THE SOIL MOISTURE AND OCEAN SALINITY (SMOS) MISSION: FIRST RESULTS AND ACHIEVEMENTS

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Résumé

La mission SMOS (Soil moisture and Ocean Salinity) a été lancée avec succès le 2 novembre 2009. Cette mission menée par l'ESA (Agence Spatiale Europénne) est dédiée à la mesure de l'humidité superficielle des sols sur les continents (avec une précision recherchée de 0,04 m^3/m^3) et la salinité des océans (objectif 0.1 psu). Ces deux quantités géophysiques sont très importantes car elle contrôle le budget énergétique à l'interface sol-atmosphère. Leur connaissance à l'échelle globale est utile pour les recherches sur le climat et la météorologie, en particulier pour les modèles de prévision numérique. Elles ont aussi un très grand potentiel un très grand nombre d'application, comme par exemple pour le suivi des ouragans ou la gestion des ressources en eau.
Les six premiers mois ont été dédiés à la recette en vol qui a permis de vérifier le satellite le segment sol et l'étalonnage. Cette phase s'est achevée avec succès en mai 2010 et SMOS fonctionne de façon opérationnelle depuis, fournissant de données à la communauté internationale. Les performances de l'instrument sont globalement conformes aux spécifications. Cependant, les interférences radio sont présentes au-dessus de l'Europe, du Moyen-Orient et de l'Asie. Ces émissions parasites dans la bande protégée perturbent la mesure de façon significative. La génération des produits de niveau 2 et 3 est une activité en cours avec des améliorations régulières de sorties.

Mots clés : SMOS, humidité des sols, salinité des océans, interférométrie et radiométrie en bande L.

Abstract

The SMOS (Soil Moisture and Ocean Salinity) satellite was successfully launched in November 2009. This ESA led mission for Earth Observation is dedicated to providing soil moisture over continental surface (with an accuracy goal of 0.04 m^3/m^3) and ocean salinity (with a goal of 0.1 psu). These two geophysical features are important as they control the energy balance between the surface and the atmosphere. Their knowledge is of interest at global scales for climatic and weather research in particular for improving model forecasts. But it also has impact on various domains, ranging from hurricane monitoring to water resource management.
The first six months after the launch, the so called commissioning phase, was dedicated to testing the functionalities of the spacecraft, the instrument and the ground segment including data processing. This phase was successfully completed in May 2010, and SMOS has since been in the routine operation phase, providing data products for the scientific community for over two years. The instrument performance and data quality fit the specifications. However, radio frequency interferences have been detected over large parts of Europe, China, Southern Asia, and the Middle East. The generation of Level 2 soil moisture and ocean salinity data is an on-going activity with continuously improved processings.

Keywords : *SMOS, soil moisture, ocean salinity, L-band, radiometry.*

1. Introduction

SMOS is an ESA (European Space Agency) led Earth Explorer mission, which was developed in collaboration with the French Space Agency, the Centre National d'Etudes Spatiales (CNES), and the Spanish Centro para el Desarrollo Tecnológico Industrial (CDTI). This collaborative approach is continuing in the operations phase: ESA is responsible for overall mission operations, instrument and ground segment operations whereas CNES is responsible for the satellite operations. The Soil Moisture and Ocean Salinity (SMOS) mission was launched on 2 November 2009 from the Plesetsk Cosmodrome (Russia). The SMOS mission objectives are (Kerr et al., 2001):

1. To provide global volumetric soil moisture estimates with an accuracy of 0.04 m^3/m^3 at a spatial resolution of 35-50 km and a temporal sampling of 1-3 days;
2. To provide global ocean salinity estimates with an accuracy of 0.1 practical salinity scale units for a 10-30 day average for an open ocean area of 200 x 200 km^2
3. To provide useful data for research in cryospheric studies.

