CHALLENGES FOR SOIL MOISTURE RETRIEVAL FROM C-BAND BACKSCATTER MEASUREMENTS IN ARID AND SEMI-ARID ENVIRONMENTS

S. Hahn, W. Wagner, M. Vreugdenhil, T. Melzer, A. Abdulrahman

Vienna University of Technology, Department of Geodesy and Geoinformation,
Gusshausstrasse 27-29, Vienna, Austria

Abstract

Space-borne Scatterometers have proven to be a valuable tool for deriving soil moisture information over land. A strong relationship between the Scatterometer backscatter measurements and the different dielectric properties of dry and wet soil made this possible in the first place. However, this assumption does often not hold in arid and semi-arid environments. In order to obtain correct and accurate soil moisture information in these areas, changes in surface characteristics influencing the backscatter and its dynamics needs to be understood. This study examines the different circumstances affecting backscatter measurements in arid and semi-arid environments, which are important in the context of the semi-empiric change detection method for soil moisture retrieval implemented in the soil WAter Retrieval Package (WARP) developed by Vienna University of Technology (TU Wien). Results show that especially sandy deserts are prone to be affected by azimuthally anisotropy and Bragg scattering, which is consistent with previous studies. The new aspect, however, is that also seasonal characteristics of anisotropy have been observed. Another remarkable finding of this study was unexpected backscatter increase during dry spells in areas identified as alluvial fans and pediments. A good understanding of backscatter characteristics in arid regions and their underlying physical processes is relevant for correction purposes (e.g. for soil moisture retrieval) and for the identification of new possible applications of Scatterometer measurements in this environment.

1 INTRODUCTION

Desert environments are in general characterised by high temperatures and low precipitation, which is also why soil moisture is very low and rather stable. Nevertheless, sporadic rainfall events are extremely important for the flora and fauna. Since desert areas are typically uncultivated and uninhabited regions, there are essentially no in-situ sensors available, for measuring the small soil moisture changes. A powerful tool, which is able to provide soil moisture information from such isolated places is remote sensing. Several satellites are currently used for the retrieval of surface soil moisture using active or passive microwave sensors (Ochsner et al. 2013). On the active side there are Metop-A and its recently launched successor Metop-B, which are both carrying the same Advanced Scatterometer (ASCAT). ASCAT was predominantly designed to measure wind speed and direction over the ocean (Figa-Saldana et al., 2002), however, due to remarkable dielectric differences between dry and wet soil, it is possible to relate backscatter measurements to soil moisture information over land. A useful soil moisture retrieval method based on ERS-1/2 backscatter measurement was developed by Wagner et al. (1999a) and successfully adapted to ASCAT. This, so-called TU Wien model, is in principle a semi-empiric change detection method. A series of model parameters are calculated based on long-term backscatter time series which are further used to correct and normalise the measurements. In the final step the normalised backscatter measurements are scaled between totally dry conditions and complete saturation, representing soil moisture in degree of saturation. However, arid and semi-arid environments are very challenging regions, not only due to the very low soil moisture content in general, but also because of special scattering characteristics. Not all of these peculiarities are currently handled in the TU Wien algorithm, leading to errors in the soil moisture retrieval. The goal of this study was to identify the major soil moisture retrieval challenges and its geophysical causes.

2 DATA AND METHODOLOGY

2.1 Metop-A ASCAT 25 km soil moisture time series

The Metop-A ASCAT 25 km soil moisture time series product is generated and distributed by the Vienna University of Technology (TU Wien) and soon part of H-SAF's (Satellite Application Facility on Support to Operational Hydrology and Water Management) product suite. For this study the product version WARP 5.5 R 1.1 has been used for investigating challenges in the soil moisture retrieval in very dry environments. The soil moisture product is derived from measurements from the Advanced Scatterometer (ASCAT) on board the Metop-A satellite. ASCAT is operating at 5.255 GHz (C-band, VV polarisation) and composed of six fan beam antennas measuring the backscattering coefficient over multi-incidence angles. Metop-A is the first of a series of three Meteorological Operational (Metop) satellites operated by the European Organisation for the Exploitation of Meteorological Satellites (EUMETSAT) and part of EUMETSATs Polar System (EPS). Metop-A has been successfully launched in October 2006 and since September 2012 the second satellite, Metop-B, is sharing the same orbit with a shift of around 50 minutes. Although Metop-B is carrying an Advanced Scatterometer as well, which also has proven to agree on very high level with ASCAT on board Metop-A (Anderson et al. 2013), the current soil moisture product is only based on backscatter measurements from ASCAT-A.

