other improvements, algorithms for correcting azimuthal effects (Bartalis et al. 2007), improved error propagation models (Naeimi 2009), and advanced freeze/thawing detection methods (Naeimi et al. 2012; Zwieback et al. 2012a). The development of the ASCAT algorithms can thus be seen to follow the so-called Pareto principle, also known as the 80-20 rule, which states that roughly 80% of the effects come from 20% of the causes.

The observations made with regard to the maturity of the EUMETSAT products are even more pronounced in the case of the off-line time series product of TU Wien. For this latter product, only in the category Utility is a maturity level of 5 reached. All other categories have low maturity levels of 2 or 3, indicating that this product is still very much a research product with significant deficits particularly with respect to all system engineering components, most importantly Software Readiness, Metadata, and Public Access. This is a reflection not only of the research orientation of the service provider (i.e., TU Wien) but also of the type of funding that has so far been available to develop this service. However, it should also be noted that the WARP software used by TU Wien is much more extensive than the WARP-NRT software used by EUMETSAT. While the first provides a research platform to investigate new algorithms and processes, the latter was purposefully designed to be slim and computationally efficient to meet the timeliness requirements of the NWP community. Therefore the efforts required for improving the maturity level of the categories Software Readiness, Metadata, and Documentation are much higher for WARP than they are for WARP-NRT. Fortunately, in 2012 the TU Wien time series product became one of the products of H-SAF, providing a funding source for supporting system engineering activities.

FIGURE 20.4
Schematic illustration of the relationship between the scientific maturity of an algorithm and the efforts needed to improve it.
20.4 Challenges Faced by Providers and Users of Soil Moisture Services

The previous section illustrated the many and complex tasks behind operational EO data services based on the example of the ASCAT soil moisture services provided by EUMETSAT in cooperation with TU Wien. An analysis of the maturity of the ASCAT services showed that at this point in time their weakest elements are related to a backlog of general system engineering tasks (software, metadata, data supply, documentation, etc.), while the science behind the products is already quite mature as evidenced by the large number of validation and application studies published in the peer review literature (Wagner et al. 2013). However, there are of course many outstanding challenges requiring further scientific research and development activities. In the following, we discuss some of these challenges, namely, those related to the instrument calibration, product validation, algorithmic improvements, masking and quality flagging, data assimilation, and application development.

20.4.1 Instrument Calibration

The calibration and validation of a satellite instrument and its derived data are some of the major tasks that have to be performed before satellite data are ready for further use. Stability of the data quality needs to be sustained in time through monitoring the instrument calibration and if necessary correcting any possible drifts. In the case of ASCAT, several measures are in place to ensure a stable instrument calibration, probably making it the best calibrated satellite sensor currently used for soil moisture retrieval. On one hand, the instrument design relies on an internal calibration system, which allows any internal instrument changes that might affect the transmitted power to be accounted for in near real time. On the other hand, an external calibration system allows the provision of an absolute calibration reference, with respect to which any further changes in the measurement system, such as variations of the antenna gain due to instrument aging, can be detected and corrected for. This absolute calibration is carried out by measuring campaigns involving the use of ground transponders, which are operated to transmit a signal that is received by the ASCAT instrument during selected satellite overpasses. The position and cross section of this signal being precisely known, comparison with that received by ASCAT allows to precisely determining the gain and the pointing of each of its antennas (Anderson et al. 2012; Figa-Saldaña et al. 2002). External calibration campaigns are carried out periodically every 2 to 3 years and each time provide an independent snapshot of the instrument absolute calibration with an uncertainty within 0.1 dB in backscatter (Wilson et al. 2010). An update of the absolute calibration is therefore not a continuous correction but introduced as a step, after careful validation of its occurrence over natural targets with known backscatter statistics, such as the rainforest or the ocean.

