Sensagri

Sentinels Synergy for Agriculture

Deliverable D3.5

Final operational SSM prototype

V 1.0

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Abstract (for dissemination)	The document describes the implementation of the SENSAGRI final operational SSM Prototype, referred to as "Soil MOisture retrieval from multi-temporal SAR data" (SMOSAR). The main software blocks and basic functional elements are depicted through the use of flow charts and pseudo-codes.
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[1] R = Document, report; DEM = Demonstrator, pilot, prototype; DEC = Websites, patent fillings, videos, etc; OTHER; ETHICS = Ethics requirement

[2] PU = Public; CO = Confidential (Consortium and Commission Services); EU-RES = Restreint UE; EU-CON Confidentiel UE; EU-SEC = Secret UE (Commission Decision 2005/444/EC)

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1. Introduction

1.1. Scope of the document

The objective of this document is to provide a compact and high-level description of the logical processing model, components and functional elements of the SENSAGRI "Soil MOisture retrieval from multi-temporal SAR data" (SMOSAR) code that implements the SSM retrieval algorithm described in the Algorithm Theoretical Basis Document [D3.8].

The retrieval algorithm is based on a Short Term Change Detection (STCD) approach, developed and validated in two ESA feasibility studies at 1 km resolution (Mattia et al., 2011 & 2019). The rationale is to exploit the frequent revisit S1 in order to decouple the soil moisture contribution from that of soil roughness and vegetation [Balenzano et al., 2011].

The software implemented in SENSAGRI, i.e., the Final Operational SSM Prototype v2 (D3.6), is an evolutionary prototype that integrates spectral information from S2 images and implements improvements based on the feedbacks of the validation activity.

The output consists of SSM maps characterized by a pixel size of 50 m and a hybrid spatial resolution, ranging between 0.1 km to 1.0 km. More precisely, the initial SSM retrieval is performed at 40 m pixel size (i.e., ~100 m resolution), then the SSM field is averaged at field scale, over those areas where the parcel borders (e.g., from the LPIS EU system) are available, and at 1 km resolution over the remaining areas. Together with the map of the SSM spatial mean at hybrid resolution, the SENSAGRI output includes a companion map of SSM spatial standard deviation also at hybrid resolution.

The description of the Software Prototype consists of flow diagrams and simple pseudo-codes of the main modules. The software modules are written in the Interactive Data Language (IDL, see [W1]) and run on Linux platforms [D3.6].

1.2. Notations, abbreviations and acronyms

CNR	Consiglio Nazionale delle Ricerche
EO	Earth Observation
ENL	Equivalent Number of Looks
ESA	European Space Agency
IREA	Istituto per il Rilevamento Elettromagnetico dell'Ambiente
S1	Sentinel-1
S2	Sentinel-2
SAR	Spaceborne Synthetic Aperture Radar
SMOSAR	Algorithm for Soil Moisture Retrieval using Sentinel 1 data
SSM	Surface Soil Moisture
STCD	Short Term Change Detection

2. Final SSM prototype architecture

The software architecture of the Final SSM Prototype is shown in Figure 1.

