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Potential for High Resolution Systematic Global Surface Soil Moisture Retrieval via Change Detection Using Sentinel-1

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***Abstract*—The forthcoming two-satellite GMES Sentinel-1 constellation is expected to render systematic surface soil moisture retrieval at 1 km resolution using C-band SAR data possible for the first time from space. Owing to the constellation's foreseen coverage over the Sentinel-1 Land Masses acquisition region—global approximately every six days, nearly daily over Europe and Canada depending on latitude—in the high spatial and radiometric resolution Interferometric Wide Swath (IW) mode, the Sentinel-1 mission shows high potential for global monitoring of surface soil moisture by means of fully automatic retrieval techniques. This paper presents the potential for providing such a service systematically over Land Masses and in near real time using a change detection approach, concluding that such a service is—subject to the mission operating as foreseen—expected to be technically feasible. The work presented in this paper was carried out as a feasibility study within the framework of the ESA-funded GMES Sentinel-1 Soil Moisture Algorithm Development (S1-SMAD) project.**

***Index Terms*—C-band, near real time, Sentinel-1, soil moisture, synthetic aperture radar.**

Manuscript received December 03, 2011; revised February 10, 2012; accepted March 02, 2012. This work was carried out within the framework of the European Space Agency (ESA)-funded GMES Sentinel-1 Soil Moisture Algorithm Development (S1-SMAD) project, under European Space Research and Technology Centre (ESTEC) contract 4000101350/10/NL/MP/ef.

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Digital Object Identifier 10.1109/JSTARS.2012.2190136

I. Introduction

THE Sentinel-1 mission is a part of the Global Monitoring for Environment and Security (GMES) program of the European Space Agency (ESA) and the European Commission (EC) and is intended to provide continuous global all-weather, day-and-night radar imaging in support of GMES applications [1]. This paper presents the potential for a systematic global near-real-time (NRT) surface soil moisture (SSM) retrieval service over the Sentinel-1 Land Masses acquisition region at 1 km resolution using C-band synthetic aperture radar (SAR) data acquired in Interferometric Wide Swath (IW) mode by the forthcoming two-satellite Sentinel-1 constellation, by means of a change detection approach. This work was carried out as a feasibility study within the framework of the ESA-funded GMES Sentinel-1 Soil Moisture Algorithm Development (S1-SMAD) project.

Soil moisture is a key parameter in the global water, energy and carbon cycles [2], [3]. Accordingly, it is an important factor in a variety of Earth sciences, including hydrology, meteorology, climatology and agronomy. Studies dealing with coarse-resolution (25–50 km) soil moisture data have already shown the high potential of ingesting such products in support of, e.g., numerical weather prediction [4], climate monitoring [5] and flood forecasting [6], [7]. Products at 1 km resolution are expected to prove useful in still more applications, including monitoring of agricultural yield at field level, catchment-scale hydrologic process studies and irrigation management.

Soil moisture can be measured accurately at point scale using *in situ* techniques [8], with new approaches such as smart sensor webs [9] potentially opening the door to capturing area-representative measurements in a more cost-effective manner. Moreover, international efforts to collect and harmonize soil moisture network data from around the world [10], [11] have greatly enhanced the availability and accessibility of *in situ* soil moisture measurements. Nevertheless, *in situ* measurements from sparse networks may not necessarily be representative of their respective surrounding areas, and funding for such networks has undergone cutbacks in many regions most adversely affected by changes in the availability of fresh water resources [12], [13]. Alternatively, soil moisture can be measured at a variety of spatial and temporal scales using remote sensing techniques [14], with microwave instruments operated at frequencies below the relaxation frequency of water molecules (9 GHz near 0 °C and

1939-1404/$31.00 © 2012 IEEE

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17 GHz at 20 °C) holding the greatest potential on account of the magnitude of the dielectric contrast between wet and dry soil at those frequencies. The magnitude of the soil's dielectric constant ε, in turn, strongly influences the intensity of the radar backscattering coefficient σ^0, which is known to grow monotonically with increasing soil moisture content [15], [16].

In the last decade, soil moisture measurements derived from spaceborne microwave radiometers and scatterometers at coarse spatial scales (25–50 km), including MetOp ASCAT [17], AMSR-E [18]–[20], Windsat [21] and SMOS [22], have increasingly become available to the user community [23]. The Soil Moisture and Ocean Salinity (SMOS) satellite, which carries a radiometer operated at L-band, was launched in 2009 and is notably the first satellite specialized specifically for the retrieval of soil moisture. SMOS provides soil moisture data at a spatial resolution in the order of 35–50 km. At the present time, only active microwave instruments providing sub-antenna footprint resolution by means of range and Doppler discrimination [24] can provide measurements from space at finer spatial scales (resolutions of 10 km and finer). Examples include the Advanced Synthetic Aperture Radar (ASAR) instrument onboard the Envisat platform [25] and the SAR instrument onboard the forthcoming Sentinel-1 satellite, both of which operate at C-band. Another example is the forthcoming Soil Moisture Active Passive (SMAP) satellite [26], which carries a conically scanning microwave instrument operating at L-band and is expected to be launched in the 2014–2015 timeframe.