The TU Wien semi-empiric change detection approach developed by Wagner et al. (1999a) and further improved by Naeimi et al. (2009a) is used to retrieve soil moisture information from the backscatter measurements. The soil moisture estimates from this method represent the water content of the upper soil layer (< 2 cm) in relative units between totally dry conditions (0%) and complete saturation (100%). The data set is available on a on a discrete global grid (DGG) with a spatial resolution of 25 km (grid spacing 12.5 km) and a temporal sampling rate of generally 1-2 days. Depending on the latitude the sampling rate can be also lower or higher.

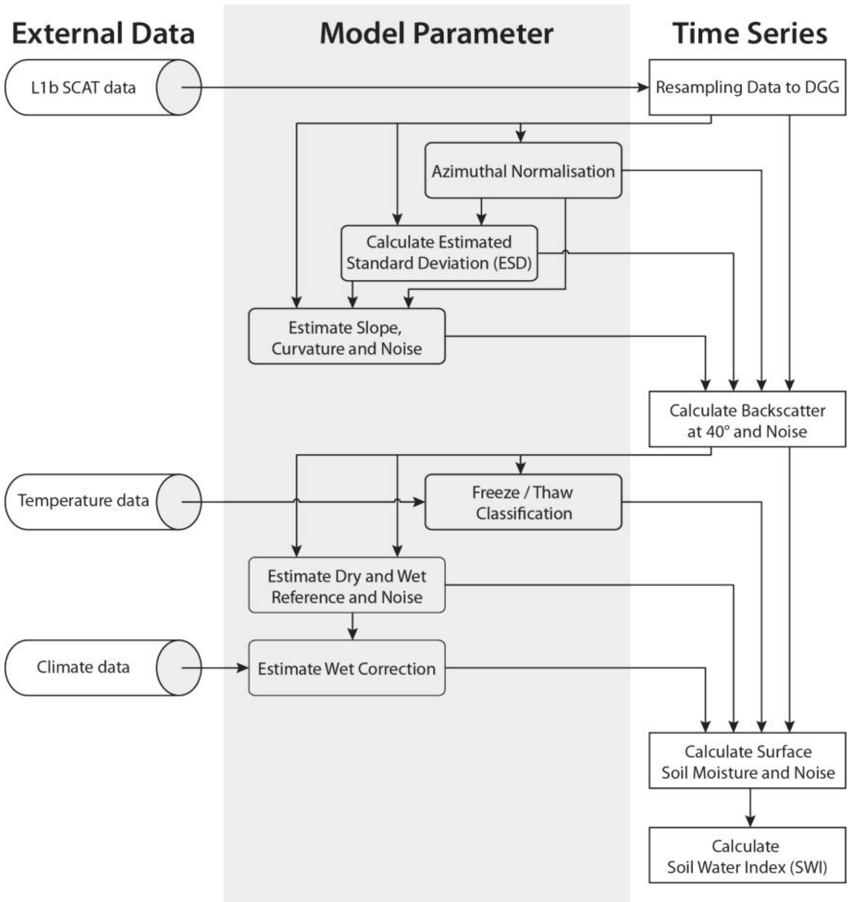

Figure 1: A flowchart of the WARP 5.5 processing steps.

In order to assign detected inconsistencies in the soil moisture product either to the underlying backscatter measurements or to the TU Wien model, both, the Level 1b data sets, as well as the model parameters have been analysed. The model parameters represent long-term scattering characteristics, which are derived during the process of the soil moisture retrieval. The software implementation of the TU Wien change detection approach is called the soil WAter Retrieval Package (WARP) and a flowchart of WARP 5.5 is shown in Figure 1.

2.2 Global Land Data Assimilation (GLDAS)

The Global Land Data Assimilation System (GLDAS) has been developed jointly by the National Aeronautics and Space Administration (NASA) Goddard Space Flight Center (GSFC) and the National Oceanic and Atmospheric Administration (NOAA) National Centers for Environmental Prediction (NCEP) making usage of ground- and space-based observation systems in order to model several land surface parameters (Rodell et al. 2004). GLDAS drives four land surface models (LSMs): Mosaic, Noah, the Community Land Model (CLM), and the Variable Infiltration Capacity (VIC).
This study has used modelled soil moisture from the Noah land surface model in order to validate the Metop-A ASCAT 25 km soil moisture time series globally. The Noah land surface model consists of four layers: 0-0.1, 0.1-0.4, 0.4-1.0, 1.0-2.0 m on global regular grid (0.25° x 0.25°). This product is available since 2000 until present, with a temporal resolution of 3 hours. In order to match the representation of the Metop-A ASCAT soil moisture product only the first layer of model has been considered.