The first two variables are two key elements describing the Earth's water cycle and have been identified as Essential Climate Variables (ECVs) by the Global Climate Observing System (GCOS) in 2006. Uncertainties in the description of the spatial and temporal dynamics in both parameters limit the predictive skill of hydrological, oceanographic and atmospheric models (Ferranti and Viterbo, 2006). SMOS observations are also starting to provide valuable information on the characterisation of sea ice and snow covered surfaces and enhance our understanding of the exchange processes between the surface and the atmosphere. A general overview of the SMOS mission can be found in (Kerr et al., 2010).
The payload of SMOS consists of a passive microwave 2 - D interferometric radiometer (Silvestrin et al., 2001), operating in L-band (1.413 GHz, 21 cm), within the protected 1,400-1,427 MHz band. SMOS measures the brightness temperature emitted from the Earth at L-band over a range of incidence angles (0 to 65^o) across a swath of approximately 1,000 km with a spatial resolution of 35 to 60 km. SMOS provides measurements in full polarization.
The choice of using L-Band as the spectral range was determined by the high sensitivity to changes of moisture in the soil (Schmugge et al., 1974), and salinity in the ocean (Thomann, 1976). Furthermore, observations at L-Band are less susceptible to attenuation due to the atmosphere or the vegetation than measurements at higher frequencies (Kerr and Njoku, 1990). It also enables a larger penetration depth into the surface soil layer than at shorter wavelengths.

The nominal life of SMOS is expected to be five years. The SMOS mission is based on a sun-synchronous orbit (dusk-dawn 6am/6pm) with a mean altitude of 758 km and an inclination of 98.44^o. SMOS has a 149-day repeat cycle with a 3-day sub-cycle. The SMOS instrument was built by a consortium of over 20 European companies led by EADS-CASA Espacio, Spain, and is mounted on a generic PROTEUS platform developed by the French space agency CNES and Alcatel (France). The sensor is shown in Figure 1.

2. Main results

SMOS is a new concept (L band passive interferometer) which has never previously been used for observing the earth. It is also the first mission dedicated to measuring surface soil moisture and ocean salinity almost directly. These two novelties brought forward two significant challenges. First the instrument was new and required development of new signal processing techniques. Secondly, the measurements were new with no existing knowledge or data records to be used when establishing retrieval algorithms. In spite of these two main challenges, the first acquisitions showed that the actual challenge had not been anticipated. This was the presence of a very large number of strong interferences sources known as RFI (radio frequency interferences) as shown in Figure 2. These illegal emitters drown the useful signal making the measurements useless or erroneous. Very quickly, ESA set up relationships with National entities (mainly in Europe and USA/ Canada) to tackle the issue and over 100 sources were successfully corrected in Europe. However, the Middle East and Asia remain an issue. The SMOS team has also developed techniques to detect and flag the sources, reducing the risks of erroneous retrievals (Oliva et al., 2012).

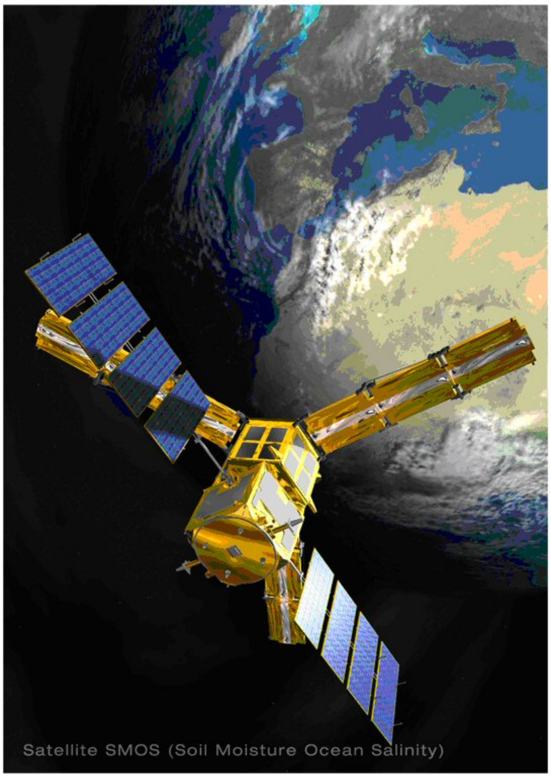

Figure 1 : Artist's view of SMOS.

