ASCAT Soil Moisture: An Assessment of the Data Quality and Consistency with the ERS Scatterometer Heritage

VAHID NAEIMI, ZOLTAN BARTALIS, AND WOLFGANG WAGNER
Institute of Photogrammetry and Remote Sensing, Vienna University of Technology, Vienna, Austria

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ABSTRACT

This article presents a first comparison between remotely sensed surface soil moisture retrieved with the European Remote Sensing Satellite-2 (ERS-2) scatterometer (SCAT) and the corresponding product provided by the Advanced Scatterometer (ASCAT) on board Meteorological Operation satellite (MetOp), the first of a series of three satellites providing, among other things, continuity of global soil moisture observations using active microwave techniques for the next 15 yr. Three months of collocated 2007 data were used from the SCAT and ASCAT, limited to two study regions with different land cover composition. The result of the assessment is satisfactory and ensures consistency of migrating soil moisture retrieval from the long-term SCAT dataset to ASCAT measurements. The influence of a shift of observation incidence angle ranges between the two instrument generations was not found to be significant for the soil moisture retrieval. The correlation coefficients ($R$) between two relative soil moisture (normalized water content) datasets compared in different incidence angle ranges are around 0.90 with root-mean-square error (RMSE) values in the order of 8.5. Results are expected to improve slightly further once the calibration of the ASCAT instrument is finalized.

1. Introduction

Microwave sensors on board remote sensing satellites offer an attractive and relatively direct way of measuring soil moisture, thanks to the strong relationship between soil moisture content and the soil dielectric constant. In contrast to pointwise in situ measurements, satellite-borne instruments delivering measurements integrated over larger areas are better suited for hydrological studies of entire catchments or geographical regions. Yet to date, because of the complexity of the interaction of microwaves with the earth's surface, retrieval methods have been mostly experimental and limited to certain climatic regions.

One of the long-term global remotely sensed soil moisture datasets available today is the dataset derived from European Remote Sensing Satellites 1 and 2 (ERS-1) and (ERS-2) scatterometers (SCATs; coarse-resolution radar instruments with superior radiometric accuracy), using a soil moisture retrieval algorithm developed at the Vienna University of Technology (TU Wien) based on a change-detection method initially presented by Wagner et al. (1999). As an improved successor of the ERS SCATs, the Advanced Scatterometer (ASCAT) instrument flies on the Meteorological Operation (MetOp) series of satellites and, thanks to the good transferability of the soil moisture retrieval method, will ensure operational continuity of coarse-resolution (25–50 km) scatterometer-based global soil moisture data for the next 15 yr (Bartalis et al. 2007).

The overall quality of a long-term, combined soil moisture dataset from SCAT and ASCAT depends highly on the absolute and relative calibration of the two generations of instruments. In this article, we compare soil moisture data retrieved from SCAT on board ERS-2 and ASCAT for the period March–May 2007. Already it is worth pointing out the preliminary nature of the results mainly because the ASCAT instrument was still in the commissioning phase during the period of the study, meaning that its calibration was not a final one. The following section will summarize the differences between the geometry and functionality of the two instruments, and section 3 will give an overview...
of the soil moisture retrieval method. The soil moisture intercomparison itself is outlined and discussed in section 4. It should be noted that the objective of this study is the evaluation of the robustness of the TU Wien retrieval algorithm in response to two different raw data inputs, the SCAT and ASCAT scatterometers, respectively, rather than validation of the retrieved soil moisture products.

2. Scatterometers on board ERS and MetOp

Scatterometers are originally designed for indirectly determining wind stress over oceans by measuring the radar backscattering coefficient ($s_0$) from the wind-induced water ripples and waves. The principle of both scatterometers on board ERS and MetOp is similar: three radar antenna beams illuminate a continuous ground swath at three different azimuth angles (45°, 90°, and 135° sideward from the direction of the satellite motion). The result is a triplet of spatially averaged $s_0$ values for each location along the swath. For both the SCAT and ASCAT instruments, the measurements have a 50-km spatial resolution along and across the swath, with ASCAT delivering an additional 25-km resolution product with experimental status (not used in the present study). ASCAT also features a symmetrical second swath (see Fig. 1), which practically increases its temporal sampling capabilities to double that of the SCAT—this is, on average 0.8 to more than 5 passes per day, depending on latitude (Bartalis et al. 2005; Gelsthorpe et al. 2000). Because of the significant width of the swath, the $s_0$ measurements come not only at three different azimuth angles (six in the case of ASCAT) but also at various incidence angles ranging from 18° to 59° for SCAT and from 25° to 64° for ASCAT. The C-band radar frequency used by both instruments is practically the same (5.300 and 5.255 GHz for SCAT and ASCAT, respectively). ERS and MetOp are sun-synchronous polar-orbiting satellites and fly at an altitude of about 800 km above the earth’s surface. For both satellites, it takes about 100 min to complete one orbit. The descending and ascending equator crossings occur at about 1030 and 2230 mean local solar time (LST) for ERS and at about 0930 and 2130 for MetOp, respectively. A more detailed description of the two instruments is given in Attema (1991) for the SCAT and Figa-Saldana et al. (2002) and Gelsthorpe et al. (2000) for ASCAT.