2.3 Data preparation and metrics used for comparison

Each of the products was given in time series format located on a fixed Earth grid. However, the arrangement and spacing of the grid points varied between the products, due to different grid definitions and spatial resolution. For this reason, a spatial matching was necessary to be able to compare the two data sets. A nearest neighbour (NN) search was carried out without averaging the Metop-A ASCAT soil moisture time series, although their spatial resolution is finer (25 km) compared to GLDAS Noah (~55 km). This choice was motivated by our aim to identify inconsistencies in the original resolution of the Metop-A ASCAT soil moisture time series without any prior manipulation of the data set. Nonetheless, the disagreement in the spatial resolution has to be considered during the assessment of the results. The soil moisture products also have a different temporal sampling, as a result of different acquisition or model characteristics. Therefore, a temporal matching was important to find adjacent measurement pairs, which can be further used for comparison. Also in this case a NN search was applied with a maximum search window of ±6 hours.
The goal of the study was to detect problems in the Metop-A ASCAT soil moisture retrieval in arid and semi-arid regions, rather than determining the absolute performance. For this reason, only the Pearson correlation coefficient was computed to be able to detect temporal dissimilarities between Metop-A ASCAT and GLDAS. Further analyses were based on the characteristics of the model parameters and the underlying raw backscatter measurements.

3 RESULTS AND DISCUSSION

3.1 Azimuthal anisotropy

In general, Scatterometers are designed to obtain backscatter measurements over a range of incidence and azimuth angles. This configuration is important since models are exploiting the multi-angle measurement capabilities to derive geophysical parameters. However, azimuthal-modulation effects are not always desirable and should be accounted for. In dry environments, sandy deserts are usually affected by this phenomenon due to the orientation of dunes and small scale ripples (Stephen and Long, 2002). The physical reasons for azimuthal anisotropy over land are mostly related to the spatial orientation of specific topographic features or to land cover (Bartalis et al., 2006).
In the TU Wien soil moisture retrieval algorithm it is important to identify and correct azimuthal anisotropy, since it based upon a change detection approach. This means, if affected backscatter measurements are not properly corrected or masked out, an azimuthal-modulation can be interpreted as a change in soil moisture. The current azimuthal correction implemented in WARP 5.5 is based upon statistics derived from historical backscatter data (Bartalis et al., 2006). In this way the backscatter measurements are bias corrected with respect to an average, long-term backscatter-incidence angle behaviour for each location independently. However, the current solution does not

account for short term fluctuations, like seasonal changes (see Figure 2). While this had already been forseen in the beginning, it was not possible to implement a remedy then. Originally, the azimuthal correction was based on ERS-1/2 Scatterometer data, which simply has an insufficient number of temporal samples to allow for a more refined correction approach. Since ASCAT, the successor instrument of the ERS-1/2 Scatterometers, has a much better temporal sampling rate and already accumulated over 5 years of data, current research at TU Wien has picked up the idea of introducing twelve monthly periods. Further analyses are planned to investigate the feasibility and benefit.

