SOIL MOISTURE PRODUCTS FROM C-BAND SCATTEROMETERS: FROM ERS-1/2 TO METOP

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ABSTRACT

Based on ERS-1/2 scatterometer data from 1992 to 2000, work carried out at the Institute of Photogrammetry and Remote Sensing (Vienna University of Technology) resulted in a multi-year, global, remotely sensed soil moisture dataset. An exciting aspect of these developments is that the ERS scatterometer instrument finds an operational continuation in ASCAT, the Advanced Scatterometer onboard the upcoming series of MetOp satellites. This paper describes the conditions of applying the soil moisture retrieval methods to future ASCAT data, thus turning the global soil moisture dataset into an important operational, long-term, near real-time, continuous and consistent resource serving the hydrometeorological, agricultural and climatological communities. Differences between the two instruments are reviewed, pointing out their possible impact on the measurement characteristics and the resulting soil moisture data.

Key words: ERS, ASCAT, MetOp, scatterometer, soil moisture.

1. INTRODUCTION

Retrieval of soil moisture is still considered an open issue and is presently the subject of extensive research. This missing parameter is an important state variable of the global energy and water and an important boundary condition for our climate system (Ref. 1). Along with snow cover, it is also the most important component of meteorological memory for the climate system over land (Ref. 2). Apart from its dominant role in the global climate system, soil moisture takes a fundamental role in climate-sensitive socio-economic activities like water management, agriculture or flood and drought hazards monitoring. Knowledge of the soil moisture state and its spatial and temporal dynamics is therefore essential for meteorological, climatological, hydrological and agronomy applications. Its importance is reflected in the present preparations for two dedicated space missions: SMOS (Soil Moisture and Ocean Salinity) by ESA with launch scheduled in 2007 and HYDROS by NASA, in 2009. Both these missions focus on passive radar techniques for soil moisture retrieval, due to better penetration depth at L-band frequencies and the better existing soil roughness modelling capabilities. However, advances in active radar techniques particularly at C-band frequencies have shown the potential of spaceborne scatterometers to retrieve top-soil moisture (Ref. 3). The developed methods (referred to as the Vienna University of Technology – VUT – model) applied to data from the ERS 1/2 scatterometers have resulted in the first global, remotely sensed soil moisture dataset. The data compares well to in-situ measurements and its quality has been found to be comparable to that of state-of-the-art modelled products. Its accuracy has been found to be around 0.05 m^3/m^3. The similar ASCAT scatterometer onboard the upcoming MetOp series of satellites offers now the possibility of an operational continuation of this soil moisture dataset.

In the present paper the conditions of applying the ERS soil moisture retrieval methods to future ASCAT data are outlined, with the aim of turning the global soil moisture dataset into an important operational, long-term, near real-time, continuous and consistent resource with many future hydrometeorological, agricultural and climatological applications. The differences between the two instruments are presented and their influence the retrieval process are discussed.

2. C-BAND SCATTEROMETER SOIL MOISTURE

The VUT-model is based on a change detection algorithm tailored to the sensor characteristics of the ERS Scatterometer. The algorithm exploits the multiple incidence angle viewing capabilities of the sensor in order to separate soil moisture and vegetation effects.

By applying the algorithm separately to time series in a predefined global grid, characteristic model parameters are derived. Unlike the case of more complex theoretical or semi-empirical approaches often preferred for retrieval purposes, these parameters describe the unique environmental conditions and account naturally for the effects of heterogeneous land cover and surface roughness. The change detection method indirectly accounts for surface roughness effects, since at the spatial scale of the C-band scatterometer (tens of kilometres), surface roughness changes due to farming activities or other effects can be assumed to have negligible effects on the time series recorded by the scatterometer. Similarly, the method accounts also for heterogeneous land cover since many land cover classes such as forests, dense shrubs, urban areas and small inland water bodies are characterised by relatively stable C-band backscatter values and hence do not need to be separately modelled.

The model considers vegetation growth and decay over grassland and agricultural regions since this may cause backscatter to change by several decibels. In these areas, the seasonal increase in biomass has thus its own contribution to the backscatter which must be eliminated to uphold the relationship between backscatter and soil moisture.

