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1. Abstract

The service defined in this document aims at providing end users with the output datasets produced using the CSME processing chain (Berry & Balmbra, 2014) in the scope of the LOTUS project.

Sentinel-3 SAR altimeter is the first SAR altimeter operative over the whole earth, especially over land. Such technique provides with altimetry waveforms every 300 meters in the along track direction.

Derivative of surface moisture from satellite radar altimetry is a relatively new application. The current technique relies on Dry Earth ModelS (DREAMS) constructed from multi-mission satellite radar altimetry in Ku, S and W bands, then fused with extensive ground truth. The use of the Sentinel-3 SAR altimeter may significantly increase the along track resolution.

The document details the requirements of end users, the already existing methods to produce soil moisture measurements and the associated services, and the description of the soil moisture service of the LOTUS project.

2. Review of user needs and requirements

Soil moisture product users have been identified from various communities: water resource, weather and climate, agriculture, and disasters/floods and hazards. From the requirements of each category, global user requirements have been defined in the previous LOTUS document "Preparing Land and Ocean Take Up from Sentinel-3 (LOTUS)' Work Package 2 'Processing of SRAL SAR mode waveforms over land", Deliverable 2.2.

Soil surface moisture is a key climate variable, with a range of practical applications from informing local climate models (e.g. Drusch, 2007; Crow et al, 2009) to crop analysis (Osborne et al, 2009) and rainfall and runoff predictions, drought development (e.g. Brocca et al, 2010: Crow et al, 2009). It also impacts on the climate system through atmospheric feedbacks (e.g. Castelli et al., 1986). Soil moisture is a source of water for evapotranspiration over the continents, and is involved in both the water and the energy cycles (Seneviratne & Stockli, 2008). This variable changes spatially and temporally very rapidly, responding to precipitation, surface and sub-surface water flow. Soil moisture was recognised as an Essential Climate Variable (ECV) in 2010.

This wide range of applications leads to a similarly diverse range of requirements.

For Global Climate Models, the spatial distribution of soil wetness state has been known as an important boundary condition to general circulation model predictions for many years [e.g. Polcher et al, 1996] both acting as a forcing and reacting to the forcing of meteorological phenomena [e.g. Castelli et al., 1996, Fischer et al., 2007]. Soil moisture and vegetation respond to local precipitation and affect the exchange of heat, moisture, and momentum with the atmosphere over time. The soil moisture and vegetation (and their regulation of land-atmosphere exchange processes) respond to the climate on the shorter time-scale of weather systems but, due to the varying accumulation of soil moisture, the influence of land surface on climate is on seasonal and inter-annual time-scales [ibid].

Soil moisture is also a key input to event-based hydrological modeling and flood forecasting, for example, require correct definition of the antecedent soil moisture condition [e.g. Grayson et al., 1992]. Soil moisture plays a critical role in agricultural activities and land atmosphere interaction (e.g. AWDN).

The importance of global measurement of soil moisture has been recognized by ESA with the successful SMOS mission (ESA SMOS) and by NASA with the forthcoming SMAP mission NASA SMAP).

Table 1 - User requirements for soil moisture product.

	Minimum requirement for soil moisture product
Temporal resolution	Tens of days
Spatial resolution	Hundreds of meters
Accuracy	1% on soil moisture content
Coverage	Local scale

2.1. Water resources

Many natural processes in the environment are driven by or in some ways related to soil hydrological processes. Monitoring soil moisture conditions provides important information for the protection and the understanding of local and regional water resources. In that sense, local coverage and quite accurate datasets are required for a good water management process.

2.2. Agriculture

Irrigation of crops represents 90% of the water used worldwide. Monitoring soil moisture in the root zone of crops optimizes irrigation. The benefits of optimizing irrigation includes increasing crop yields, saving water, protecting local water resources from runoff, saving on energy costs, saving on fertilizer costs and increasing the farm's profitability. In such a process, high temporal and spatial resolutions are needed.

2.3. Weather and climate

The global carbon cycle, weather and climate are all heavily influenced by soil moisture. Soil can be both a major source of atmospheric CO2 and a major storage reservoir for carbon with soil moisture being a driving force. In order to estimate the CO2 fluxes, global soil moisture maps with good accuracy are needed.

Soil moisture is important for forecasting both temperature and precipitation. As the temperature raises the evaporation rate of soil moisture increases. The increased soil moisture evaporation helps to cool the ground. Almost Near real time data with good coverage and accuracy are required to include soil moisture/weather interactions in the forecast models.

2.4. Disasters/floods and Hazards

Soil moisture is a key variable in water-related natural hazards including floods and landslides. High-resolution observations of soil moisture and landscape freeze/thaw status will lead to improved flood forecasts, especially for intermediate to large watersheds where most flood damage occurs. Surface soil moisture state is key to the partitioning of precipitation into infiltration and runoff, and thus is one of the major pieces of information, which drives flood prediction modelling. For such application, a short repeat pass is needed covering selected area with a correct accuracy.

