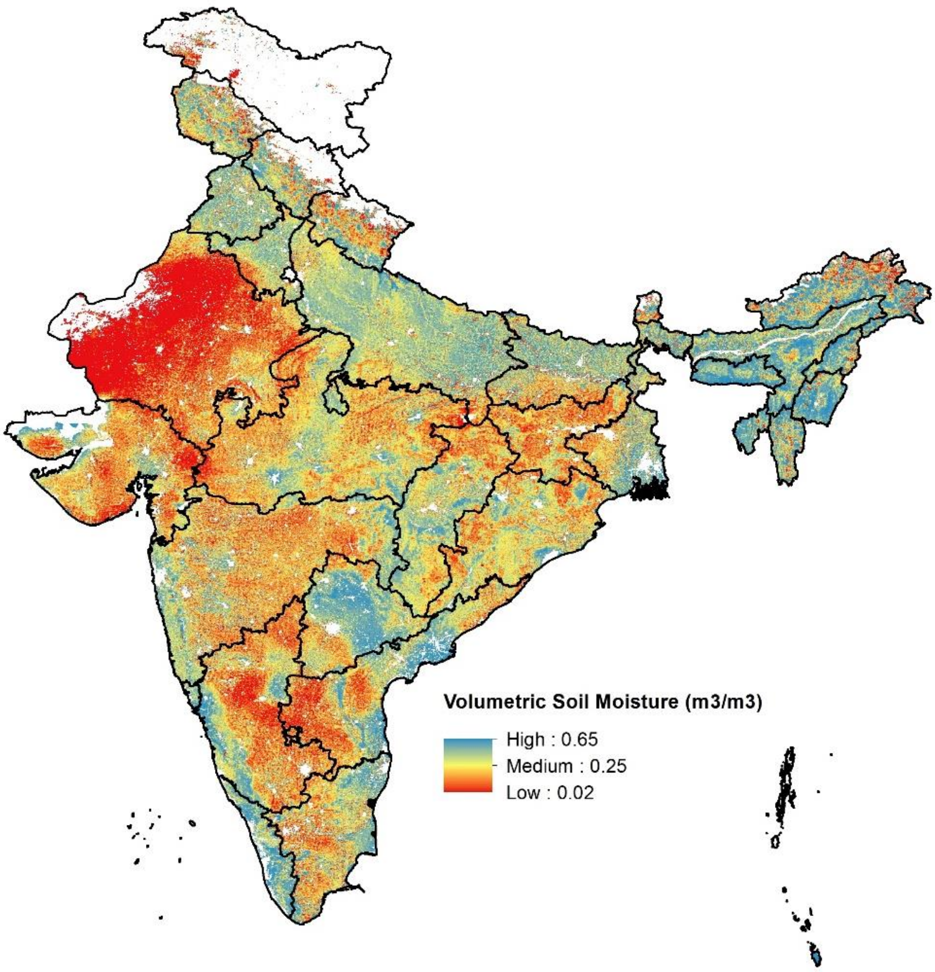
# Algorithm Theoretical Basis Document

## *Operational High Resolution (~500m) Surface Soil Moisture (Active/Passive) Product* over India

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| **11** | **Abstract** | This Algorithm Theoretical Basis Documents (ATBDs) provide the physical and mathematical descriptions of the algorithm used for ***Operational High-resolution (500m) Surface Soil Moisture (Active/Passive) data product over India*** using EOS-04 (RISAT-1A) C-band SAR and SMAP radiometer data. The ATBD's includes a description of physics of the problem, retrieval algorithm and validation results over multiple sites. | | | |
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**Introduction:**

Soil Moisture (SM) is an essential parameter which plays significant role and provide critical information for decision making in agricultural applications including irrigation scheduling and management, crop water requirement and yield forecasting etc. Soil moisture is also fundamental data source used by multiple stakeholders (central government agencies, state government agencies and others) to monitor crop growth stage and to forecast agricultural yields. Satellite derived soil moisture products are currently being used for large-scale drought assessment and other applications. However, currently available satellite derived operational soil moisture products from spaceborne microwave radiometers are not adequate for finer soil moisture (sub km scale) monitoring due to coarse spatial resolution which is prime requirement of agricultural and other fine scale applications.

Currently, there are two L-band microwave radiometer-based satellite missions in orbit dedicated to measuring the Earth's surface soil moisture: 1) soil moisture and ocean salinity SMOS) launched by the European Space Agency in November 2009, and 2) soil moisture active and passive (SMAP) launched by the NASA (National Aeronautics and Space Administration) in January 2015. Both missions generate global maps of surface soil moisture at ~2–3 day intervals with a spatial resolution of about 30–40 km and a target accuracy of ±0.04 m3/m3.

In order to improve spatial resolution, Soil Moisture Active Passive (SMAP) mission was designed and launched in January 2015 with collocated L-band radar and L-band radiometer for global soil moisture at 1km & 3 km scale by combining radar and radiometer observations based on active-passive approach. It was supposed to get benefits of *higher resolution* from SAR and *higher sensitivity* towards soil moisture from radiometer. Unfortunately, L-band radar of SMAP stopped working after two and half months due to some anomaly in high power amplifier and limited with only radiometer observation over globe, since July 2015. To meet the requirement of agricultural and other fine scale applications, different approaches/methods have been proposed to spatially disaggregate the coarse SMOS and SMAP observations based on synergies between multisensory observations and different physical assumptions.

In order to compensate the L-band radar observations for active-passive, Sentinel-1 C-band SAR data was selected as an alternative for merging with SMAP radiometer data to generate 1km & 3km scale soil moisture with limited area as Sentinel-1 scene. These 3km SMAP-Sentinel product has been tested and validated over SMAP core cal/val sites with good accuracy levels [Das et. al. 2019 RSE, Gurjeet Singh et al. 2019]. However, these products are still not tested extensively below km scale (sub km <1km) over different cropland types. Even though, there are some constraints in terms of temporal frequency and coverage of C-band SAR with respect to SMAP L-band radiometer, it demonstrated the potential of C-band SAR data for disaggregating coarse L-band radiometer observations to fine scale over global croplands.

Das et al. [13] demonstrated that the active–passive algorithm developed for the SMAP mission is also capable of working with different combinations of coarse resolution passive microwave (L-/C-band radiometer) and high-resolution active microwave (L-/C-band SAR) observations. In this context, the merging of available fine-scale SAR data from other satellites with coarse resolution SMAP L-band radiometer observations in the active–passive algorithm can offer a potential solution to disaggregate the SMAP radiometer observations at high resolution.

**Objectives and Background:**

ISRO’s follow-on Radar Imaging Satellite EOS-04 (RISAT-1A) C-band SAR was launched on 14-February 2022 by ISRO‟s own PSLV C-52 to cater the requirements of multiple earth observation applications for user and scientific community. EOS-04 is a Low Earth Orbit (LEO) satellite to be operated in a Sun Synchronous Polar Orbit (SSPO) with 6 AM-6 PM Equatorial Crossing Time (ECT) at an altitude of 524.87 km carrying a Synthetic Aperture Radar (SAR) payload. EOS-04 Spacecraft is configured using ISRO’s RISAT-1 heritage bus and capabilities are fully exploited with respect to accommodation, power generation, thermal management etc. EOS-04 SAR is capable of providing data in various resolution modes catering to a variety of applications as demonstrated in its precursor mission RISAT-1. Patnaik et al. 2021 demonstrated the potential of RISAT-1A (EOS-04) with 8- beam Medium Resolution ScanSAR (MRS) that poses significant advantages for applications in wider swath, improved revisit times and scope for large area inventories and highlighted the new MRS beam in light of the application potentials for agriculture, soil moisture, forest, land hydrology, geoscience and cryosphere theme. The main objective of EOS-04 mission is to provide continuity of data to the users. To cater to the applications, the SAR payload of EOS-04 shall operate in C-Band frequency range (5.4 GHz) and in Side-Looking Radar mode with performance parameters for different modes as per table-1.