In order to do so, the seasonal change of the relationship between backscatter and incidence angle is modelled, making it possible to statistically estimate typical wet and dry condition backscatter signatures for different periods of the phenological cycle (see Fig. 1). Using these signatures, vegetation effects are corrected for and time series of the topsoil moisture content are obtained, ranging from the typically driest values to the typically wettest ones. In order to allow a comparison with soil moisture measurements over greater depths (up to about one meter) a two-layer water balance model, which only considers the exchange of soil water between the topmost remotely sensed layer and the 'reservoir' below, was used to establish a relationship between the topsoil series and the profile soil moisture content (Ref. 3). The water content in the soil profile is estimated by convoluting the surface soil moisture series with an exponential filter.

3. TRANSITION FROM ERS TO METOP AND SOIL MOISTURE DATA CONTINUITY

The advanced scatterometer (ASCAT) on board the meteorological operational (MetOp) platforms is the follow-on for European scatterometers (Ref. 4). ASCAT will be part of EUMETSAT's Polar System (EPS) and will be nearly identical to the ERS scatterometer. It is designated to be an operational system with the intention to ensure data continuity over an initial period of at least 14 years, starting in 2005.

In principle, the VUT-model developed for the ERS Scatterometer should be directly applicable to ASCAT data. Since the methods involve statistically determining typical minima and maxima, applying them *exclusively* to the new ASCAT data would start yielding reliable results only after approximately 3 years. Given the fact that the statistical parameters in question have already been determined using ERS data, retroactive integration of the new data could start already at the beginning of the MetOp mission series. This would result in a valuable soil moisture dataset with unprecedented continuity and coverage. Nevertheless, slight differences in the design and operation of the two sensors (see Table 1) oblige a careful merging of measurements, involving accurate characterization of the error properties of both time series. The following points review the influence of the different instrument characteristics on the soil moisture retrieval.

3.1. Temporal Resolution

The ASCAT sensor will use six antennae instead of the three of the ERS Scatterometer. This, combined with the fact that ASCAT will be a dedicated instrument not sharing operational time with other instruments, will significantly increase the temporal resolution of the backscatter time series, especially important for areas like Europe (where SAR operation usually has priority over the scatterometer onboard ERS) and tropical regions, where the ERS scatterometer has a too low sampling rate to be able to detect important rain events. Fig. 2 compares the 2-day swaths for the two instruments at continuous operation and Fig. 3 shows the latitude dependency of the *average* number of measurements per area unit. The ASCAT scatterometer will provide on average from 4 to 20 backscatter triplets per day and 25 km $\times$ 25 km area unit, with approximately double as many measurements at high latitudes.

The increased temporal resolution will benefit the overall quality of the topsoil moisture series and of the profile soil moisture in particular. However, different exponential filters used to model the water content profile might have to be applied to the different portions of the total time series.

3.2. Spatial Resolution

One of the improvements of the ASCAT sensor in contrast with the ERS scatterometer is a planned product with an increased spatial resolution of 25 km. It is clear that in the foreseeable future modellers who have so far worked with 0.5–2 degree resolution cells will move more and more towards resolutions comparable to 25 km because of data availability. Recent tests of reprocessing ERS Scatterometer data to a resolution of 25 km show very promising results concerning the separation of physically meaningful details in comparison to the 50 km resolution product. Figure 4 compares ERS backscatter images of 25 and 50 km resolution over the central-northern part of European Russia. The coniferous forest patterns of the land cover map are clearly more recognizable in the 25 km product, similarly to the humid grassland and water areas as well as the contour and location of the strongly 'reflecting' city of Moscow.

A change of scale from 50 to 25 km resolution could have an impact on the model itself. Effects such as seasonal roughness changes due to agriculture (which at the moment are assumed to be within the noise level) need to be thoroughly investigated.

