ACCURACY AND STABILITY REQUIREMENTS OF ERS AND METOP SCATTEROMETER SOIL MOISTURE FOR CLIMATE CHANGE ASSESSMENT

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ABSTRACT

Soil moisture is one of the Essential Climate Variables (ECVs) urgently required for assessing impacts and feedbacks of global warming on the land surface. Recent advances in algorithm development have made it possible to retrieve soil moisture from operational microwave radiometers (SMMR, SSM/I, AMSR-E, Windsat, etc.) and scatterometers (ERS Scatterometer, Metop ASCAT). Thus it is now for the first time possible to construct multi-decadal soil moisture time series, whereas the accuracy and the spatio-temporal resolution of the retrieved soil moisture data improve in general over time. In this article we will discuss the long-term stability of soil moisture data derived using the C-band scatterometer on board the two ERS satellites (1991−present) and the Advanced Scatterometer (ASCAT) on board the three Metop platforms (2006−2020). The usefulness of scatterometer soil moisture time series for registering geophysically meaningful long-term trends is highly dependent on the calibration stability of the backscattering coefficient measurements from which they originate. We also revisit the presumably perfect volume scattering properties of tropical forests and thus their suitability for radar sensor vicarious calibration. We discuss the effects of the calibration differences between the two scatterometer generations and make some recommendations to improve the long-term consistency of the combined soil moisture data set.

1 INTRODUCTION

The importance of soil moisture in controlling the energy fluxes and water exchange between land and atmosphere is incontestable. Together with snow cover, it is the most important component of meteorological memory for the climate system over land [1]. Soil moisture has thus been declared an Essential Climate Variable (ECV): its long-term, global characterisation is required for assessing the impacts and feedback mechanisms of global warming on the land surface. Some authors have suggested 30 years as the minimum data length for observing trends in the hydrologic cycle [2]. With the gradual appearance of remotely-sensed soil moisture products from operational microwave radiometers (SMMR, SSM/I, AMSR-E, Windsat, etc.) and scatterometers (ERS Scatterometer, Metop ASCAT), the overall accuracy and spatio-temporal resolution and coverage of available soil moisture datasets has been improving over time. Therefore, the confidence of merging various products to obtain multi-decadal soil moisture time series has also been steadily increasing. With the successful launch of the Soil Moisture and Ocean Salinity (SMOS) mission in November 2009, the same multi-mission synergy approach could present the opportunity to critically assess the accuracy of soil moisture data derived using a novel L-band interferometric radiometer which was especially designed to measure soil moisture with high accuracy.

In this paper we will focus on soil moisture time series derived using the C-band scatterometer on board the two ERS satellites (in orbit since 1991) and the Advanced Scatterometer (ASCAT) on board the three Metop platforms (2006−2020). Soil moisture is retrieved using the methods developed by Vienna University of Technology (TU Wien) [3-5]. The algorithm makes strong use of change detection, and is, as such, highly dependent on the relative and absolute calibration of the scatterometers. While many studies have already assessed the accuracy of these soil moisture data for particular regions or time periods, little is yet known about the long-term stability of the derived soil moisture data. An essential precondition for reliably detecting long-term trends in Level 2 soil moisture (e.g. expressed in % volumetric soil moisture per decade) is a stable calibration of the scatterometer Level 1 product (σ^0, backscattering coefficient expressed in dB).

In the following sections we present three small studies carried out to better understand the long-term stability and comparability of data originating in the ERS and ASCAT scatterometers.

2 ERS-ASCAT BACKSCATTER COLLOCATION STUDY

In terms of instrument geometry the ERS and ASCAT scatterometers are very similar: they both measure σ^0 as a function of incidence angle θ and azimuth angle φ. For the Level 1 product, measurements from both instruments come at locations in a swath grid (so-called *nodes*) arranged as a square lattice with a fixed

Proc. 'ESA Living Planet Symposium', Bergen, Norway
28 June – 2 July 2010 (ESA SP-686, December 2010)