3. The soil moisture retrieval method

As the scatterometer sweeps over the land surface, the resulting backscattering coefficient $s_0$ consists of contributions from parameters such as topography, surface roughness, vegetation and surface soil moisture content. The intensity of $s_0$ measured by the scatterometer naturally depends also on the observation incidence angle. Figure 2 illustrates the $s_0$ versus incidence angle $\theta$ relationship separately for SCAT and ASCAT over the selected regions shown in Fig. 3 and during March–May 2007. In the TU Wien soil moisture retrieval method, $s_0(\theta)$ measurements are normalized to a reference incidence angle (set to $\theta = 40°$) after modeling the behavior of $s_0$ versus $\theta$ (Wagner et al. 1999).

In a change-detection approach based on time series analysis, it can be assumed that the topography and surface roughness factors undergo insignificant changes during the yearly cycle and thus are responsible for a constant contribution to the backscattering coefficient. Vegetation does change, however, which usually leads to seasonal changes in $s_0$ as a result of volume scattering.
in canopies, foliage, and so on. In the soil moisture retrieval method discussed in the present study, the yearly cycle of vegetation is semiempirically modeled by determining the long-term seasonal behavior of the $\sigma^0$ versus $\theta$ relationship, based on ERS-1–ERS-2 SCAT $\sigma^0$ acquisitions during more than 10 years (1991–2007) and resampled into time series for each location on a discrete global grid. Once the seasonal variation of vegetation is known at each location for the reference incidence angle, its contribution can be eliminated from backscatter normalized to that reference angle. What is left in the backscattered signal is the contribution of surface soil moisture due to the large difference in dielectric constant between dry and wet soil. By scaling normalized backscatter between its historically lowest and highest values, a relative measure for surface soil moisture is obtained, ranging from 0 (the dry condition reference) to 100 (the wet condition reference). The method also provides corrections of the backscatter for possible azimuthal anisotropies (additional variations in $\sigma^0$ according to look angle) and for certain (arid) regions where no saturated wet conditions had been registered during 1991–2007, prompting for the replacement of the historically highest values with values derived from external datasets.

More details about the soil moisture retrieval algorithm are found in Wagner (1998), Wagner et al. (1999), and Scipal (2002). Some validation studies can be found in Wagner et al. (2003), Dirmeyer et al. (2004), Ceballos et al. (2005), Dirmeyer et al. (2004), Scipal et al. (2005), Pellarin et al. (2006), and Fontaine et al. (2007).

4. Soil moisture comparison between SCAT and ASCAT

Because of the very similar geometry and functionality of the SCAT and ASCAT instruments, the retrieval of ASCAT soil moisture could ideally take place in a straightforward fashion by processing ASCAT $\sigma^0$ values in conjunction with the long-term scattering parameters of ERS-1–ERS-2 SCAT (dry and wet references and parameters describing vegetation seasonality, among others). The quality of such ASCAT soil moisture will, however, depend on factors such as the

**FIG. 2.** SCAT and ASCAT backscattering coefficients vs respective incidence angles measured over the studied regions (a) A and (b) B during March–May 2007.

**FIG. 3.** Study region locations and land cover (USGS 1999).
possible presence of biases between the SCAT and ASCAT $\sigma^0$ values, as well as the not entirely overlapping incidence angle range of the two instruments.

In this section a cross comparison between SCAT and ASCAT soil moisture was performed, looking at how the two datasets relate when compared in different circumstances (different land cover, incidence and azimuth angles, and so on). Because of the limited geographical coverage of ERS-2 after 2003 (Crapolicchio et al. 2007), the comparison had to be limited to two selected regions located in North America and West Africa (Fig. 3). More importantly, though, a final assessment was not yet possible because of two main reasons. First, at the time of the study, the backscattering coefficients delivered by ASCAT had only been preliminarily calibrated, with full reprocessing of the dataset expected after the end of the instrument commissioning phase. Second, the ASCAT soil moisture data was derived using the same ERS-1–ERS-2 SCAT long-term scattering parameters from 1991 to 2007 as was used in the case of the SCAT soil moisture. It will take a few years into the MetOp mission before enough ASCAT data are gathered to update the scattering parameters and balance out any probable biases toward SCAT data.