3. Review of the state of the art technologies

There are several reliable ways to measure soil moisture. We describe here the more common instruments types for in-situ and remote measurements. All the different solutions described below have a satisfactory level of maturity and are currently available in the market. So far, their use does not imply any type of legal.

3.1. In-situ sensing solutions

We are describing here the in-situ sensors available and suitable for our application, i.e. precise and reliable measurement of soil moisture with a reasonable price. For such reason, neutron probes (expensive) and gypsum and resistive blocks (not reliable) are not considered.

3.1.1. Frequency Domain Reflectometry (FDR) Sensors

Description

This method of measurement uses an oscillator to propagate an electromagnetic signal through a metal line or other waveguide, but with this method, the difference between the output wave and the return wave frequency is measured to determine soil moisture.

Reliability and Accuracy

Frequency Domain Reflectometry (FDR) probes are considered accurate but must be calibrated for the type of soil they will be buried in. For reliable measurements, it is extremely critical to have good contact between the sensor (or tube) and soil. However, these sensors can read in high salinity levels, where TDR sensors fail.

Timeliness

They offer a faster response time compared to Time Domain Reflectometer (TDR) probes and can be connected to a standard data logger to collect readings.

Cost-effectiveness

Some devices are relatively inexpensive compared to TDR due to use of low frequency standard circuitry

Resilience

Careful installation is necessary, tends to have larger sensitivity to temperature, bulk density, clay content and air gaps than TDR. However, their life expectancy is more than 20 years.

Examples

Examples of sensors in this category include the AquaSPY C-probe, and the Sentek EnviroSCAN Probe.

Observations

While frequency-capacitance type soil sensors are called “FDR” sensors, this is somewhat of a misnomer because many of these probes only use a single frequency and not a “domain” of many

frequencies. The Delta-T Theta probe is a coaxial differential amplitude reflectometer and Decagon's ECHO probe is a time of charge capacitor type sensor.

3.1.2. Time Domain Reflectometry (TDR) Sensors

Description

Sensors that use the Time Domain Reflectometry (TDR) function in a somewhat similar way to FDR probes, but the mechanics behind the measurement system are different. TDR sensors propagate a pulse down a line into the soil, which is terminated at the end by a probe with wave guides. TDR systems measure the water content of the soil by measuring how long it takes the pulse to come back.

TDR soil moisture measurement devices require a device to generate the electronic pulse and need to be carefully calibrated in order to precisely measure the amount of time it takes for the pulse to propagate down the line and back again. They are also sensitive to the saline content of salt and relatively expensive compared to some measurement methods. However, TRD devices do respond quickly to varying soil moisture.

Reliability and Accuracy

TDR-based sensors have a very high accuracy and reliability

Timeliness

Measurements done with a TDR sensors must be repeated to ensure accuracy, therefore they are not as fast in response as FDR sensors.

Cost-effectiveness

These sensors are not really cost-effective. TDR probes are relatively expensive equipment due to complex electronics.

Resilience

Their life expectancy is more than 20 years.

Examples

Some examples of this sensor include the Campbell CR616 and the IMKO Trime.

Observations

The sensors have relatively small sensing volume but minimal soil disturbance.

Other relevant indicators

The sensors have potentially limited applicability under highly saline conditions or in highly conductive heavy clay soils.

3.1.3. Capacitance Sensors

Description

As mentioned before, capacitance sensors are a type of FDR sensor that only uses a single frequency and not a "domain" of many frequencies. Decagon Devices 10HS and ECHO volumetric water content sensors, for example, are time of charge capacitor sensors.

The capacitance of soil depends on how moist it is. If two parallel conducting probes are placed in the soil, then they form a capacitor with the soil as the dielectric. As the moisture of the soil changes, the relative permittivity of the soil changes and as a result the capacitance between the probes changes.

Reliability and Accuracy

These meters have the advantage of being reasonably independent of the soil mineralization, and the metal in the soil probes can be insulated and so are less prone to oxidize or otherwise deteriorate from being in direct contact with the soil. The readings they offer are not as accurate as FDR and TDR sensors, but they give a very clear and good indication of soil moisture tends and changes. To increase the accuracy achieved with capacitance sensors, soil specific calibration is needed.

Timeliness

These types of sensors are very fast in response, giving the measurement in less than 200ms.

Cost-effectiveness

Capacitance sensors are the cheapest option in the market when compared with TDR or FDR more complex sensors.

Resilience

Their life expectancy is around 2 to 5 years, depending on environmental and use conditions. Examples Decagon Devices 10HS or ECHO sensors, Delta-T Theta probes, etc.

Observations

These types of sensors are temperature dependent and decrease their accuracy in close to saturation soil situations. However, they are very easy to integrate in data loggers and wireless monitoring systems, compared with FDR and TDR sensors.

Other relevant indicators

Although capacitance sensors are worse in terms of reliability and accuracy of their readings, they are good enough for most of the desired applications. Their cost-effectiveness are one their major characteristics and that's why their use has increased in the last years.

