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THE SMOS-HR MISSION: SCIENCE CASE AND PROJECT STATUS

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ABSTRACT

The need of a mission ensuring the continuation of L-band measurements from space with increased spatial resolution with respect to the current generation of sensors is discussed. The status of the SMOS-High Resolution (HR) mission project, currently under a Phase A study at CNES, is presented.

Index Terms— L-Band, Passive Radiometry, Vegetation Optical Depth, Soil Moisture and Ocean Salinity satellite

1. INTRODUCTION

The Soil Moisture and Ocean Salinity (SMOS) satellite [1] has provided systematic passive L-band (1.4 GHz) observations from space since 2009. SMOS data has allowed a large number of science and operational applications, including some well beyond its first objective of mapping soil moisture and ocean salinity. For instance, the optical depth, which is related to vegetation water content, can be used as proxy for above ground biomass allowing to study the evolution of global carbon stocks [2]. L-band brightness temperatures allow to monitor thin sea ice sheets [3] frozen soil [4], snow wetness [5] melting events and internal temperature in Antarctica [6][7]. SMOS data are assimilated operationally by the European Centre for Medium Range Weather Forecasts (ECMWF) [8]. SMOS sea surface salinity measurements allowed to start the European Space Agency (ESA) Climate Change Initiative (CCI) for sea surface

salinity (SSS). SMOS soil moisture time series are included in the ESA soil moisture CCI and could be used to rescale time series from other sensors not originally designed to measure soil moisture [9].

2. THE NEED FOR HIGHER SPATIAL RESOLUTION

The present and future of L-band radiometry has been discussed by Kerr et al. [10] and a large survey of user requirements for the next generation of L-band sensors has also been reported recently [11]. A revisit time of 1-3 days and a sensitivity similar to that of SMOS is considered to be enough for most of applications. However, a requirement of higher spatial resolution has been expressed.

The assimilation of SMOS and SMAP SSSs in ocean models improve the accuracy of simulated SSSs by 7 to 12% and improving the spatial resolution down to the order of 10 km would represent an even more significant breakthrough [12]. Actually, 10 km observations are expected to capture 95% of the SSS spatial variance [13].

SMOS and SMAP have been used to assess ocean circulation and salt transport in the ocean by eddies [14], which is a process that needs to be taken into account to link salinity and freshwater fluxes, to better characterize water exchanges between upper and deep ocean and, between coastal and open ocean regions. Improved spatial resolution is needed to

characterize the mesoscale and sub-mesoscale variability and to extend these capabilities to the high latitude oceans, where the spatial variability of salinity occurs at smaller scales and where the ice proximity might introduce large contaminations that would be easier to identify with high resolution observations, in particular in the Arctic Ocean [15]. Approaching the ice and land edge to ~ 10 km is necessary for a better monitoring of desalination related to ice melts and river plumes. Freshening by large scale river plumes such as that of the Amazon also requires higher spatial resolution observations in order to understand the small scale features that affect the ocean circulation or the air-sea exchanges, such as the air-sea CO_2 fluxes [16]

A better separation of ice and open water is not only needed to correct SSS measurements. The detection and monitoring of thin (< 1 m) sea ice sheets is an important subject itself [3], as it is not possible using altimeters and the ice extension in the Arctic is directly related to global warming. The study of melting events in Antarctica, mostly close to the coasts, also require higher spatial resolution [6].

L-band observations allow to detect and map soil freezing and thaw. Comparison of different freeze/thaw products clearly show increasing disagreement in areas near abundant surface water, snow and ice, and wetlands, showing the limitations of the spatial resolution used to obtain them [4]

Regarding soil moisture, a roadmap for high resolution SM was discussed by Peng et al. [17], who summarized the soil moisture spatial resolution needs for different applications. A high level of requirements for soil moisture with resolutions of 5-10 km is given for numerical weather prediction (NWP) and even for climate modeling. The global numerical weather prediction (NWP) models by ECMWF show a positive impact of the assimilation of SMOS surface soil moisture in near-surface atmospheric variables in the Northern Hemisphere [8]. ECMWF models are currently running at 9 km resolution. Higher resolution than that of the current generation of L-band sensors will be needed to keep a significant impact of soil moisture assimilation for the next generation of global NWP models.

A high level of requirements for 5-10 km resolution is also quoted for watershed-based hydrology, precipitation and evapotranspiration estimation and drought monitoring, while landslide prediction, flood forecasting, precision agriculture and erosion modelling require even higher resolutions (< 1 km) [17].

Of course, downscaling approaches by merging data with different resolutions remain possible. However, it has been shown in the context of soil moisture downscaling, that the quality of the final downscaled dataset is directly related to the initial spatial resolution [18]. It has also been shown that the performances of the SMAP+Sentinel-1 high resolution (1 km) SM with respect to in situ measurements, improve when the high resolution disaggregated data is aggregated back to coarse resolution [19]. In other words, even if downscaling remains a useful approach, when the final goal for some applications is to have soil moisture data at less than 1 km resolution with a good accuracy, it is definitely needed to start with 10 km rather than 40 km as SMAP or SMOS or 60 km in case of smaller antennas than the current generation of L-band radiometers. Due to the relatively low signal-to-noise ratio, oversampling strategies with low resolution scanning instruments will never replace a high native spatial resolution.