Soil moisture retrieval using active microwave data is a challenge on account of the confounding influence of the geometric and dielectric properties of the Earth's surface on the backscattered signal [27]. An exact signal decomposition could in theory be obtained by solving Maxwell's equations, with recent advances in computational electromagnetics allowing for finding numerical solutions to Maxwell's equations even for three-dimensional problems [28]. Even so, signal inversion techniques will always require that simplifying assumptions be made, particularly if the soil moisture retrieval is to be carried out on a global scale. As the impact of simplifying assumptions on the ability of the retrieval model to correctly describe the physical measurement process is, in general, not adequately understood, it is not possible *a priori* to predict which soil moisture retrieval approach will perform best in the context of the Sentinel-1 mission. Once the mission is rendered operational, different retrieval approaches—e.g., analytical inversion of empirical models, iterative least squares matching using semi-empirical forward models, lookup tables, Bayesian approaches, possibilistic methods, or neural networks trained with theoretical models—ought to be evaluated in order to identify the most robust and accurate approach [29], [30]. In this paper, a change detection model developed and already extensively tested in a SAR context using the Global Monitoring (GM) mode of the ASAR instrument onboard the Envisat platform [31], [32] is adopted.

Underlying change detection techniques is the assumption that the backscatter cross-section over soil surfaces across short time scales changes primarily on account of variations in soil moisture, while surface roughness and vegetation vary more slowly [33]. The TU Wien method is a change detection approach originally developed for the ERS scatterometer at a spatial resolution of 50 km [34]–[36], later adapted to MetOp ASCAT at 25 km [17] and Envisat ASAR GM mode at 1 km [32], respectively. The method has been extensively validated using *in situ* measurements, modeled soil moisture data and other satellite-based retrievals, with retrieval accuracies approaching the accuracy goals of SMOS and SMAP; see, e.g., [37] for results obtained for the ERS scatterometer, [38] for ASCAT and [39] for ASAR GM mode. Even more recent validation studies using ASCAT and SMOS suggest that the ASCAT change detection approach gives retrievals comparable to—and in some regions even slightly better than—the SMOS Level 2 algorithm [40], [41]. The ASCAT Level 2 surface soil moisture product is distributed operationally by EUMETSAT in NRT, within 130 minutes of acquisition.

The proposed NRT SSM retrieval algorithm for Sentinel-1 in IW mode is an adaptation of the TU Wien method most closely akin with the method's earlier adaptation to Envisat ASAR GM mode [32]. Among the ASAR modes, GM mode offers the best balance between radiometric, spatial and temporal resolution in support of change detection-driven SSM retrieval. With ASAR GM mode data at 1 km resolution provided at a radiometric resolution of 1.2 dB, the quality of SSM retrieval is expected to benefit considerably from the foreseen radiometric resolution of Sentinel-1 IW mode, which is expected to be in the order of 0.05–0.07 dB when aggregated to a spatial resolution of 1 km. The temporal resolution of the Sentinel-1 constellation in IW mode over the Land Masses acquisition region—with an outlook to coverage every six days globally and nearly daily over Europe and Canada depending on latitude [42]—is, likewise, expected to contribute favorably to calibration of the TU Wien model, vis-à-vis what has been possible with data acquired in Envisat ASAR GM mode.

User requirements for a systematic global NRT SSM retrieval service are reasonably well known, owing to the proliferation in availability of soil moisture products over the past decade. Requirements common to operational users are: (i) high temporal resolution, (ii) long-term availability of the SSM data, (iii) availability of SSM time series for user model calibration (at least one year), (iv) well-known spatio-temporal error characterization, and (v) free and easy access.

In the following section, a review of attributes of the Sentinel-1 mission relevant to the retrieval of surface soil moisture is given, with Section III presenting the adaptation of the TU Wien method for Sentinel-1 accordingly. Section IV discusses the processing chain of the proposed NRT SSM retrieval software (S2M-NRT), as implemented within the framework of the S1-SMAD project, which runs on model parameters computed in non-NRT by the so-called reprocessing facility (S2M-RF). The processing chain of the proposed S2M-RF is taken up in Section V. In support of evaluating processor timeliness for delivery of SSM products in NRT, Section VI provides a runtime analysis of the S2M-NRT software demonstrator implemented within the framework of the S1-SMAD project on simulated Sentinel-1 input data.

