POTENTIAL OF SENTINEL-1 FOR HIGH-RESOLUTION SOIL MOISTURE MONITORING

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ABSTRACT

Soil moisture is a crucial variable for a large variety of applications with different requirements on the spatial and temporal resolution of the observations. Coarse-scale instruments can provide data operationally with a nearly-daily global coverage at a spatial resolution of several hundreds of square kilometers, whereas SAR instruments provide a spatial resolution of less than one hectare to about one square kilometer but with a revisit time varying from several days to several months. This study uses coarse-scale MetOp ASCAT data and higher resolution Envisat ASAR data taken in the GM mode and the WS mode together with in-situ measurements to demonstrate (i) the potential of Sentinel-1 to capture very local soil moisture variations and (ii) the expected impact of the significantly improved radiometric accuracy of Sentinel-1 compared to existing soil moisture missions.

Index Terms— Soil Moisture, Synthetic Aperture Radar, Sentinel-1

1. INTRODUCTION

A large variety of remotely sensed soil moisture data sets is available for scientific and operational use, providing measurements with a spatial resolution of about 25 - 50 km (e.g. ERS, ASCAT, AMSR-E and SMOS). The coarse scale of these data sets is sufficient for many applications, e.g. data assimilation for numerical weather prediction or climate research [1, 2], but several studies demonstrated also the need for space-borne soil moisture observations at finer scales, e.g. for hydrological applications or agricultural monitoring and irrigation management [3].

High-resolution soil moisture maps can be obtained from Synthetic Aperture Radar (SAR) instruments (e.g. Envisat ASAR and RADARSAT-2), which are normally designed to acquire data in different scanning modes and only upon user requests. This acquisition strategy results in inhomogeneous data archives with image products differing in terms of the spatial resolution (from less than one hectare to about one square-kilometer), the measurement frequency (several days to several months), and varying radiometric accuracy. The choice of the data set for a particular application is hence always a tradeoff between those three properties. The Sentinel-1 mission, planned within the framework of the Global Monitoring for Environment and Security (GMES) program of the European Space Agency (ESA) and the European Commission (EC), will be the first mission that provides high-resolution C-band SAR data on an operational basis using a fixed acquisition scenario with a significantly improved radiometric accuracy compared to current instruments [4].

Several studies proposed methods to retrieve soil moisture from Sentinel-1 data [5, 6]. The aim of this study is to demonstrate the potential of the upcoming Sentinel-1 mission for capturing spatio-temporal dynamics of soil moisture, which cannot be resolved by currently available coarse-scale sensors. A secondary aim is to demonstrate the expected impact of the improved radiometric accuracy of Sentinel-1 compared to already existing SAR instruments. Coarse-scale (25 km) soil moisture observations from MetOp ASCAT will be compared to ENVISAT ASAR measurements at 1 km spatial scale taken in the Global Monitoring mode (GM) as well as upscaled from the 150 m Wide Swath (WS) mode. Finally the three products will be compared to in-situ point measurements drawn from the International Soil Moisture Network (http://ismn.geo.tuwien.ac.at).

2. DATA SETS

The choice of appropriate data sets to demonstrate the future potential of Sentinel-1 is critical since no single instrument comes close to all of its proposed properties in terms of revisit time, spatial resolution and radiometric accuracy. A set of coarse-scale operationally available measurements from MetOp ASCAT, high-resolution SAR observations in different modes from Envisat ASAR, and point-scale in-situ measurements was chosen for this purpose.

2.1. MetOp ASCAT

The ASCAT instrument onboard the MetOp satellite is a real aperture radar observing in C-band (λ = 5.7 cm) in VV polarization with a spatial resolution of 25 km, sampled to a 12.5 km grid, covering the entire globe every 1-3 days. Soil moisture is provided on an operational basis retrieved using the TU-Wien method [7]. Measurements from the first MetOp satellite (MetOp-A) are available since 2007. A second MetOp satellite (MetOp-B) was launched in autumn 2012, carrying an identical ASCAT instrument, what improves the temporal coverage of the data set.

2.2. Envisat ASAR

The ASAR instrument onboard the Envisat satellite (2002-2012) acquired SAR data in C-band for different polarizations in different acquisitions modes of which the Global Monitoring (GM) mode and the Wide Swath (WS) mode provided the best spatio-temporal coverage. GM data is acquired in HH polarization at a spatial resolution of 1 km providing on a global average 400 measurements during the entire life time, whereas the WS mode observes in both, HH and VV polarization at 150 m spatial resolution with on average 70 measurements for the same overall observation duration. The number of available acquisitions is shown in Figure 1. Soil moisture is retrieved using an adapted change detection approach based on the TU-Wien method [8].