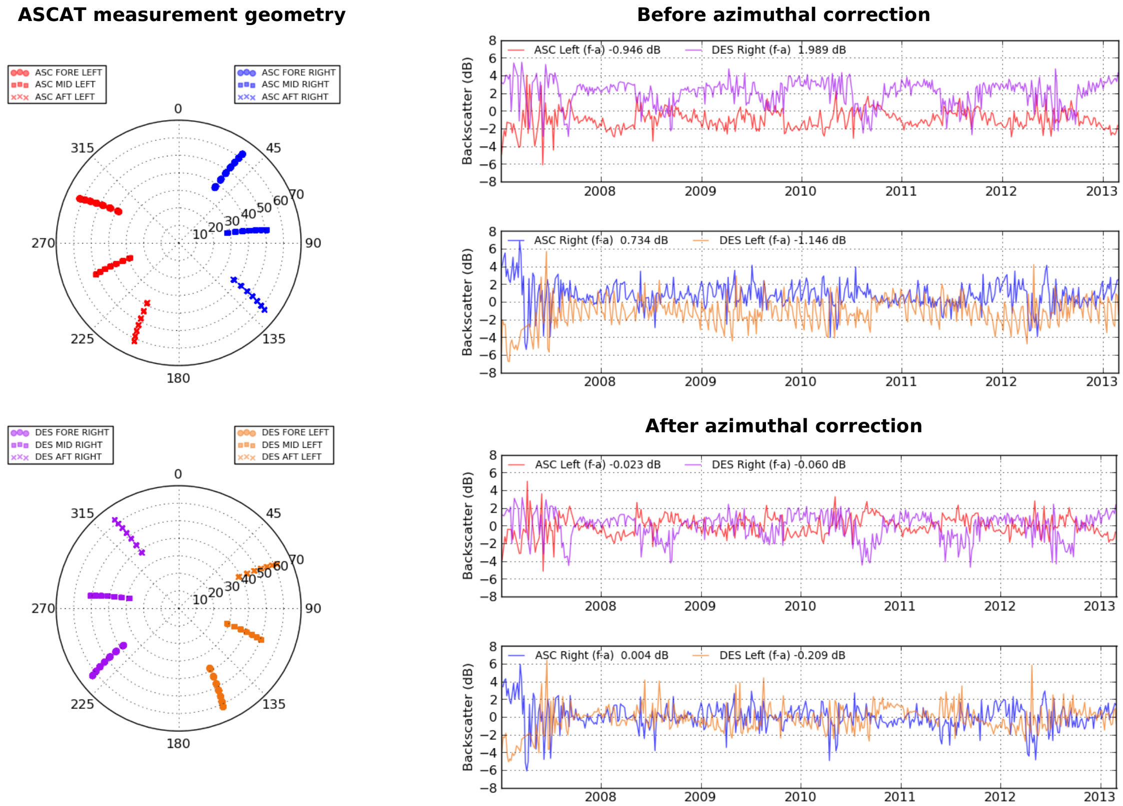

Figure 2: The left side illustrates the measurement geometry of Metop ASCAT for ascending (upper) and descending (lower) orbit direction on a polar plot. The azimuth direction is shown on the phase axis and the incidence angle on the radius axis. On the right side are the temporal differences between backscatter from the For and Aft beam, before (upper) and after (lower) the azimuthal correction. A clear seasonal signal can be observed for ascending left (red) and descending right (purple), which is still visible after the azimuthal correction. The grid point is located in Chad (GPI: 877709 Latitude: 15.71° Longitude: 17.50°).

3.2 Bragg scattering

A special scattering mechanism appears for slightly rough surfaces (RMS height < λ/8) when they show a repetitive predominant pattern comparable in size with the wavelength λ of the incident wave. In such cases, backscattered waves are subject to constructive interference at certain discrete incidence angles. For Scatterometer backscatter measurements this, so-called Bragg scattering, can be mainly observed in sandy deserts over land, because of small wind-induced ripples on the surface of dunes. Stephen and Long (2005) tried to model microwave backscatter from erg surfaces in the Sahara Desert with two scales of surface features. They found that Bragg scattering occurred at slip-sides at incidence angles equal to the angle of repose of sand.

Apart from ordinary outlier detection, no dedicated method dealing with Bragg scattering currently exists in the TU Wien soil moisture retrieval algorithm implemented in WARP 5.5. For some locations the conventional approach is sufficient, but for other areas it fails to filter affected measurements (see Figure 3). In order to deal with this situation, it is planned to investigate robust methods masking Bragg scattering. Although the best solution would be preserving the backscatter measurement by subtracting the amount of Bragg scattering, such a correction would have to be based on a physical model of high accuracy (±1 dB). However, based on the Metop ASCAT's sampling geometry it is very unlikely that such a model can be formulated.

