# SMOS INSTRUMENT PERFORMANCE AFTER MORE THAN 11 YEARS IN ORBIT

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## ABSTRACT

ESA's Soil Moisture and Ocean Salinity (SMOS) mission [1] has been in orbit for over 11 years, and its Microwave Imaging Radiometer with Aperture Synthesis (MIRAS) in two dimensions keeps being fully operational. This 11-year long lifetime of SMOS, so far, has enabled the calibration and Level-1 processor team to improve the calibration procedures and the image reconstruction resulting in a new version of the Level-1 data processor, v724. To present the main performance features of this new version and the improvement in the calibration procedures constitute the main objective and content of this presentation.

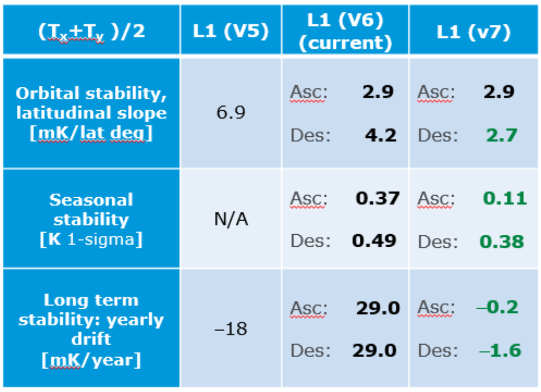
***Index Terms*—** SMOS, aperture synthesis, radiometry

## 1. INTRODUCTION

ESA's Soil Moisture and Ocean Salinity (SMOS) mission was launched 2 November 2009 and has been producing since high-quality soil moisture and ocean salinity global maps with an average resolution of 40 km, its original mission objective having been fulfilled [2]. The Centre d'Etudes Spatiales de la Biosphère (CESBIO), L'Institut Français de Recherche pour l'Exploitation de la Mer (IFREMER) and the Barcelona Expert Centre (BEC) are the main institutes responsible of the scientific outcome of SMOS.

Beyond its starting goal, different scientific groups were able to culminate their research providing new products from SMOS. Some examples: the Finnish Meteorological Institute (FMI) generates global maps of permafrost; IFREMER has been able to measure high winds in hurricanes/typhoons and offers global maps of wind over ocean; and the Alfred Wegener Institut (AWI) estimates thin sea ice thickness from SMOS extending the range of ESA's CryoSat mission into improved sea ice maps. Furthermore other investigations about additional geophysical retrievals are on-going, like that by the Universitat Politècnica de Catalunya (UPC) which is obtaining promising results in their measurement of the Total Electron Content (TEC) of the ionosphere.

*Table I – Key stability performance figures for the Level-1 processor versions v505, v620 and v724 (green bold means improvement in v724 over previous versions)*



| $(T_x+T_y)/2$ | L1 (V5) | L1 (V6) (current) | L1 (v7) |
|---|---|---|---|
| **Orbital stability, latitudinal slope [mK/lat deg]** | 6.9 | Asc: **2.9**<br>Des: **4.2** | Asc: **2.9**<br>Des: **2.7** |
| **Seasonal stability [K 1-sigma]** | N/A | Asc: **0.37**<br>Des: **0.49** | Asc: **0.11**<br>Des: **0.38** |
| **Long term stability: yearly drift [mK/year]** | −18 | Asc: **29.0**<br>Des: **29.0** | Asc: **−0.2**<br>Des: **−1.6** |

As unexpected as significant is the obtained L-band radiation map of the Sky, a unique observation for its uniformity, accuracy and precision, impossible to reach from ground. The icing on the cake comes with the efforts to estimate the L-band brightness temperature of the Sun, which correlates well with, even surpasses, the necessarily discontinuous ground based measurements.