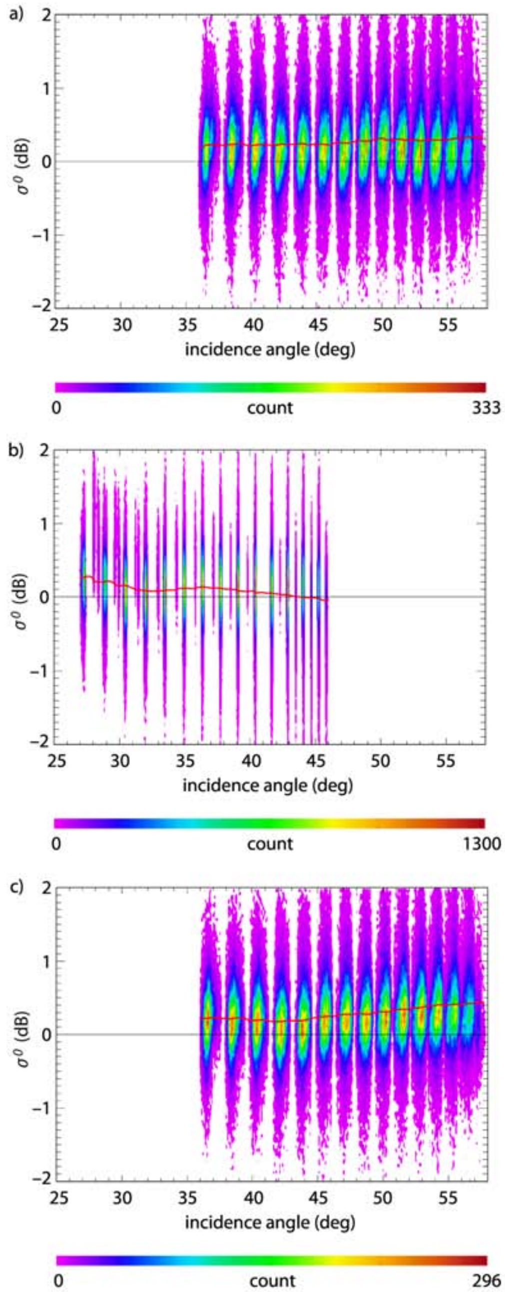

Figure 1. Collocated ASCAT – ERS-2 σ^0 differences according to incidence angle for a) fore , b) mid and c) aft beams. The red lines indicate moving average values with a window width of 5°.

width and a length increasing as the platform advances. For each overpass, every node will actually hold a σ^0 triplet, thanks to sets of three side-looking antennae, denoted fore, mid and aft. The nominal Level 1 product for both instruments has a spatial resolution of 50 km, whereas the orbit inclinations and ascending node times are comparable [6-12].

After the launch of the first ASCAT instrument on board Metop-A in late 2006, the ERS-2 continued operating even though it had suffered a number of problems, particularly the loss of its data recorder (meaning its coverage is now limited to areas close to a number of receiving stations) and the loss of stabilisation gyros (which in the meanwhile has been satisfactorily corrected for, at the cost of more complex data processing) [13-15]. It should thus be possible to collocate ERS-2 and ASCAT σ^0 measurements taken almost simultaneously and under almost the same observation geometry. To do this, we selected pairs of ERS-2–ASCAT σ^0 values from 2007–2008 that fulfilled the following conditions:

- maximum distance between the observed pairs: 12.5 km;
- maximum difference in θ : 1° ;
- maximum difference in φ : 5° ;

For ERS-2, values from the Wind Scatterometer Fast Delivery Product were used [16], after having eliminated σ^0 duplicates due to reception of the same data by two or more receiving stations. The ASCAT σ^0 data was reprocessed by EUMETSAT following calibration with all three ground-based transponders during early 2008.

The above conditions are met periodically (approximately every 9 days), with ASCAT measurements occurring practically always around 1 hour earlier than the ERS-2 ones. Obviously, the collocation is only possible for the common geographical coverage and incidence angle range of the two instruments, and only for the right swath of ASCAT. All occurrences of σ^0 pairs were included, without separating between land and sea. Figure 1 shows the beam-wise (fore, mid, aft) collocated σ^0 differences between ASCAT and ERS-2 against incidence angle. On average, ASCAT σ^0 seems approximately 0.22 dB higher than ERS values. Furthermore, fore- and aft beam σ^0 differences increase with increasing θ while mid-beam differences decrease.