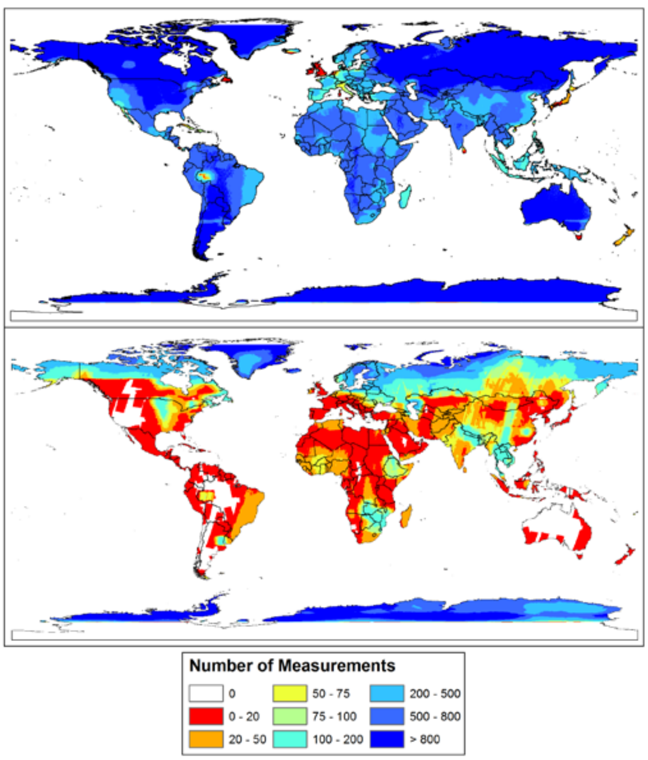

Figure 1: Available measurements (2002-2012) of Envisat ASAR in the GM mode (top) and the WS mode (bottom).

2.3. Sentinel-1

The Sentinel-1 mission is part of the Global Monitoring for Environment and Security (GMES) program of the European Space Agency (ESA) and the European Commission (EC). Two identical satellites, carrying a C-band SAR instrument, are planned to be launched: the first one at the end of 2013, the second one within the following 18 months. The mission's goal is to acquire a complete coverage of Europe and Canada every two to four days and a complete global coverage every 6 days at a spatial resolution of 5 x 20 m², permanently using the Interferometric Wide Swath (IW) mode, which can be operated in different polarizations (VV, VV+VH, HH or HH+HV). Other modes are only available for emergency requests. Near Real Time (NRT) products are expected to be available after maximum 3 hours after acquisition.

2.4. The International Soil Moisture Network

The International Soil Moisture Network (ISMN) is a centralized data hosting facility that collects and harmonizes in-situ soil moisture measurements from data providers worldwide and makes it available to users on a cost-free basis [9]. Currently the ISMN holds data sets from 38 networks operating altogether more than 1400 stations of which more than 200 are operating in NRT. The data base covers a time period from 1952 to now, most measurements are taken after 2000. For this study, only measurements from the HOBE network (http://www.hobe.dk), located in central Denmark, were used because its stations are the only ones that provide a sufficient temporal measurement overlap with both, ASAR GM and WS observations.

3. METHODOLOGY

Soil moisture is highly variable in space and time, but coarse-scale instruments, which provide data on an operational basis with a very high radiometric accuracy are not able to capture local variations that are of interest e.g. for agricultural applications [3]. 25 km ASCAT data are qualitatively compared to 1 km ASAR data in order to demonstrate the potential of high-resolution measurements of Sentinel-1 for capturing spatio-temporal dynamics in soil moisture that cannot be resolved by current coarse-scale instruments.

ASAR measurements taken in the Global Monitoring mode are available with a rather good temporal coverage, but have a poor radiometric accuracy of about 1.2 dB. Wide Swath data has a significantly improved radiometric accuracy when averaging to the 1 km scale, i.e. about 0.2 dB, but only few measurements are available (Figure 1). Sentinel-1 is expected to have an even better radiometric accuracy of about 0.05 - 0.07 dB, again for an averaged 1 km product [5]. The improvements for capturing spatio-temporal variations in soil moisture with a certain quality are demonstrated by calculating standard performance metrics, i.e. the temporal correlation (R) and the Root-Mean-Square-Difference (RMSD), using in-situ soil moisture observations as a reference.