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II. SENTINEL-1

The space segment of the GMES Sentinel-1 mission is expected to consist of at least two identical near-polar sun-synchronous orbiting satellites, each at a mean altitude of 693 km and equipped with a C-band SAR instrument operating at a center frequency of 5.405 GHz with support for HH-HV and VV-VH simultaneous co- and cross-polarization receive channels. The first of the satellite pair, Sentinel-1A, is expected to be launched in 2013, with the launch of its sister satellite Sentinel-1B foreseen 18 months thereafter. The two satellites are each designed for a nominal lifetime of 7 years, extendable to 12 [43].

A. Acquisition Strategy

In support of interferometric applications, the reference orbit of both satellites is expected to be maintained within the same Earth-fixed orbital tube radius of 50 meter-rms for the duration of the mission's nominal lifetime. In the aim of satisfying the constraints imposed by the mission's observation requirements, overlap between data takes within an orbit cycle is minimized. Moreover, data takes are expected to match closely across cycles with respect to length, acquisition mode and relative ordering within the cycle—yielding predictable acquisition geometry and spatial coverage—unless acquisitions are made within the framework of the GMES Emergency Management Service (EMS) [43].

A total of four acquisition regions have been defined in the published Sentinel-1 Payload Data Ground Segment (PDGS) documentation, with each Sentinel-1 nominal imaging mode operated over a specific set of regions. These four acquisition regions are Arctic/Antarctic, Maritime Transport Zones (MTZs), Land Masses and Ocean [44]. The Sentinel-1 constellation is expected to cover Land Masses globally every six days, with nearly daily coverage foreseen over Europe and Canada [42].

B. Characteristic Local Incidence Angles

A consequence of the stability of the acquisition strategy is the stability of the acquisition geometry across orbit cycles. Accordingly, it is expected—in stark contrast to, e.g., Envisat ASAR—that any single point on the Earth's surface will be acquired at effectively one of a finite set of respective so-called characteristic local incidence angles. This number is expected to range from as few as one at the equator to as many as three at the poles. The set of characteristic local incidence angles associated with any point on the Earth's surface can be determined, respectively, by means of orbit simulation once the starting point of the orbit is known.

C. Systematic NRT Processing Over Land Masses

In support of satisfying timeliness requirements, baseline Sentinel-1 NRT products are expected to be processed—in partially overlapping slices of configurable length—directly at the Core Ground Stations (CGSs) to which the corresponding raw data is downlinked. Such data is subject to an NRT-first downlink strategy, with maximum onboard data latency kept under one orbit. NRT products are expected to be made available within 3 hours of sensing in general, and within 1 hour if acquired within the visibility of a CGS. However, systematic processing in NRT within the framework of the Sentinel-1 core PDGS at the CGSs is foreseen only over the Arctic/Antarctic, MTZs and Ocean acquisition regions.

In contrast to baseline NRT products, baseline products with less stringent timeliness requirements—in particular those generated from data acquired over Land Masses—are expected to be processed at associated Processing and Archiving Centers (PACs), with an aim to keeping onboard data latency under two orbits [44]. Downlinked data from such data takes is expected to typically be split over different stations or over different passes. In general, it is not expected that it will be possible to process such downlinked partial data takes on an individual basis, since a partial data take might be too short or might fail to include internal calibration information [43]. Non-NRT baseline Level 0 products are accordingly expected to be processed over the entirety of their respective data takes, upon completion of an assembly stage. Baseline non-NRT products are expected to be made available within 24 hours of acquisition.

The so-called collaborative PDGS of the Sentinel-1 mission is expected to provide a mechanism for augmenting the timeliness of the core PDGS—for instance by allowing systematic NRT processing over the Land Masses acquisition region—by adding appropriately equipped Local Ground Stations (LGSs) to the ground station network. Moreover, the collaborative PDGS is expected to allow for the integration of so-called hosted user processors, such as an implementation of the S2M-NRT. In support of processing and disseminating SSM products in NRT, the SSM retrieval processor would accordingly have to be run at the LGS level within the framework of the collaborative PDGS, alongside DEM geocoding and radiometric calibration in NRT of data acquired over Land Masses. Such geocoding and calibration of Level 0 products is not expected to impact NRT timeliness, since calibration and geocoding parameters can be known *a priori* in view of the foreseen stability of the mission's acquisition geometry.

D. Interferometric Wide Swath Mode

Sentinel-1 SAR instrument data can be acquired in any one of four exclusive nominal imaging modes, namely in the low bit rate Wave (WV) mode or in the high bit rate StripMap (SM), Interferometric Wide Swath (IW) or Extra Wide Swath (EW) modes, respectively. The Land Masses acquisition region is expected to be acquired in IW mode by default, with the SM and EW modes available for emerging user requests and for continuity with the earlier ERS and Envisat missions.