2.1. Sea surface salinity

Salinity is known to play an important role in the dynamics of the thermohaline overturning circulation, ENSO (El Niño-Southern Oscillation), and is the key

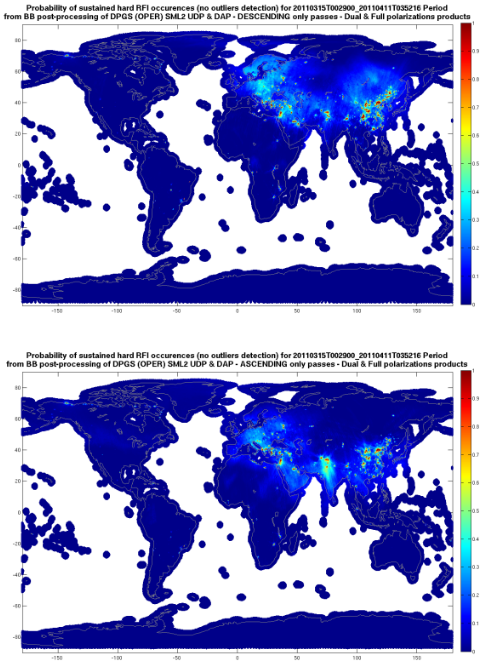

Figure 2 : Interferences over the globe as detected by SMOS. The data is represented as the probability of interferences over one month, for descending and ascending passes (above and below, respectively) (Richaume et al., 2005).

tracer for the marine branch of the global hydrologic cycle, which comprises most of the global precipitation and evaporation. Multi-decadal Sea Surface Salinity (SSS) trends have been documented in tropical and northern latitudes that are likely signatures of evaporation or precipitation trends, as predicted under global warming scenarios. Our basic knowledge of the global SSS distribution is derived from the compilations of all the available oceanographic data collected over time. The SSS in situ observing system has expanded significantly during the last decade, in particular with the full deployment of the Argo array, providing an average of one sample every 300-400 km square every ten days. Notwithstanding these gains of the past decade, the in situ sample density remains sparse to resolve climatologically important seasonal to inter-annual signals on the spatial scales over which SSS is known to vary significantly (∼100 km). Since the 1970s, satellite oceanography has made tremendous progress, and today satellite observations over the ocean are key components of global climate observing systems. While sea surface temperature, sea level, sea ice, ocean colour properties and sea state are routinely monitored using satellite data, SSS observations from space were not available until the launches of SMOS and NASA/Aquarius missions (10 June 2011). Salinity remote sensing is based on the microwave emission properties of the sea surface. At a given radio frequency, the latter depends partly on the dielectric constant of sea water, which in turn is partly related to salinity and temperature. The strength of the emission (called total power) can be measured remotely with a microwave radiometer and given coincident sea surface temperature measurements, so SSS can be retrieved in theory. It is more complicated in practice, however, as several external factors affect the brightness temperature seen by the radiometer and must be corrected (radiation from extra-terrestrial sources, atmosphere, ionosphere and surface roughness). SMOS operates at L-band (frequency of ∼1.4 GHz, wavelength ∼21 cm), within the protected 1400-1427 MHz band (Boutin et al., 2012). The choice for this frequency was determined to maximize the sensitivity to changes in salinity and to minimize atmospheric contributions to the signal. Based on the known SSS spatio-temporal variability scales, the satellite missions aim at producing global maps of sea surface salinity with an accuracy of 0.1-0.2 over a time scale of one month, and at a spatial resolution of about 100 km. This is a challenging objective for several major reasons.

First, the sensitivity of L-band brightness temperatures to variations in SSS is at best about 1 K per salinity unit. This sensitivity is very weak given that spatial and temporal variability in open-ocean SSS does not exceed several units, and that the instrument noise is typically 2-5 K (Boutin et al., 2012).

Secondly, there are many geophysical sources of brightness at L-band that corrupt the salinity signal, and the scene brightness models used to account for these sources have uncertain accuracy. Moreover, the technical approach developed in order to achieve adequate radiometric accuracy for the SMOS satellite, as well as spatial and temporal resolution compromising between land and ocean science requirements, is polarimetric interferometric radiometry. The interferometric image reconstruction processing is complex, and generates residual biases which affect the accuracy of the retrieved SSS.