3.3. Radar Frequency

There is a slight shift of about 45 MHz between the centre frequencies of the ERS Scatterometer and ASCAT instruments, due to historical instrument design reasons (Ref. 5). When compared to the central frequency itself, in the order of 5.3 GHz, this shift has no major influence

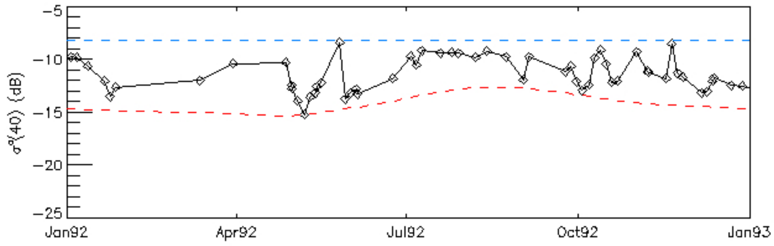

Figure 1. Example of $\sigma^0(40)$ backscatter time series and typical boundaries for wet conditions (blue dashed line) and dry conditions corrected for vegetation effects (red dashed line). The location is Fort Dodge, Iowa, USA.

Table 1. ERS Scatterometer and MetOp ASCAT comparison (Ref. 7).

	ERS Scatterometer	MetOp ASCAT
Radar frequency	5.300 GHz	5.255 GHz
Number of swaths	1	2
Full performance swath width	400 km	500 km
Reduced performance swath width	500 km	550 km
Minimum incidence angle	18°	25°
Maximum incidence angle	57°	65°
Nominal spatial resolution	45 km	50 km
Experimental spatial resolution	none	25 km
Interbeam stability	0.46 dB	0.46 dB
Radiometric resolution at minimum crosswind	8.5–9.7 %	3.0–9.9 %
Radiometric resolution at maximum upwind	6.5–7.0 %	3.0 %

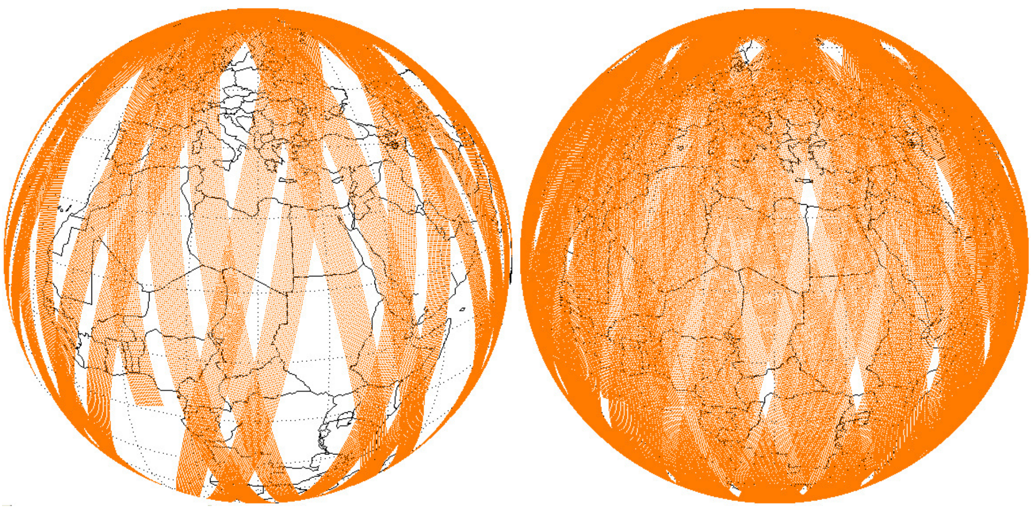

Figure 2. Comparison between 2-day coverage of the ERS Scatterometer operated continuously (left) and the equivalent coverage of the ASCAT scatterometer.

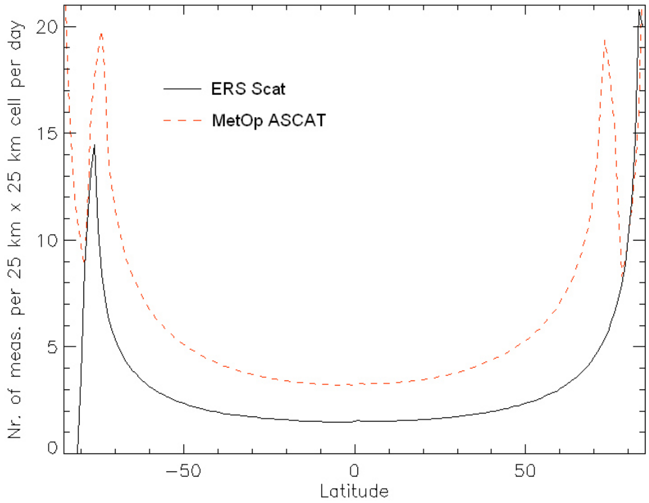

Figure 3. Daily average number of acquired backscatter triplets per 25 km $\times$ 25 km cell as function of latitude.