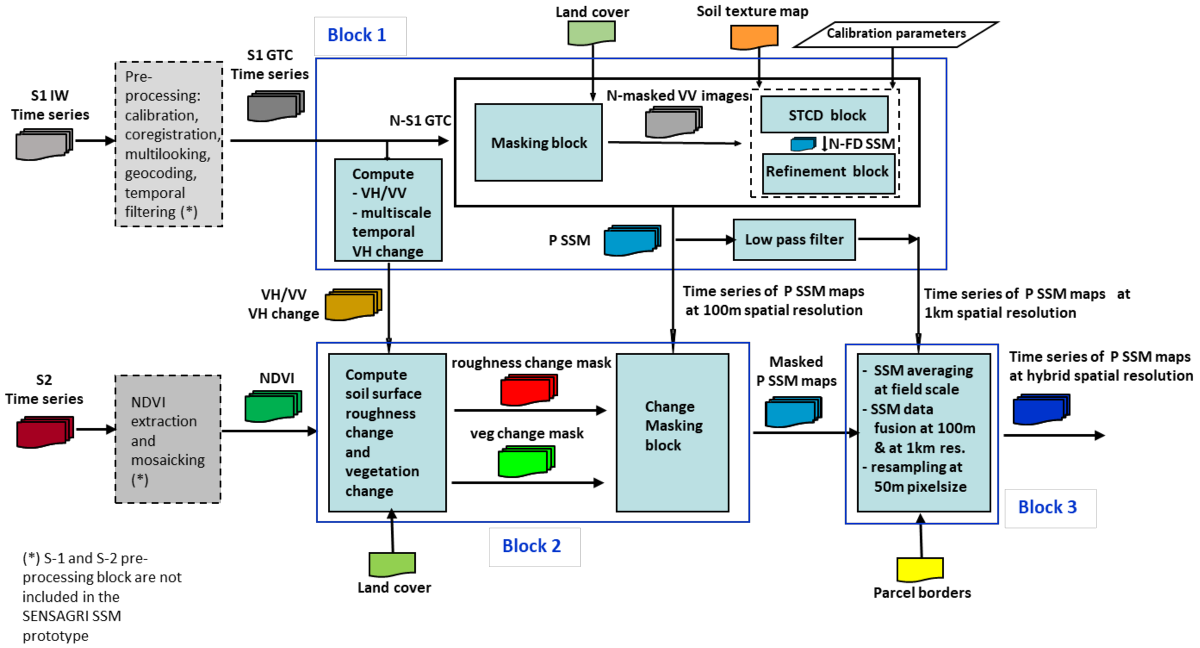

Figure 1. Architecture of the final implementation of the SSM prototype.

Three main processing blocks can be identified:

1. Block 1: the SSM retrieval block, which contains the core of the software implementing SMOSAR, i.e., the STCD block. It implements the STCD retrieval algorithm [D3.8], works at 40 m pixel scale, and transforms time series of N-S1 IW GTC VV & VH pre-processed images into N-SSM maps at 1 km resolution. For this task, ancillary data such as quasi-static land cover and soil texture maps are required.

2. Block 2: the S-1 & S-2 integration block, which masks the SSM maps at 40 m pixel scale for the abrupt change of roughness and vegetation that may bias the SSM retrieval. The masking exploits the synergy between S1 VH and S2-NDVI data. If NDVI is not available (e.g., due to cloud cover), then the ratio of VH/VV is used.

3. Block 3: the SSM data fusion block, which implements: a) the averaging of the masked SSM maps at field scale by exploiting the parcel borders, wherever available; and b) the fusion of SSM maps at two different spatial resolutions, i.e. the product at field scale, and the product at 1km resolution, wherever parcel borders are not available. Finally, the output SSM map are resampled to a pixel size of 50m.

For the sake of clarity, Figure 1 also illustrates the S1 and S2-NDVI pre-processing blocks, which are not included in the delivered software [D3.6].

The pre-processing for S1 data (i.e. GRD IW product [W2]) consists of the calibration, co-registration, multi-looking, geocoding and temporal filtering. As a result, the S1 pre-processed images (i.e. S1 GTC, i.e. Geocoded Terrain Corrected) have a pixel size of 40m and ENL higher than 100 [Oliver and Quegan, 1998].
For S2 data (i.e. MSI L2A geocoded products [W3]), S2-NDVI is extracted and mosaicked to obtain a NDVI image with the same dimensions and pixel size of the correspondent S1 GTC images.

A detailed description of the three blocks is reported in the following sub-sections.

2.1. Block 1: SSM retrieval block

The functional processing steps of Block 1 (Figure 2), are:

a) reading of all input data, namely time series of N-S1 IW GTC (VV & VH), land cover and soil texture maps, calibration parameters;
b) masking the N-S1 VV images to obscure those areas characterized by a poor SAR sensitivity to SSM due to the presence of dense vegetation (Masking block);
c) transforming the time series of N-S1 VV (masked) images into time series of N-SSM maps using the STCD algorithm (online processor). The block includes the conversion of the retrieved dielectric constant into SSM values, and the temporary storage of intermediate SSM maps (denoted as N-FD SSM maps, FD=Fast Delivered);
d) temporal averaging of the FD SSM maps using the refinement block (offline processor). As a result, a single P SSM map (P=precision), at high resolution (~100m) and characterized by a reduced SSM variability, is obtained for each date;
e) applying a low pass filter to the P SSM maps in order to obtain maps at 1 km;
f) computing the S1 VH/VV ratio and the multiscale temporal change of S1 VH at pixel scale as intermediate maps for input to Block 2.