Finally, man-made radio frequency interferences (RFI) emanating from the world coasts contaminate the data in many key ocean areas (the North Atlantic, the Bay of Bengal,. . .). Researchers involved in the Centre Aval de Traitement des Données SMOS (CATDS) have nevertheless deciphered the intricacies of this new data set and developed algorithms to generate first-time satellite estimates of sea surface salinity. Two examples of these monthly maps are shown in Figure 3.

The maps show the salient basin scale features, such as the elevated SSS in the Atlantic relative to the other basins, and the general correspondence of lower SSS with climatologically high precipitation or river runoff zones and higher SSS in high evaporation zones. Comparison of the satellite estimates with in situ observations reveal an overall accuracy in the order of 0.3, with a degraded quality at high latitudes partly because of a decreased sensitivity of the measurement in cold seas. While clear progress is still needed to reach the mission requirements, many interesting results have already been revealed.

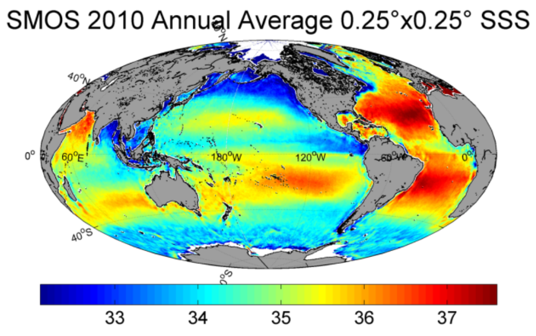

Figure 3 : CATDS composite maps of Sea surface salinity (Reul et al., 2012)

2.2. Soil moisture

Soil moisture is a much easier target at L-band as the amplitude of the signal can reach 100 K for the whole soil moisture range. The problem is nevertheless complicated by the presence of vegetation, of topography, freeze-defreeze cycles, snow cover or water bodies. To cope with these issues, a very specific retrieval algorithm was thus developed (Kerr et al., 2012) and implemented from launch. The algorithm has been undergoing continuous validation using ground sites and subsequent improvements. As already stated, RFI constitutes an issue, so results obtained in Europe and Asia are always difficult to interpret. Sites in the Unites States have proved to be much more useful (Albitar et al., 2012; Jackson et al., 2012). The detailed results are available on IEEE TGRS SMOS Special Issue.

Globally, the retrieval algorithm performs well in terms of coverage with the big caveat of the RFI which affects mainly Europe and Asia. Although this should be qualified since possible errors such as those due to default contributions are not included, the quality of the results is almost within expectations (0.04 m^3/m^3). This is encouraging when one considers that the satellite has been operating for only two years. Good results are obtained over RFI free low vegetation and encouraging results over moderately dense forests (Rahmoune et al., 2012).
Globally soil moisture retrievals are in the correct range of values with a general tendency to underestimate ground measurements. The underestimation is strongly increased by RFI, as could be expected. However, in some cases and after a heavy rainfall event, the soil moisture values obtained seem too high (sometimes exceeding 0.65m^3/m^3). This may be due to ponding effects, saturation of the upper soil layer or retrieval errors.
Another point of concern is the way cold areas are processed. If freeze thaw is easily detected (soil appears suddenly dry when it freezes and vegetation becomes transparent when frozen), the main issue at this level is the fact that a high spatial resolution is required to monitor freeze thaw, especially in the transition areas. Snow cover is more complex. When dry, snow is almost transparent, and SMOS is sensitive to the relatively warm soil underneath. However, when the snow is wet, it is rather opaque. All the intermediary cases (both in term of snow state and spatial distribution), make retrieval in transition areas very difficult and the product is prone to being erroneous. Another source of concern is linked to water bodies. There are no available dynamic maps of water bodies at a fine enough resolution. And water bodies do change with time, be it through seasonal variations, floods or even tides. An error of 2% on the water body surface can lead to an error in soil moisture corresponding to 0.01 m^3/m^3.
Evaluation of the retrieval algorithm has been on-going since the onset of the commissioning phase. At first all efforts were concentrated on the Australian area where an extensive campaign (AACES for Australian Airborne Cal Val Experiment for SMOS) took place (Rudiger et al., 2011). It was then the main area with active vegetation (it was winter in the Northern Hemisphere), with the added advantage of being practically RFI free while an intensive airborne campaign was taking place. After, the focus shifted to other areas such as Africa (Niger and Benin), the watershed sites in the USA, the various Cal-Val sites in Europe, and the SCAN sites as shown in Figure 4.