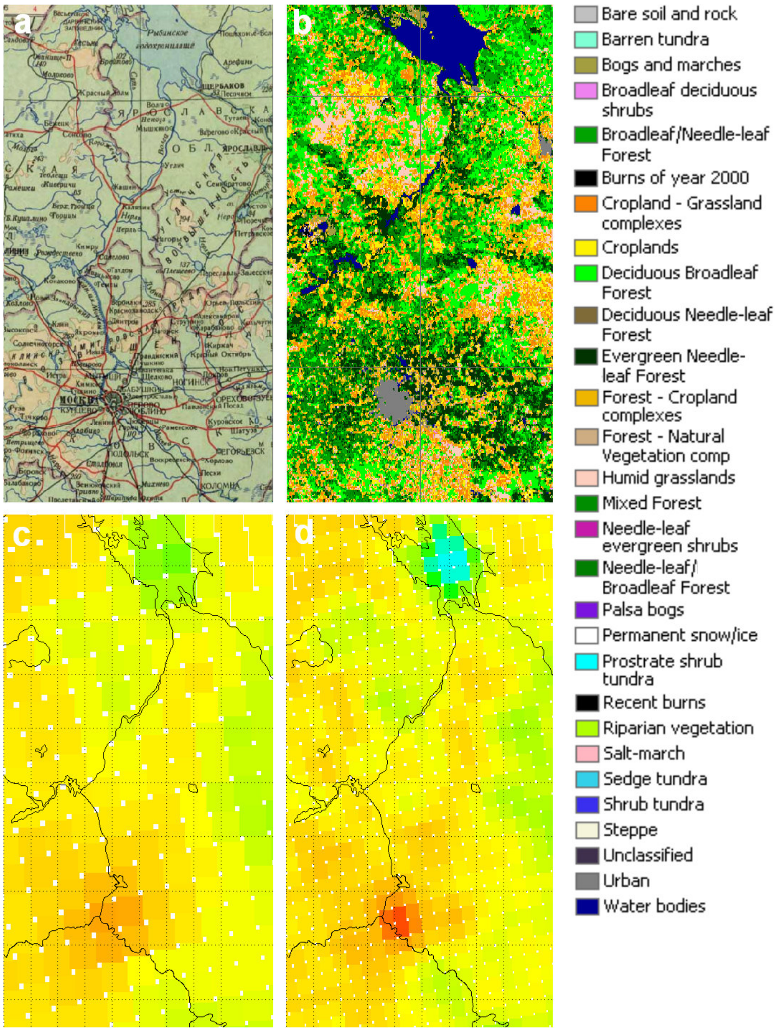

Figure 4. Comparison between the ERS scatterometer 50 and 25 km resolution products, (c) and (d) respectively. The features of the GLC2000 land cover map in (b) are recognisable to a higher degree of details in the 25 km resolution backscatter plot. The legend belongs to the land cover map in (b). Backscatter values are not corrected for incidence angle and originate from ERS-2 orbit number 21711 (cycle 43), acquisition time June 15, 1999, 19:16.55 (ascending node). Source for (a): http://www.veslo.ru/maps.html.

on the consistency of the soil moisture data. This fact is verified by simulations with the Integral Equation Model.

3.4. Incidence Angle Range

Table 1 reveals that the incidence angle range for the ASCAT instrument will be shifted to higher values compared to ERS. Within the soil moisture retrieval algorithm, the available range of incidence angles has an influence on the sensitivity of the backscatter measurements to soil moisture content. In natural units, the sensitivity decreases approximately exponentially with increasing incidence angle, due to the more pronounced attenuation of microwaves in the vegetation canopy at higher incidence angles. The approximately 7° incidence angle shift could thus induce uncertainties in the model. In that case, the improved measurement certainty provided by the increased temporal resolution will be dampened, but the exact quantitative effect is difficult to foresee.