**Table-1: EOS-04 Payload Specifications**

| **Parameters** | **Specifications** |
|---|---|
| Altitude | 524.87 km |
| Orbit | Sun synchronous (6 AM -descending / 6 PM equatorial crossing) |
| Frequency | 5.4 GHz $\pm$ 37.5 MHz |
| Polarization Combination | Single / Dual / Full /Hybrid polarimetry (Transmit circular, receive linear) |
| Antenna Roll Bias (deg) | ± 36° |
| Range Coverage (Km) | 100-650 (either side of flight track) |
| Look Angle (deg) | 11.5 - 49.6 |
| Incidence Angle (deg) | 12.4 – 55.5 |

In past, multiple research studies have demonstrated that Surface Soil Moisture (SSM) can be estimated at high spatial resolution with good level of accuracy using multi-temporal Radar Imaging Satellite (RISAT-1) C-band Dual Polarization SAR data over agricultural crop land [Dharmendra Pandey et. al. 2016 & Rucha Dave et. al. 2019]. It was also demonstrated that C-band SAR data is much capable with promising results over different crop stages (early and mature) for soil moisture estimation [Rucha Dave et. al. 2019]. In context of active-passive approach, Gurjeet Singh et al., 2021 evaluated the capability of ingesting ISRO's Radar Imaging Satellite-1 (RISAT-1) C-band SAR observations in the SMAP active–passive algorithm to obtain soil moisture at 1, 3, and 9 km over the agricultural region, dominant by paddy that experiences seasonal flooding.

Multiple efforts have made for the estimation of soil moisture using SAR data by applying empirical, theoretical and semi-empirical models. Some of the studies also demonstrated the potential of machine learning approaches and time-series approach for soil moisture retrieval using C-band SAR data which also could be the potential algorithm for operational soil moisture products. Due to some constraints of theoretical models, requiring so multiple field parameters and empirical model being simple but site specific, semi-empirical models have been emerged as finding the middle ground between both of them with limited number of target and sensor parameters' requirement. However, it also requires field specific tuning and corrections to provide more accurate soil moisture with low bias. Overall, each approach/algorithms has its own merits and demerits that need to be considered into account during selection of operational algorithm for deriving high-resolution soil moisture at national level.

In order to meet the operational requirements of user agencies (Ministry of Agriculture & Farmer Welfare, GoI and other stakeholders) for sub km scale (~500m) soil moisture from EOS-04 C-band SAR and considering limitations of algorithms/data required, active-passive approach [Das et. al. 2019 RSE] has been adopted and modified for deriving sub km (<1km) soil moisture over Indian croplands to meet agricultural requirements.

SMAP radiometer measurements in the L-band frequency range are sensitive to surface (~0- 5 cm) soil moisture, but the effective ground resolution is about 36 km which is not adequate for agricultural applications over India. The EOS-04 C-band SAR provides higher resolution (~33 m) backscatter measurements in systematic dual polarimetric MRS (Medium Resolution ScanSAR) mode with 17 days repeativity which can be utilized to disaggregate SMAP 9 km (optimally interpolated) brightness temperature to 500m and further for RT model based soil moisture inversion at 500m.

This ATBD proposes a high-resolution surface soil moisture by merging the active (EOS-04 C-band SAR) and passive (SMAP radiometer) measurements to derive ~500m soil moisture map as level-4 value added product (L4 SM) that meets the operational requirements of user agencies (Ministry of Agriculture & Farmer Welfare, GoI and other stakeholders). Objective of the present ATBD is to describe the algorithms and different aspects associated with the retrieval of ***high-resolution Surface Soil Moisture (Active/Passive) Data Product*** over India from EOS-04 C-band SAR and SMAP radiometer observation. Present document also outlines the validation activities for the retrieved soil moisture over multiple sites.

**Inputs:** Details of input datasets required for algorithm are given in table-1 and 2.

- **Satellite Data**

**Table-1**

| Sr. No. | Parameters | Data Products | Spatial Resolution | Source |
|---|---|---|---|---|
| **1.** | SAR backscatter $\sigma°$ in HH & HV pol with Local Incidence Angle (LIA) map | EOS-04 L2A MRS Dual Pol (HH+HV) Backscatter in UTM projection | ~33 m | Bhoonidhi Portal, NRSC (https://bhoonidhi.nrsc.gov.in/ |
| **2.** | Brightness Temperature | SMAP Enhanced L2/L3 Radiometer Half-Orbit 9 km EASE-Grid Soil Moisture | ~9km | NSIDC PODAAC |

- **Ancillary Data**

In addition to satellite data, multiple parameters are required to retrieve soil moisture using Radiative Transfer (RT) model and to improve the retrieval accuracy.

**Table-2**

| Sr. No. | Parameters | Source |
|---|---|---|
| **1.** | Soil Temperature | GSFC GMAO |

| | | |
|---|---|---|
| **2.** | Vegetation Water Content (VWC) | MODIS NDVI [T. Jackson/R. Hunt approach] based on vegetation climatology |
| **3.** | Soil Attributes (sand & clay fraction) | Soil Grid 250m |
| **4.** | Land Cover Type | MODIS IGBP 500m |
| **5.** | Digital Elevation Model | SRTM Topography |
| **6.** | Permanent Ice & Snow cover | MODIS IGBP 500m |
| **7.** | Urban fraction | MODIS IGBP 500m |
| **8.** | Water fraction | MODIS IGBP 500m |
| **9.** | b, ω, and τ Vegetation Parameters | land cover-driven table lookup |
| **10.** | h Roughness Parameter | land cover-driven table lookup |

**Algorithm functional specifications:**

**Active-Passive Algorithm:**

The adopted active-passive algorithm has two parts (a) the disaggregation of the radiometer brightness temperature from SMAP radiometer using the radar backscatter spatial patterns within the radiometer observations and (b) Retrieval of High-Resolution Soil Moisture.

**A. Disaggregation of Brightness Temperature**

The originally developed SMAP Active-Passive algorithm (Das et al., 2014; Entekhabi et al., 2014; Das et al., 2018) is given as:

$$T_{B_p}(M_j) = T_{B_p}(C) + \beta(C)\bullet\{[\sigma_{pp}(M_j) - \sigma_{pp}(C)] + \Gamma\bullet[\sigma_{pq}(C) - \sigma_{pq}(M_j)]\} \quad \textbf{(1)}$$