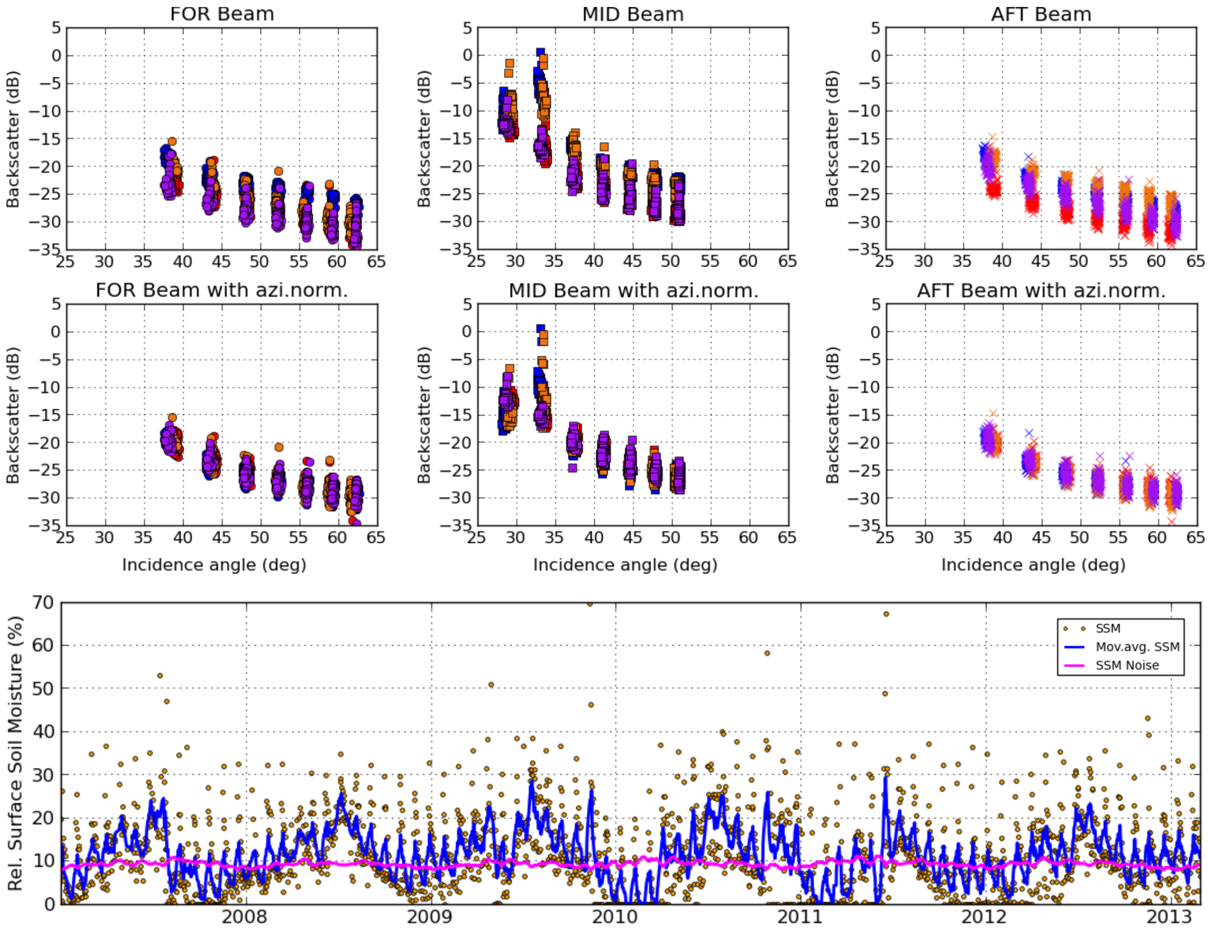

Figure 3: The first row shows the backscatter - incidence angle characteristics, separated for the For, Mid and Aft beam. The second row illustrates the same, but after the azimuthal correction. The time series in the bottom demonstrates the influence of Bragg scattering on the final soil moisture estimates. The grid point is located in the Taklamakan desert in China (GPI: 2090939 Latitude: 39.96° Longitude: 86.17°).

3.3 Vegetation correction

As mentioned earlier, ASCAT is measuring backscatter over a range of incidence angles. A strong dependency between these two parameters makes a direct comparison of backscatter from different incidence angles impossible. In the TU Wien model the backscatter incidence angle relationship is approximated by a second order Taylor polynomial, which is used to normalise the backscatter to a common reference incidence angle (Wagner et al., 1999a; Naeimi et al., 2007). In this way the incidence angle discrepancies can be resolved, however, the normalisation process is complicated by the fact that the backscatter incidence angle dependency is also affected by the seasonal vegetation cycle. Figure 4 shows the backscatter incidence angle behaviour of vegetated surfaces simulated for different soil states. It appears that vegetation growth is changing the slope and curvature of the backscatter incidence angle relationship and results into “crossover” angles for dormant and fully grown vegetation. If these crossover angles are determined correctly, this allows compensating for vegetation effects (Wagner et al., 1999b).

This study has focused on areas in very dry environments with no or only very limited vegetation. Therefore, not many changes in slope and curvature were expected. Surprisingly, this was not the case for some dedicated sandy deserts in North Africa and the Arabian Peninsula (not shown for brevity). There seems to be unusual variations which are definitely not related to vegetation. In such cases the previously discussed concept is no longer valid and can lead to errors in the soil moisture estimates (see Figure 5). This topic is the subject of ongoing research, as the underlying physics have not been fully explored yet. However, for the time being the goal is to identify all affected locations where the vegetation correction should not be applied.