Level 0 IW mode data is expected to be provided at a single-look spatial resolution of 5×20 m, acquired across an incidence angle range of 30–45 degrees and over a swath width of 250 km. Upon downlink, raw IW mode data is expected to be systematically processed in non-NRT—as part of the baseline—up to Level 1 multi-looked Ground Range Detected (GRD) products in Medium Resolution (MR) at 88×89 m and High Resolution (HR) at 20×22 m, respectively, by the core PDGS. Systematic generation in NRT of DEM-geocoded IW mode GRD products at 1 km resolution over the Land Masses acquisition region is foreseen as a potential hosted user product [43], within the framework of the collaborative PDGS. Aggregated to 1 km, the

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radiometric resolution of data acquired in IW mode is expected to lie in the order of 0.05–0.07 dB.

E. Data Volumes and Archiving

Taking into account only a single Sentinel-1 satellite, total data volumes for only Level 0 data across all acquisition regions are expected to reach ca. 320 TB *per annum*, amounting to ca. 2.3 PB (petabytes) in the course of 7.5 years [44]. Level 0 products are expected to contain the Flexible Dynamic Block Adaptive Quantization (FDBAQ)-compressed [45] raw instrument source packet data alongside annotations in support of subsequent calibration and post-processing. Availability of archived Level 0 products is foreseen for 25 years following the end of the space segment operations [43], with the most accurate version of the antenna pattern expected to be made available—in the form of annotation data—within two weeks of acquisition. Total Level 1 data volumes for baseline products are expected to be 4–5 times larger than those for Level 0. Accordingly, it is foreseen that within the framework of the core PDGS, Level 1 data will be generated on the fly as needed, rather than undergo systematic archiving. Again owing to the steady acquisition geometry, these sizable data volumes are not expected to impact NRT timeliness.

III. The TU Wien Method for Sentinel-1

The TU Wien backscatter model expresses backscatter measurements $\sigma^0(\theta, t)$ [dB], where θ [deg] and t are the local incidence angle (LIA) and time, respectively, at which the measurement was acquired, in terms of empirical model parameters and the degree of surface soil water saturation $m_s(t) \in [0, 1]$, which gives the volume of water present in the soil relative to the volume of the soil's pores [46]. Adapting the TU Wien backscatter model—originally developed for the ERS scatterometer at 50 km [34]–[36] and later modified for MetOp ASCAT at 25 km [17]—to 1 km DEM-geocoded Envisat ASAR GM mode data, $\sigma^0(\theta, t)$ is decomposed according to

$$\sigma^0(\theta, t) = \sigma^0_{\mathrm{dry}}(30) + \beta(\theta - 30) + S m_s(t) \tag{1}$$

where $\sigma^0_{\mathrm{dry}}(30)$ [dB] is the dry reference at a reference local incidence angle of 30°, S [dB] is the sensitivity of σ^0 to changes in surface soil moisture and β [dB/deg] is termed the slope [32]. The dry reference is assumed to correspond closely with the soil wilting point. The slope β—which accounts for the incidence angle dependency of backscatter measurements—is estimated from the slope of the line of best fit in a least squares sense to a long time series of DEM-geocoded backscatter measurements σ^0 in dB plotted as a function of local incidence angle θ, noting that this dependency is approximately linear in the incidence angle range of 20° to 40° of ASAR GM mode [32]. A backscatter measurement $\sigma^0(\theta, t)$ is normalized to the reference angle of 30° according to

$$\sigma^0(30, t) = \sigma^0(\theta, t) - \beta(\theta - 30). \tag{2}$$

By reorganizing the terms in (1) and plugging in (2), the degree of surface soil water saturation $m_s(t)$ is given by

$$m_s(t) = \frac{\sigma^0(30, t) - \sigma^0_{\mathrm{dry}}(30)}{S}. \tag{3}$$

The Sentinel-1 mission is expected to feature an acquisition strategy such that backscatter measurements for any point on the Earth's surface be acquired at up to only three respective characteristic local incidence angles (up to three at high latitudes, as few as one along the equator), for acquisitions not made within the framework of the GMES Emergency Management Service (EMS) [43]. Accordingly, normalization as carried out in (2) is rendered neither possible in general nor necessary in practice. Let $\Theta(\sigma^0)$ be the set of characteristic local incidence angles θ_{char} available at the location corresponding to the backscatter measurement $\sigma^0(\theta, t)$. A local incidence angle θ at which a backscatter measurement $\sigma^0(\theta, t)$ was acquired is defined to correspond to a characteristic local incidence angle $\theta_{\mathrm{char}} \in \Theta(\sigma^0)$ if θ_{char} minimizes $\mathrm{abs}(\theta - \theta_{\mathrm{char}})$ over the available characteristic local incidence angles in $\Theta(\sigma^0)$, subject to the condition that $\mathrm{abs}(\theta - \theta_{\mathrm{char}}) < T$, for some tight angular threshold T. The proposed adaptation of the TU Wien backscatter model presented in (1) to the context of the Sentinel-1 mission is given by

$$\sigma^0(\theta, t) = \sigma^0_{\mathrm{dry}}(\theta_{\mathrm{char}}) + S m_s(t) \tag{4}$$

where θ is understood to correspond to θ_{char}. Accordingly, surface soil water saturation $m_s(t)$ for Sentinel-1 is retrieved according to

$$m_s(t) = \frac{\sigma^0(\theta, t) - \sigma^0_{\mathrm{dry}}(\theta_{\mathrm{char}})}{S}. \tag{5}$$