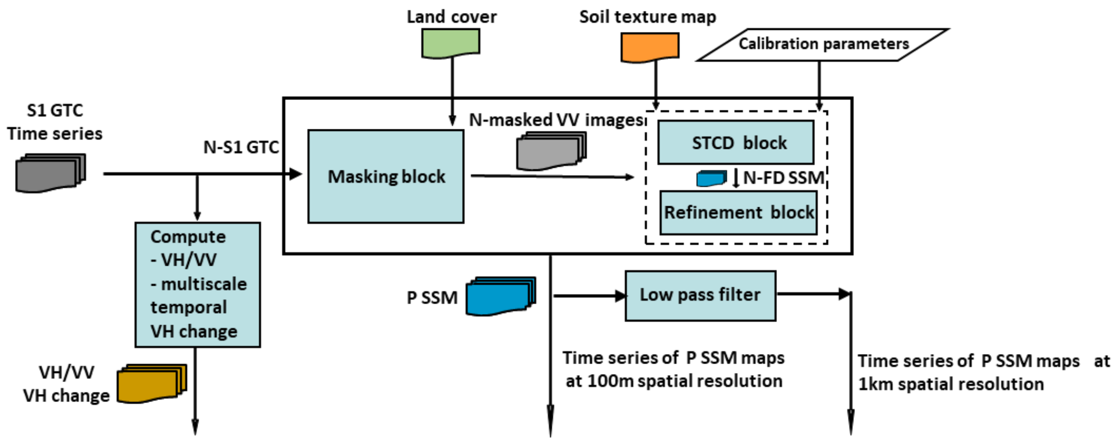

Figure 2. Block 1: SSM retrieval block.

In the following sub-sections, the blocks shown in Figure 2 are described in terms of input/output data and the pseudo-codes of the implemented modules.

2.1.1. Masking block

The masking block creates and applies a mask to each group of N-S1 GTC VV images (e.g. N=4) in order to leave unmasked only agricultural and sparsely vegetated areas whose dominant scattering mechanism is the attenuated surface scattering.

Table 1 lists the main input/output data of the masking block.

The mask creation is a two-step process:

1. In the first step, a global land cover map (e.g. CCI land cover [W4]) is used to mask urban areas, water bodies, forests, etc. Only agricultural and short vegetated areas are not masked. A first level mask (i.e. Mask1) is obtained and applied to mask the N-VH images.
2. then, in the second step, an adaptive thresholding classification method is applied to the masked VH S1 data to further identify those agricultural/sparsely vegetated areas dominated by volume scattering [D3.8]. The classification method, developed in Satalino et al. (2014), uses the iterative approach of the Kittler-Illingworth method (Kittler and Illingworth, 1986; Ye et al., 1988), to segment the S1 time series.

Figure 3 shows the masking block components, i.e. the modules devoted to the Mask1 and Mask2 extraction and then the Masking of the N-VV images. Figure 4 reports the details of the Mask2 extraction module, which is based on the Adaptive threshold method.

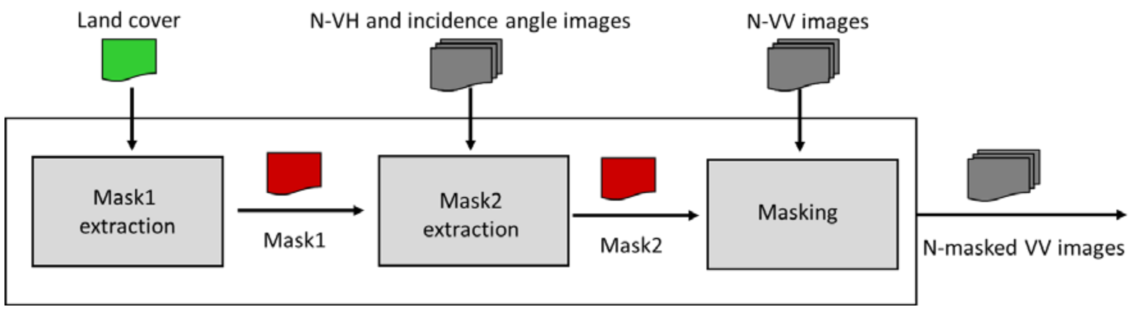

Figure 3. Masking block.

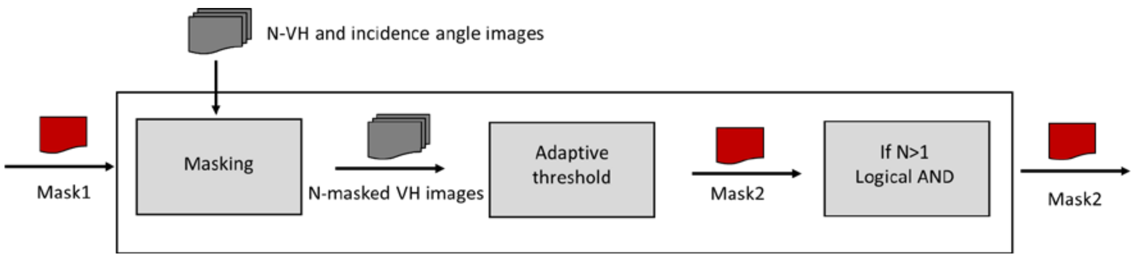

Figure 4. Mask2 extraction module.