Where, $T_{B_p}(C)$ [K] and $T_{B_p}(M_j)$ [K] is the radiometer-based brightness temperature at coarse resolution (~9 km) and at the desired high-resolution (500m). The radar backscatter aggregated to coarse-resolution is $\sigma_{pp}(C)$ [dB] and $\sigma_{pq}(C)$ [dB], co-pol and cross-pol, respectively from EOS-04 C-band SAR data. The radar backscatters $\sigma_{pp}(M)$ [dB] and $\sigma_{pq}(M)$ [dB] are at the desired high-resolution (500m). $\beta(C)$ [K/dB] and $\Gamma$ [dB/dB] are sensitive parameters of the active-passive algorithm. The parameter $\beta(C)$ represents the covariation between $T_{B_p}(C)$ and $\sigma_{pp}(C)$ of the SMAP radiometer and radar observations, respectively, and the parameter $\Gamma$ represents the vegetation-induced heterogeneity within the coarse resolution radiometer cells that is detected by the high-resolution $\sigma_{pp}(M_j)$ and $\sigma_{pq}(M_j)$ radar observations. The parameter $\beta(C)$ can be statistically estimated based on a time-series regression using pairs of spatially averaged radar data $\sigma_{pp}(C)$ from EOS-04 C-band SAR and SMAP radiometer $T_{B_p}(C)$ and $\Gamma$ is estimated as $\left[\frac{\delta\sigma_{pp}(M_j)}{\delta\sigma_{pq}(M_j)}\right]_C$. The value of $\Gamma$ is specific to the particular grid cell C. It is estimated based on the collection of co-polarized and cross-polarized SAR backscatter cross-section within each coarse grid cell (C). To overcome the limitation of times-series data requirements for generating $\beta(C)$ as per equation (1), a snapshot retrieval approach (Jagdhuber et al., 2018) adopted here to estimate the covariation parameter $\beta'(C)$ from the EOS-04 SAR and SMAP radiometer observations as given in equation (2), (3) .

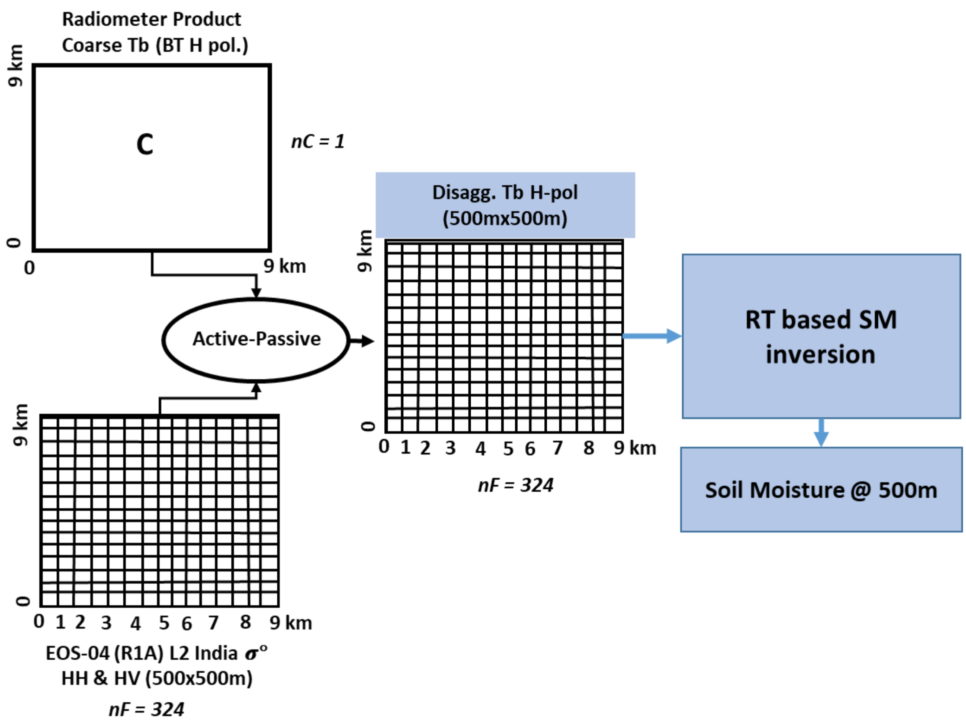


Figure 1: Methodology for *Active-Passive Snapshot Physical Approach*

$$T_{B_p}(M_j) = \left[\frac{T_{B_p}(C)}{Ts} + \beta'(C)\bullet\{[\sigma_{pp}(M_j) - \sigma_{pp}(C)] + \Gamma\bullet[\sigma_{pq}(C) - \sigma_{pq}(M_j)]\}\right] \bullet Ts \quad (2)$$

Where $T_S$ [K] is the emission temperature of the surface soil. The snapshot $\beta'(C)$ is retrieved at each coarse grid cell (C) for every overlap between the EOS-04 C-band SAR and SMAP observations and is computed as (Jagdhuber et al., 2019):

$$\beta'(C) = \frac{\frac{T_{B_p}(C)}{Ts} - (\gamma + (1-\omega)(1-\gamma))}{|S_{pp}(M_j)|^2 - \mu_{pp-pq} \bullet |S_{pq}(M_j)|^2} \tag{3}$$

In equation (3), ω is the effective single scattering albedo, $\gamma = e^{\frac{-\tau}{\cos\theta}}$ the vegetation loss term, and θ is the incidence angle. These approaches to estimate $\beta'(C)$ and $\mu_{pp-pq}$ (equivalent to $\Gamma$) do not require time series of $T_{Bp}$ (C) and $\sigma_{pp}$(C). This snapshot approach is capable of accommodating L-band, C-band and X-band combinations of the radiometer and SAR observations at different incident angles. On any given day, the snapshot estimate of the covariance parameter ($\beta'(C)$) is unique and is dependent on the radiometer $T_{B_p}$ (emissivity), SAR backscatter, $\omega$ (the effective single scattering albedo), and $\gamma = e^{-\tau/cos\theta}$ the vegetation loss term where ($\tau$) is vegetation optical density and θ is incident angle (Jagdhuber et al., 2018). $\beta'(C)$ in Eq. (3) results from eliminating smooth surface Fresnel reflectivity from the tau-omega model and variations in co-polarized backscatter that is due to soil moisture and not vegetation (Jagdhuber et al., 2018). The numerator is the measured surface emission minus the vegetation volume scattering and emission. The denominator is similarly the co-polarized backscatter minus the volume scattering (Jagdhuber et al., 2019). The volume scattering component in the co-polarized backscatter is the total co-polarized backscatter minus the projection of the cross-polarized backscatter onto the co-polarized backscatter. All computation are done to disaggregate brightness temperature from ~9km to 500m as per methodology given in figure (1). Figure-1 shows the nested grid topology of the EASE2 grid radiometer brightness temperature (9 km) with single pixel, EASE2 grid radar backscatter cross-section (0.5 km) with 324 elements, and desired disaggregated radiometer brightness temperature with 324 elements.

### B. Retrieval of High-Resolution Soil Moisture

The downscaled brightness temperature $T_{B_p}(M_j)$ at 500m is then passed into the tau-omega model (zeroth order radiative transfer model) [11] to retrieve surface soil moisture at 500m as per figure-1. Various ancillary data and lookup tables are used in the tau-omega model to retrieve soil moisture. Prominent ancillary data are NDVI climatology from MODIS, sand & clay fraction from soil grid 250m database, and land surface temperature (LST) from NASA GMAO, and the parameters are albedo ($\omega$), surface roughness (h), and vegetation coefficient (b) detailed for IGBP land cover classes.