3.2. Remote sensing solutions

Scientific investigation on the analysis of soil moisture using satellite sensors has a long history: it began with the availability of the first satellite images. Research has been done using different sensors, spanning different parts of the measured electromagnetic spectrum, leading to several methodologies to estimate soil moisture content. All the algorithms developed are based on the inversion of models, of analytical or empirical nature, that relate variables measurable by satellite sensors to near-surface

soil moisture. Depending on the sensor employed to image the Earth's surface, different spatial and temporal resolutions can be achieved, thus the selection of the appropriate sensor will be related to the type of monitoring that is being pursued. Due to their independence from solar illumination and cloud coverage microwave sensors result to be the most suitable sensors for soil moisture monitoring at watershed scale in areas often covered by clouds.

Microwave sensors acquire measurements in the frequency range from 0.3 GHz to 300 GHZ (i.e. a wavelength that spans from 1 m to 1 mm). There are two main types of such instruments: passive and active.

3.2.1. Passive microwave sensors

Passive microwave sensors or radiometers measure the radiation emitted by the Earth's surface in the field of view of the instrument.

Although radiometers do not require solar illumination and the atmosphere has a small impact on the measured signal, the resolution of such instruments is in the order of several kilometres making them useful only for studies on the global scale, and therefore not suitable for irrigation water management applications at fine scale. Also in case of radiometer the key parameter that modify the measured brigthness temperature is the dielectric constant, which is highly dependent on soil moisture.

3.2.2. Active microwave sensors

Active microwave sensors or radars send out pulses of electromagnetic radiation and measure the amount that is backscattered in the direction of the sensor. Having their own source of illumination, such sensors can acquire data at night and day and in presence of cloud coverage. Over land, the backscattered radiation is mainly dependent on soil temperature and its dielectric properties, the latter being directly influenced by soil moisture.

SAR and Scatterometer

The backscatter data recorded by microwave radars such as "Scatterometer" and "SAR" are also sensitive to changes in soil moisture among other parameters. Scatterometers, with a spatial resolution of several kilometres, have been used with success for studies on the global scale, while SARs, with a spatial resolution that can be as small as a few meters, is suitable for studies on the local scale.

The methodologies developed for the estimation of soil moisture from Scatterometer and SAR sensors are based on the following idea: the microwave radiation backscattered from sparsely vegetated surfaces is related to dielectric properties of the illuminated area, surface characteristics (roughness, topographic conditions) and instrument characteristics. The soil's dielectric constant is highly dependent on soil moisture; typical dielectric constant of dry soil is around 3 while the one of water is 80. Theoretical models (e.g. small perturbation model, geometric optics model) are able to represent the backscattering variations due to changes in soil moisture content, surface roughness and vegetation attenuation. However, from an operational point of view, these models cannot be employed due to the restrictive assumptions made when building them. Therefore, empirical models may be more useful and robust to estimate soil moisture operationally.

Satellite Altimetry

There has been interest in the possibility of using satellite altimetry to measure soil moisture for many years (Guzkowska et al, 1990). Altimeters collect series of measurements beneath the satellite from nadir-pointing instruments and therefore do not achieve global coverage; however there is global sampling and the possibility to create timeseries at the frequency of the satellite repeat orbit period. However, whilst the altimeter backscatter is known to vary at a given target in response to soil surface moisture, the rapid and complex changes in soil composition and roughness, together with terrain variation, mean that backscatter varies on a small spatial scale. Even using repeat arcs, the across-track variation in satellite overpass of +/- 1km is sufficient to change the received backscatter pattern significantly, critically limiting the measurement of soil moisture using this technique.

An approach to retrieve soil surface moisture from satellite altimetry has been developed over the past few years, using satellite radar altimetry to measure soil surface moisture. This approach requires detailed Dry Earth ModelS (DREAMS) crafted from multi-mission satellite radar altimetry at Ku, C and S band (with additional information obtained at W band from Cloudsat where available), recalculated and cross-calibrated over land calibration sites. These data are fused with detailed terrain and surface type information, including surface roughness (large and small-scale), and surface composition information sourced from both remote sensing and in-situ observations. These Dry Earth Models (DREAMS) can be independently created only in regions where the soil surface moisture falls to zero for at least two months of the year, and this has constrained the first development of this technique to arid and semi-arid terrain, where existing remote sensing methods encounter difficulty (Berry et al., 2013; Berry, et al., 2012; Berry & Carter, 2010; 2011; Bramer & Berry, 2010.). This approach has been progressed into soil surface moisture estimates from the ERS2, Envisat and Jason2 altimeters in desert and semi-arid terrain under the ESA SMALT project (Berry et al., 2012; SMALT, 2014). These DREAMs have been analysed and re-crafted for the long repeat pattern of Cryosat2, and their performance has been tested with Cryosat2 LRM and SAR data. Figure 1 and Figure 2 show the location of an example profile of two repeat arcs of Cryosat2 data over the Gibson desert, with the recalculated and cross-calibrated backscatter together with the underlying DREAM pixels to illustrate the rapid across-track variation in the DREAM and the correspondence between LRM and SAR mode backscatter.