Table 1. Main input/output data of the Masking block.

input	• stack of N-S1 GTC VV images and the correspondent incidence angle images • stack of N-S1 GTC VH images • land cover map
output	• N-masked VV images

The modules in Figure 3 and Figure 4 are briefly described by the following pseudo-code:

- *Mask1 extraction*

```
read the external land cover map
extract the classes agricultural/sparsely vegetated areas and compute
    mask1 i.e.:
    if land cover==selected_class then set mask1=1 else set mask1=0
```

- *Mask2 extraction*

```
read mask1
for each VH image (from 1 to N, N>=1):
    read the VH and θ images
    compute VH γ0 coefficient
    mask the VH γ0 images by using mask1
    apply the adaptive threshold algorithm by using the masked VH γ0 images
endfor
if N>1 then apply a logical AND to the N-mask2, and get a unique mask2,
    i.e.:
    if mask2_1 == 1 AND … AND mask2_N == 1 then mask2=1 (i.e. non-volume
    scattering) else mask2=2 (i.e. volume scattering)
```

- *The adaptive threshold algorithm*

```
for each masked VH γ0 image (from 1 to N, N>=1):
   read the masked VH γ0 image
   starting from the threshold th0, estimate the parameters of the pdfs
    fitting the two subsets defined by th0
   iterate: updated threshold by using the crossover point of the two
    Gaussian pdfs until threshold becomes stable
   set th as the optimal threshold
   apply th to the masked VH γ0 image and return a mask2 i.e.:
    if VH γ0 <= th then mask2=1 (i.e. non-volume scattering)
    else mask2=2 (i.e. volume scattering)
endfor
```

- *Masking N-VV SAR images*

```
read mask2
for each VV image (from 1 to N, N>=1)
    mask the VV image by using the mask2, i.e.
```

```
        if mask2==0 (i.e. forests, urban areas, water bodies, …) OR mask2==2
        (i.e. volume scattering) then set VV=0
   endfor
```

As a result, only surfaces dominated by soil attenuated scattering are left unmasked. The backscatter of these surfaces can be represented by:

$$\sigma_0^{VV} \approx \sigma_0^s \cdot \tau^2 \qquad (1)$$

where σ_0^s is the soil surface contribution and τ^2 is the two-way vegetation transmissivity (see [D3.8]).

2.1.2. STCD Retrieving block

The STCD block (also denoted as the online processor) transforms N-masked VV images into N-FD SSM maps. This is accomplished by the modules shown in Figure 5, which implements:

1. a solver for the undetermined constrained linear system, which retrieves the α_{VV} Fresnel reflection coefficients from the time series of S1 backscatter changes. This module requires constraining α_{min} & α_{max} parameters that are estimated at low resolution (e.g., 36 km) using a lookup table stored in the calibration file, read in input;
2. the conversion of the retrieved α_{VV} coefficient into dielectric constant ε_S, that is performed by the analytical inversion of the α_{VV} definition[D3.8];
3. the conversion of dielectric constant ε_S into SSM, which is based on the Hallikainen Model (1985) and requires soil texture (i.e. clay and sand maps, e.g. ISRIC soil texture [W5]).

The mathematical details are reports in [D3.8] and the main input input/output data are summarized in Table 2.

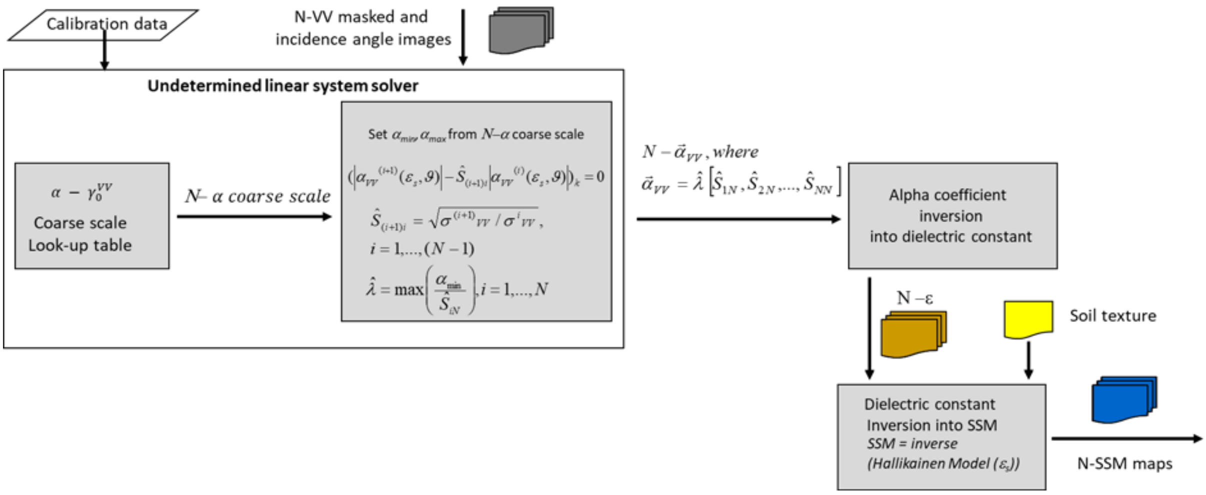

Figure 5. STCD Retrieving block.