The sensitivity S to changes in surface soil moisture is estimated by the observed dynamic range $\sigma^0_{\mathrm{wet}}(\theta_{\mathrm{char}}) - \sigma^0_{\mathrm{dry}}(\theta_{\mathrm{char}})$ of the backscatter measurements at the location under consideration, where $\sigma^0_{\mathrm{wet}}(\theta_{\mathrm{char}})$ is the wet reference at θ_{char}. Analogously to the dry reference, the wet reference is assumed to correspond closely with the soil saturation point.

A. Model Parameter Retrieval

The respective references with respect to characteristic local incidence angle θ_{char} could be obtained and stored per gridpoint of a global grid at 1 km resolution according to

$$\sigma^0_{\mathrm{wet}}(\theta_{\mathrm{char}}) = \frac{1}{N_{\mathrm{wet}}} \sum_{i=N-N_{\mathrm{wet}}}^{N_{\mathrm{wet}}} \sigma^0_i(\theta_{\mathrm{char}}) \tag{6}$$

and

$$\sigma^0_{\mathrm{dry}}(\theta_{\mathrm{char}}) = \frac{1}{N_{\mathrm{dry}}} \sum_{i=1}^{N_{\mathrm{dry}}} \sigma^0_i(\theta_{\mathrm{char}}) \tag{7}$$

where the N available measurements σ^0_i at the gridpoint under consideration are understood to be sorted in ascending order and N_{wet} and N_{dry} serve only to robustify the resulting references with respect to outliers. N_{wet} and N_{dry} are derived according to statistical methods akin to [32], i.e., by taking into account the proportion of SSM measurements for which $m_s > 0.95$ and $m_s < 0.05$, respectively, obtained over recent years. Until an adequate number of 1 km Sentinel-1 IW mode GRD measurements are judged to be available, the references could be bootstrapped using Envisat ASAR GM mode Level 1b data at 1 km

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and subsequently normalized to the appropriate characteristic local incidence angles θ_{char}, respectively.

B. Retrieval Error Model

The SSM retrieval error is determined by the noise of the Sentinel-1 SAR instrument in IW mode and the respective uncertainties of the model parameters. Denoting the noise of Sentinel-1 IW mode GRD σ^0 measurements by $\Delta\sigma^0$ and the errors of the corresponding model parameters σ^0_{dry} and σ^0_{wet} by $\Delta\sigma^0_{\mathrm{dry}}$ and $\Delta\sigma^0_{\mathrm{wet}}$, respectively, the retrieval error Δm_s of m_s can be estimated by means of Gaussian error propagation with respect to (5) according to

$$\Delta m_s^2 \approx \left(\frac{\Delta\sigma^0}{S}\right)^2 + \left(\frac{(m_s-1)\Delta\sigma^0_{\mathrm{dry}}}{S}\right)^2 + \left(\frac{m_s\Delta\sigma^0_{\mathrm{wet}}}{S}\right)^2 \tag{8}$$

where $\Delta\sigma^0$ is set to 0.1 dB (rather than to the anticipated 0.05–0.07 dB radiometric resolution of IW mode at 1 km) in order to render the model more conservative as a first estimate. Following the reasoning in [32], and assuming that the errors $\Delta\sigma^0_{\mathrm{dry}}$ and $\Delta\sigma^0_{\mathrm{wet}}$ are 5% of the observed dynamic range S of the backscatter measurements, i.e., $\Delta\sigma^0_{\mathrm{dry}} = \Delta\sigma^0_{\mathrm{wet}} = 0.05\ S$, the maximum retrieval error $\Delta m_{s,\max}$ is given by

$$\Delta m_{s,\max} \approx \sqrt{\left(\frac{0.1}{S}\right)^2 + 0.0025}. \tag{9}$$

While for Sentinel-1 this error model may still be subject to refinement in the future, its adaptation to Envisat ASAR GM mode has already proven useful for predicting the root mean square error (RMSE) and correlation between SSM data derived from ASAR GM mode and soil moisture data simulated by hydrological models [47].