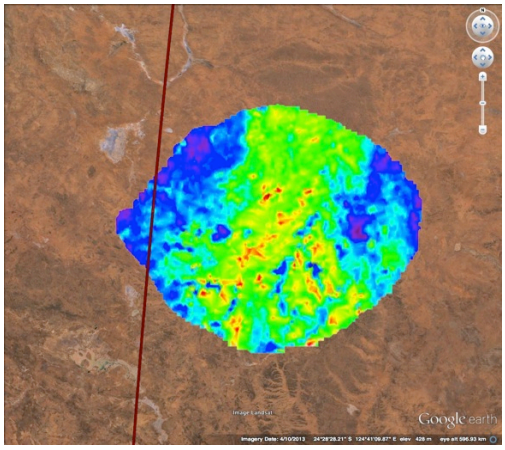

Figure 1 - Cryosat2 LRM and SAR Track location over Gibson desert DREAM

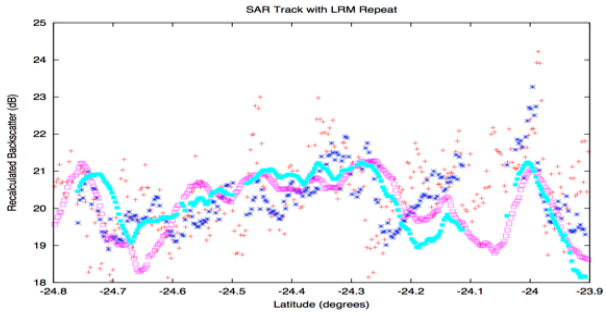

Figure 2 - Cross-calibrated recalculated Cryosat2 SAR mode (red) and LRM (blue) backscatter with underlying DREAM pixels (SAR pink, LRM green)

The LOTUS CSME test products were generated for both Jason2 and Cryosat2, as track-based averaged soil surface moisture. Figure 3 shows the LOTUS Kalahari DREAM with the location of Jason2 tracks (the Cryosat2 high track density precludes plotting these on top). Figure 4 shows the soil surface moisture track based average measurements from Cryosat2 (LRM mode) and Jason2 repeat arcs, demonstrating good agreement from these geographically disparate datasets (Berry & Balmbra, 2015).

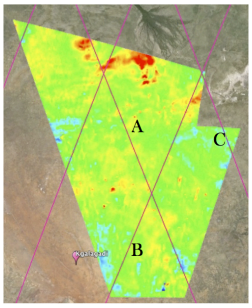

Figure 3 - Example DREAM of Kalahari desert showing location of Jason2 repeat tracks

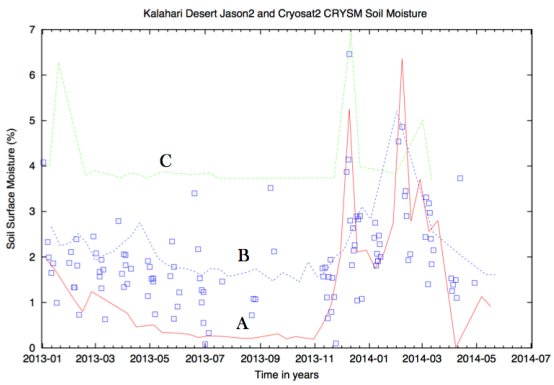

Figure 4 - Cryosat2 and Jason2 soil moisture arc based average soil moisture estimates over Kalahari desert

To illustrate existing products from other sensors, Figure 5 shows the weekly average soil moisture measurement using combined active and passive measurements (Wagner et al., 2012) over the Kalahari Desert for January 2013 (first month of the validation year for CSME products). Averaging to this extent provides complete spatial coverage; the pixel size is 0.25 degrees. These techniques therefore have the advantage of global coverage every few days: however, the coarse spatial resolution limits analysis of detail, for example in desert margins. Forecasting from previous altimeter missions, Sentinel3 should enable much finer spatial resolution to be achieved under the altimeter arcs.

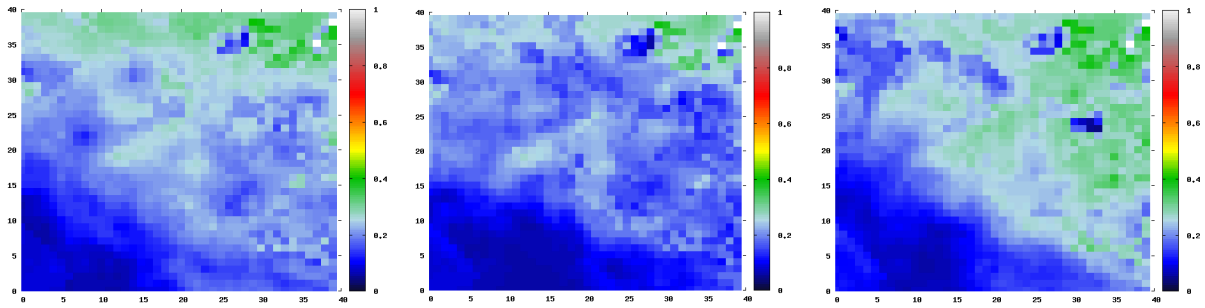

Figure 5 - Active and Passive combined product over Kalahari desert for weeks1,2,3 of 2013 (data described in Wagner et al., 2012) illustrating pixel size constraint of 0.25 Degrees

4. Service requirements and specifications

Specific service requirements have been listed above from which the service will be based.