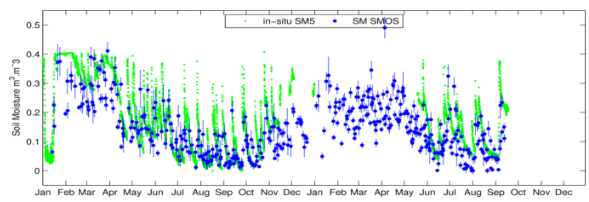

Figure 4 : Time series over site 2059 with filtering for Percentage of RFI < 30%, SM_retrieval quality (DQX < 0.07 and Tau_DQX<0.15).

Quantitative evaluation of the L2 algorithm has been described in several papers. Globally, the results are very satisfying for the low vegetation cases in areas that are not overly affected by RFI, such as in the United States or Australia. Conversely, in Europe for instance, results so far are degraded. Findings are currently poor over forested areas, but intensive research is being carried out to better understand the reasons why. Results are very good over arid areas. From the range of results obtained it can be said that roughly depending on area and RFI levels, the soil moisture estimate accuracy ranges between 0.02 and 0.06 m^3/m^3 with, in some cases, even higher values, while correlations between ground measurements can range from 0.5 to 0.85. Usually SMOS fares very well especially when considering that it is a new sensor when compared with satellites having a much longer track records.

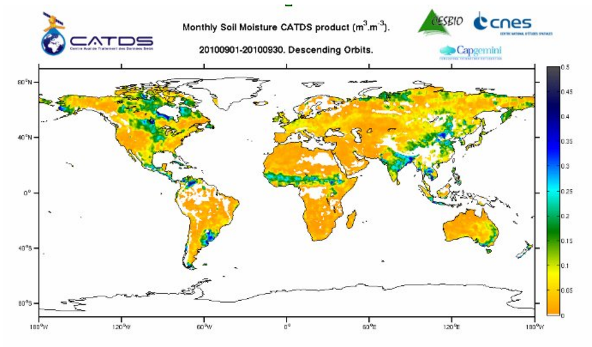

Figure 5 : Global map of soil moisture derived from SMOS data for the month of August 2010. Colour scale is soil moisture expressed in m^3/m^3 (Berthon et al., 2012).

3. New results

As agreed, as soon as SMOS started delivering data, while groups were working on the validation and improvements of the first products, other groups started to work on the level 3 and potentially 4 as well as on finding new products and science applications. Some examples are available on the SMOS blog[1].

The range of investigation is quite wide. Some looked at Antarctica (Picard et al., 2011) and snow stratification or SMOS calibration (Cabot et al., 2012), while others studied the evolution of an iceberg around the continent (Slominska et al., 2012). Also noticeable the mapping and monitoring of thin sea ice with SMOS showing that SMOS could be useful to retrieve sea ice thickness up to half-a-meter in the Arctic (Kaleschke et al., 2012) to name but a few studies.

3.1. Over the oceans

Combined with other satellites and in situ observations (altimetry, surface temperature, colour, ARGO profiles,..), SMOS measurements proved to be very useful in monitoring the seasonal cycle and advection pathways of the major fresh water pools of the world ocean (e.g., Amazon and Congo river plumes, Far Eastern Pacific Fresh Pool (Alory et al., 2012), . . .).

SSS freshening events detected under high rain zones are also very promising to improve precipitation estimates over the oceans (Figure 6). The impact of these data sets on improving ocean circulation modelling through assimilation is an on-going activity.