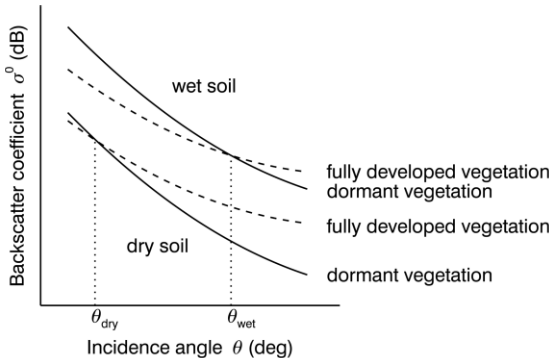

Figure 4: Cross-over angle concept (after Wagner et al. (1999b)).

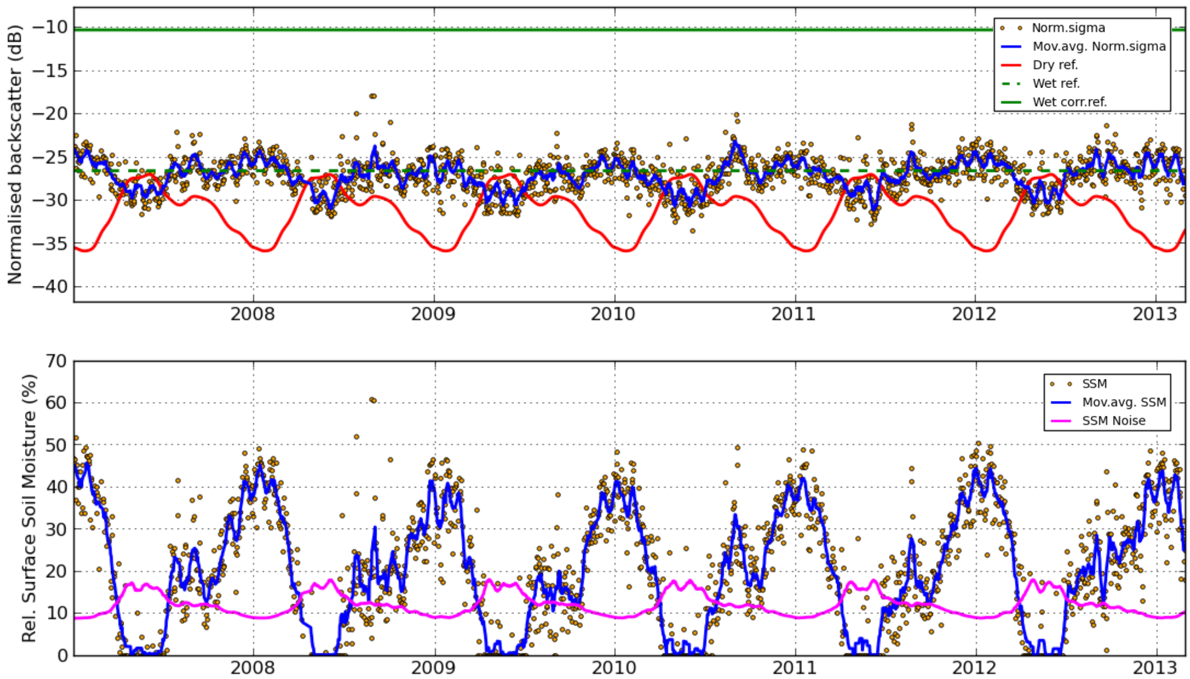

Figure 5: The upper time series shows the normalised backscatter, dry and wet reference, as well as the corrected wet reference. The lower time series illustrates the soil moisture, after scaling the backscatter between dry and wet. Apparently, the dry reference introduces an artificial signal to the soil moisture time series, which is due to the vegetation correction derived from the slope and curvature parameter.

3.4 Unexpected backscatter characteristics

In order to assess the temporal dynamics of the soil moisture time series from Metop ASCAT, the Pearson correlation coefficient has been computed against Noah GLDAS soil moisture (see Figure 6). As expected, many areas show a positive correlation indicating a good temporal agreement. However, some dedicated very dry areas, mainly in North Africa and in the Arabian Peninsula, show a strong negative correlation (< - 0.7). This inverse relationship has been noticed earlier by other authors (Wagner et al. 2003, Naeimi et al. 2009), but has not been further investigated. It appeared that this behaviour can be traced back to the normalised backscatter time series, showing a sudden drop after a rainfall event, followed by an increase during the drying phase (see Figure 7). This is actually contrary to the normal case, where an increase of the backscatter is expected as a result of an increased dielectric constant due to wet soil, followed by a steady decline during the drying phase. A hypothesis which might explain this unexpected backscatter behaviour suggests that in these areas a thin soil layer is covering bedrock underneath it. In such a case, the backscatter from a very dry soil actually originates largely from the bedrock below, due to the high penetration depth of the signal. However, as soon as it starts to rain, the backscatter is reducing, since the penetration depth of the