Table 2. Main input/output data of the STCD Retrieving block.

Input	• stack of N-masked VV images and the correspondent local incidence angle images • soil texture • Calibration parameters
Output	• N-FD SSM maps (FD=Fast Delivery)

The pseudo-code describing the STCD Retrieving block is:

- *Undetermined linear system solver*

read N-VV masked, θ
read Look-up Table $\alpha_{VV} - \gamma_0^{VV}$ from Calibration parameters
set N-α_{VV} from N-VV, θ at coarse scale
set α_{min}, α_{max} from N-α_{VV}
compute $\hat{S}_{(i+1)i} = \sqrt{\sigma^{(i+1)}{}_{VV} / \sigma^{i}{}_{VV}}, i = 1,\ldots,(N-1)$
compute $\hat{\lambda} = \max\left(\frac{\alpha_{\min}}{\hat{S}_{iN}}\right), i = 1,\ldots,N$
compute $\vec{\alpha}_{VV} = \hat{\lambda}\left[\hat{S}_{1N}, \hat{S}_{2N}, \ldots, \hat{S}_{NN}\right]$ at pixel scale

- *Alpha coefficient inversion into dielectric constant*

for each α_{VV} map(from 1 to N)
   read α_{VV} map and the corresponding θ image
   compute $\varepsilon_s = f_i(\alpha_{VV}, \vartheta)$ by inverting its analytical function
endfor

- *Dielectric constant inversion into soil moisture*

read soil texture map
for each ε_s map(from 1 to N)
   read ε_s map
   compute SSM map=inverse(Hallikainen empirical expression(ε_s))
endfor

2.1.3. Refinement block

The rationale of the refinement is that SMOSAR processes time series of N-S1 images using a sliding-window of N=4 S1 images each time. This means that multiple (partially correlated) estimates of the SSM maps for the same S1 acquisition date will be available. The refinement block, also denoted by the offline processor, implements a temporal averaging of the multiple FD SSM maps estimated on the same S1 acquisition date. Its scope is to reduce the SSM variability.

Indeed, under the assumption that the SSM output maps are unbiased and represent normally distributed estimates of the true local SSM values, the offline SSM refinement implies a reduction of the root mean square error of a factor ≤2 (for N=4).
The presence of multiple SSM map on the same date can be easily understood looking at the Figure 6, which depicts the processing pipeline.
At time T, SMOSAR processes a sliding window including N images (first row, i.e. images from k-3 to k). At the subsequent time step T+1, the group of N images shifts of one position (second row, i.e. images from k-2 to k+1 as image k-3 leaves out and image k+1 enters in). And so on. This implies that N SSM estimates referred to the same acquisition date k are obtained (images in column k). Therefore, they can be averaged to obtain a single refined P SSM product (P=Precision).

The input Input/output data employed in this step are reported in Table 3.

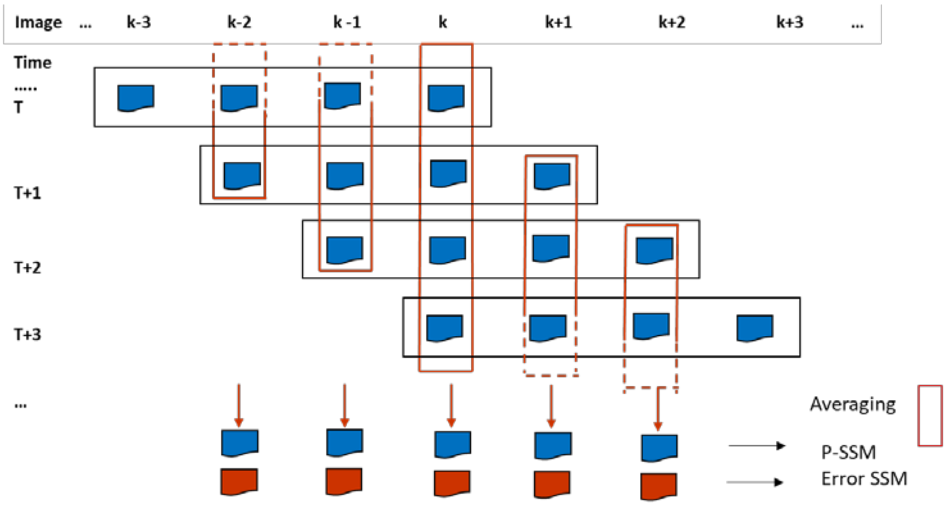

Figure 6. Refinement block.

