THE POTENTIAL OF SENTINEL-1 FOR MONITORING SOIL MOISTURE WITH A HIGH SPATIAL RESOLUTION AT GLOBAL SCALE

Wolfgang Wagner, Daniel Sabel, Marcela Doubkova, Annett Bartsch, Carsten Pathe

Institute of Photogrammetry and Remote Sensing, Vienna University of Technology, Gusshausstrasse 27-29, 1040 Wien, Austria, Emails: ww@ipf.tuwien.ac.at, ds@ipf.tuwien.ac.at, mdo@ipf.tuwien.ac.at, ab@ipf.tuwien.ac.at, cp@ipf.tuwien.ac.at

ABSTRACT

The European Space Agency is currently developing Sentinel-1, a constellation of two polar-orbiting C-band radar satellites for operational Synthetic Aperture Radar (SAR) applications. The Sentinel-1 mission is designed for continuous and operational monitoring. The goal is to map the European land mass once every four days in Interferometric Wide Swath (IWS) mode, and the global land surface at least once every 12 days. Because such a high temporal sampling rate is expected to be very useful for monitoring soil moisture and other dynamic hydrologic process variables, we discuss the potential of the Sentinel-1 SAR mission for global soil moisture monitoring.

1. INTRODUCTION

In recent years coarse-resolution (25-50 km) soil moisture data derived from active and passive microwave sensors such as ASCAT [1], AMSR-E [2, 3] and Windsat [4] have increasingly become available. Within the next years also soil moisture data derived from the Soil Moisture and Ocean Salinity (SMOS) missions will become available [5]. Validation and applications studies have already demonstrated the great potential of these soil moisture products in regional to global scale applications such as numerical weather prediction [6], climate monitoring [7] and flood forecasting [8]. However, a much larger number of applications could be addressed if soil moisture data at a resolution of 1 km or finer become available. Such a high spatial resolution can only be achieved by active microwave instruments that provide sub-antenna footprint resolution by means of range and Doppler discrimination. The concept of range and Doppler discrimination is employed by side-looking Synthetic Aperture Radar (SAR) instruments designed to acquire high resolution backscatter images. It can also be employed by conically scanning radar instruments, such as in the case of the Soil Moisture Active Passive (SMAP) mission foreseen for launch by NASA in 2013 [9]. In this paper we discuss the potential of the Sentinel-1 SAR mission, foreseen to be operated over the period 2012 to 2030, for global soil moisture monitoring.

2. FROM ENVISAT TO SENTINEL-1

Soil moisture retrieval from Synthetic Aperture Radar (SAR) is challenging due to the confounding influence of surface roughness and vegetation on the signal. A multitude of approaches utilising different backscatter models (empirical, semi-empirical, theoretical models), inversion approaches (direct inversion, look-up tables, neural networks), and SAR techniques (multi-temporal, multi-frequency, interferometry, polarimetry) have been extensively studied. Yet, as Barrett et al. [10] conclude in a recent review on the subject, only at large spatial scale some progress has been made while at field scales accurate soil moisture retrieval from SAR remains an enigma.

Among the most promising retrieval approaches is change detection, where a reference image is subtracted from each individual SAR image in an attempt to correct for roughness and vegetation effects specific to each pixel of an image [11]. The basic idea behind change detection is that the backscatter cross section of natural surfaces changes over short timescales mainly due to variations in soil moisture [12], while vegetation or surface roughness are assumed to be constant or only slowly varying. Change detection has been found to work particularly well for spaceborne scatterometers probably because its underlying assumptions are well suited when working at coarse spatial scales [13]. Also, the high temporal sampling rate of scatterometers (daily to weekly) is advantageous because it allows capturing dynamic soil moisture changes.

In contrast to scatterometers, spaceborne SAR systems have in general been designed to achieve a high spatial resolution at the expense of repetitive and continuous coverage. This has hampered the development and application of change detection approaches [14]. The first SAR sensor that offers frequent coverage over major parts of the world's land surfaces is the ENVISAT Advanced Synthetic Aperture Radar (ASAR) operated in Global Monitoring (GM) mode. ASAR uses a coherent, active phased array system operated at C-band (5.3 GHz) which offers flexibility in the generation and control of the radar beam. Therefore ASAR can be operated in several different stripmap and ScanSAR modes. The Global Monitoring (GM) mode is one of the

two ASAR ScanSAR modes and acquires images over a 405 km swath with a spatial resolution of 1 km at HH or VV polarisation. This mode could in principle be operated continuously but due to operation conflicts with the other ASAR modes, coverage is irregular and much reduced, particularly over regions with many conflicting uses (e.g. Europe). Another shortcoming of GM mode is its low radiometric resolution (1.3 dB).