4.1. Requirements convention and acronyms

- "SHALL" is used to indicate a mandatory requirement
- "SHOULD" indicates a preferred solution but is not mandatory
- "MAY" indicates an option
- "WILL" indicates a statement of fact or intention.
- "N.A. " for Non Applicable.

The trace code will be compiled as follow:

R-XXX-NNN,

where XXX is a two/three letter acronym for the service section (see Table xxx), and NNN is the requirement number in this category.

Table 1 - This table provides the service section trace codes.

Targeted Service Sections Trace Codes	Label
IN	Service inputs
DP	Data processing
OUT	Output product
QA	Quality assessment
DEL	Delivery platform

4.2. Service inputs

Table 2 - Service input requirements

Trace Code	Service requirement
R-IN-001	Sentinel SRAL L1B products shall contain time indexed data
R-IN-002	Sentinel SRAL L1B products shall contain geolocated data (latitude, longitude)

4.3. Data processing

Table 3 - Data processing requirements

Trace Code	Service requirement
R-DP-001	The data processing unit shall run on a server
R-DP-002	The data processing unit shall have a Matlab/IDL license.

4.4. Output product

Table 4 - Output product requirements

Trace Code	Service requirement
R-OUT-001	The output products should be delivered in a user-friendly format
R-OUT-002	The output products should be delivered in the input format of the existing services

4.5. Quality assessment

Table 5 - Quality assessment requirements

Trace Code	Service requirement
R-QA-001	The quality assessment processing shall check the readability of the data
R-QA-002	The quality assessment processing shall check the format
R-QA-003	The quality assessment processing shall check the scientific quality of the data

4.6. Delivery platform

Table 6 - Delivery platform requirements

Trace Code	Service requirement
R-DEL-001	The delivery platform should be free of charge access

5. Service architecture definition and description

5.1. Product definition

Surface soil moisture estimates are derived over desert and semi-arid terrain by analysing each 20Hz waveform and computing the altimeter backscatter, applying all required corrections and scaling factors. These values are then compared with a DRy EArth Model (DREAM), which encodes the detailed variation in this parameter expected over the surface in dry earth conditions. The requirement for DREAM creation presently constrains this application to deserts and semi-arid terrain.

From a comparison of the measurement with the model it is then possible to calculate the surface soil moisture. Because the highest spatial frequency variations in this parameter (resulting from changes in small-scale roughness and surface composition) are not captured in the DREAMs, some filtering and averaging of the values is essential. Accordingly the SM_2_LAN product is not envisaged to be released. There are thus only two products envisaged for this parameter, at levels 3 and 4. The level 3 product contains along-track filtered and averaged mean soil moisture estimates (SMMEs) for each pass; the level 4 product contains time series for each SSME.

It is noted that Cryosat2 currently overflies all DREAM regions in LRM mode. However, this technique is applicable to both SAR and LRM mode data.
To illustrate the product concept, Fig. 7 shows a plot of cycle 10 of ERS2 SMALT products (35 days of data) over the Kalahari desert, illustrating the spatial coverage and percentage soil moisture measured (SMALT 2014).

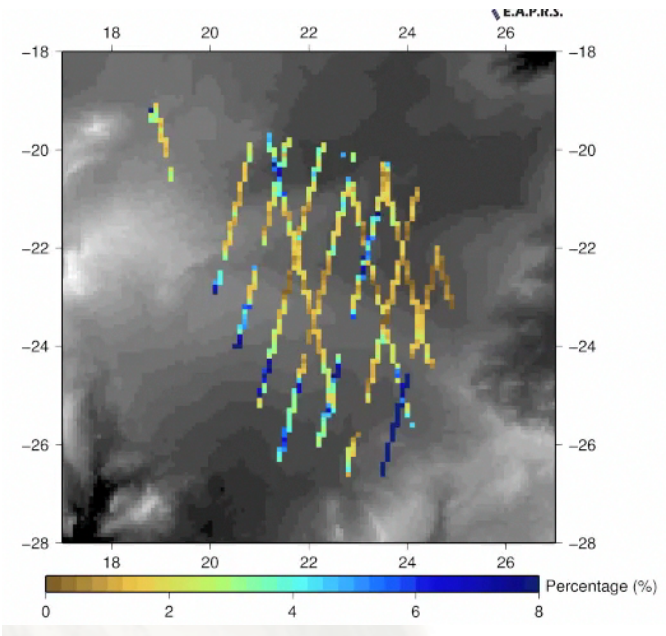

Figure 6 - Visual representation of one cycle of ERS2 SMALT products over the Kalahari desert

Table 2 - L3 Soil Moisture geophysical parameters description

Parameter	Instr. Operation Mode	Description
Filtered and averaged along-track surface soil moisture estimates	SAR	A series of along-track averaged surface soil moisture values (as % soil moisture) for pixels within each pass over a DREAM.