**Flow Chart & Operational implementation:**

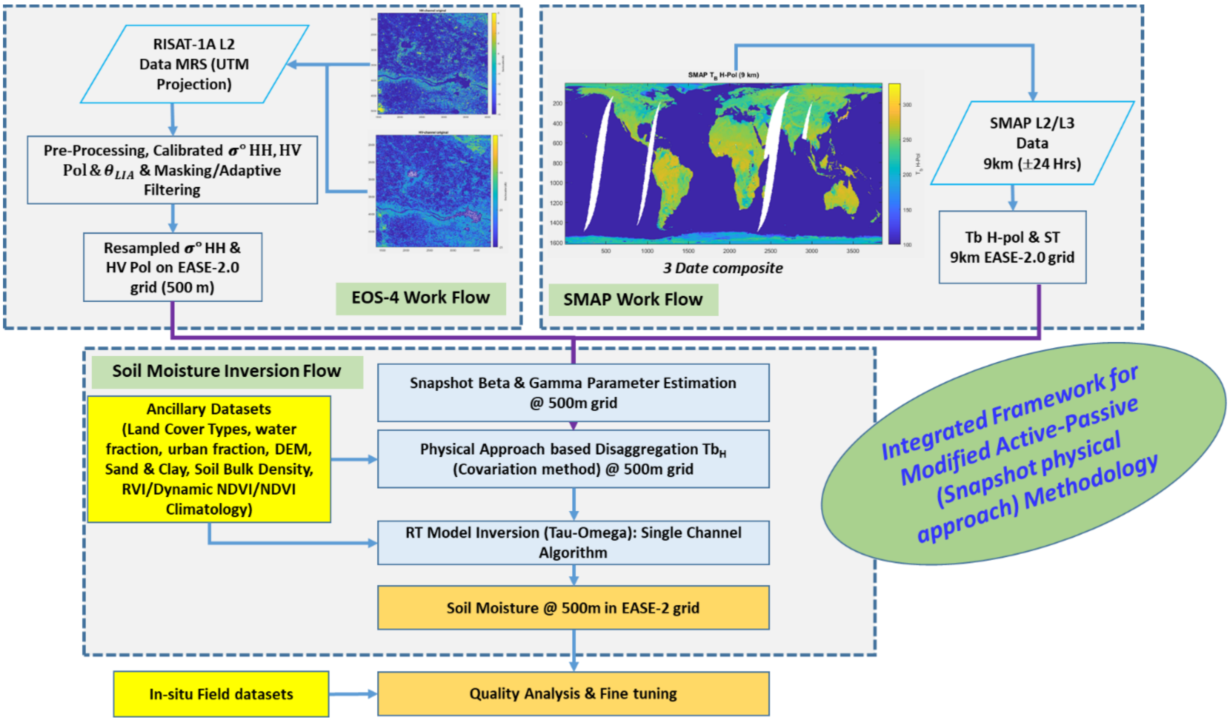


Figure 2: Flow diagram for High resolution Surface Soil Moisture *(EOS04-SMAP)* at 500m

A simplified flow chart of the ***EOS04-SMAP*** Active-Passive algorithm implementation is shown in figure- 2. It has three workflows (a) EOS-04 workflow (b) SMAP workflow (c) Soil Moisture Inversion workflow which is operationally implemented in MATLAB framework and a standalone application (EOS-04 Soil Moisture processor) has been developed to generate operational soil moisture for each EOS-04 MRS scene acquired over India.

**Outputs:**

| Table-3 | | | | | | |
|---|---|---|---|---|---|---|
| **Sr. No.** | **Parameters** | **Units** | **Spatial Resolution** | **Valid ranges** | **Data format and type** | **Source** |
| **1.** | Surface Soil Moisture (SSM) | Volumetric ($m^3/m^3$) | ~500m | 0.02-0.65 | Geotiff & float32 | Bhoonidhi Portal, NRSC |

**Validation:**

It is essential and strongly recommended to evaluate high-resolution soil moisture products (EOS04-SMAP) over various landcovers and hydroclimatic domains for accuracy assessment before it is operationally used for scientific research and operational applications at user ends. We have done extensive field expedition in sync with EOS-04 systematic satellite passes (MRS mode descending orbit), covering *Kharif* and *Rabi* cropping seasons from June 2022 to Feb 2023 over multiple sites. We evaluated *high-resolution soil moisture product (EOS04-SMAP)* for typical Indian conditions of extreme seasonal variability that leads to changes from very wet to dry soil, especially cropland regions.

**Data required:**

In order to test the performance of active-passive based soil moisture algorithm, in-situ soil moisture observations are required with spatially distributed sample points within pixel.

**Methods for validation and site details:**

There are two types of cal/val sites (1) Core cal/val with dense measurements in Anand dist. (Gujarat), Ludhiana dist. (Punjab) and Hisar dist. (Haryana); (2) Sparse cal/val sites in Kanpur dist. (UP) and Berambadi watershed (Karnataka) which has been selected over Indian agricultural croplands to evaluate the performance of operational high resolution (~500m) Surface Soil Moisture (Active/Passive) data product over India as per figure-3. In order to design standard sampling scheme, a *Multiscale Field Sampling Plan (MFSP)* based on Grid Sampling Methods for core soil moisture cal/val sites has also been defined which envisage the grid sampling within 100mx100m with multiple smaller crops/fields. There are minimum 5 sampling points (one centre and four corner points) within 100mx100m grid where soil and crop parameters are being measured and then averaged to get/represent field mean at 100 m grid. It also supports validation of 500m, 1km and 3km grid for upscaling in-situ soil moisture measurements. Field sampling are done in highlighted grid of 500 m (Green) and 100 m (Blue) grid sample. Total no. of sampling points within 100 m and 500 m grid are 5 and 45, respectively. Details are represented in figure-4. Figure-5 also shows gridding pattern for sampling over core cal/val sites. Soil and crop parameters are measured using handheld probes on regular basis in sync with EOS-04 (RISAT-1A) MRS systematic passes (6 AM) over respective sites. As of now, Multiscale Field Sampling Plan (MFSP) is only applicable to core SM cal/val sites. Currently, field sampling plan over Kanpur and Berambadi sites are not following Multiscale Field Sampling Plan (MFSP) which will be adopted in near future with respect to coming NISAR and RISAT-1B missions.