The retrieval of geophysical parameters from the instrument data are in many cases tuned to, or empirically derived from, a given instrument calibration. This is also the case of the ASCAT surface soil moisture data generated by WARP-NRT, which at the time of writing (December 2012) relies on a set of empirically derived model parameters using ASCAT data with an instrument calibration corresponding to the years 2007 and 2008. Introducing a new instrument calibration into the processing is therefore not straightforward and a good understanding of the expected impact of a calibration update on the geophysical parameter, in this case soil moisture, is very important. For ASCAT, NRCS changes in any of the antenna beams of the order of ±0.2 dB result in changes in surface...
soil moisture index of the order of approximately 6%–8% for most parts of the globe (see Figure 20.5), as has been shown in previous studies (Hahn et al. 2012). Areas with higher impact (up to 20%) are observed, but they correspond to tropical forested areas where the backscatter response stems from the canopy instead. As a conclusion, the effect of a change in calibration of one of the beams on the order of ±0.1 dB is difficult to observe as a soil moisture change. On the contrary, a permanent and consistent shift in the calibration of all beams beyond ±0.1 dB would, however, be problematic for climate change applications.

As a general guideline, introducing in the processing chain observed instrument absolute calibration changes in the NRCS over ±0.2 dB for any given beam or of ±0.1 dB consistently for all beams should trigger an update of the empirically derived model parameters. However, this requires reprocessing of the soil moisture time series, which cannot be done regularly, nor in near real time. What has been done in such a case, during the introduction by EUMETSAT of the 2010 NRCS absolute calibration in the operational Level 1 backscatter processing, is to adopt at the same time a so-called back-calibration in the WARP-NRT soil moisture processor. This back-calibration consists of compensating the calibration changes back to the previous calibration state in order to keep the output soil moisture series consistent and unaffected. The full benefit of the NRCS calibration update can only be taken on board through reprocessing of the soil moisture time series, at which time the NRT products can be brought up to date with the state-of-the-art instrument calibration. The frequency of such reprocessing efforts depends on the rate of calibration changes. For the ASCAT mission the analysis of the external calibration campaigns suggests that this frequency is 2 to 3 years.

20.4.2 Product Validation

The validation of the ASCAT soil moisture data is, like for any other remotely sensed soil moisture product, challenging, as there is no reference dataset that can be considered to represent the truth. When the satellite data are compared to in situ soil moisture measurements, the main problems are the significant scale gap (area representative 25–50 km data vs. point-like in situ data) and differences in soil layers (thin remotely sensed top-soil layer vs. in situ probes installed at depths of 5 cm or more), and when compared to

![Simulated soil moisture errors assuming that the absolute calibration bias is constantly 0.22 dB all over the world. (Adapted from Hahn, S. et al., IEEE Transactions on Geoscience and Remote Sensing, 50, 2556–2565, 2012.)](image-url)
modeled soil moisture data, uncertainties stem from the land surface model itself and its input data, for example, precipitation (Crow et al. 2012). Therefore scientists have put forward many different validation strategies involving, for example, the implementation of densely instrumented validation sites (Jackson et al. 2010), the organization of extensive field and airborne campaigns (Delwart et al. 2008), the simultaneous comparison to in situ and modeled soil moisture data (Matgen et al. 2012), and advanced statistical methods such as the triple collocation method (Zwieback et al. 2012b) or the $R$ metric (Crow et al. 2010). There are important lessons to be learned from all of these approaches, and clearly each approach lets us better understand the strengths and weaknesses of the satellite soil moisture data. This understanding is essential for improving the retrieval algorithms, the associated error estimates, and the quality flags as discussed in the next sections.

In many cases the different validation approaches complement and/or reinforce each other (Brocca et al. 2011; Parinussa et al. 2011a). Nonetheless, it also happens that the validation results obtained with two or more different validation approaches may disagree. There is also often a disagreement on how the obtained results are to be interpreted, which is, in particular, the case when the evidence that points to an error in the satellite retrievals is believed to be weak or in contradiction to previous results. In such situations the providers of satellite-based soil moisture data services tend to await further validation results, before engaging in algorithmic research and development to solve the identified problem.