Figure 2 shows the collocated σ^0 values as a scatterplot. The differences seem to increase slightly with decreasing backscatter.

3 SOIL MOISTURE DEPENDENCY ON INCIDENCE ANGLE

A good way of comparing the calibration of the two generations of instruments is by computing long-term node-wise averages of surface soil moisture in the along-track direction. This effectively reveals any biases in surface soil moisture m_s according to incidence angle θ. Ideally, the averaged $m_s(\theta)$ function should be constant, or at least its shape for data from the different instruments should be similar. Figure 3 a) and b) show the monthly averages of $m_s(\theta)$ for ERS-1 (January

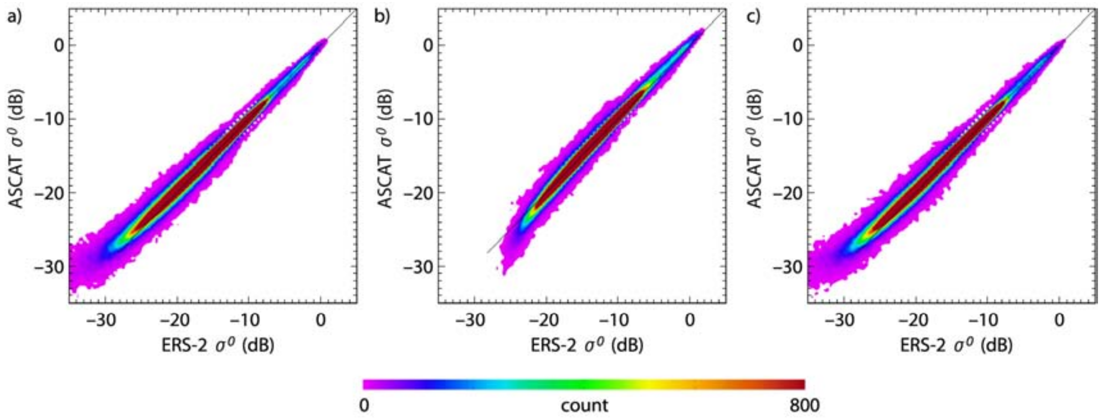

Figure 2. Collocated ERS-2 – ASCAT σ^0 *scatterplot for the a) fore-, b) mid- and c) aft beams.*

1992 to December 1995) and ERS-2 (January 1997 to December 2000) respectively. Several observations can be made from the images. Firstly, the global surface soil moisture seems to describe a yearly cycle, with highest values in summer (July–August) and lowest in winter. This is in agreement with the position of the Earth's land masses predominantly in the northern hemisphere, where summer rains occur frequently, and where winter frost often means lower backscatter values.

Secondly, ERS-1 and ERS-2 apparently had a slightly different calibration: although in both cases the overall yearly average surface soil moisture is reasonably constant and around 38%, the incidence angle behaviour is clearly different from one instrument to the other. In addition, the ERS-1 values seem to have less variability than those of ERS-2. Note at this point the importance of including a comparable amount of data from each month of the year when computing the yearly average.

Thirdly, the similarity in shape of the different monthly curves for one and the same instrument hints towards the consistent seasonal normalisation of σ^0 with respect to a reference incidence angle, which in the scatterometer soil moisture retrieval algorithm is chosen to be 40°. This means that even if the normalisation is not equally efficient at all incidence angles, at least it seems to perform equally good (or bad) for all seasons.

The monthly curves for April–May 1996, when there was an overlap in ERS-1 and ERS-2 operation, are shown in Figure 3 c). The incidence angle behaviour is similar to cases a) and b). Interestingly (and rather conveniently), the curve resulting from averaging $m_s(\theta)$ functions from both ERS scatterometers is more constant than the individual ERS-1 and ERS-2 averages.

As already mentioned, more recent ERS-2 scatterometer data have been affected by acquisition problems, effectively reducing the data coverage to regions around a number of receiving stations, mainly in the northern hemisphere. Two years worth of monthly averages (January 2007 to December 2008) are displayed in Figure 3 d). The shape of the curve is preserved from the earlier stage of the mission, but the overall average is around 4 percentage points higher. The exact reason for this increase is not clear: it could be related to 1) different instrument calibration and/or 2) the aforementioned reduction in the geographical measurement area and/or 3) actual climatological changes in global soil moisture since the period 1992–2000.