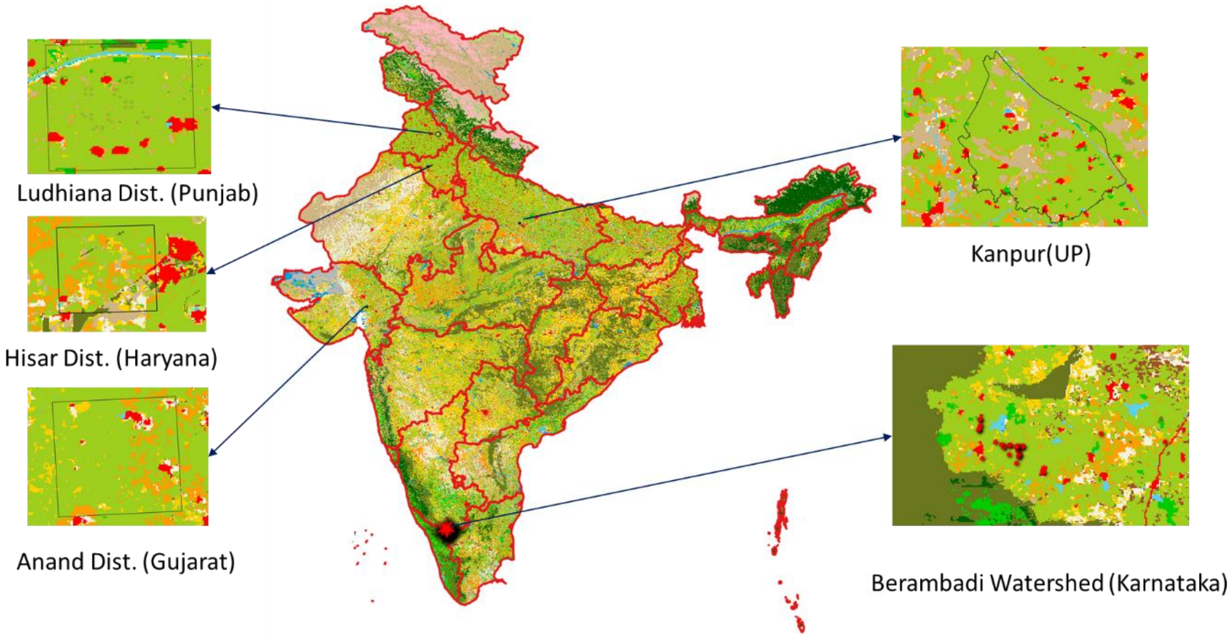


Figure 3: Soil Moisture Cal/Val sites over India

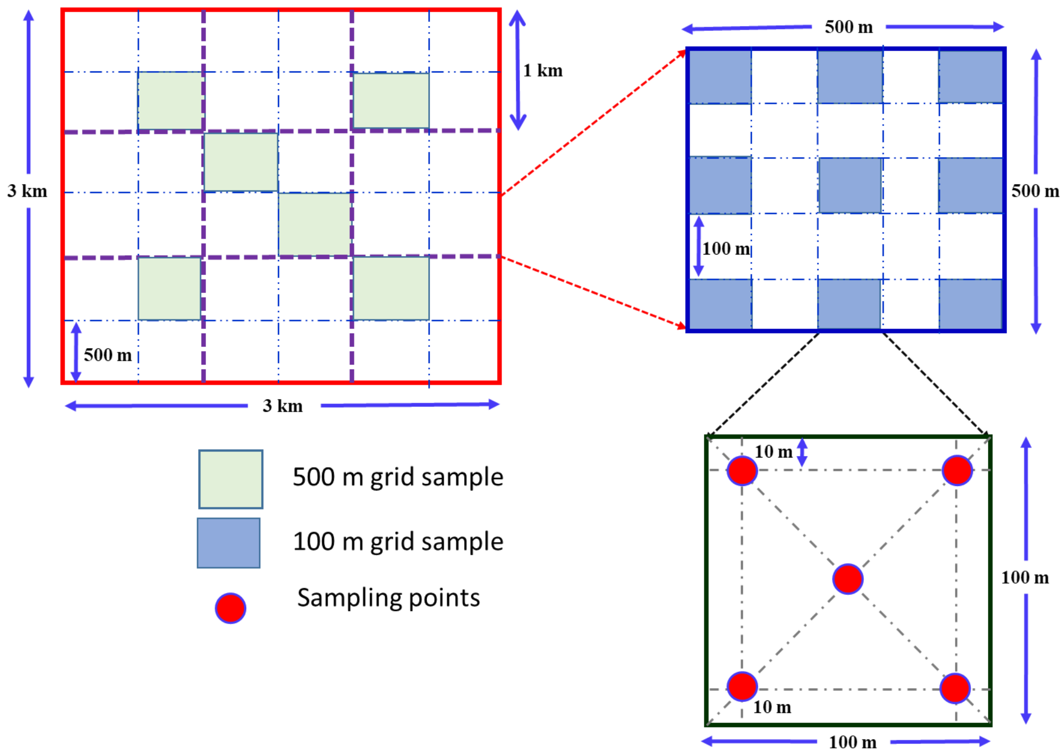


Figure 4: Multiscale Field Sampling Plan based on Grid Sampling Methods for Core Soil Moisture Sites

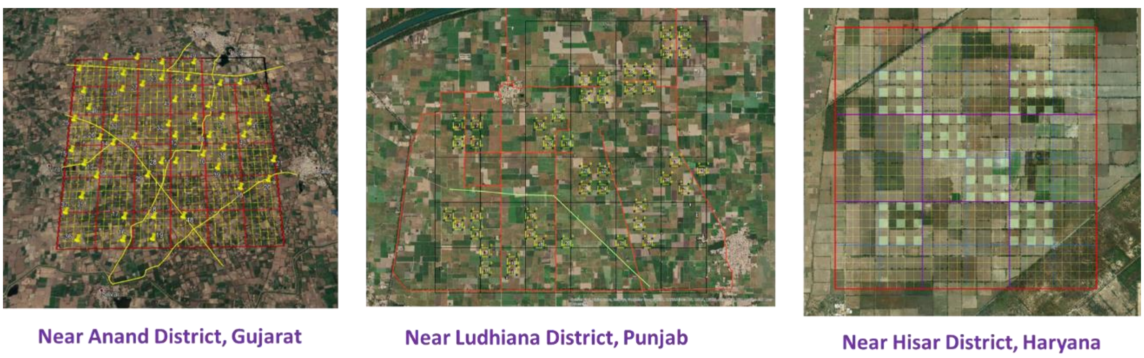


Figure 5: Core SM cal/val sites over Anand (Gujarat), Ludhiana (Punjab) and Hisar district (Haryana)

**In-situ measurements:**

Figure 6: *(Top)* Field data collection using core sampler in agricultural fields *(Bottom)* Sample analysis at soil laboratory at HARSAC, Hisar (Haryana).

For in-situ field measurements, gravimetric sampling methods was adopted as direct method which is very accurate and considered as "Reference" for performance evaluation of satellite soil moisture. In gravimetric method, soil samples are collected from fields using core sampler and are oven dried at 125°C for over 24-48 hours (depending on soil texture) in laboratory as shown figure 6. Bulk density for each sampling point are derived from known volume sample ring and dry soil. However, gravimetric method is very time consuming and labour intensive method in case of covering large area mapping within the satellite pass over respected sites. In order to optimize the field data collection, soil moisture probes are used to measure field soil moisture indirectly to cover large areas as shown in figure 7. Before using commercial/research grade soil moisture probes for field data collections, it has to be calibrated using gravimetric methods as reference to ensure the required accuracy level [8].


Figure 7: Soil moisture probes for field measurements

**Results & Discussion:**

Total 422 (*500m spatial grid cells) samples* over all five sites shown in Fig. 3 were utilized to assess the performance of High Resolution Surface Soil Moisture (EOS04-SMAP) product. All the ground-based Volumetric Soil Moisture (VSM) measurements within the corresponding grids are (arithmetically) averaged to upscale them to 500m spatial resolution. The selected 422 grids are spatially distributed and have a variety of soil texture, crop conditions and topographic conditions. High Resolution Surface Soil Moisture (EOS04-SMAP) product is only available every 17 days over sites and its temporal overlap with ground-based VSM measurements over the study site is very sparse. Therefore, we adopted a simple approach to validate above product on daily basis over multiple sites. In this approach, a standard performance metrics is estimated on each date using spatially well-distributed satellite soil moisture retrievals and corresponding aggregated (averaged) up-scaled VSM within 500m pixel (in case of multiple points lying in same pixels) for each sites. However, there might be biases in the 500m grids to be similar due to spatial autocorrelation. With this assumption, we have total 37 days (considering all five sites) available for comparing the EOS04-SMAP soil moisture data against the up-scaled in-situ VSM. Scene wise retrieved volumetric surface soil moisture maps are shown over all five sites from figure 9 to figure 14. These maps shows the temporal dynamics of surface soil moisture at high resolution, varying from dry to wet spell. We have also processed three full cycles of EOS-04 datasets (>1000 scenes) to generate all India soil moisture maps as shown in figure 15. Bias, root mean square error (RMSE) and unbiased root mean square error (ubRMSE) were chosen as the standard performance metrics for validation activities. The standard performance statistics for soil moisture validation are presented in Table-4.