Nevertheless, ASAR GM mode has served as an ideal test bed for testing the applicability of change detection for retrieving soil moisture from temporally dense SAR time series at 1 km spatial resolution. Adapting the change detection method originally developed for the ERS scatterometer, Pathe et al. [15] retrieved surface soil moisture data from ASAR GM time series acquired in HH polarisation over Oklahoma, USA, using the following formula

$$\sigma^0(\theta,t) = \sigma^0_{dry}(30) + \beta(\theta - 30) + Sm_s(t) \qquad (1)$$

where σ^0 is the backscattering coefficient (dB), θ is the incidence angle (deg), t is the time, $\sigma^0_{dry}(30)$ the dry backscatter reference (dB), β is the slope (dB/deg), S is the sensitivity of σ^0 to soil moisture changes (dB), and m_s is the surface soil moisture content (%). Besides its simplicity, an attractive feature of the method is that it works without the need for auxiliary data, i.e. all model parameters (σ^0_{dry}, β, S) can be directly derived from the ASAR time series for each pixel. Eq. 1 can then be directly inverted to yield maps of surface soil moisture content m_s for each measurement $\sigma^0(t)$. Within the ESA funded SHARE project this algorithm was used for monitoring soil moisture over continental scale areas, firstly in southern Africa [16] but later extended to Australia and selected areas in North and South America (http://www.ipf.tuwien.ac.at/radar/share/).

The results of the SHARE project have demonstrated the viability of the approach, even though the quality and usability of the ASAR GM surface soil moisture data is strongly impacted by the intermittent coverage and poor radiometric resolution of this mode. These two basic limitations will be overcome by the Sentinel-1 mission consisting of two C-band SAR satellites. The first two satellites are foreseen for launch in 2012 and 2013 respectively. The SAR instrument on board of Sentinel-1 has four modes, but over land it will be operated mainly in Interferometric Wide Swath (IWS) mode which images a 250 km wide swath at 5×20 m spatial resolution in either VV+VH or HH+HV polarisation [17]. Given a duty cycle of 20 minutes it is expected that the two planned Sentinel-1 satellites can cover Europe in IWS mode within about 4 days and the entire global land mass within about 6-12 days.

3. OPERATIONAL USER REQUIREMENTS

Thanks to the increasing availability of soil moisture data derived from coarse-resolution microwave sensors (ERS-1/2 scatterometer, METOP ASCAT, AMSR-E, SMMR, Windsat, etc.) and from the 1km ENVISAT ASAR Global Monitoring (GM), the requirements of operational users of soil moisture products are reasonably well understood. While their exact requirements, e.g. with respect to the spatial resolution and the retrieval accuracy, may vary depending on the application, there are a number of requirements that are shared by all operational users:

-High temporal sampling rate (daily to weekly)
-Guaranteed data availability in the future
-Availability of time series for model calibration
 (minimum one year)
-Near-real-time data availability (< 3 h after sensing)
-Well-known spatio-temporal errors
-Free and easy access

All these requirements together are currently only met by the operational METOP ASCAT 25 km surface moisture product produced by EUMETSAT in its central processing facility in Darmstadt. The product is disseminated within 130 minutes after sensing via EUMETCast. However, as discussed above, the use of the ASCAT surface soil moisture product is restricted to regional to global scale applications due to the coarse resolution of the sensor (25 km). Using down-scaling techniques, such as e.g. applied in EUMETSAT's Hydrology SAF, the 25 km ASCAT data can be disaggregated to a finer spatial scale [18], but without question a finer resolution of the native soil moisture product is expected to be of high value for applications. With Sentinel-1 the above listed requirements could potentially be met at a much finer spatial scale, making it a very attractive sensor for a broader soil moisture user community.