3.5. Local Time of the Descending Node

The advantage of satellites in sun-synchronous orbits like ERS or MetOp is that passage over any given latitude takes place at the same local solar time for each ascending or descending orbit. ERS has its time of the descending node (the sub-satellite track crossing the Equator from north to south) at approx. 10:30 AM whereas the equivalent time for MetOp is envisaged to be one hour earlier. The side-looking characteristics of the instruments combined with the double swath of ASCAT and its different incidence angle range results in slightly different local solar times for the backscatter measurements than the ones corresponding to the sub-satellite track. As Fig. 5 shows, the 1 hour difference at the Equator passage can actually mean that the time difference between ERS and MetOp measurements can range between 30 minutes and over 2 hours during descending orbits at the Equator. At higher latitudes, the range of timing differences between the two instruments gets larger and from around latitudes of 50° and more it is actually possible that ERS measurements occur before some of the ASCAT measurements. Also, the ASCAT measurements themselves are more spread out in time due to the double swath. It is important that such timing differences are taken into consideration. Binning of measurements into days should be done carefully. ASCAT backscatter measurements will on average take place earlier than ERS measurements, an aspect that is important to remember when comparing for instance soil moisture time series derived from the two sensors: topsoil moisture conditions especially early in the morning or late in the afternoon can vary substantially when measured one or two hours apart. The best way to avoid situations where such discrepancies are wrongly interpreted, as well as for the data accuracy assessment and improvement of the retrieval algorithms would be to calculate relative instrument bias from data *simultaneously* collected by the two spacecraft over permanent, stable targets.

3.6. Calibration

The ASCAT scatterometer will feature a superior relative and absolute calibration procedure than its ERS counterpart (Ref. 4). This being said, the most important for the performance of the change detection algorithm is the calibration of the two instruments relative to each other. Any inter-sensor calibration discontinuity will necessarily shift the measured backscatter. When the new, shifted backscatter values are related to the statistically derived minima and maxima serving as wet and dry boundary conditions, the result can be a sudden change of wetness at the boundary of the two time series. Simulations show (Fig. 6) that an inter-sensor calibration offset of as little as 0.1 dB will yield a considerable increase of wetness, especially in regions where the backscatter does not vary much during the year, as in mountainous regions. Again, to avoid false climatological interpretations and to improve the data accuracy assessment and the retrieval algorithms, it is desirable to operate the instruments simultaneously.

4. CONCLUSION AND PERSPECTIVES

With the upcoming ASCAT instrument a very long-term (25 years), seamless, consistent and continuous data base of remotely sensed soil moisture seems to be within reach. A development goal will be to deliver operational 25 km soil moisture products in quasi-real time (2-3 hours after reception) with an accuracy of about 0.05 m^3/m^3 from 2006 onwards. Within an adequate hydrometeorological framework, soil moisture maps could be disseminated over the medias similarly to weather forecasts. Further, such a data base would be an important step towards a future unified service gathering all possible soil moisture data from different sensors.

From a climatology point of view, a concern is that data gaps in satellite remote sensing usually introduce uncertainties that are *comparable or even larger* than the investigated signal (Ref. 6) and lead to erroneous modelling. For the success of the long-term soil moisture database it would thus be highly desirable *to continue* the ERS-2 mission until about six months into the operational lifetime of the first ASCAT instrument. This would allow to study in particular the impact of calibration and local time of overflight. In order to achieve an integrated product of the highest quality it is equally desirable that the whole ERS backscatter dataset be reprocessed from 50 to 25 km.