Table 3. Main input/output data of the Refinement block.

Input	• stack of FD SSM maps on the same acquisition date
Output	• a single P SSM map (P=precision)

The pseudo-code describing this block is:

- *Refinement block*

```
for each acquisition date
   read all the FD SSM maps available
   compute the mean of the maps
   write the mean as a single P SSM map
endfor
```

2.1.4. Low pass filter

The low pass filter is applied to each P SSM map to get a spatially averaged and resampled SSM map. The spatial averaging is obtained by an averaging window of size S (e.g. 13x13), with the purpose of reducing the standard deviation of the SSM of a factor of approximately 1/√S. The resampling is performed by using the resampling parameter S, obtaining a reduction of the spatial resolution from ~100m to approximately 1km. As a result of this averaging, a spatial mean (P_SSM_MAP.img_mean), and standard deviation (P_SSM_MAP.img_stddev) maps are obtained.

The pseudo-code describing this block is:

- *Low pass filter*

```
for each P SSM map
   read the P SSM map
   apply a spatial averaging using a S-pixel averaging window
   resample the map by using a factor S
   write the averaged/resampled P SSM map (mean and std.dev. layers)
endfor
```

2.1.5. VH/VV and multiscale temporal VH change

This block computes the VH/VV and the multiscale temporal VH change products from S1 data. These products are employed in Block2 to estimate surface or vegetation change masks, for identifying abrupt changes of surface roughness due to tillage changes [D6.13] or those due to a rapid change of the crop biomass [D3.8], respectively.
The VH/VV product is obtained simply computing the ratio of the VH and VV polarizations (values expressed in the linear scale) of each S1 data.
The multiscale temporal VH change product is obtained by computing the temporal VH change ($\Delta VH=VH(t_2)$ - $VH(t_1)$, values expressed in dB at time t_2 and t_1) at (field) local scale (LS) and at medium scale (MS), e.g. over an area of 5kmx5km (i.e. ΔVH_{LS} and ΔVH_{MS}, respectively). This objective is indeed to identify VH change events that occur only at field scale, but not at medium scale. This is accomplished by using a threshold approach for the two scales, i.e., th_{LS} and th_{MS}, respectively.
Figure 7 shows the block and its input/outputs.

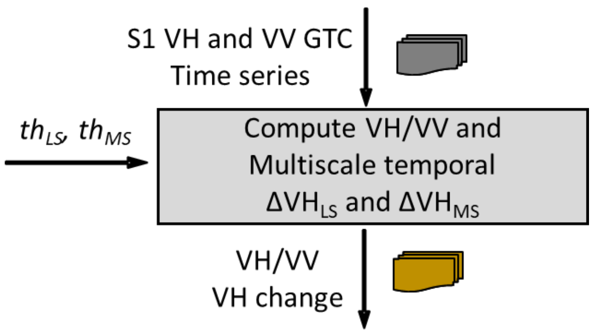

Figure 7. VH/VV and multiscale temporal VH change block.

The input Input/output data of this step are reported in Table 4.

Table 4. Main input/output data of the VH/VV and multiscale temporal VH change block.

Input	• VV at time t_k • VH at time t_k and t_{k-1} • th_{LS}, th_{MS}
Output	• VH/VV at time t_k • VH change (t_k-t_{k-1})

The pseudo-code describing this block is:

- *Multiscale temporal VH change block*

```
for each time k (from 2 to T)
   read VV at time tk
   read VH at time tk and tk-1
   compute VH/VV at time tk
   set thresholds thLS and thMS
   compute ΔVHLS and ΔVHMS (tk-tk-1)
   if abs(ΔVHLS)> thLS AND abs(ΔVHMS)< thMS then set VH change = 1
   write VH change at time tk
   write VH/VV at time tk
endfor
```

2.2. Block 2: S-1&S-2 integration block

The functional processing steps of Block 2, which masks the P SSM maps at high resolution (Figure 8), are:

a) reading of the VH changes, VH/VV, NDVI maps, Land cover and of P SSM maps at 100m resolution;
b) estimating the soil roughness and vegetation change masks by using the S1-VH changes and S2-NDVI (or alternatively VH/VV in case of lack of NDVI);
c) masking of P SSM maps at 100m resolution by using the change masks computed in b).