Using the same ASCAT data as in the previous section, we also computed the equivalent ASCAT $m_s(\theta)$ curves, separately for both the left and right swaths of the instrument (Figure 4). The functions are hardly constant, displaying an abrupt decrease in soil moisture with increasing incidence angle. The left and right beam behaviour is relatively symmetric, with a small "wiggle" observed in the right swath. Similarly to the ERS case, the yearly average curve follows closely the curves for October. An attempt to average the curves over the incidence angle range puts the ASCAT yearly cycle about 7–8 percentage points higher than the ERS-1/2 curves for 1992–2000. This means that, unless the difference is geophysically meaningful, successful merging of data from the two generations of sensors cannot be done without prior careful cross-calibration. Nevertheless, after having seen the σ^0 biases in Figure 1, this should in no way be surprising.

4 GAMMA-NOUGHT OVER TROPICAL FORESTS

To reduce the dependency of σ^0 on the observation incidence angle θ, it is common practice to define $\gamma^0 = \sigma^0 / \cos\theta$. For targets displaying strong volume scattering, this new variable should be conveniently constant.

The explanation to the discrepancies in incidence angle behaviour between the ERS and ASCAT scatterometers may lie in what was highlighted at the latest ASCAT Science Advisory Group (SAG) meeting held at EUMETSAT in October 2009. There it was noticed