signal quickly gets attenuated by the wet soil layer and consequently, the bedrock below can no longer contribute to the overall signal.
Looking at optical satellite images, many areas can be linked to alluvial fans or pediments. Both types of landforms are typically covered by a thin, discontinuous veneer of soil and alluvial material underlain by bedrock. This composition also supports the previously mentioned hypothesis concerning the backscatter behaviour. However, further data and analyses are needed to completely identify the underlying physical processes of these unexpected scattering characteristics.

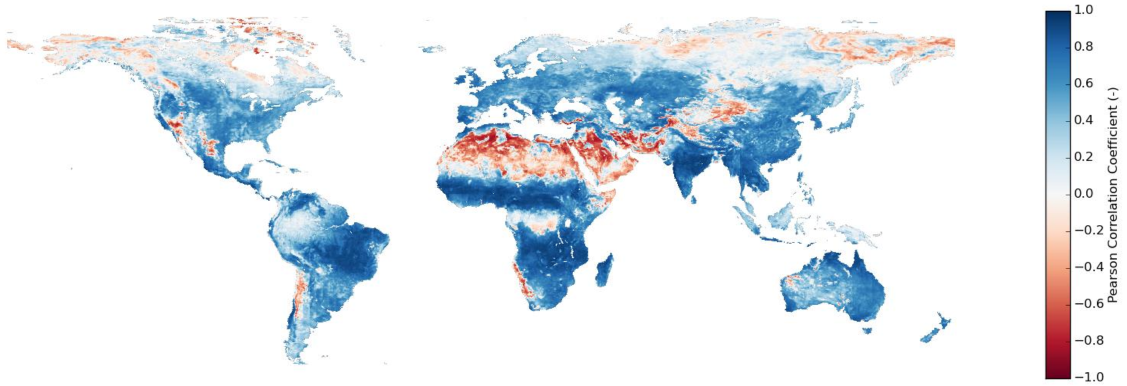

Figure 6: Pearson correlation coefficient between Metop ASCAT WARP 5.5 R 1.1 and Noah GLDAS soil moisture for the period of January 2007 to December 2012.

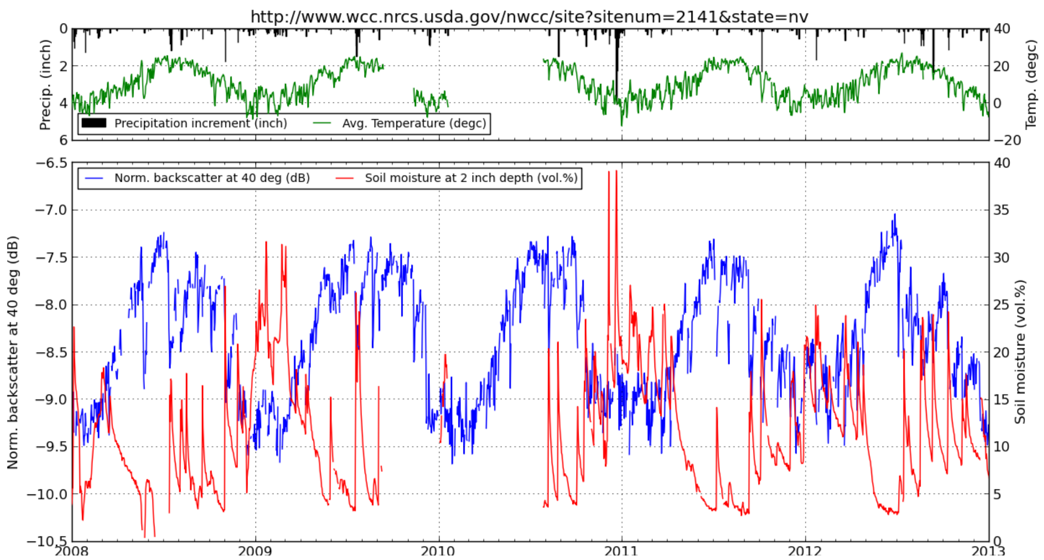

Figure 7: Metop-A ASCAT normalised backscatter (GPI: 1925078 Latitude: 36.24° Longitude: -115.56°) vs. SCAN site Kyle Canyon, Nevada (Site number: 2141).