All this wealth of scientific outcome from SMOS has been possible thanks to its long life. That is the greatest value of the mission. Over 11 years in orbit have allowed the SMOS data processing teams, both at engineering as well as at scientific level, understanding the fluctuations of the signals, the anomalies and drifts, sometimes small, even very tiny, otherwise large, like those caused by Radio-Frequency Interference (RFI). Still today are we finding ways of improving the calibration and the retrieving techniques.

This paper presents the reader with an overview of the part corresponding to the brightness temperature measurements and their calibration.

## 2. OVERVIEW OF THE LEVEL-1 PROCESSOR

After introducing some modifications with the learnings from the first 6 months of the Commissioning Phase of the mission, SMOS first Level-1 data processor version, v340, entered into operation in June 2010. By the time the data record reached its first two years, better corrections had been found and some new calibration steps were added. A new v505 version was deployed in March 2012 and the first mission data reprocessing took place. It was necessary three more years to correct the smaller spatial and temporal (orbital, seasonal and yearly) deviations and come with version v620, which started to run in April 2015, following a second mission data reprocessing. V620 is still in operation by the time of this writing, but for little longer as it will soon be replaced by the new v724.

The main focus in the development of v724 was the improvement of the orbital, seasonal and yearly stabilities. To make that happen, large data sets had to be processed and results verified and compared among the different options. This exercise was first done at Level-1 by using brightness temperature ocean models (of limited accuracy) as well as by checking spatial consistency over incidence angle and correlating temporal anomalies with those observed by a ground radiometer at Dome-C in Antarctica. The second step of the exercise consisted in assessing the impact and performance of the new Level-1 processor in the soil moisture and ocean salinity retrievals. As it can be understood, the process was not fully sequential, but with several iterations and interactions, within each level and across levels. The length and depth of such assessment, together with the smaller amplitude of the corrections involved, by comparison with previous processor versions, explain the much longer time that was required to give birth to v724. This version is expected to be operational by May 2021, when the third mission reprocessing has ended.

In parallel to the assessment of v724, other three versions of the Level-1 processor have been completed: v730, v740 and v750, the latter being selected as the next operational processor after v724. The main purpose across these three versions has been the filtering of RFI, the improvement of the Sun correction and the estimation of the Sun brightness temperature. If the performance assessment of v750 goes smoothly it could be in the operational chain around the middle of next year 2022.

## 3. PERFORMANCE RESULTS AT LEVEL-1

A summary of the Level-1 v724 key stability performance parameters is shown in Table I against those of the previous two versions. Improved figures are bolded in green. Clearly v724 has improved stability at all temporal scales. The sections below detail other performance parameters of v724 as well as a brief introduction to the higher processor versions up to v750. The results and improvements that v724 has brought to those will be presented at the conference.

### 3.1 Spatial Ripple

SMOS images present some systematic spatial ripple determined by a combination of a number of factors. In v724 the ripple (evaluate across the entire field of view) has been slightly reduced with respect to v620, from 1.6 to 1.5 K in X-polarization and from 2.0 to 1.7 K in Y-polarization.

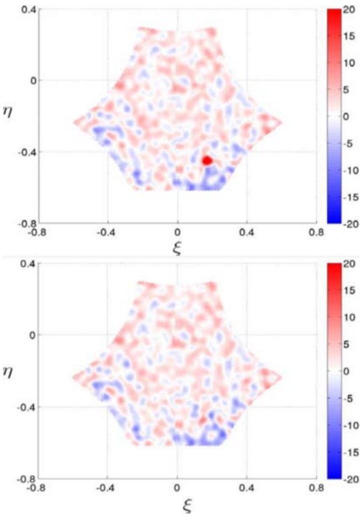


*Figure 1 – V724 Sun Correction when in the back hemisphere*

## 3.2 Signature over Incidence Angle

SMOS field of view is about 65° wide meaning that every pixel is seen over a number of snapshots through a range of incidence angles. The number of snapshots and the range of incidence angles reduces, in general, the further the pixel is from the satellite track. To make the evaluation of the performance of the Level-1 processor as independent as possible from any model, observations over a reduced cluster of pixels centred at Dome-C in Antarctica are collected for the whole range of incidence angles between 0° (nadir) and 60°. The root mean square (rms) of the deviations of the measurements from a polynomial fit at each polarization is taken as one of the performance figure. In the whole field of view it has been reduced by about 0.1 and 0.2 K for X and Y-pol respectively. Another important value is the brightness temperature difference at nadir (which should be ideally 0 K). V724 has reduced it from 1.1 K (in v620) down to 0.2 K.