4. GLOBAL SENTINEL-1 SOIL MOISTURE

Compared to ENVISAT ASAR GM mode, Sentinel-1 IWS mode will have a much improved spatial, temporal and radiometric resolution, while working at nearly the same centre frequency (5.4 versus 5.3 GHz). In addition, Sentinel-1 will acquire data also in cross-polarisation (HV or VH). Therefore, the transfer of the ASAR GM change detection method to Sentinel-1 IWS data is expected to be relatively straight forward, with the potential for several improvements. One improvement could be to retrieve soil moisture at a spatial resolution finer than 1 km. However, with increasing spatial resolution the spatio-temporal variability of surface roughness and vegetation becomes more pronounced (e.g. tillage of agricultural fields). This is expected to increasingly invalidate the basic

assumptions of the ASAR GM change detection approach. Another improvement could be to use the cross-polarisation to correct for seasonal vegetation effects in the co-polarised backscatter measurements. Unfortunately, the relative strengths of vegetation backscatter effects on co- and cross-polarised C-band data are not yet well understood. Therefore, any of these potential improvements will require intensive research and demonstration before an operational implementation can be envisaged.

Considering the operational mission statement of Sentinel-1, it is thus proposed to apply, in a first step, the current ASAR GM change detection method to Sentinel-1 IWS co-polarised data averaged to 1 km. Due to the better penetration of HH polarised waves through vertically oriented vegetation (grasses, crops) HH polarisation is preferred [19]. Improved methods could be implemented in a second step, after more research has demonstrated their validity and robustness. The specifications of such a potential 1 km Sentinel-1 surface soil moisture product and of the low-resolution IWS backscatter image used as input for the soil moisture retrieval are given in Tab. 1 and Tab. 2 respectively.

Spatial resolution/ Sampling	1 km/500 m
Temporal resolution Europe Global	3-6 days 6-12 days
Accuracy	0.04-0.08 m^3m^{-3} over grassland and agricultural areas
Dissemination	Within 180 minutes after sensing
Data fields	-Measurement time (UTC) -Surface soil moisture (%) -Relative error (%) -Dynamic quality flags (snow cover, frozen soil conditions, inundation, etc.)
Data mask	Forests, steep terrain, desert landscapes, etc.

Table 1: Specifications of a potential 1 km Sentinel-1 surface soil moisture product

Spatial resolution/ Sampling	1 km/500 m
Radiometric resolution	< 0.05 dB (relative) < 0.3 dB (absolute)
Geometric Accuracy	< 100 m
Product latency	160 minutes after sensing
Polarisation	HH & HV or VV & VH

Table 2: Specifications of a potential low-resolution Sentinel-1 IWS image of high radiometric accuracy obtained by averaging the original IWS image.

Due to the simplicity of the change detection model given by Eq. 1, the technical implementation of the method for Sentinel-1 IWS mode is relatively straight forward. The implementation involves, amongst other tasks, setting up of a data base structure suitable for time series analysis, precise georeferencing and radiometric calibration of the IWS images, procedures for estimating the model parameters σ^0_{dry}, β, and S for each 1 km pixel, and finally the retrieval of soil moisture from each IWS image.

5. SCIENTIFIC CHALLENGES

While the simplicity of the change detection model is an important advantage when considering the technical implementation, it raises questions concerning the scientific validity of the method. The first concern is that the model assumes a linear relationship between surface soil moisture and the backscattering coefficient expressed in logarithmic units (dB) for both bare and vegetated surfaces. This has been observed in many experimental data sets [12, 20]. However, the linear model assumption is in general not supported by theoretical models used for simulating backscatter from bare soil and vegetation. For example, the Integral Equation Model (IEM), which is currently the standard model for simulating bare soil backscatter, exhibits an exponential relationship between the backscattering coefficient in dB and the soil dielectric constant, whereas for dry soils IEM predicts a high sensitivity of σ^0 to soil moisture changes, while for wet soils σ^0 is almost constant [21, 22]. Without question, the encountered discrepancies between theoretical predictions and experimental findings will stimulate new research on bare soil backscatter modelling.

Another unresolved issue is that the sensitivity S derived by applying the change detection model (1) is in general larger than what would have been expected from vegetation backscatter models (particularly at large incidence angles). To investigate attenuation effects range-resolving radar systems for separating the backscatter response from different layers of the vegetation canopy and the ground can be used [23]. Using such an instrument, Brown et al. [19] found that commonly used radiative transfer models of vegetation in general significantly overestimate the attenuation of microwaves by a wheat canopy in C-band. Closely connected to this issue is the question how seasonal vegetation phenology impacts the retrieval using Eq. 1? Pathe et al. [15] treated the model parameters σ^0_{dry}, β, and S as constants, even though vegetation growth is expected to prompt an increase of σ^0_{dry} and β, and a decrease of S. As a result, one would expect that ASAR GM soil moisture maps derived with constant model parameters exhibit season-dependent biases reflecting this model deficiency. But surprisingly such biases are not evident in the ASAR GM soil

moisture maps. Possibly, the high noise level and sparse temporal sampling of the ASAR GM data make it difficult to observe them, but it could also be the case that our expectations are wrong!