4 SUMMARY AND OUTLOOK

This study has provided insight into soil moisture retrieval challenges in arid and semi-arid environment based on the Metop ASCAT 25 km soil moisture product. Four main issues have been identified and discussed: azimuthal anisotropy, Bragg scattering, vegetation correction and unexpected backscatter characteristics. Except for azimuthal anisotropy, none of these are currently dealt with in the latest version of the Metop ASCAT soil moisture retrieval algorithm implemented in WARP 5.5. In this context, further work is planned to incorporate methods for masking or, if feasible, correcting the backscatter measurements. An interesting question for future studies is to determine the physics of the scattering process in case of pediments and alluvial fans.

5 ACKNOWLEDGEMENTS

We gratefully acknowledge EUMETSAT through the “Satellite Application Facility on Support to Operational Hydrology and Water Management (H-SAF)” and ESA’s “Climate Change Initiative Phase 1 Soil Moisture Project”.

6 REFERENCES

Anderson, C., Figa Saldana, J., Wilson, J., Bauch, H., Duff, C., Miller, J. (2013) Calibration and Validation of the Advanced Scatterometer on Metop-B. EUMETSAT Meteorological Satellite Conference.

Bartalis, Z., Scipal, K., Wagner, W. (2006) Azimuthal anisotropy of scatterometer measurements over land. IEEE Transactions on Geoscience and Remote Sensing, **vol 44**, 8, pp. 2083-2092.

Figa-Saldana, J., Wilson, J. J. W., Attema, E., Gelsthorpe, R., Drinkwater, M. R., Stoffelen, A. (2002) The Advanced Scatterometer (ASCAT) on the Meteorological Operational (MetOp) Platform: A Follow on for European Wind Scatterometers. Canadian Journal of Remote Sensing, **vol 28**, 3, pp. 404-412.

Long, D.G., Drinkwater, M.R. (2000) Azimuth variation in microwave scatterometer and radiometer data over Antarctica. IEEE Transactions on Geoscience and Remote Sensing, **vol 38**, 4, pp. 1857-1870.

Naeimi, V., Scipal, K., Bartalis, Z., Hasenauer, S., Wagner, W. (2009) An Improved Soil Moisture Retrieval Algorithm for ERS and METOP Scatterometer Observations. IEEE Transactions on Geoscience and Remote Sensing, **vol 47**, 7, pp. 1999-2013.

Ochsner, T. E., Cosh, M. H., Cuenca, R. H., Dorigo, W. A., Draper, C. S., Hagimoto, Y., Kerr, Y. H., Njoku, E. G., Small, E. E., Zreda, M. (2013) State of the Art in Large-Scale Soil Moisture Monitoring. Soil Science Society of America Journal. accepted.

Rodell, M., Houser, P.R., Jambor, U., Gottschalck, J., Mitchell, K., Meng, C-J., Arsenault, K., Cosgrove, B., Radakovich, J., Bosilovich, M., Entin, J.K., Walker, J.P., Lohmann, D., Toll, D. (2004) The Global Land Data Assimilation System. Bulletin of the American Meteorological Society, **vol 85**, pp. 381-394

Stephen, H., Long, D.G. (2003) Surface statistics of the saharan ergs observed in the γ_0 azimuth modulation. IEEE International Geoscience and Remote Sensing Symposium Proceedings, pp. 1549-1551.

Stephen, H., Long, D.G. (2005) Micorwave Backscatter Modeling of Erg Surfaces in the Sahara Desert. IEEE Transaction on Geoscience and Remote Sensing, **vol 43**, 2, pp. 238-247.

Wagner, W., Lemoine, G., Rott, H. (1999a) A method for estimating soil moisture from ERS Scatterometer and soil data. Remote Sensing of Enviroment, **vol 70**, pp. 191-207.

Wagner, W., Lemoine, G., Borgeaud, M., Rott, H. (1999b) A study of vegetation cover effects on ERS scatterometer data. IEEE Transaction on Geoscience and Remote Sensing, **vol 37**, 2, pp. 938-948.

Wagner, W., Scipal, K., Pathe, C., Gerten, D., Lucht, W., Rudolf, B. (2003) Evaluation of the agreement between the first global remotely sensed soil moisture data with model and precipitation data. Journal of Geophysical Research Atmospheres, **vol 108**, D19, pp. 9.1-9.15.