Another problem often encountered is that results from two or more independent validation studies cannot be directly compared to each other. This is a consequence of the lack of agreed standards and best practices in the validation of satellite soil moisture data. Consequently, there are not currently any internationally agreed values for the retrieval error of ASCAT, SMOS, AMSR-E, or any of the other suited satellite sensors. This is particularly a problem for users who thus lack an important guidance for their decisions on which soil moisture data to use for which application. It is also a problem for space agencies that require target numbers for designing the next generation of EO sensors. This lack of best practices in the validation of satellite soil moisture dataset is therefore currently an important topic for several international organizations such as the Global Climate Observing System, the Global Energy and Water Cycle Experiment, the Committee on Earth Observation Satellites, and the intergovernmental Group on Earth Observation. Thanks to their efforts first international initiatives such as the International Soil Moisture Network could already be launched successfully (Dorigo et al. 2011). Nonetheless, the path toward universally agreed best practices is probably still quite long, requiring the active participation of data providers and users alike.

### 20.4.3 Algorithmic Improvements

Once sufficient empirical and/or theoretical evidence has been brought together to conclude that an algorithm, or part thereof, is suboptimal or wrong under particular environmental circumstances, data providers can start investigating new algorithms to solve this problem. Such scientific investigations can have many different outcomes. One outcome may be that the reasons behind the algorithmic problem become better understood but that, unfortunately, no solution to solve it is yet known. Another equally unsatisfying outcome may be that an algorithmic solution may exist but that it does not fit in the overall retrieval strategy applied for a given satellite soil moisture data product. In both cases, the only alternative may be to provide error fields and quality flags to mask observations affected by this issue. Finally, the scientific investigation may of course also be successful, providing an algorithm prototype that is found to work satisfactorily over the selected
Remote Sensing of Energy Fluxes and Soil Moisture Content

study sites. One may think that from here on the transfer to the operational processing framework should be reasonably fast, but unfortunately this is, in general, not the case.

As described in Section 20.2 and illustrated in Figure 20.4 for the case of the ASCAT soil moisture data services, substantial challenges are faced regarding the operational implementation and development of scientific algorithms. Independent and flexible algorithm implementations such as scientific prototypes are fundamental to the validation of the first integrated operational prototype. In the case of ASCAT soil moisture WARP-NRT, coded in C++ for performance reasons, an independent implementation in IDL was used to verify and validate its implementation. The complete process of developing the first WARP-NRT operational prototype initially off-line, validating it with respect to the scientific prototype, and integrating it into the operational environment took at least a year, which is not unusual from other experiences at EUMETSAT with similar developments.

The integration of further algorithm improvements in an already mature operational implementation can also be time consuming. Once new algorithmic improvements have been successfully implemented and validated in the scientific development environment, a smooth migration to the operational system is not always a straightforward task either. For example, differences in the software environment, operating system, programming language, or code library used in the algorithm development with respect to those used in operations may lead to problems such as incompatibility of interfaces, inconsistency of scientific results, or difficulties in system configuration and/or operability. At that time, the establishment of a common development and testing framework is therefore recommended in order to allow a controlled migration and validation of new improvements. In this context, a common shared code library constitutes one of the basic elements of such a framework, together with a version control tool, in order to keep a common track of changes. This setup allows running the same piece of code in different environments while at the same time producing results that can be directly compared, thereby reducing the costs and complexity of the overall software development, integration, validation, and implementation process. All necessary validation and testing can already be done in the off-line environment before it is committed into the operational one and the integration time is shorter, reducing the risk of having to troubleshoot recoding errors.

Once the new algorithmic updates have been integrated successfully into the operational environment, the next challenge is to prepare the users for the upcoming modifications in the product. They might use the NRT product in an operational fashion and switching to a new version is not possible instantaneously without having a strong impact on downstream data services. In this case, it is recommended to set up, when possible, a dissemination stream of the new product, in parallel to the currently operational one. This parallel dissemination phase may last several weeks, allowing users to adapt their processing environment to the modifications coming with the new product.