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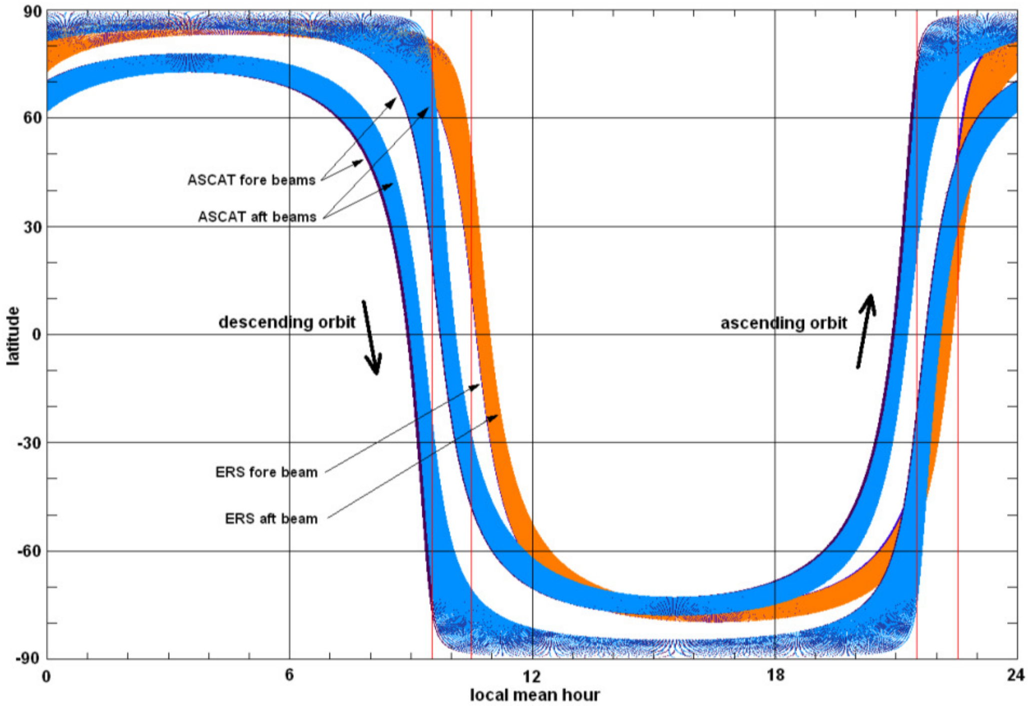

Figure 5. The relationship between the times of the day (local solar time) when ERS and ASCAT measurements are expected to occur and the geographic latitude.

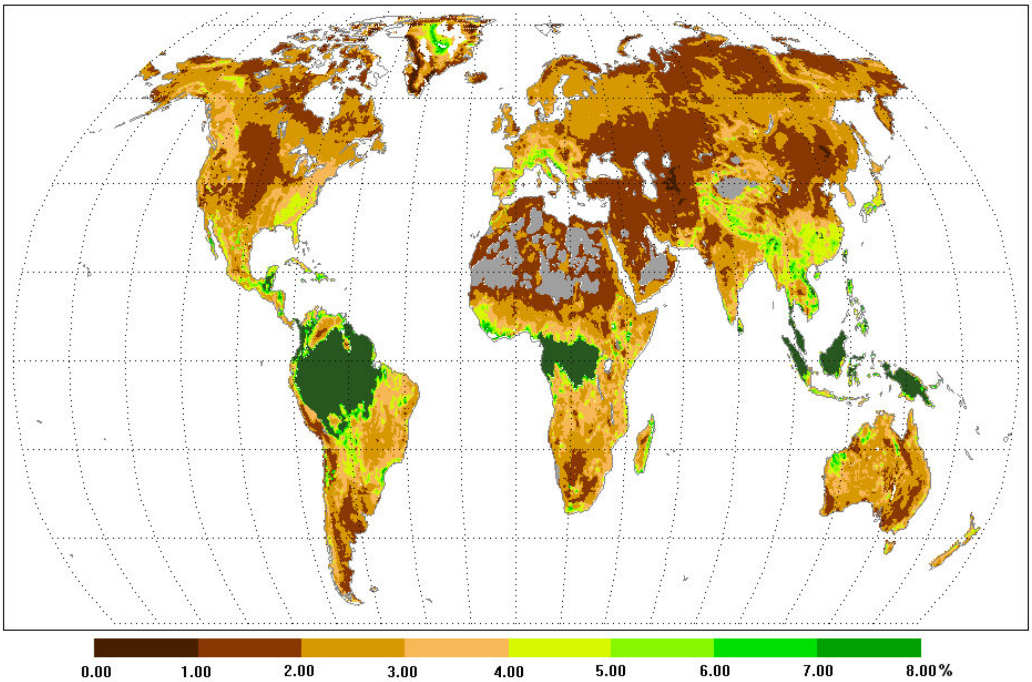

Figure 6. Percentual increase of wetness as effect of a 0.1 dB negative calibration offset between the ERS scatterometer and ASCAT. Desert (grey) and tropical forest (dark green) areas are masked in this figure.

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