## 3.3 Sun Correction

SMOS is sensitive to any source of L-band radiation that is in the front hemi-sphere, like the Sun. In fact, the Sun is so bright that even when it is behind MIRAS (the SMOS payload) its footprint can be detected. As SMOS is in a sun-synchronous orbit, the Sun revolves around the orbit normal once per orbital revolution an angle that depends on the day of the year. Half of the orbit the Sun is in front of MIRAS, half of the orbit behind. Correcting for the side lobes of the Sun response is important because they can contaminate the pixels of the image located along the lines joining the real Sun image with its six aliases. The Sun correction has much improved in v724 in both cases, when in the front as well as when in the back. For illustration, Fig. 1 shows the correction of the Sun in a snapshot when it is in the back hemisphere.

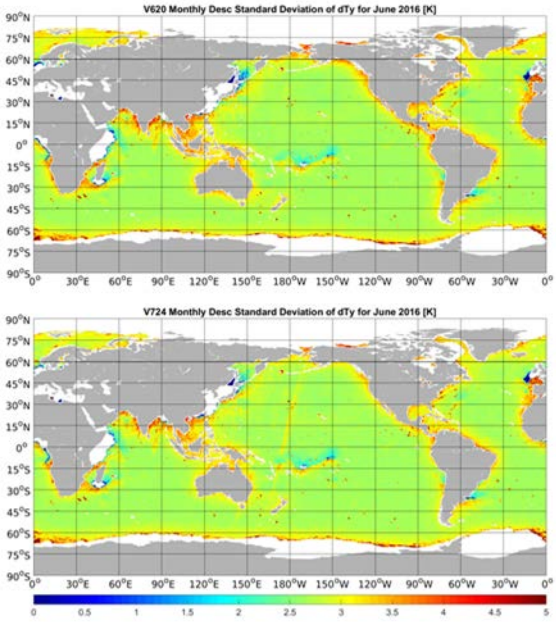


*Figure 2 – Land-Sea Contamination (Dec. monthly rms in Y-pol) comparison between v620 (top) and v724 (bottom)*

## 3.4 Land-Sea Contamination

Land-sea contamination refers to an excess of brightness temperature measured around continental masses. An important contributor to this signal is any existing unbalance between the amplitude calibration factor applied to the visibility sample at the origin V(0,0) and that factor applied to the rest of the samples of the visibility function. Another reason is the spread of the energy in the alias regions into the alias-free field of view due to antenna pattern uncertainties. The magnitude and extent of the land-sea contamination has changed in v724 with respect to v620, depending on polarization: X-pol shows a slight degradation whereas Y-pol and Stokes-4 have improved, Stokes-3 changing its spatial pattern distribution. The major improvement brought by v724 is that the variation of the value the land-sea contamination for a given pixel is more stable across passes. The reduction in the monthly rms value is of about 1 K, as shown in Fig. 2.