The first study region (Fig. 3a) in North America (region A) was chosen for its land cover diversity (crop-, grass-, and shrubland, and different forest types); its large water areas are excluded from the analysis. Also, a conservative snow climatology based on Special Sensor Microwave Imager (SSM/I) data (Nolin et al. 1998) was used to mask out $\sigma^0$ triplets that are likely to be affected by snow cover. Region B (Fig. 3b) consists of the semi-arid Sahel area of West Africa as well its extensive savannas and some tropical forests along the Atlantic coast. In the north, the region also comprises some Saharan sand desert areas.

To illustrate the temporal sampling capabilities of both instruments as well as the variability of surface soil moisture in time, Fig. 4 shows an example of time series for both SCAT and ASCAT datasets at a location (Fig. 3, cross symbol) in northern Iowa. This area is categorized as cropland–pasture (USGS 1999). To obtain meaningful correlations between the two datasets, time series such this one were checked for SCAT–ASCAT acquisition pairs separated by no more than one hour. A total of 96 650 and 77 527 such acquisition pairs were found within the period of study for regions A and B, respectively. Figure 5 shows as an example of the spatial patterns of soil moisture retrieved from SCAT and ASCAT for the regions A and B.

Despite the aforementioned preliminary calibration of ASCAT, comparing original $\sigma^0$ values separated by at most 1° incidence angle yields a very high correlation (scatterplots in Fig. 6), an encouraging (and somewhat expected) sign for the good consistency between the two sensors. For high backscatter ranges, some small biases are noticeable in the fore and aft cases. The triplet-wise difference $\delta = \sigma^0_{\text{fore}} - \sigma^0_{\text{aft}}$ between the fore and aft beam $\sigma^0$ values (measured under the same incidence angle because of instrument geometry) can be considered a good measure of the noise level of the individual $\sigma^0$ measurements; this level also includes the backscatter dependency on the azimuth angle (Early and Long 1997; Naeimi et al. 2007). For the three months of this study, the computed standard deviation of $\delta$ for SCAT measurements (presumed to be well calibrated) is 0.34. This value matches the three RMSE values of 0.29, 0.35, and 0.35 in Fig. 6 very well, meaning that, at least for this
study region, the calibration of ASCAT can be considered close to final.

In Fig. 7a, relative soil moisture values acquired with SCAT and ASCAT are compared. The correlation coefficient is about 0.92 and the RMSE is 8.42, which is comparable to the approximately 10% noise level characterizing the retrieval method over nonforested temperate and tropical climates; this is equivalent to the 0.03–0.07 m³m⁻³ volumetric soil moisture accuracy between the wilting level and the field capacity obtained by Wagner et al. (2003).

Figures 7b and 7c show the relationship in Fig. 7a separated according to morning (descending) or afternoon (ascending) passes. No significant difference can be seen in either the correlation coefficient $R$ or RMSE, which is expected because the acquisition time should not have any influence on the performance of the instruments.

As mentioned in section 2, the incidence angle range of the two instruments does not overlap entirely. Research about ocean wind direction retrieval after the launch of the ERS instruments prompted an increase of the incidence angle range of ASCAT (Figa-Saldana et al. 2002). Figures 7d–g give a first impression of the effects of the increase in incidence angle range on the soil moisture retrieval algorithm. In terms of the instrument midbeams, the design differences result in

**FIG. 5.** Examples of soil moisture spatial patterns observed by (top) ASCAT and (bottom) SCAT: (a) North America and (b) West Africa.

**FIG. 6.** Relationship between SCAT and ASCAT backscattering coefficients $σ^0$(dB) for region A limited to $\leq 1^\circ$ difference in incidence angle for (a) fore beams, (b) midbeams, and (c) aft beams.
FIG. 7. Relationships between SCAT and ASCAT surface soil moisture (percent) for region A for (a) all measurements; (b) ascending passes only; (c) descending passes only; (d) incidence angles limited to the midrange (25°–47°); (e) incidence angles limited to the near and far ranges (18°–25° for ERS; 47°–53° for ASCAT); (f) incidence angles limited to the mid- and far ranges (25°–47° for ERS; 47°–53° for ASCAT); (g) incidence angles limited to the near and midranges (18°–25° for ERS; 25°–47° for ASCAT); (h) incidence angle difference ≤1°; (i) incidence angle difference >1°; (j) azimuth angle difference ≤5°; (k) azimuth angle difference >5°; and (l) azimuth angle difference ≤5°, and incidence angle difference at ≤1°. All incidence and azimuth angles refer to the midbeams of both instruments.
three incidence angle ranges: a near range \((18^\circ - 25^\circ)\) for the SCAT only, a common midrange \((25^\circ - 47^\circ)\), and a far range \((47^\circ - 53^\circ)\) for ASCAT only. As expected of the four very similar images, Fig. 7d, when only comparing surface soil moisture for the common incidence angle range, has the highest correlation coefficient and the lowest RMSE. The extreme case of comparing the two nonoverlapping ends of the incidence angle range (Fig. 7e) results in the lowest correlation and highest noise. The two intermediate cases, when comparing soil moisture from the common incidence angle with the two nonoverlapping ends of the range separately (Figs. 7f and 7g), display similar and intermediate values. Overall, no significant anomalies are observed between the four scatterplots, thus prompting for a reassessment of the reasonable robustness of the retrieval method over the incidence angle range. The final confirmation will arrive once more data is processed and the (incidence angle dependent) ASCAT calibration offsets are in place. As additional evidence that correlation does not increase significantly with decreasing incidence angle difference, a scatterplot where the incidence angle differences are limited to at most \(1^\circ\) is shown in Fig. 7h, with results similar to Fig. 7i. Furthermore, even though the noise of the soil moisture pairs with incidence angle differences more than \(1^\circ\) (Fig. 7i) is marginally higher, it is still of acceptable magnitude.