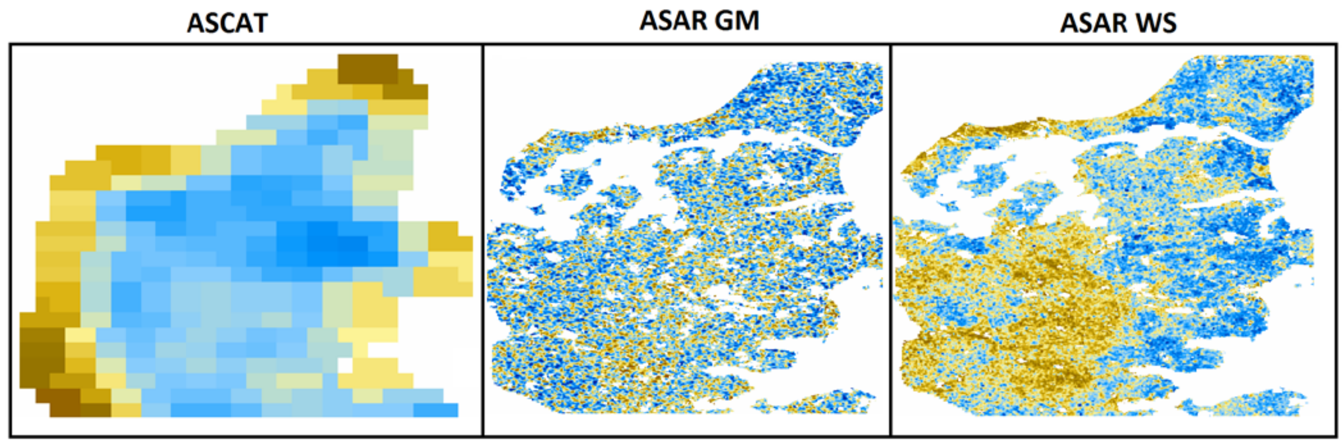

Figure 2: Soil moisture image over Northern Denmark from October 9th, 2007 taken from ASCAT (left; ascending path), ASAR GM mode (middle; descending path) and ASAR WS mode (right; ascending path). Water bodies are masked out in the ASAR images.

4. RESULTS AND DISCUSSION

Figure 2 shows the soil moisture state over Northern Denmark at October 9th, 2007 retrieved using ASCAT, ASAR GM mode and ASAR WS mode, respectively. The coarse scale (25 km) ASCAT image only shows generally wet conditions with a slightly dryer area in the central inland and some artificial border effects at the coast line, whereas the ASAR WS product clearly resolves distinct dry and wet patterns at the 1 km scale. The same dry and wet patterns can be also seen in the ASAR GM image but are blurred due to a very high noise level. The much better signal-to-noise-ratio (SNR) of the WS mode is caused by the averaging from the original 150 m to the 1 km resolution. The radiometric accuracy of ASCAT is close to the accuracy of the 1 km averaged ASAR WS product (~0.2 dB), but its coarse-scale antenna design precludes resolving local soil moisture variations.

Figure 3 shows the correlations and unbiased root-mean-squared-differences (ubRMSD) between the in-situ stations of the HOBE network and the satellite products. ASAR WS observations show the best correlation and the lowest RMSD. ASCAT has better correlations but also higher RMSD values than ASAR GM which is probably caused by the large scale difference introducing scaling errors.