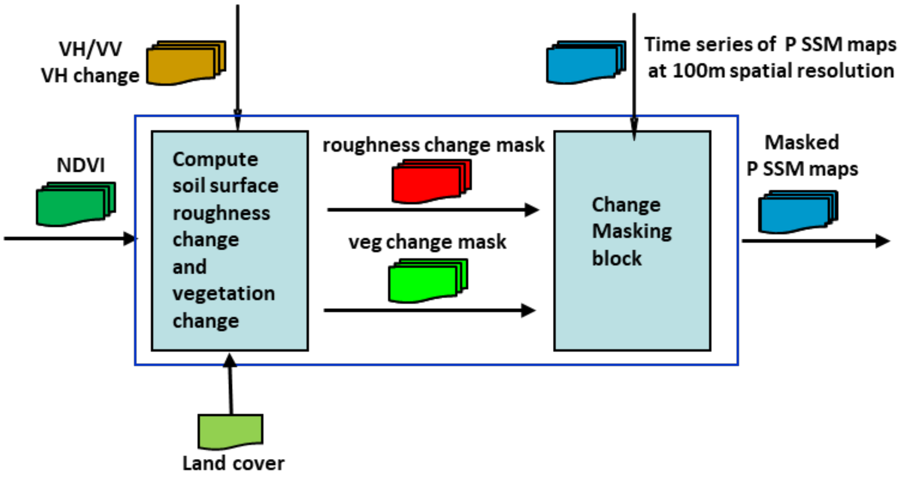

Figure 8. Block 2: S-1&S-2 integration block.

In the next sub-section, the description of the compute soil surface roughness and vegetation block is provided. For the change masking block, a further description is not included as it is a straightforward masking.

2.2.1. Compute soil surface roughness and vegetation changes

The task of this block is to identify whether the identified VH change is due to abrupt changes of soil surface roughness (caused by tillage changes [D6.13]) or of vegetation [D3.8].

For this purpose, S2-NDVI values are used to identify: i) bare or scarcely vegetated soil surfaces (over agricultural areas find by the land cover map) and ii) fast changing vegetated surfaces.

More precisely, bare soil surfaces (i.e. surfaces with positive low values of NDVI and a low absolute NDVI difference, $\Delta NDVI=NDVI(t_2) - NDVI(t_1)$, at time t_2 and t_1) are those where tillage changes can occur. Whereas fast changing vegetated surfaces (i.e. those with a significant absolute $\Delta NDVI$) are those where an abrupt change of vegetation can occur. These checks are performed at time t_2 and t_1, and qualified using the appropriate thresholds, i.e., th_{NDVI} and $th_{\Delta NDVI}$.

In case NDVI is not available (e.g. due to cloud cover), then the polarization ratio (PR) of VH/VV is used. Indeed, its temporal behaviour over crops is similar to that of NDVI [D6.13].

Once the nature of the VH change is determined, then the change on S1 image is appropriately masked.

The functional elements of this block are shown in Figure 9.

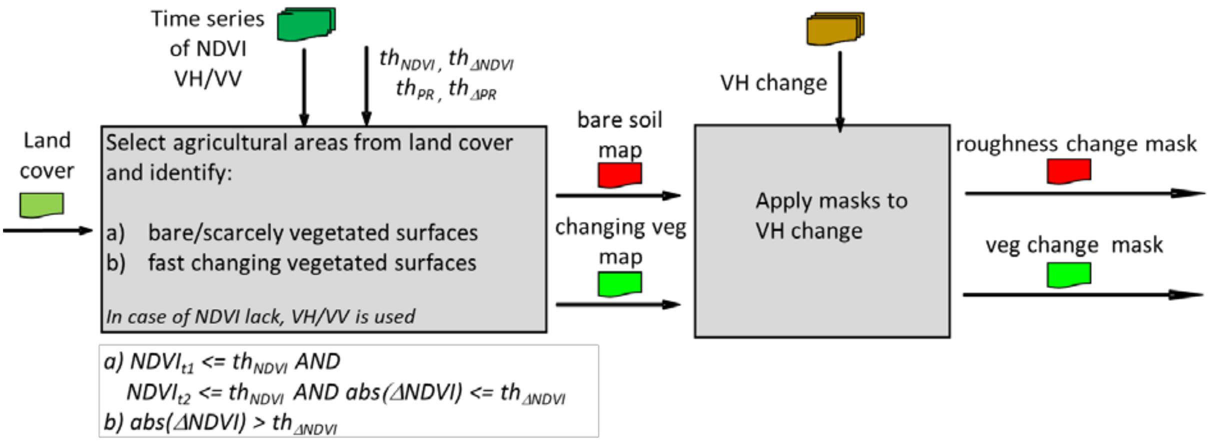

Figure 9. Soil surface roughness and vegetation block.