## 3.5 Latitudinal, Orbital, Seasonal and Yearly Stability

The objective of v724 of improving the spatial and temporal stability of the brightness temperatures has been overall fulfilled. The latitudinal drift (slope of the deviations from an

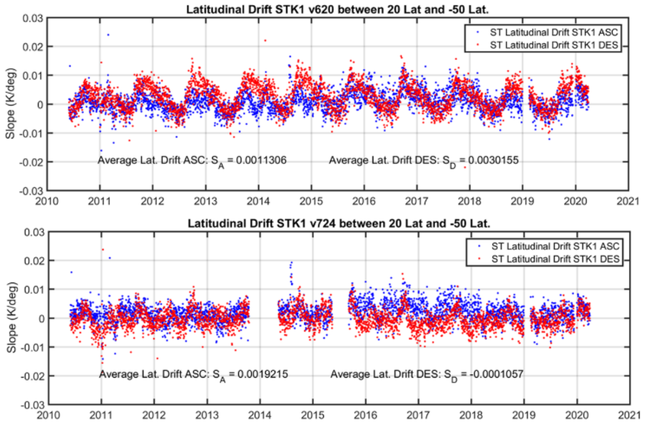


*Figure 3 – Latitudinal Drift (Stokes-1): v620 (top), v724 (bottom)*

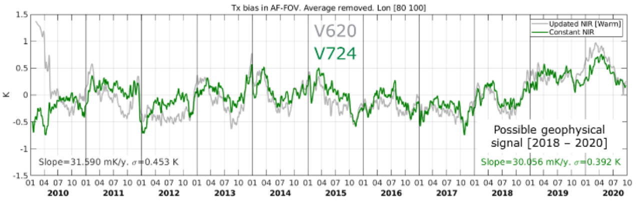


*Figure 4 – Y-pol Brightness Temperature over Antarctica*

ocean model that are correlated with latitude) has been reduced by about 50% as illustrated in Fig. 3.

Similarly, the orbital, seasonal and yearly stability has been much improved with v724. This major improvement in stability has enabled scientists to relate trends observed over the Pacific Ocean with geophysical changes compatible with climate change. Similarly, the trend observed since 2018 over Antarctica has captured the attention of the cryosphere community. This is shown in Fig. 4 where a positive trend is clearly visible in the brightness temperature after 2018.

### 3.6 Processor Versions beyond v724: v730, v740 and v750

In parallel to the evaluation of the performance of v724 the work has continued in further versions of the Level-1 processor, ending in what will be the operational processor after v724, the v750. The main focus has been the filtering of RFI sources. Version v750 is expected to provide scientist with a significant improvement in areas polluted by interference. An example of v750 RFI filtering capability is presented in Fig. 5. The other major feature of this version is the provision of the L-band brightness temperature of the Sun of interest to the radio-astronomy community [3].

## 4. CALIBRATION METHODS

The calibration plan remains essentially the same as the original one [4], except for the addition of weekly calibrations

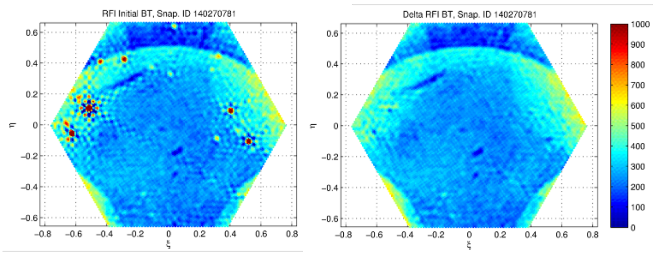


*Figure 5 – V750 RFI Filtering: before (left), after (right)*

of the receiver detection circuits to track their small offset variations, and several algorithm improvements.

However the different thermal environment seen by the antennas during the bi-weekly Cold Sky calibrations by comparison to that during the nominal pointing to ground, hampers the accurate estimation of the critical antenna losses. In order to alleviate this problem, the so-called Warm Calibrations were introduced in October 2014 and two Hot Calibrations were performed in 2020. The main idea behind those calibrations is to command the usual Cold Sky manoeuver at the right time to have the Sun shining over the array to keep the physical temperature of the antennas similar to when they are pointing towards the Earth. It is expected that the use of the Hot calibration might enhance the understanding of the antenna losses over physical temperature in Level-1 versions higher than v750.

## 5. CONCLUSIONS

This paper will present the most recent status of SMOS instrument performance and calibration after over 11 years in orbit.

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