Because ASCAT exhibits a second swath, the number of azimuth angles under which it carries out measurements is up to 12 (three beams in two swaths in both ascending and descending pass directions) compared to 6 for the SCAT. For the additional six azimuth angles of ASCAT, no azimuthal normalization of \(\sigma^0\) can be performed before the acquisition of a statistically meaningful amount of ASCAT data. For comparing differences in soil moisture that this discrepancy might induce, reasoning similar to the one separating the incidence angles was used. Figure 7j shows the now familiar soil moisture scatterplot, this time with differences in azimuth angle limited to \(5^\circ\) at most. For the considered study region A (at a not-too-high latitude), this limitation effectively eliminates data originating in the additional (left) swath of ASCAT and avoids mixing soil moisture from ascending and descending passes. A scatterplot of all the other soil moisture pairs (azimuth angle difference larger than \(5^\circ\)) is shown in Fig. 7k. Although the correlation and noise levels are superior for the former image, the two plots are not very different. The best correlation of all the surface soil moisture scatterplots is featured in Fig. 7l, where both azimuth and incidence angles have been limited to at most \(5^\circ\) and \(1^\circ\), respectively.

As far as region B (West Africa) is concerned, the three months of this study fall into the period of the year with constantly low precipitation, a fact demonstrated by the significantly lower dynamic range of the soil moisture when compared to the North American case. Also, the original \(\sigma^0\) values are typical of more arid regions, with values centered \(-15\) dB (Fig. 8). Some biases are visible in all three beams. Compared to region A, the correlation is practically identical but the RMSE levels are higher. Still, the three noise values of 0.54, 0.55, and 0.43 compare very well with the standard deviation of \(d\) values of SCAT for this region, which is computed as 0.41.

An additional source of noise in region B are the sand desert areas, which often display very strong azimuthal effects as a result of volume scattering in very dry substrata or scattering in the Bragg domain, caused by wind-induced small-scale terrain features (Bartalis et al. 2006). The influence of this noise becomes clear when soil moisture values are plotted separately according to how they agree in the azimuth angle at which they were observed (Figs. 9b and 9c). Both correlation and noise degrade when the azimuth angle difference is not limited to \(5^\circ\) with clearly noticeable clusters of soil moisture pairs with larger azimuthal differences.

As a final note, Fig. 10 points out the importance of keeping the observation time difference of the two sets of soil moisture measurements as small as possible when
wanting to perform meaningful correlation studies. For region A, the observation time difference threshold was varied between 1 and 60 h and the corresponding $R$ and RMSE values for the SCAT–ASCAT collocated soil moisture pairs were computed. The very dynamic nature of surface soil moisture is demonstrated by the large negative rate of change of the correlation versus time relationship, with the RMSE values increasing correspondingly. After approximately 12 h difference in observation times, the correlation coefficient drops from 0.92 to below 0.80 and the RMSE values increase from 8 to above 12.

5. Conclusions

Although at the time of the present study the calibration of the ASCAT instrument was not final, the three-month long comparison to soil moisture derived from ERS-2 SCAT showed positive results. In terms of temporal sampling and operational continuity, ASCAT clearly outperforms its predecessor. Differences in the geometry and operation principles of the two sensors are small and the soil moisture derived from them is satisfactorily consistent, especially in the North American study region. In the semiarid West African region, the conditions were in general constant and dry during the study period, meaning a smaller dynamic range. This and the known azimuthal anisotropy effects in the region induced higher uncertainties in the comparison. A general average value of the goodness of the match between the two relative soil moisture datasets would be a correlation coefficient of 0.90 and a root-mean-square error in the order of 8.5. It has also been shown that the increase in the acquisition incidence angle range of ASCAT compared to SCAT has no significant effect on the performance of the soil moisture retrieval algorithm. Also, the issue of (and a note of warning for) the high temporal dynamics of surface soil moisture has been raised, yielding a fast decrease of the correlation between the datasets while the difference in acquisition time increased.

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