Because the soil moisture user community works with time series data at specific locations, the L4 product contains time series of each Soil Moisture Mean Estimate (SMME) produced at L3 from Sentinel3 repeat arc data.

Table 3 - L4 Time series for Soil Moisture

Parameter	Instr. Operation Mode	Description
Time series	SAR	The soil moisture community requires time series at spatially collocated locations, thus a time series for each along-track-averaged SSME is foreseen, derived from the repeat passes.

5.2. Global architecture of the service

An altimeter soil surface moisture service will follow the general form of the ESA SMALT project (ESA SMALT, 2013), with measurements made directly underneath the altimeter track and individual measurements averaged to overcome the high noise on individual estimates. The Cryosat2 Soil Moisture test products (CSME) were generated as track based estimates, to minimise the impact of unmodelled residual high frequency variations in surface backscatter not fully captured within the DREAMs. It is expected on the basis of the ESA SMALT project (ibid) that this severe averaging constraint can be relaxed to generate a series of measurements along each arc, with additional development to the DREAMs to exclude residual paleo-hydrology signatures.

To examine the probable spatial constraints on Sentinel3 soil moisture products, example outputs from the ESA SMALT project are considered here. The differences from the original Simpson Desert SMALT DREAM for one year of a typical track of ERS2 sigma0 is shown in Fig.6. Limited high frequency noise is evident, with soil moisture signatures clearly apparent in the higher along-track differences from the DREAM.

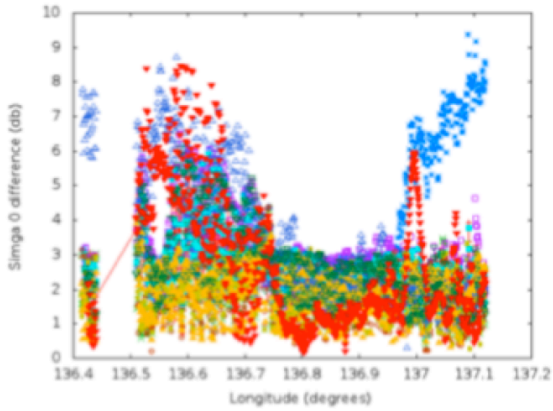

Figure 7 - ERS2 Multi-Cycle Sigma0 difference from SMALT DREAM for example Simpson desert track

For the Simpson desert, interpolating along-track to 18" pixel size and forming time series for each pixel produced good coherence, as illustrated in the example time series shown in Fig 7 for 4 adjacent pixels on the track from Fig.6. This was determined as the maximum spatial resolution for SMALT products. Since the Simpson Desert is free from paleo-hydrology signatures, and thus has a very coherent DREAM, this is a good indicator of the finest spatial resolution expected for soil moisture products from Sentinal3.

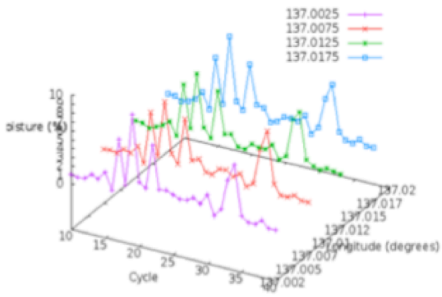

Figure 8 - ERS2 sigma0 difference from SMALT DREAM timeseries for adjacent 'pixels' for example track in Figure 7

The maximum spatial resolution for other desert regions was determined to be 27" (ibid) as the small-scale changes in surface roughness and composition are greater over the other deserts considered, and the SMALT DREAMS were not able fully to capture this variation. It is therefore recommended to use this as the initial guide to product resolution for Sentinel3. The actual spatial resolution will be determined using Sentinel3 data when these are available. It is noted that the LOTUS DREAMS are very significantly enhanced w.r.t the SMALT DREAMS, as evidenced by the successful retrieval of Jason2 surface soil moisture estimates from not only the LOTUS test desert regions, but also all other desert regions for which DREAMS have been constructed. It is therefore probable that higher spatial resolution will be feasible for Sentinel3 soil moisture products.

The retrieval of surface soil moisture from Sentinel3 SAR mode data is expected to be enhanced significantly w.r.t Cryosat2 because of the availability of repeat arcs of SAR mode data. This will allow

detailed analysis and enhancement of the DREAMs, by analysis of repeat arc behaviour. Crucially, the range of desert models considered can be extended to all those used in SMALT and then to semi-arid regions.