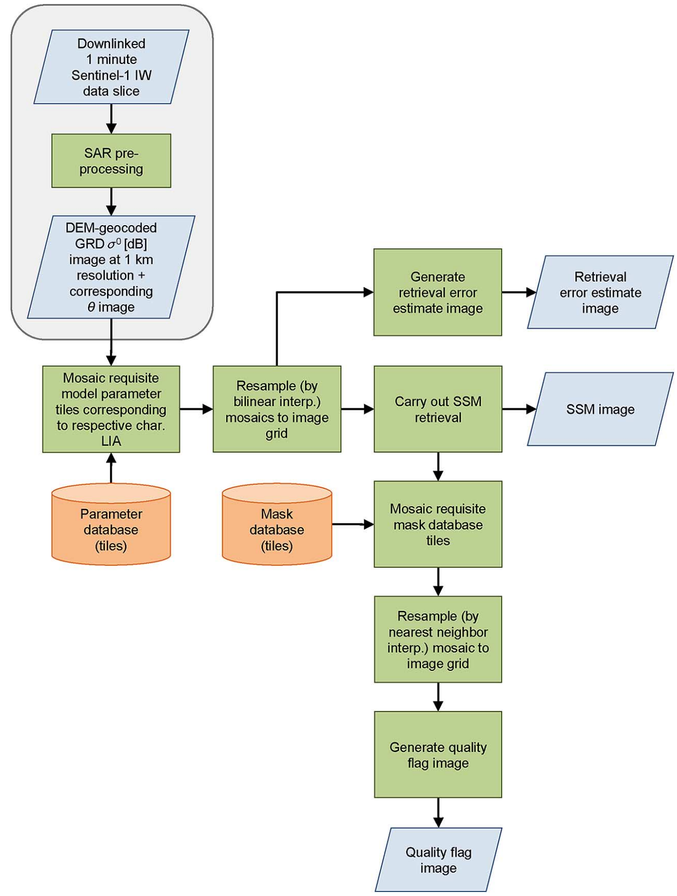

Fig. 1. The part of the flow chart enclosed in the rounded rectangle supplies the DEM-geocoded IW mode GRD slices at 1 km resolution and associated local incidence angle (LIA) images required as input by the proposed S2M-NRT and is assumed to be implemented elsewhere in the Sentinel-1 (collaborative) PDGS. The remainder of the diagram depicts the data-driven processing chain of the proposed S2M-NRT, as implemented within the framework of the S1-SMAD project. Note that the S2M-NRT is accordingly parallelizable over input slices.

IV. NRT SSM RETRIEVAL

The processing chain of the proposed data-driven NRT SSM retrieval processor (S2M-NRT) is depicted in Fig. 1. Starting with a 1 minute DEM-geocoded GRD slice at 1 km resolution acquired in IW mode, the S2M-NRT processor identifies the requisite model parameters corresponding to the geocoded slice. These model parameters—pre-computed in non-NRT by the reprocessing facility—are stored at regularly spaced gridpoints and indexed by characteristic local incidence angle θ_{char}. The S2M-NRT software demonstrator written within the framework of the S1-SMAD project stores those gridpoints in the form of a regular tiling of the plate carrée projection. Accordingly, once the requisite tiles have been identified, they are retrieved from the parameter database in which they are stored, the appropriate set of parameters they contain (according to respective corresponding characteristic local incidence angles) are mosaicked, and those mosaics are then resampled to the grid of the geocoded input slice. With input backscatter measurements σ^0 and corresponding wet and dry references, respectively, all in the same grid, surface soil water saturation $m_s(t)$ is finally computed per pixel of the input slice according to (5). Since extreme weather events can cause an input DEM-geocoded backscatter measurement $\sigma^0(\theta, t)$ to lie outside the interval defined by its corresponding references, $m_s(t)$ is set to 0 if negative, or to 1 if greater than 1. Provided a soil porosity map at 1 km resolution is available, volumetric surface soil water saturation $m_v(t)$ can be estimated by multiplying $m_s(t)$ with soil porosity [48].

A. Quality Flag Image

Not all land cover classes lend themselves to meaningful retrieval of surface soil moisture. In order to address this fact in the S2M-NRT software demonstrator implemented within the framework of the S1-SMAD project, a binary mask is provided alongside the SSM image output by the S2M-NRT, giving an indication of meaningfulness of each output $m_s(t)$ pixel. The choice of whether to use an output $m_s(t)$ value thus rests squarely with the user, regardless of the value of its corresponding quality flag. A pixel is masked out if it corresponds to any of the following U.S. Geological Survey (USGS) Global Land Cover Characterization (GLCC) [49] land cover classes: (i) Urban and Built up Land, (ii) Evergreen Broadleaf Forest, (iii) Water Bodies, (iv) Barren or Sparsely Vegetated, or (v) Snow or Ice. Class (iv) encompasses desert areas; in the case of class (ii), backscatter is dominated by volume scattering in forest canopy. Additionally, a pixel is masked out in the quality

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flag image if temporal correlation between DEM-geocoded $\sigma^0(\theta, t)$ at 1 km and the same measurements aggregated to a coarser (regional) scale at 25 km lies below a threshold. This last criterion is driven by the nature of across-scale interaction of soil moisture [50]. When m_s is updated such that it lie within the interval defined by its references, the corresponding pixel is masked out in the quality flag image.