Finally, a last concern related to the change detection model is that even though its parameters σ^0_{dry}, β, and S have a clear physical definition and unit, their dependence on geophysical land surface properties is yet only understood in qualitative terms. For example, the comparison of the spatial patterns of these model parameters with land cover maps clearly reveals the strong influence of forest cover upon the parameters (e.g. S decreases with increasing forest cover), but there are not yet any functional models that relate the parameters to physical attributes (e.g. models that relate of S to forest biomass, forest gap fraction, or the like). As long as such physical dependencies are not known more precisely, we have to accept the phenomenological nature of Eq. 1. Yet, the more we will learn about the physical behaviour of the model parameters, the better our physical understanding of the whole retrieval process will become.

6. CONCLUSIONS

In the next few years we will see a proliferation of satellite based soil moisture services. At coarse spatial scales (25-50 km) microwave instruments like SMOS, ASCAT and Windsat will provide global soil moisture data with increasing accuracy. At a finer spatial scale, SMAP aims at delivering soil moisture data with a resolution of about 5 km derived from its L-band radar measurements. In this paper we propose setting up an operational service to derive 1 km soil moisture data from Sentionel-1 SAR observations using a change detection approach that has been developed and demonstrated for the ENVISAT ASAR Global Monitoring mode. While the technical implementation of such a service seems to be relatively straight forward, much more scientific research is needed for improving our physical understanding of the change detection model used in the retrieval. This understanding will lead to a better quantitative description of the retrieval errors and, very likely, to model improvements (e.g. use of cross-polarised IWS measurement for correcting for seasonal vegetation effects). Also, more research is still needed to investigate the strengths and limitations of the different microwave techniques currently used for soil moisture retrieval (passive versus active, L-band versus C-band, physically-based versus change detection models, etc.). Fortunately, advanced error characterisation methods such as triple collocation [24] or data assimilation [25] have also become increasingly available. These methods provide spatial error maps for the different soil moisture products, thus complementing validation approaches based on point scale *in situ* observations.

8. REFERENCES

[1]   Z. Bartalis, W. Wagner, V. Naeimi, S. Hasenauer, K. Scipal, H. Bonekamp, J. Figa, and C. Anderson, "Initial soil moisture retrievals from the METOP-A Advanced Scatterometer (ASCAT)," *Geophy. Res. Lett*, vol. 34, pp. L20401, 2007.

[2]   R. de Jeu, W. Wagner, T. Holmes, H. Dolman, N. C. van de Giesen, and J. Friesen, "Global soil moisture patterns observed by space borne microwave radiometers and scatterometers," *Surveys in Geophysics*, vol. 29, pp. 399-420, 2008.

[3]   E. G. Njoku, T. J. Jackson, V. Lakshmi, T. K. Chan, and S. V. Nghiem, "Soil moisture retrieval from AMSR-E," *IEEE Transactions on Geoscience and Remote Sensing*, vol. 41, pp. 215-229, 2003.

[4]   L. Li, P. Gaiser, T. J. Jackson, R. Bindlish, and J. Du, "WindSat soil moisture algorithm and validation," presented at Geoscience and Remote Sensing Symposium 2007 (IGARSS 2007). IEEE International, Barcelona, Spain, 2007.

[5]   Y. H. Kerr, "Soil moisture from space: Where are we?" *Hydrogeology Journal*, vol. 15, pp. 117-120, 2007.

[6]   K. Scipal, M. Drusch, and W. Wagner, "Assimilation of a ERS scatterometer derived soil moisture index in the ECMWF numerical weather prediction system," *Advances in Water Resources*, vol. 31, pp. 1101-1112, 2008.

[7]   Y. Y. Liu, A. I. J. M. Van Dijk, R. de Jeu, and T. R. H. Holmes, "An analysis of spatiotemporal variations of soil and vegetation moisture from a 29-year satellite-derived data set over mainland Australia," *Water Resources Research*, vol. 45, pp. W07405, 2009.

[8]   L. Brocca, F. Melone, T. Moramarco, and R. Morbidelli, "Antecedent wetness conditions based on ERS scatterometer data," *J. Hydrol.*, vol. 364, pp. 73-87, 2009.

[9]   M. Spencer, Y. Kim, and S. Chan, "The soil moisture active/passive (SMAP) radar," presented at IEEE radar Conference, Rome, Italy, 2008.