20.4.4 Masking and Quality Flags

The accuracy of satellite soil moisture data is affected by many environmental conditions, most notably the density of the vegetation, the presence of urban areas and open water surfaces, and the occurrence of snow and frost. To make the measurements useful to users, it is thus important to attach to each soil moisture value additional data fields describing its reliability, accuracy, and proficiency. Without any ancillary data the quality of the product remains doubtful causing exclusion for specific applications. For example, Numerical Weather Prediction (NWP) centers desire a suitable set of quality flags, which allows automatic selection of data of sufficient quality for assimilation. Hence quality screened data
are preferred at the cost of some data loss. In case of the ASCAT swath-based soil moisture product operationally produced by EUMETSAT several quality indicators are included. The necessity of these indicators comes from the fact that the retrieval is performed for every NRCS measurement acquired over land without exception, although in certain situations, for example, when snow or open water dominates the satellite footprint, a successful retrieval of soil moisture is hardly possible or even impossible. Thus an attentive masking of unreliable data is very important.

The indicators can be grouped into quality flags and advisory flags with respect to their functionality. The quality flags are directly derived from the ASCAT data and describe the intrinsic quality of the soil moisture retrieval (e.g., noise, processing, and correction flags). On the other side, the advisory flags support the user in judging the validity of the soil moisture product in those situations that could not have been identified during the retrieval because of certain limitations in the geophysical model (e.g., snow, frozen soil, topography, inundation, or wetland). Therefore these indicators originate from external datasets and complement the quality flags. However, the identification of reliable external datasets is a challenging task and depends primarily on temporal and spatial data availability. Furthermore, also property rights and operational readiness need to be clarified for those external datasets. In the simplest form, quality flags can be defined as probabilities, which are based on analysis of historical data. This elementary but practical approach overcomes some of the aforementioned issues for the NRT products. However, those probabilistic flags should not be used in favor of actual reanalysis data if, for example, users are interested in analyzing only historic time series. In other words, whenever possible the best reference dataset available shall be used in order to mask unreliable measurements, keeping in mind the limitations of the reference data as well.

20.4.5 Data Assimilation

Satellite-based surface soil moisture data are of high interest for data assimilation applications. Sensors such as ASCAT, AMSR-E, and SMOS achieve global coverage in less than 3 days, which ensures that the variability of the surface soil moisture content in time and space is captured. When EUMETSAT's ASCAT surface soil moisture product was declared operational in 2008, it was the first ever operational satellite soil moisture product. Despite the increasing availability of satellite-based soil moisture products from a range of sensors (such as SMOS and AMSR-E), ASCAT remains the only operational product of soil moisture from space for data assimilation. Its short latency makes it relevant for NRT applications, including NWP and hydrological forecast. Several operational meteorological centers, such as the Met Office, Météo-France, and ECMWF, already use ASCAT surface soil moisture data for monitoring and/or data assimilation either in operational mode (de Rosnay et al. 2012b; Dharssi et al. 2011) or for research applications (Mahfouf 2010).

Bias correction is a crucial component of data assimilation systems that ensures data assimilation corrections for random errors in the models. Most advanced data assimilation systems, which were developed by the NWP community to analyze atmospheric variables (e.g., 4D-Var approaches), rely on adaptive bias correction approaches as described in the review paper by Dee (2006). In contrast, global land data assimilation systems are decoupled from the atmospheric data assimilation systems (de Rosnay et al. 2012b), and they use simpler stand-alone bias correction approaches (e.g., Draper et al. 2011). Therefore discontinuities in the land surface model or in the observational characteristics require updating bias correction parameters used by the data assimilation systems. Hence, for
NRT applications, excellent communication and synchronization between data providers and users are critical to ensure that satellite product upgrades are well prepared before implementation and dissemination. In the future, land surface data assimilation systems will develop further in order to account for adaptive bias correction approaches similar to those used in atmospheric 4D-Var. This will make it possible to account for upgrades in surface-related satellite product more easily.

Although different data assimilation approaches are used in the community, as described by de Rosnay et al. (2012a), mainly based on Extended Kalman Filter (de Rosnay et al. 2012b; Draper et al. 2011), Ensemble Kalman Filter (Draper et al. 2012), or simple nudging (Dharssi et al. 2011; Scipal et al. 2008), they all rely on similar bias correction and quality control approaches. Appropriate use of ASCAT quality flags enables to select the best quality observations in preprocessing, which can then be used in an optimal way in the data assimilation schemes. For all these approaches, the land surface model used in the data assimilation scheme describes the physical processes that control land–atmosphere interactions, including vertical transfer of soil moisture between the surface and root zone reservoirs. Beside NWP and hydrological forecast applications, data assimilation of ASCAT surface soil moisture constitutes a physically based root zone soil moisture retrieval approach in which the observed surface soil moisture is propagated downward by a land surface model infiltration processes. In the context of the EUMETSAT H-SAF project ASCAT root zone soil moisture profile (Figure 20.6) is produced in NRT, based on ASCAT data assimilation in the ECMWF land surface data assimilation system (Albergel et al. 2012; de Rosnay et al. 2012b).