B. Emergency Services

In the event that backscatter measurements $\sigma^0(\theta, t)$ be acquired within the framework of the GMES Emergency Management Service (EMS) [43], the respective local incidence angles θ might not correspond to any characteristic local incidence angle θ_{char} available at the location in question. A database of slope parameters β obtained from a long time series of 1 km DEM-geocoded Envisat ASAR GM mode data would provide an avenue for normalizing any such emergency backscatter measurement to the characteristic local incidence angle $\theta_{\mathrm{char}} \in \Theta(\sigma^0)$ that minimizes $\mathrm{abs}(\theta - \theta_{\mathrm{char}})$, once again subject to $\mathrm{abs}(\theta - \theta_{\mathrm{char}}) < T$, for some tight angular threshold T. The thus normalized input data could then be used for retrieval of surface soil water saturation $m_s(t)$ according to (5).

V. Reprocessing Facility

The purpose of the proposed non-NRT reprocessing facility (S2M-RF) is twofold. The S2M-RF is responsible primarily for computing revised wet and dry references (cf. Section III-A) using data made available since the last revision to the references. In support of providing user access to SSM data derived using the most accurate available antenna pattern calibration parameters, it also serves to compute revised S2M-NRT outputs (in non-NRT) for images that had already been computed in NRT since the last update to their calibration annotations, respectively.

The proposed schedule-driven processing chain for the S2M-RF is depicted in Fig. 2; the same processing chain could in principle be invoked explicitly, e.g., in the event that changes be made to how wet and dry references are retrieved. Given a set of new 1 km DEM-geocoded IW mode GRD images, each image (and its associated local incidence angle image) is first resampled to the grid of the parameter database and stored as a time series. One way to store such time series is in the form of a tiling akin to that of the parameter database discussed in Section IV. In the case of inputs that had already been fed to the S2M-RF at an earlier point in time, but for which updated calibration annotations are made available, the original entries in the parameter database are identified and respectively adjusted to reflect the revised annotations. Once the historical time series database has been augmented with all new or revised 1 km DEM-geocoded IW mode GRD input images, wet and dry references are computed per gridpoint and indexed according to respective characteristic local incidence angle. Note that measurements that do not correspond to any of a gridpoint's characteristic local incidence angles are not taken under consideration by the S2M-RF for computing the references. Finally, the set of 1 km DEM-geocoded IW mode GRD input images are reprocessed in non-NRT by the S2M-NRT using the revised parameter database.

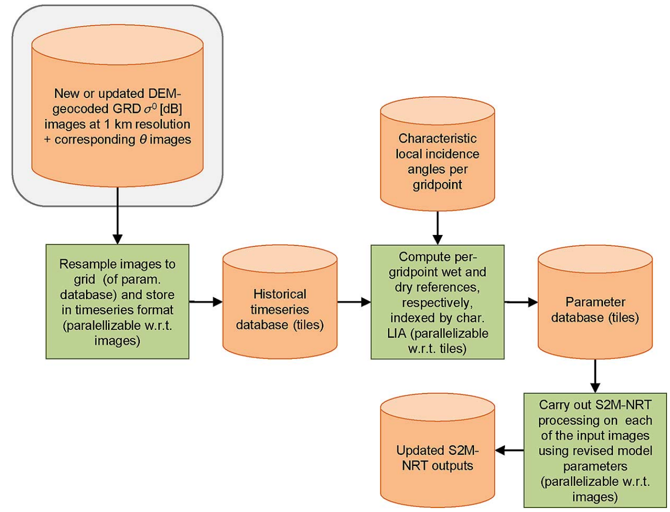

Fig. 2. The part of the flow chart enclosed in the rounded rectangle supplies the input data required by the proposed S2M-RF, and is assumed to be implemented elsewhere in the Sentinel-1 (collaborative) PDGS. The remainder of the diagram depicts the schedule-driven processing chain of the proposed S2M-RF.

Such a schedule-driven update to the parameter database could—as a tentative estimate—be carried out once every two years. As revisions of the parameter database entail ingestion overhead for users, a balance ought to be struck between keeping model parameters up to date and mitigating such user overhead.