The input Input/output data are reported in Table 5.

Table 5. Main input/output data of the soil surface roughness and vegetation block.

Input	• Land cover • VH change (t_k-t_{k-1}) • VH/VV at time t_k and t_{k-1} • NDVI at time t_k and t_{k-1} • th_{NDVI} and $th_{\Delta NDVI}$; th_{PR} and $th_{\Delta PR}$
Output	• roughness change mask at time t_k • vegetation change mask at time t_k

The correspondent pseudo-code is:

- *Soil surface roughness and vegetation block*

```
read land cover
read threshold parameters
for each VH change map at time tk
   read VH change, NDVI at time tk and tk-1,VH/VV at time tk and tk-1
   compute ΔNDVI=(NDVI(t2) - NDVI(t1)) and ΔVH/VV
   define bare soil map:
      NDVIt1 <= thNDVI  AND  NDVIt2 <= thNDVI AND abs(ΔNDVI) <= thΔNDVI
      if NDVI not available then use VH/VV, ΔVH/VV
   Define changing veg map:
      abs(ΔNDVI) > thΔNDVI
      if NDVI not available then use ΔVH/VV
```

```
    mask VH change by the bare soil map and get the roughness change mask
    mask VH change by the changing veg map and get the veg change mask
endfor
```

2.3. Block 3: SSM averaging and data fusion block

The functional processing steps of Block 3, which compute the P SSM maps at hybrid spatial resolutions (Figure 10), are:

a) reading the parcel borders, of the masked P SSM maps at 100m resolution and of the P SSM maps at 1km resolution;
b) averaging the masked P SSM maps at high resolution by using parcel borders; this averaging process produces a spatial mean and standard deviation layers;
c) fusing the SSM data at different resolution; the fusion is applied both to the mean and std.dev. layer;
d) resampling the output map to 50m pixel size.

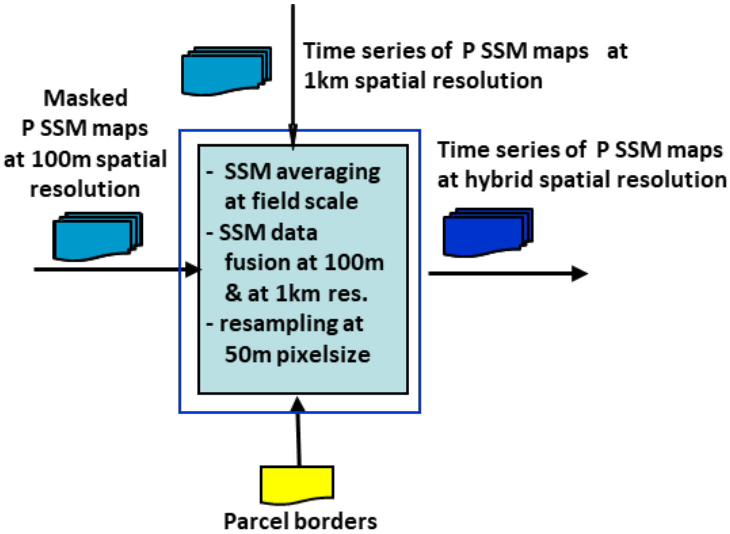

Figure 10. Block 3: SSM averaging and data fusion block.

The input Input/output data of this step are reported in Table 6.

Table 6. Main input/output data of the SSM averaging and data fusion block.

Input	• masked P SSM maps at 100m resolution • P SSM maps at 1km resolution • parcel borders
Output	• hybrid P SSM maps at 100m resolution

The correspondent pseudo-code for these steps is:

- *SSM averaging and data fusion block*

```
read parcel borders
for each SSM map
   read the masked high res P SSM map, the low res P SSM map
   average the masked high res P SSM map by using parcel borders and save
      the mean and standard deviation layers;
   overimpose (layer per layer) the averaged masked high res P SSM map to
      the low res P SSM map
   resample all the layers of the output map to 50m pixel size
   save the output product
endfor
```

3. Summary

The main processing blocks of the Final operational SSM prototype, which exploit the synergy of S1 & S2 data, have been described by means of flow charts and pseudo-codes. The core of this software is the STCD retrieval algorithm, which is based on a change detection approach requiring dense (e.g., 6-days revisit) time series of S1 data.

The SENSAGRI SSM product is characterized by a hybrid resolution, ranging from field scale (~100 m) to 1 km resolution, and improved accuracy due to the masking of abrupt changes of surface roughness and vegetation layer, which tend to bias the SSM retrieval.

Reference documents

[D3.6] Software of the final operational SSM prototype exploiting S1&S2, V 1.0, User Manual.

[D3.8] Final SSM Algorithm Theoretical Basis Document.

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