**20.4.6 Application Development**

Users interested in using satellite soil moisture data for developing specific applications such as, for example, flood prediction or agricultural management, face many scientific and technical challenges. Therefore the path from, first, considering using satellite soil moisture data to successfully applying them in specific applications normally takes years. The first challenge for users lies probably in the difficulty of changing their perception about the exploitable information content of coarse-resolution (25–50 km) satellite data such as
Satellite-Based Surface Soil Moisture Data Services

provided by ASCAT, SMOS, and AMSR-E. Indeed, for many small- to medium-scale applications (<400 km²), the spatial resolution of these soil moisture products is usually considered not sufficient, and hence many scientists simply do not take these products into account. However, this position is not justified for all small- to medium-scale applications. For instance, Brocca et al. (2012a) demonstrated that the ASCAT soil moisture product can be a valuable additional information for improving runoff prediction in small to medium catchments (<200 km²) (see Figure 20.7). Similar conclusions have been obtained by Brocca et al. (2012b) for the prediction of the displacement rate of a well-monitored landslide in central Italy. As a matter of fact, the high temporal resolution, which is going to be further increased with the recent launch of ASCAT-B, is the main added value of the ASCAT soil moisture product from the application viewpoint. Another challenge faced by users is to select the most suitable satellite product for their application. This is not straightforward because several different data products are, in general, available from just one instrument (as was discussed for ASCAT in Section 20.2); with more satellites the diversity of products in terms of their physical content and format specifications increases substantially.

Moreover, not only the spatial–temporal coverage but also the resolution and the long-term availability of the different satellite soil moisture products are important information for the users, as well as understanding how to assimilate the data into their models. In that context, guidelines about the modeling structure (one or more soil layers, equations coupling surface and root zone layers, etc.) that should be used for optimizing the use of satellite soil moisture data can be very useful. One important aspect is that many applications require the knowledge of soil moisture for the root zone, that is, for a layer depth of 1–1.5 m, while satellite data are only available for a surface layer of less than 5 cm. In these cases, the SWI product (Albergel et al. 2008; Wagner et al. 1999) or assimilated profile soil moisture data might be the better choice for many users. Nonetheless, they should be fully aware on how these value-added products are obtained, for example, in the case of SWI how to select the value of the involved parameter $T$ (characteristic time length).

![Figure 20.7](image)

**FIGURE 20.7**
(See color insert.) Comparison between observed and simulated discharge by assimilating the ASCAT-derived Soil Water Index for a sequence of 21 flood events that occurred in the Niccone basin (central Italy); the simulated discharge without assimilation is also shown as reference. The enlargement for four selected flood events is also shown in the lower panels where it highlighted the higher benefit due to the assimilation for the October and November 2005 events.
A further challenge that limits the use of satellite data by users working in environmental problems is also related to the format and the data volume. Indeed, many users are not used to work with large datasets (tens of gigabytes to terabytes), which is why it is important for satellite data providers to find the right choice between the number of meta data fields and size of the soil moisture data files. With respect to the ease of use, the availability of files in more widely known formats, for example, GEOTIFF, NETCDF, or ASCII files, may increase the number of users potentially able to use the data themselves.