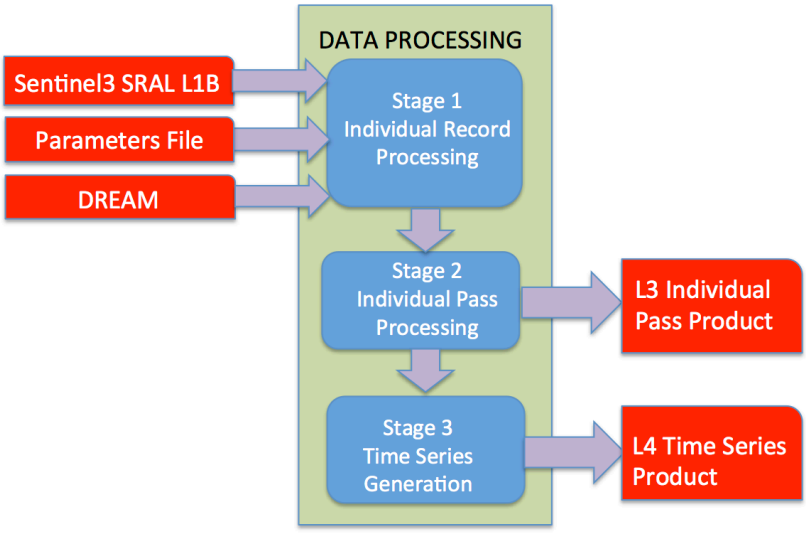

Figure 9 - Data Processing Diagram for S3 Soil Moisture Product Generation

The overall processing architecture of the S3 soil moisture processing chain defined in the ATBD (Berry & Balmbra, 2014) is illustrated in Figure 9, and discussed in the following sections.

5.3. Service Inputs

The current dissemination scenario for Sentinel3 altimeter data involves L1B being made available to all users (date of this information Nov. 2015). Thus the soil moisture generation for Sentinel3 (Figure 9) is assumed to run from L1B input data at 20Hz. Whilst an augmented spatial resolution of 80Hz may be made generally available, this is not envisaged as required at this stage for the soil moisture application. However, thus is a novel application with rapidly developing science and applications: thus this requirement may change. An external parameters file holds empirically determined parameters required for soil moisture processing; these are mission dependent and must be calculated once S3 data are available. Parameters currently included on the basis of Cryosat2 soil moisture determination are listed in Table 2.

Table 4 - Auxiliary Parameters File

Name	Units	Comment
A_L	Microwatts	Empirically determined amplitude lower limit
A_U	Microwatts	Empirically determined amplitude upper limit

W_L	Bins	Empirically determined width lower limit
W_U	Bins	Empirically determined width upper limit
Masked	dB	Exotic unit set to exclusion value in DREAM
Offset	dB	Exotic unit set for each DREAM
Limit1	dB	Exotic unit set for each DREAM
Limit2	dB	Exotic unit set for each DREAM
M1	None	Scaling factor 1
M2	None	Scaling factor 2
N_points	None	Number of points used to create s_{mean}

Experience from the ESA SMALT project shows that the user community has a strong requirement for time series at specific locations: thus whilst along-track products have a role in any NRT service, the offline product is envisaged to be primarily as time series.

Essential parameters for the calculation are defined in the ATBD (Berry & Balmbra, 2014).

5.4. Processing chain

Detail on the proposed processing chain is given in this section. Key variables used in the processing of Sentinel3 data are summarised in Table 3.

Table 5 - Key Variables

Symbol	Descriptive Name	I/O	Origin
s_{0CRY}	Sigma0 value recalculated from waveform amplitude using scaling factors	Internal	Calculated in processing
Sig_A	Scaling parameter for backscatter calculation	Input	From configuration file
Sig_B	Scaling parameter	Input	From configuration file
P_i	Waveform power in bin i	Input	Input from Sentinel3 L2 data file and rescaled to microwatts
i	Bin number	Input	Assigned at S3 L1B data read-in

A	Waveform Amplitude	Internal	Calculated in processing
W	Waveform Width	Internal	Calculated in processing
S_{0CRY_ADJ}	S_{0CRY} scaled for DREAM comparison	Internal	
S_{0diff}	Sigma0 difference from DREAM	Internal	Calculated in processing
S_{0DREAM}	Sigma0 value from DREAM pixel	Internal	Input from DREAM
S_{mean}	Mean Sigma0	Internal	
S_{rms}	RMS of mean Sigma0	Internal	May be output to inform error estimates
Soil_Moisture	Percentage soil moisture estimate	Output	Calculated in processing

Several stages of processing are defined in the ATBD. An overview of this processing is given here.

5.4.1. Stage 1 Individual Record Processing

The flow diagram for Stage 1 processing is shown in Figure 10.

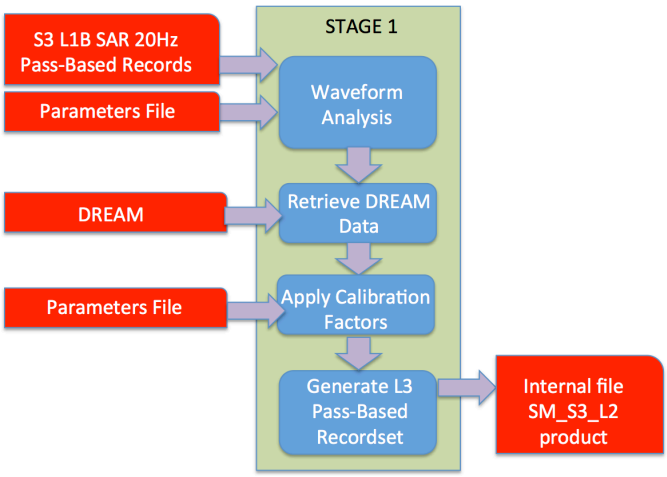

Figure 10 - Sentinel3 Stage 1 Individual Record Processing for Soil Moisture Retrieval

Detailed information on the algorithms and prcessing chain are given in the ATBD (Berry & Balmbra, 2014). This first stage involves processing of individual records within a pass.