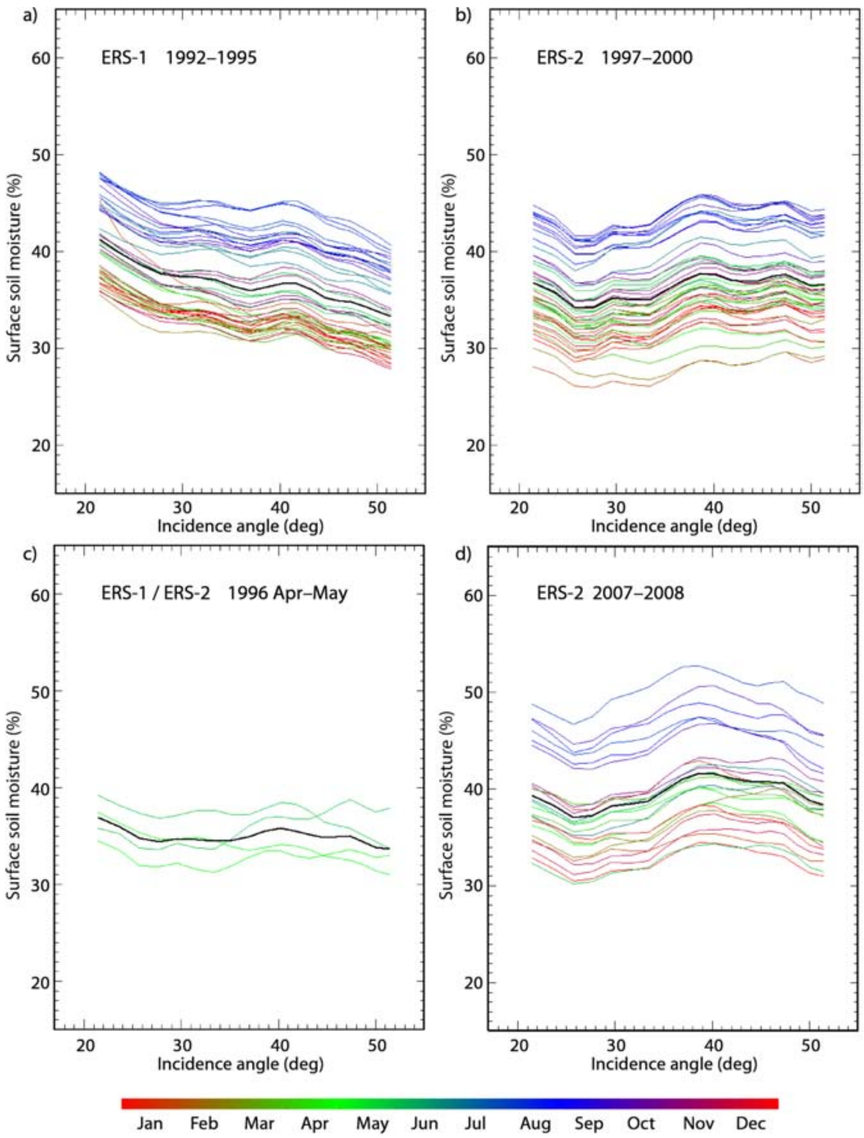

Figure 3. Monthly global average surface soil moisture (volumetric %) vs incidence angle for a) ERS-1, 1992–1995; b) ERS-2, 1997–2000; c) ERS-1 and ERS-2 for 1996 April–May; d) ERS-2, 2007–2008. Black lines indicate the overall average of the monthly curves

that the two instrument generations undergo somewhat different calibration procedures: ASCAT is calibrated using ground-based transponders only (located in Turkey), whereas the ERS scatterometers were calibrated using a combination of transponder measurements and vicarious calibration using tropical forest as a natural reference target. As a result, the ERS scatterometers depicted tropical forest as a perfect volume scatterer, with γ^0 being practically constant over the whole incidence angle range, while for ASCAT γ^0 decreases from near to far range by about 0.6 to 0.8 dB (Figure 5, based on the same ASCAT data as in the previous sections). While within instrument specifications, this is nevertheless an important factor to consider for long-term trend studies. As a matter of fact, simulations with the soil moisture processor based on long-term scattering parameters from ERS have shown that an increase of σ^0 of 0.2 dB equally and separately for each of the scatterometer beams results in an increase of surface soil moisture of around 5–6 percentage points. As a γ^0 difference (in decibels) is equivalent to the same decibel difference for σ^0, this could explain the systematically low soil moisture values at high incidence angles observed in the previous section.

5 CONCLUSIONS AND OUTLOOK

In this article we presented some preparatory work to support the merging of backscatter and soil moisture

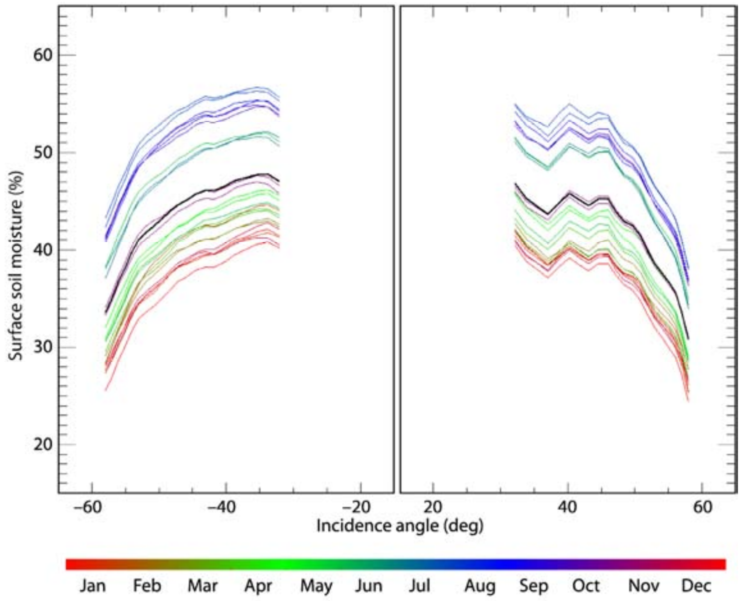

Figure 4. Monthly surface soil moisture vs incidence angle behaviour for ASCAT during 2007–2008. Black lines indicate the overall average.

time series from the ERS scatterometers and ASCAT. This is of interest especially in the light of long-term soil moisture variations being used as a climatological indicator. Merging data from the different instruments cannot be done without understanding the effects of the calibration differences. Our preliminary findings indicate that further cross-calibration between ASCAT and the ERS scatterometers is needed and not necessarily trivial. For the period 2007–2008, the collocation study shows that, at least for the common incidence angle range, ASCAT σ^0 values are on average approximately 0.22 dB higher than those of ERS-2. This is confirmed also by the $m_s(\theta)$ study, where ASCAT soil moisture is systematically higher than its ERS-2 equivalent. The latter observation could nevertheless also be influenced by the reduced availability of ERS-2 data over much of the Earth land surface for these two years.