For the case of high Surface Wind speed estimates over the ocean, SMOS data seems also extremely promising. As upwelling radiation at 1.4 GHz is significantly less affected by rain and atmospheric effects than at higher microwave frequencies, the SMOS measurements also proved (Reul et al., 2012) to offer unique opportunities to complement existing ocean satellite high wind observations that are often erroneous in these extreme conditions. SMOS large spatial swath and frequent revisit time

[1] http://www.cesbio.ups-tlse.fr/SMOS_blog/

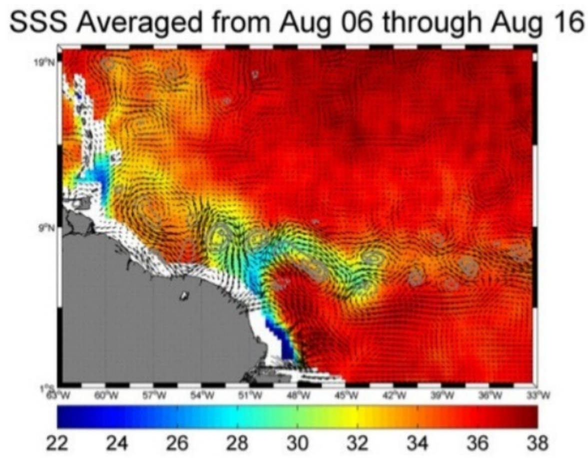

Figure 6 : Fresh water outflow of the Amazon as seen by SMOS early August 2010 (Reul et al., 2012).

intercepted the category 4 hurricane Igor nine times during its most intense phases in September 2010.

Much less affected by rain, SMOS data can provide improved estimates of the evolution of the maximum surface wind speed and the radii of 34, 50 and 64 knot surface wind speeds. The SMOS sensor is thus closer to a true all- weather satellite ocean wind sensor with the capability to provide quantitative and complementary surface wind information which are of great interest for operational Hurricane intensity forecasts.

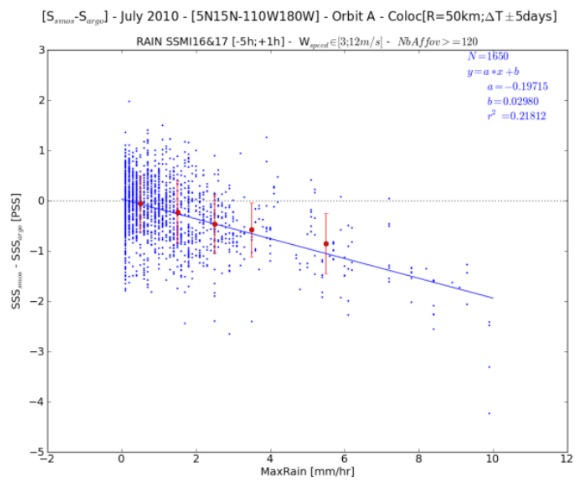

Figure 7 : The relationship between rainfall and departure between Argo buoys and SMOS values of sea surface salinity (Boutin et al., 2012).

3.2. Over land

Over land SMOS has also proved to open up a full new set of possibilities. The very first evidence to appear is its ability to monitor very quickly flood events and their extent in spite of cloud cover. In many instances SMOS has delivered maps of floods even providing some accurate details such as during the Mississippi floods in 2011

where the actual position of broken levies could be spotted. It was also used in January 2011 to infer whether hurricane Yasi would cause or not significant new flooding (linked to actual soil moisture) which SMOS did successfully.
Figure 7 shows an example of how SMOS can follow rainfall by simply measuring soil moisture. Assimilation algorithms are currently being developed to provide actual estimates of rainfall events.
Of course one can infer root zone soil moisture from surface soil moisture estimates as depicted in Figure 8. This is a typical Level 4 products produced by the Centre Aval de traitement des Données SMOS (CATDS)[2].