This produces an internal product, which forms the input for the next stage of processing. This product was not deemed suitable for release (ibid).

5.4.2. Stage 2 Record Sequence Processing

The processing from the internal data files is pass-based. The processing scheme is considered in detail in the ATBD (ibid) and outlined here in Figure 11. This processing generates the first external product at L3.

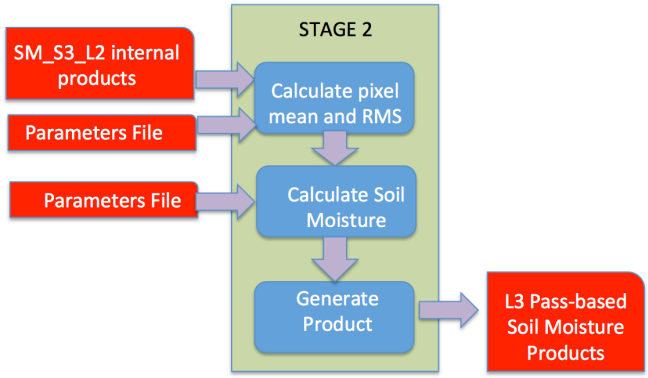

Figure 11 - Sentinel3 Stage 2 Record Sequence processing for Soil Moisture Retrieval

The processing chain uses external data files to deliver empirically determined parameters to the processing chains. These parameters and their use are detailed in the ATBD (ibid).

Above these stages is the Level 3 product. Users of these data state a requirement for time series in the region of interest. Accordingly, the along-track product will be produced for defined 'pixels', producing one estimate per pixel. This generalisation of product location then allows time series to be constructed for each pixel. This concept is illustrated for an example ERS2 SMALT backscatter sequence (prior to soil moisture calculation) for adjacent pixels over the Simpson Desert in Figure 8.

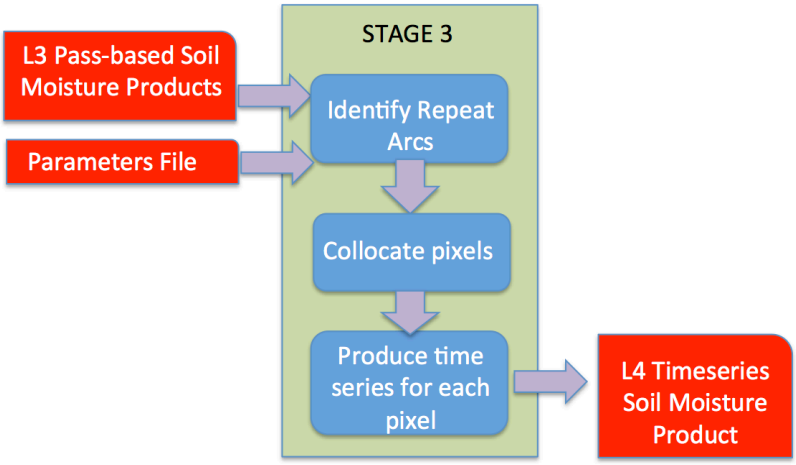

Figure 12 - Sentinel3 Stage 3 Timeseries Generation Processing for Soil Moisture

5.5. Quality assessment

Establishing an efficient quality assessment concept will guarantee the overall quality of the service implementation and of the final deliverables

Table 6 - Key element of a QA concept

QA concept element	Additional details	Responsibility
Data format verification	Detect inconsistencies in the format	Value adding specialist
Data content verification	Detect missing values, wrong values	Value adding specialist
Statistical and scientific evaluation	Evaluate datasets to record outliers	Value adding specialist

5.6. Data packaging and delivery platform

The data is made available for the end user through an ftp platform. As soon as the data is processed, verified, and validated, the files are uploaded to the ftp server. The access is free of charge, but a previous registration is needed to get a login to the platform.

Table 7 - Data Format and Delivery

Data Format and delivery
Delivery channel: on-line via FTP **Spatial (geographical) data**: NetCDF CF 1.6 data **Reports, statistics**: MS Office (word, excel, powerpoint) and PDF format

6. Summary

This document describes the soil moisture service based on the future Sentinel-3 SAR altimeter along-track and time series products defined in the LOTUS project. The datasets have been produced using the CSME processing chain (Berry & Balmbra, 2014).

Derivative of surface moisture from satellite radar altimetry is a relatively new application. The current technique relies on Dry Earth ModelS (DREAMS) constructed from multi-mission satellite radar altimetry in Ku, S and W bands, then fused with extensive ground truth.

As Sentinel-3 SAR altimeter is the first SAR altimeter operative over the whole earth, in particular over land. Such instruments significantly improve the resolution in the along track direction (300 meters) with a repeat pass. Improved products will be delivered to end users through the soil moisture service defined in this document.

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