**Table-4**

**Performance assessment of the *EOS04-SMAP Soil Moisture Product* With Ground-Based VSM Measurements**

| Sites | Bias ($m^3/m^3$) | RMSE ($m^3/m^3$) | ubRMSE ($m^3/m^3$) | N (Avg. 500m pixels) | Total point Samples | Dates |
|---|---|---|---|---|---|---|
| **Ludhiana (DVS*)** | 0.03 | 0.099 | 0.068 | 33 | 264 | 6 |
| **Hisar (DVS*)** | -0.036 | 0.073 | 0.051 | 85 | 202 | 8 |
| **Anand (DVS*)** | -0.014 | 0.088 | 0.076 | 136 | 1098 | 10 |
| **Berambadi (SVS#)** | -0.145 | 0.168 | 0.076 | 88 | 295 | 7 |
| **Kanpur (SVS#)** | -0.138 | 0.156 | 0.067 | 80 | 101 | 6 |
| **Total** | | | | **422** | **1960** | **37** |

**DVS: Dense validation Site, #SVS: Sparse Validation Site; N is total number of averaged samples at 500m pixels.*

The EOS04-SMAP soil moisture product underestimates the soil moisture with a bias from 0.014 to 0.036 $m^3/m^3$ over Anand and Hisar core cal/val sites and overestimate with bias of 0.03 $m^3/m^3$ over Ludhiana. It also shows high underestimation of the soil moisture with a bias of 0.138 to 0.145 $m^3/m^3$ over Kanpur and Berambadi sparse validation sites. Metric "RMSE" shows the retrieval accuracy estimates of 0.099, 0.073, 0.088, 0.168 and 0.156 $m^3/m^3$ over Ludhiana, Hisar, Anand, Berambadi and Kanpur sites, respectively. The lowest RMSE was observed over Hisar and highest over Berambadi. However, RMSE is highly affected by bias so it may not be the true representative of accuracy level of retrieval. Therefore, ubRMSE have also been computed over all sites, regardless the bias over a particular site. ubRMSE was found within range of 0.051-0.076 $m^3/m^3$ over five sites. Best accuracy (lowest ubRMSE) was observed over Hisar sites and worst accuracy was at Anand and Berambadi sites.

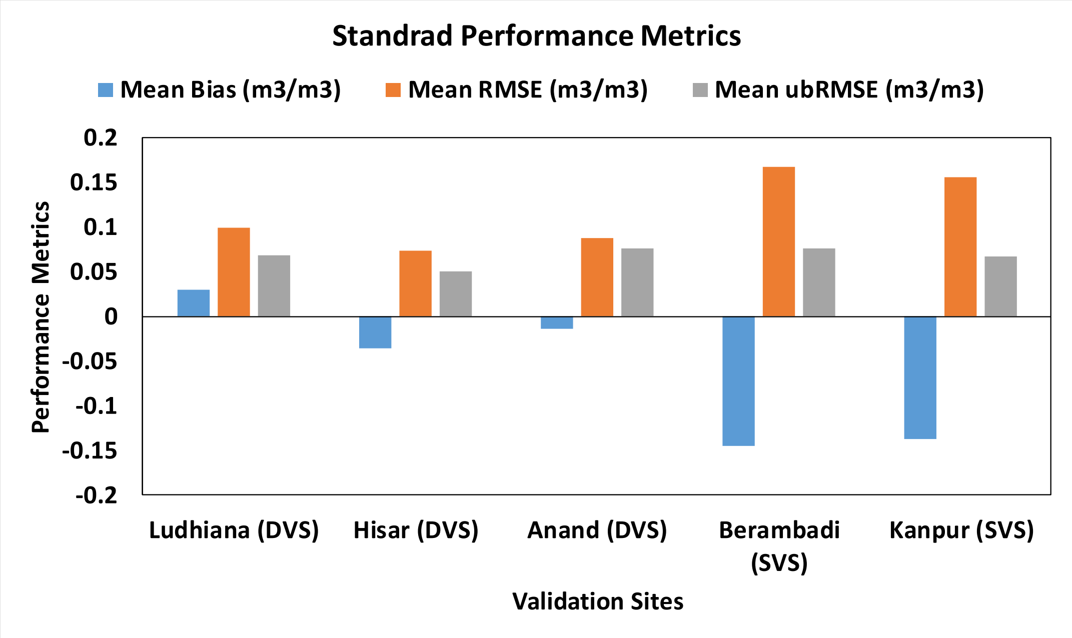


Figure 8: Standard performance metrics (Bias, RMSE & ubRMSE) of Operational High Resolution Surface Soil Moisture (Active/Passive) Data Product over validation sites

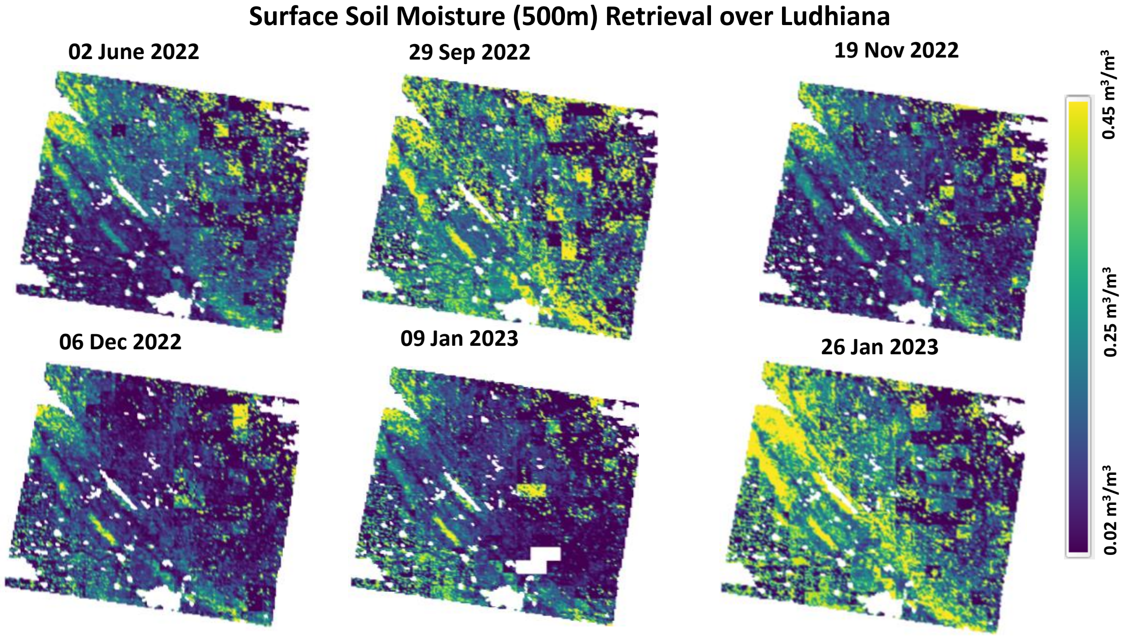


Figure 9: Multi-temporal High Resolution Surface Soil Moisture (SSM) over Ludhiana sites from June 2022 to 26 Jan 2023