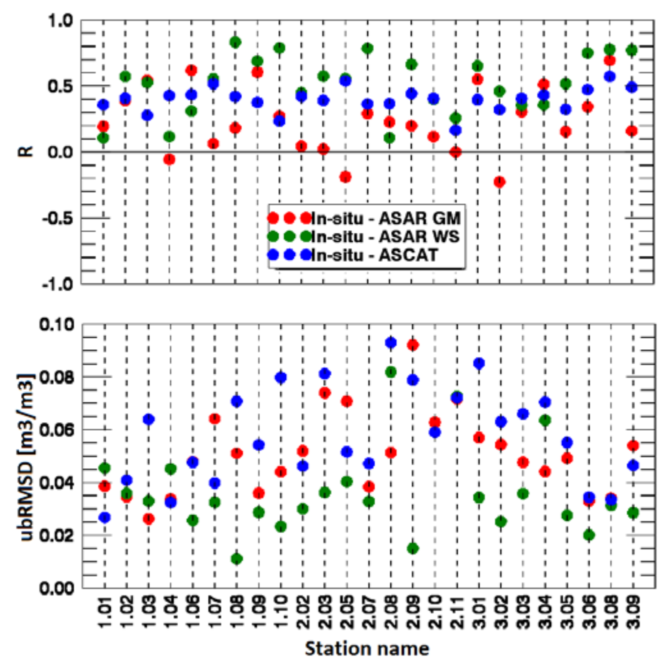

Figure 3: Correlation (top) and unbiased RMSD (bottom) between the in-situ stations of the HOBE network (x-axis) and ASCAT, ASAR GM, and ASAR WS, respectively.

The limited temporal overlap of all three satellite data sets with the same in-situ stations makes it critical to obtain statistically significant results. After filtering for a correlation probability level of 0.05 only 7 stations remain (Figure 4). However, the relative performance stayes the same except for the increase of the in-situ correlation with ASAR GM, which is now higher than with ASCAT. Compared to the ASAR WS data, Sentinel-1 is expected to have a significantly improved radiometric accuracy (3-5 magnitudes) with respect to the 1 km product, which is expected to outperform also the operational coarse-scale products. Sentinel-1 is planned to provide data with a spatial resolution of 5 x 20 m² also on an operational basis, thus providing a temporal coverage that is currently only available for coarse-scale instruments. Acquisition modes of available SAR instruments with a similar spatial resolution were only used experimentally providing only a few high-resolution images over the entire life time. The use of a significantly higher spatial resolution will also reduce artificial scaling errors when looking into local soil moisture dynamics.

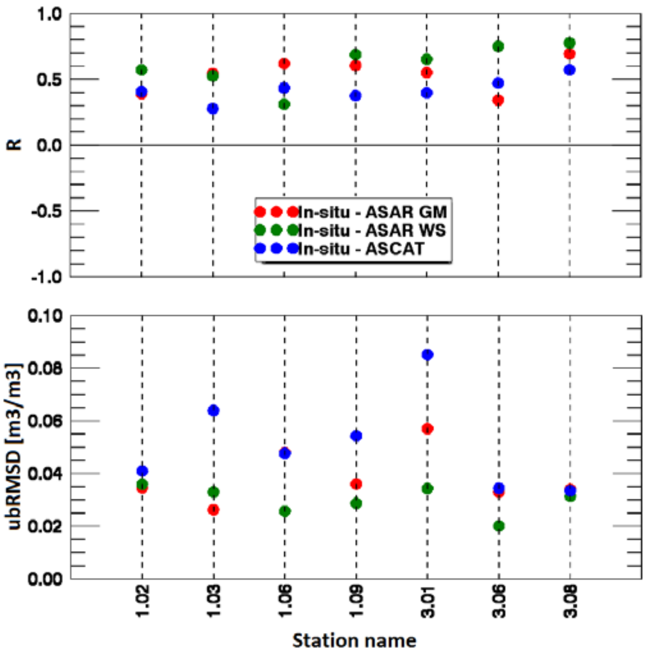

Figure 4: Correlation (top) and unbiased RMSD (bottom) between the in-situ stations of the HOBE network (x-axis) and ASCAT, ASAR GM, and ASAR WS, respectively, filtered for significant correlation ($p \leq 0.05$).

5. CONCLUSION AND OUTLOOK

This study used Envisat ASAR and MetOp ASCAT data to demonstrate the capability of SAR instruments for resolving spatial soil moisture variations that are not seen from coarse-scale instruments. Current SAR instruments only provide very unfrequent measurements mainly upon requests and are hence often incapable of sufficiently resolving temporal soil moisture dynamics. Furthermore, in-situ measurements were used to demonstrate the performance improvements of ASAR data by averaging the WS mode measurements to the 1 km scale of the GM mode measurements in order to increase the radiometric accuracy.

Sentinel-1 will provide data on an operational basis with a temporal coverage currently only provided from coarse scale instruments. Its radiometric accuracy is expected to outperform any existing soil moisture sensor with respect to their observation scale. This superior temporal coverage and radiometric accuracy, together with its original spatial resolution of 5 x 20 m² will make it possible to capture spatio-temporal soil moisture dynamics which were not observable from space before.

6. ACKNOWLEDGEMENTS

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