20.5 Conclusions and Prospects

In this chapter the operations and challenges of satellite-based soil moisture services have been discussed based on the example of the ASCAT soil moisture data services operated by EUMETSAT in cooperation with TU Wien. Thanks to the heritage from the scatterometer flown on board of ERS-1 and ER2-2, these services are long-standing and relatively mature when compared to other satellite soil moisture data services such as the ones based on SMOS or AMSR-E. Nonetheless, as an assessment of the Bates maturity index suggests, even the ASCAT services do not yet meet all the criteria of fully operational EO data services as defined by Bates and Privette (2012). Among other aspects, moderate to significant code changes are still expected, as validation efforts and scientific investigations of new algorithms continue to show the need to further improve the ASCAT soil moisture data. Additionally, as much of the initial development of these services relied on research funding, there are still a few general systems engineering tasks pending, for example, related to the handling of metadata or the completeness of the documentation. Fortunately, the services became part of the EUMETSAT Satellite Application Facility (SAF) on Support to Operational Hydrology and Water Management (H-SAF) in 2012, which provides a stable framework for improving the operational aspects of these services step by step in the coming years.

The experiences from the ASCAT soil moisture data services illustrate that the efforts required to move from a pure science-based dataset to an operational EO data service are much more extensive than what most scientists would expect. Scientists should be mindful of the complexity of the retrieval approach they choose, as with an increasing complexity of the algorithms the costs of the operational implementation and running of these services increase quickly. The same is true if data from several input data sources are needed. High algorithmic complexity and input data requirements may also imply that, once the EO service is operational, algorithm developers lose their scientific agility as any change in the algorithms may generate overproportionally high costs in the implementation. This helps understanding why the algorithms used for generating the different satellite soil moisture products do, in general, not undergo any significant changes any longer once the services are operational. In fact, if the required changes are too significant, then it may be better to abandon the original algorithms altogether, replacing them with new algorithms, although that normally requires substantial effort in software implementation.

Fortunately, the basic soil moisture retrieval algorithm of the ASCAT soil moisture NRT services is a mathematically simple change detection algorithm that only requires the ASCAT data as input (Wagner et al. 1999). External data sources are currently only used for data masking and quality control. As a result, it has been possible to implement
these services relatively quickly, with the NRT ASCAT soil moisture data service being declared operational only about 2 years after the launch of METOP-A. With an increasing understanding of the strength and weaknesses of the product, it will now also be possible to improve selected parts of the algorithm and processing chain step by step. Planned improvements relate to the introduction of snow and frost detection algorithms, an adaptation of the algorithm over deserts and barren land, and enhanced vegetation correction methods. These algorithmic updates will require the use of external data sources such as NWP forecast fields to support the detection of freeze/thaw events or the use of satellite derived leaf area index data to improve the modeling of vegetation effects. Such improvements will have a strong impact on the complexity of the ASCAT processing environment, which is why any complex algorithmic upgrade will only be considered if positive effects on the quality of the data are clearly demonstrated.

Most of the challenges faced by the ASCAT soil moisture data service equally apply to the other satellite soil moisture services (SMOS, AMSR-E, etc.). Fortunately, there is a lot to be learned from each, which will ensure that all of these data services will improve step by step. The most obvious benefit from a cooperation of the different satellite teams lies in the joint validation of the satellite products, eventually leading to more standardized validation protocols. Furthermore, the insights gained from joint validation work will help to better characterize the instrument calibration, the scientific algorithms, and the service specifications. It can thus be expected that the overall quality of the soil moisture services (retrieval accuracy, error characterization, accessibility, ease of use, etc.) based on ASCAT, SMOS, AMSR-E, and other microwave instruments will improve significantly in the coming years.

A direct consequence of these service improvements is that the soil moisture data retrieved from the different satellite instruments will become more similar, a trend that could already be noted in the last few years (de Jeu et al. 2008). This will not only facilitate the use of these data but also open the possibility to create a range of merged soil moisture products designed for specific applications. The good correspondence between some soil moisture datasets has in fact already made it possible to merge these to create long-term soil moisture data series suitable for climate change studies (Dorigo et al. 2012; Liu et al. 2012; Wagner et al. 2012). Furthermore, one can expect to see more and more soil moisture datasets derived from multi-instrument observations that aim to exploit the complementary information content of active and passive remote sensing data acquired in the visible, infrared, and microwave domain of the electromagnetic spectrum (Kolassa et al. 2012; Piles et al. 2011). All this taken together shows that the prospects of satellite-based soil moisture data services are extremely good and that, consequently, the number of scientific and operational users of these services can be expected to grow rapidly in the next years.

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