VI. Timeliness

Downlinked Sentinel-1 NRT data is expected to be processed in partially overlapping slices of configurable length. Given a foreseen Sentinel-1 ground speed of 6.8 km/s, a 1 minute slice acquired in IW mode corresponds to approximately 408 km in the along track and 250 km in the across track (the IW mode swath width), amounting to an area of ca. 102,000 km² (cf. Fig. 3). The mosaicking and resampling of model parameter tiles is what dominates the running time of the S2M-NRT software demonstrator, with the number of tiles covering a slice depending on the projection employed and the slice's location on the Earth's surface. In the plate carrée projection, a simulated 1 minute DEM-geocoded IW mode GRD slice at 1 km resolution corresponds to a total of ca. 60 tiles at the equator and ca. 120 over Scandinavia.

The S2M-NRT software demonstrator implemented within the framework of the S1-SMAD project was written in IDL and tested under Windows on a 3.07 GHz 8-core PC. Simulated 1 minute DEM-geocoded IW mode GRD slices at 1 km resolution and corresponding wet and dry references were pre-computed over the Land Masses acquisition region for half an orbit (cf. Fig. 4), by leveraging version 4.2 of ESA's Earth Observation CFI orbit simulation software [51] and a global backscatter model [52]. For each simulated slice, the S2M-NRT software demonstrator output an SSM image, a retrieval error estimate

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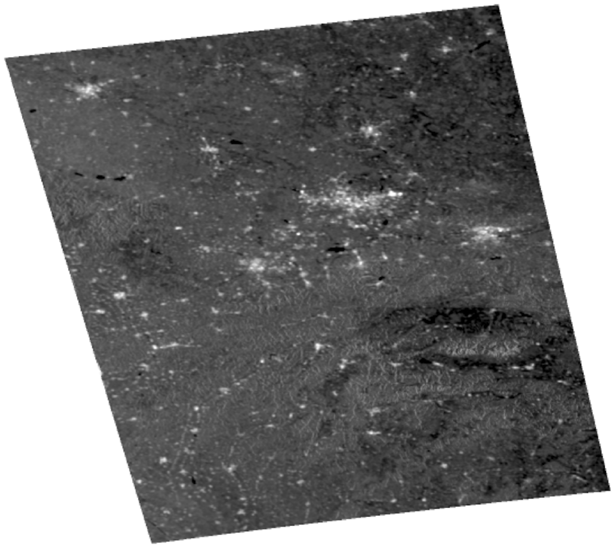

Fig. 3. Simulated 1 minute DEM-geocoded Sentinel-1 IW mode GRD slice at 1 km resolution (ca. 408 km in the along track, 250 km in the across track) over central Europe, used as input to the S2M-NRT software demonstrator in support of evaluating the timeliness of the S2M-NRT. The simulated backscatter measurements were obtained from a global backscatter model. The simulated slice is provided in the plate carrée projection.

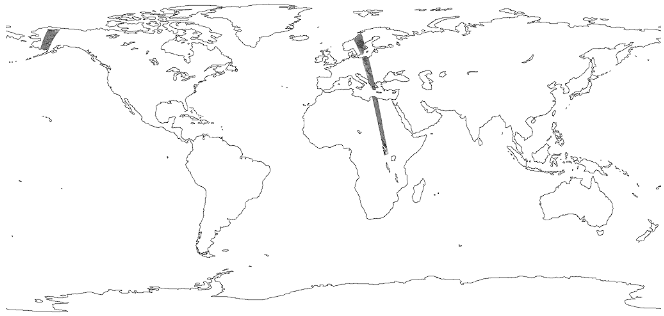

Fig. 4. The ground track—restricted to the Land Masses acquisition region—along which simulated 1 minute DEM-geocoded IW mode GRD slices at 1 km resolution were generated in support of evaluating the timeliness of the S2M-NRT.

image and a quality flag image, respectively, in under 2 seconds.

VII. Conclusion

The radiometric, spatial and temporal resolutions at which Sentinel-1 IW mode C-band SAR data is expected to be acquired render the Sentinel-1 mission a promising platform for systematic surface soil moisture retrieval at 1 km over the mission's Land Masses acquisition region, exceeding the possibilities for retrieval using SAR data acquired by the earlier Envisat mission. The software demonstrator that implements the change detection-driven surface soil moisture retrieval algorithm presented in this paper was shown to support even the most stringent variety of NRT timeliness defined within the context of the Sentinel-1 mission. Retrieval in NRT with respect to time of acquisition—subject to the mission operating as foreseen—is expected to be technically feasible within the framework of the hosted user environment of the mission's payload data ground segment.

Acknowledgment

The work carried out in this paper within the framework of the S1-SMAD project builds upon earlier work carried out in support of the Soil Moisture for Hydrometeorological Applications (SHARE) and Sigma Nought Statistics over Land Activity (Sigma0) projects, also funded by ESA. The authors would furthermore like to thank the reviewers for their helpful commentary and constructive criticism of the manuscript.

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