[10]   B. W. Barrett, E. Dwyer, and P. Whelan, "Soil moisture retrieval from active spaceborne microwave observations: An evaluation of

current techniques," *Remote Sensing*, vol. 1, 2009.

[11]   M. S. Moran, D. C. Hymer, J. Qi, and E. E. Sano, "Soil moisture evaluation using multi-temporal synthetic aperture radar (SAR) in semiarid rangeland.," *Agricultural and Forest Meteorology*, vol. 105, pp. 69-80, 2000.

[12]   Y. Kim and J. J. Van Zyl, "A time-series approach to estimate soil moisture using polarimetric radar data," *IEEE Transaction on Geoscience and Remote Sensing*, vol. 47, pp. 2519-2527, 2009.

[13]   W. Wagner, J. Noll, M. Borgeaud, and H. Rott, "Monitoring soil Moisture over the Canadian Prairies with the ERS Scatterometer.," *IEEE Trans. Geosci. Rem. Sens.*, vol. 37, pp. 206-216, 1999.

[14]   W. Wagner, G. Blöschl, P. Pampaloni, J.-C. Calvet, B. Bizzarri, J.-P. Wigneron, and Y. Kerr, "Operational readiness of microwave remote sensing of soil moisture for hydrologic applications," *Nordic Hydrology*, vol. 38, pp. 1-20, 2007.

[15]   C. Pathe, W. Wagner, D. Sabel, M. Doubkova, and J. B. Basara, "Using ENVISAT ASAR Global Mode data for surface soil moisture retrieval over Oklahoma, USA," *IEEE Transaction on Geoscience and Remote Sensing*, vol. 47, pp. 468-480, 2009.

[16]   A. Bartsch, "SHARE - Soil moisture monitoring in Africa," *GEOconnexion International*, vol. 7, pp. 46-47, 2008.

[17]   E. Attema, P. Bargellini, P. Edwards, G. Levrini, S. Lokas, L. Moeller, B. Rosich-Tell, P. Secchi, R. Torres, M. Davidson, and P. Snoeij, "Sentinel-1: The Radar Mission for GMES Land and Sea Services," *ESA Bulletin*, vol. 131, pp. 10-17, 2007.

[18]   W. Wagner, C. Pathe, M. Doubkova, D. Sabel, A. Bartsch, S. Hasenauer, G. Blöschl, K. Scipal, J. Martinez-Fernandez, and A. Löw, "Temporal stability of soil moisture and radar backscatter observed by the Advanced Synthetic Aperture Radar (ASAR)," *Sensors*, vol. 8, pp. 1174-1197, 2008.

[19]   S. C. M. Brown, S. Quegan, K. Morrison, j. C. Bennett, and G. Cookmartin, "High-Resolution Measurements of Scattering in Wheat Canopies - Implications for Crop Parameter Retrieval," *IEEE Transactions on Geoscience and Remote Sensing*, vol. 41, pp. 1602-1610, 2003.

[20]   I. Champion and R. Faivre, "Sensitivity of the radar signal to soil moisture: Variation with incidence angle, frequency, and polarization," *IEEE Transaction on Geoscience and Remote Sensing*, vol. 35, pp. 781-783, 1997.

[21]   R. Bindlish and A. P. Barros, "Multifrequency soil moisture inversion from SAR measurements with the use of IEM," *Remote Sensing of Environment*, vol. 71, pp. 67-88, 2000.

[22]   A. K. Fung and K. S. Chen, "Dependence of the surface backscattering coefficients on roughness, frequency and polarization states," *International Journal of Remote Sensing*, vol. 13, pp. 1663-1680, 1992.

[23]   M. Kurum, R. H. Lang, P. E. O'Neill, A. Josef, T. Jackson, and M. Cosh, "Estimation of canopy attenuation for active/passive microwave soil moisture retrieval algorithms," presented at Microwave Radiometry and Remote Sensing of the Environment (MICRORAD 2008), Firenze, Italy, 2008.

[24]   K. Scipal, T. Holmes, R. de Jeu, V. Naeimi, and W. Wagner, "A possible solution for the problem of estimating the error structure of global soil moisture data sets," *Geophysical Research Letters*, vol. 35, pp. L24403:1-4, 2008.

[25]   W. Crow and X. Zhan, "Continental-scale evaluation of remotely sensed soil moisture products," *IEEE Geoscience and Remote Sensing Letters*, vol. 4, pp. 451-455, 2007.