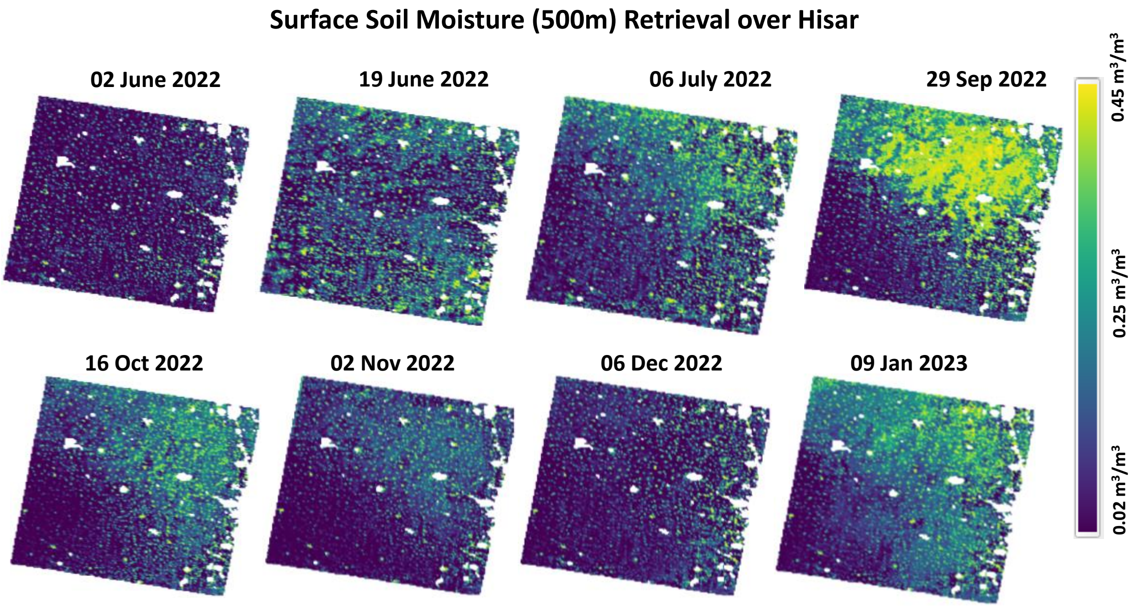


Figure 10: Multi-temporal High Resolution Surface Soil Moisture (SSM) over Hisar sites from June 2022 to 9 Jan 2023

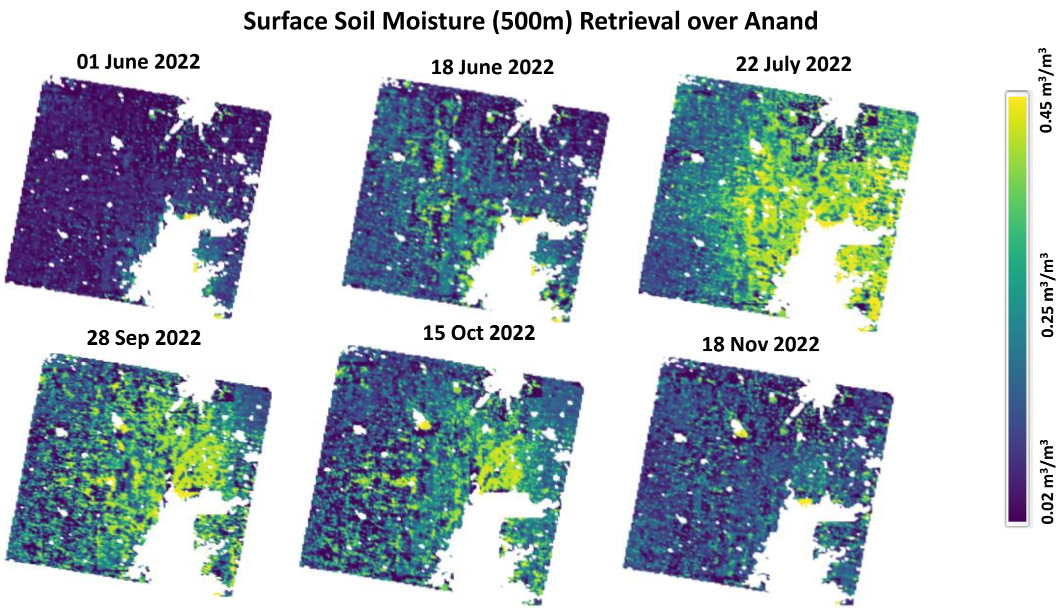


Figure 11: Multi-temporal High Resolution Surface Soil Moisture (SSM) over Anand sites from June 2022 to Nov 2022

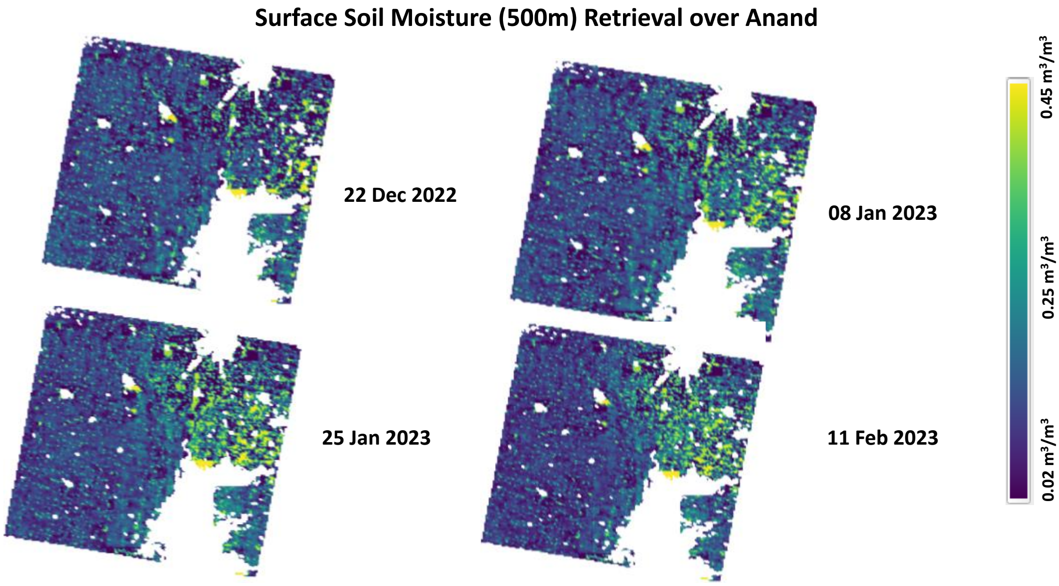


Figure 12: Multi-temporal High Resolution Surface Soil Moisture (SSM) over Anand sites from Dec 2022 to Feb 2023

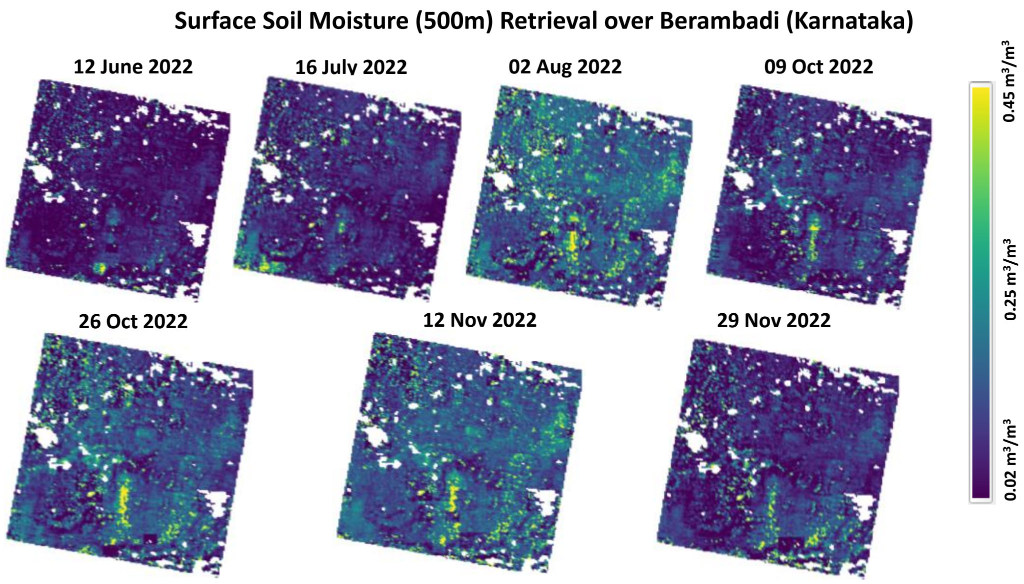


Figure 13: Multi-temporal High Resolution Surface Soil Moisture (SSM) over Berambadi watershed (Karnataka) sites from June 2022 to Nov 2022