Furthermore, the average 2007–2008 soil moisture from ERS-2 seems in turn slightly higher than the soil moisture measured by ERS-1 and ERS-2 during 1992–2000. In this case the climatological effects might not be negligible.

Another ERS–ASCAT discrepancy is the not constant nature of the ASCAT $m_s(\theta)$ functions While the equivalent functions for ERS-1 and ERS-2 are not entirely constant themselves, and do not overlap perfectly,

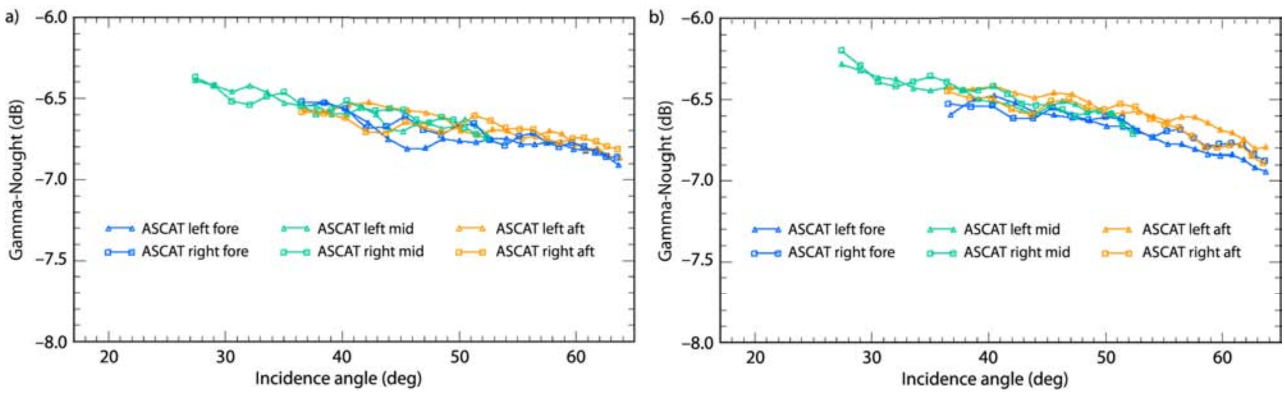

Figure 5. Gamma-Nought (dB) vs incidence angle behaviour for ASCAT over the Amazon tropical forest area for a) ascending and b) descending passes. The considered rectangular area extends between latitude [–5., –2.5], longitude [–70., –60.5].

$m_s(\theta)$ for ASCAT shows a more pronounced decrease towards the higher end of incidence angles. The difference in soil moisture between the inner and outer edges of the swaths is 13–15 percentage points. The most affected incidence angle range is the one above 55°, not present for ERS and thus missing also in the semi-empirically-derived and ERS-based scattering parameters used in the soil moisture retrieval algorithm.

It is worth pointing out again that, for the two distinct inputs (ASCAT and ERS σ^0), both the applied soil moisture algorithm and its other required input data were exactly the same. The presented differences in soil moisture are thus actually acting as a proxy to identify differences in σ^0 calibration.

The very good ASCAT radiometric performance and antenna pointing accuracy, its thorough calibration using transponders [17, 18] as well as its unusual use of relatively high incidence angles at far swath might challenge the present perception of $\gamma^0(\theta)$ as being constant. ASCAT has shown that radiometric accuracies beyond the rather generously set mission requirements are possible. For long-term soil moisture monitoring via multimission data it seems necessary to pay more attention to vicarious calibration and take advantage of exactly this extra accuracy capability.

As an outlook towards future activities and improvements, scatterometry applications for climate change assessment will greatly benefit from the timely reprocessing of the entire ERS-1 and ERS-2 σ^0 dataset with the best available calibration, currently ongoing at ESA. This would ensure a consistent dataset with improved quality, irrespective of the historical ups and downs of the ERS missions (especially true for ERS-2). In addition, the outcome dataset will have a 25 km spatial resolution, very similar to the ASCAT high-resolution product.

ACKNOWLEDGEMENTS

This study was carried out within the "Global Monitoring of Soil Moisture for Water Hazards Assessment (GMSM)" project funded by the Austrian Space Applications Programme (ASAP).

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