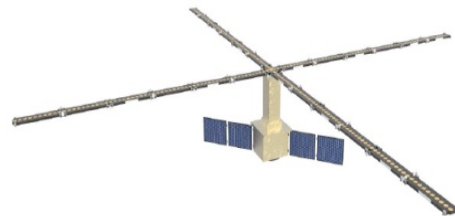


Figure 1. Sketch of the SMOS-HR satellite

3. PROJECT STATUS

Taking into account the requirements discussed in Section 2 different technical solutions were studied [11] and the SMOS-HR concept was proposed with the goal of obtaining a spatial resolution of ~ 10 km [18]. This requires a typical antenna size of 18 m. Taking into account the difficulty of deploying a real aperture of this size, SMOS-HR will be composed by an array of small elementary antennas. During the Phase 0 study at the French Centre National d'Etudes Spatiales (CNES) several array geometries were studied with hexagonal and cartesian patterns [20]. The cartesian layouts (a four-arms cross or a square) were preferred because the fourth arm is, in principle, redundant. Taking this into account, the antennas in one arm can be displaced in a quincunx way allowing to densify the sampling of the spatial frequencies plane and to reduce the aliasing of reconstructed images [21]. A further step in this direction was done and irregular antenna distributions were also studied [22]. In spite

of an overall irregular distribution, it is possible to ensure that there is a minimum redundancy in the sampled spatial frequencies so that the array can be calibrated. However, irregular distributions are considered too complex to implement in an actual instrument and the quincunx antenna positioning in one arm is the preferred configuration for SMOS-HR. Regarding the two Cartesian antenna array layouts, the four-arms cross (Figure 1) was preferred due to a reduced risk during the deployment phase.

The Phase A study started in 2021 at CNES in the context of the concept proposed at the end of the Phase 0. The mission objective is to increase the spatial resolution at least by a factor of two with respect to SMOS (< 15km at Nadir) while keeping or improving its radiometric sensitivity (~0.5-1 K) and with a revisit time no longer than 3 days.

The current design of SMOS-HR is an antenna array with a four-arms cross layout (Fig. 1). A central hub, located on the platform, will carry a dozen of antennas and the four deployable arms will carry 40 antennas each for a total number of 171 elementary antennas. The typical antenna spacing d is $\sim 0.95 \lambda$, where λ is the wavelength (21 cm) but the spatial frequencies will be sampled at $d/\sqrt{2} \lambda$, reducing the aliasing of reconstructed images [21]. The total length of the arms from the phase centre to the tip is 8.2 meters. However, even if there are baselines of up to 16 meters, the spatial frequencies plane is only densely sampled up to $8.2\sqrt{2} = 11.6$ meters. The spatial resolution at Nadir over the Earth Surface can be approximated as $H * \tan(1.2 \frac{\lambda}{D})$ where H is the orbit height and D the equivalent size of the synthesized antenna. Therefore, with $D = 11.6$ meters and an orbit height of 679 km, the spatial resolution at Nadir is approximately 15 km.

In contrast to a real aperture, for which the photon collecting area increases as the square of the antenna size, in the case of an interferometer, the actual collecting area increases only linearly with the size. In other words, with all other parameters constant, when the antenna array size increases, the sensitivity decreases by approximately the same factor. However, the sensitivity of SMOS-HR will be better than that of SMOS thanks to a number of improvements such as the multi-bit digitization of the signal and the simultaneous acquisition of two orthogonal polarizations, which avoid dividing the integration time to obtain full polarimetric measurements as in the case of SMOS. In addition, taking into account that the same point in the surface is observed by

different consecutive snapshots, the sensitivity for geophysical applications will be under 1 K.

The SMOS-HR hub contains the correlator combining signals for all antenna pairs and generating a common clock signal for instrument synchronization. SMOS-HR will have advanced on-board RFI filtering capabilities thanks to correlation in sub-bands.

In the current concept, the antenna array will be operated as an aperture synthesis interferometer. However, alternative approaches such as operating the array using Digital Beam Forming are also being explored [23]. Regarding the ground segment, alternative approaches with respect to the snapshot-based algebraic inversion are being studied. This includes, image reconstruction using deep learning approaches [24] and simultaneous multi-snapshot image reconstruction approaches [25].

Finally, an hybrid connected/unconnected interferometer was also studied. It consists in a central carrier similar to the SMOS-HR discussed above surrounded by several tens of nano-satellites providing baselines of up to 40 meters to reach a resolution of ~ 4 km [26]. However, this concept, known as SMOS-Next, would require to launch first a demonstrator of unconnected interferometry in space.

4. SUMMARY

After the success of the SMOS and SMAP missions, which served as pathfinders to investigate many new applications of passive L-band observations, it becomes clear that the spatial resolution of the next generation of L-band sensors should have an increased resolution with respect to the current generation. This is the goal of the SMOS-HR mission, ensuring the continuity of L-band observations from space with a spatial resolution at least a factor of two better than that of SMOS or SMAP.

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