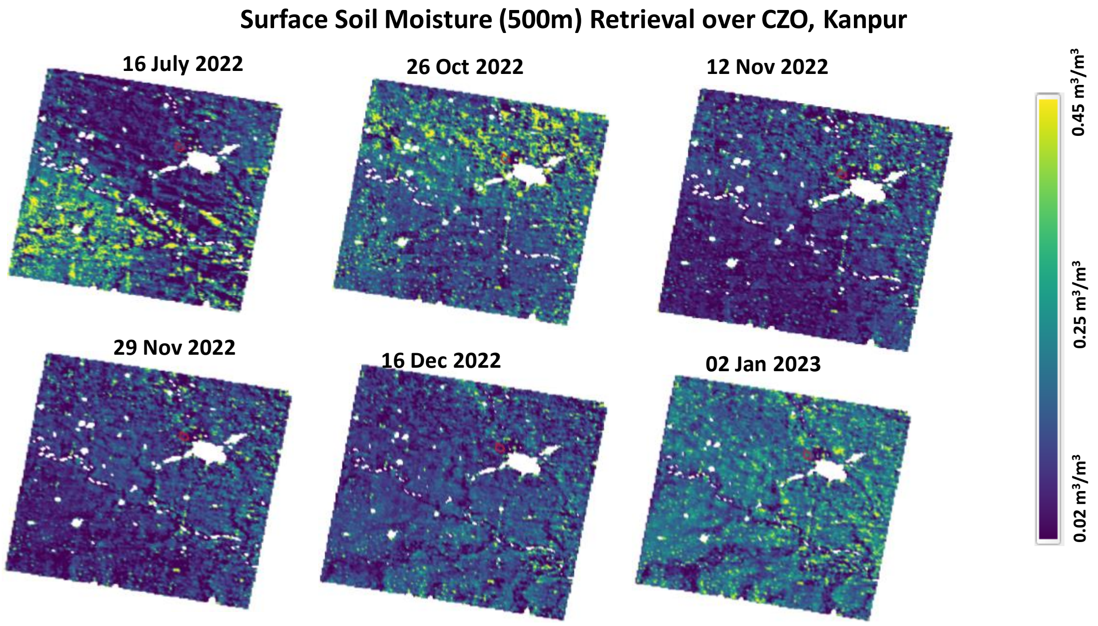


Figure 14: Multi-temporal High Resolution Surface Soil Moisture (SSM) over Critical Zone Observatory, Kanpur (UP) sites from July 2022 to Jan 2023

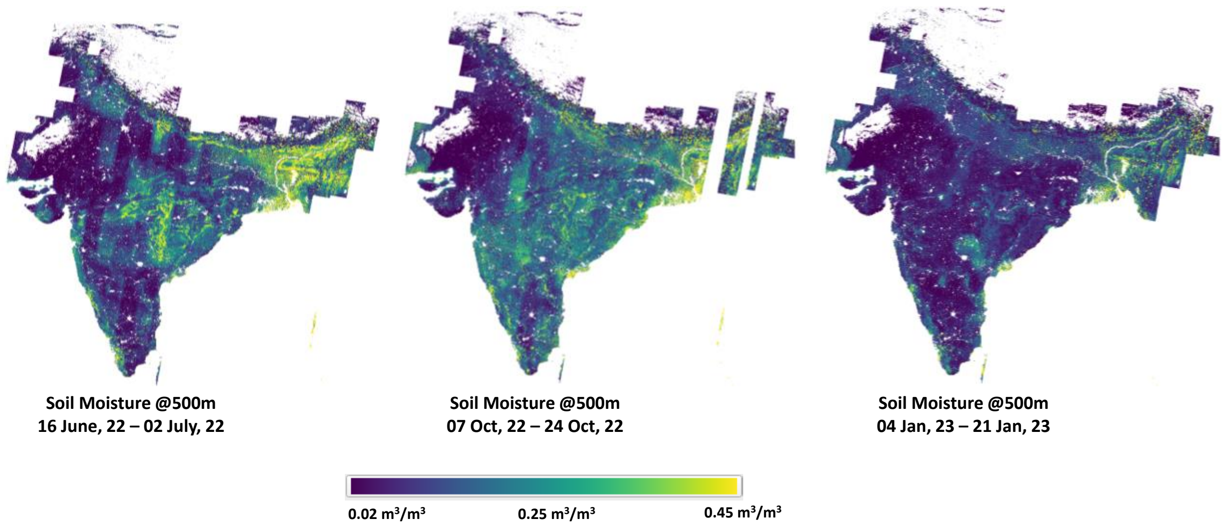


Figure 15: High Resolution Surface Soil Moisture (SSM) over India for three full cycles (EOS04)

**Technical constraints:**

Co-located measurements are ideally *(in-principle)* considered for active-passive approach. However, there might be temporal gaps between EOS-04 SAR and SMAP radiometer observations due to non-overlapping coverage of EOS-04 and SMAP orbit passes. Temporal difference (±24 hrs) between EOS-04 SAR and SMAP radiometer observations might add more errors in soil moisture accuracy due to change in field conditions within that time gaps. It will be more likely to happen during monsoon season

(Kharif) in case of rains between time of passes between EOS-04 SAR and SMAP radiometer which may change soil moisture conditions.

**Conclusion & Future scope:**

In order to meet the agricultural requirements of sub-km resolution soil moisture, a downscaling framework was developed to disaggregate coarse brightness temperature from SMAP radiometer using ISRO's high resolution EOS-04 (RISAT-1A) C-band SAR data and further, to retrieve soil moisture using radiative transfer model (Tau-omega model) as physical approach. Developed method is purely based on Active-Passive approach to combine coarse radiometer & high resolution SAR observation and mainly driven by covariation relation between brightness temperature and SAR backscatter in HH & HV polarization. This covariation depends on the vegetation conditions, land cover heterogeneities, soil texture etc. It also does not need time series of SAR data so snapshot based soil moisture product can be generated using single scene of SAR and coarse scale brightness temperature from radiometer. These attributes make the active-passive soil moisture algorithm operationally very feasible over national scale. The testing and validation using multi-temporal in-situ and SAR datasets demonstrated that the algorithm is capable to meet the agricultural requirements. This sub-km high-resolution (500m) fortnightly EOS-04 soil moisture product will have multiple geophysical applications for societal benefits. The EOS-04 high resolution operational (500 m) soil moisture data will be available to the public and user community through Bhoonidhi portal of National Remote Sensing Centre (NRSC) for science & applications. In order to further improve the soil moisture retrieval accuracy, currently used static and dynamic model parameters will be upgraded and tested over more sites for checking the robustness of developed method. It is further needed to downscale and test the efficacy of developed ***Active-Passive*** approach at finer resolution (~50m to 100m) over various landcovers types.

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