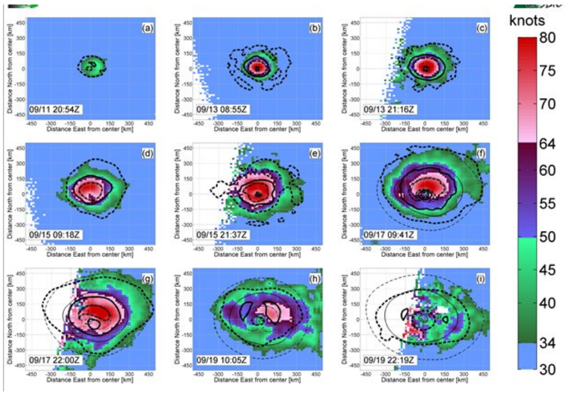

Figure 8 : The evolution of a hurricane as it evolves in the Atlantic. For each over pass SMOS delivers information on wind speed at sea level (Reul et al., 2012).

From root zone soil moisture, the natural step forward is to provide information on potential droughts which can be assessed after the event by simply monitoring soil moisture and vegetation drying but also by deriving a drought index as done again in preparation of the L4 delivered by CATDS in collaboration with Princeton University (USA) and with an example given in Figure 9.

In addition to these specific studies for CATDS, there are also studies on disaggregation so as to obtain soil moisture at a finer scale for water resource management purposes (Merlin et al., 2010a,b). The approach has been tested in Australia and in Spain (Catalonia) for instance. All these venues are very promising, and are part of the different level 4 products being elaborated for CATDS with many others such as a water stress index and a fire risk index or even a freeze thaw characterisation. The latter relies on the ability to infer a pseudo dielectric constant from SMOS data. The dielectric constant was used to monitor the cold spell over Europe at the end of the 2011-2012 winter.

Last but not least, with the advent of Aquarius and soon SMAP, work has started on the potential synergisms between the sensors. For instance, currently, an inter calibration of the SMOS and Aquarius missions is underway.

[2]SMOS CATDS data is available on http://www.catds.fr/

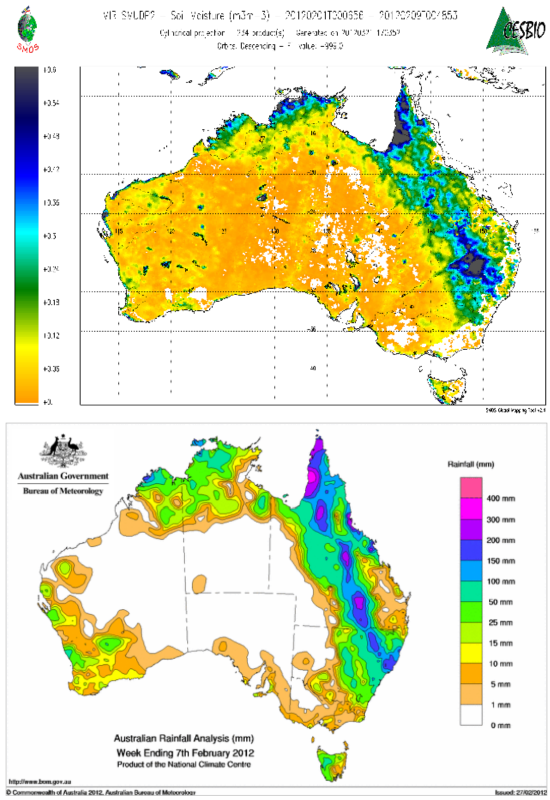

Figure 9 : Above: Heavy rainfall on Australia as seen by SMOS through soil moisture values. **Below**: The Australian Bureau of Meteorology estimates during the first week of February 2012 (Mialon et al., 2011).

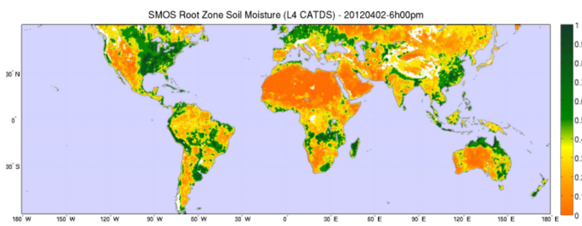

Figure 10 : Root zone soil moisture as estimated from SMOS data (Albitar et al., 2012).

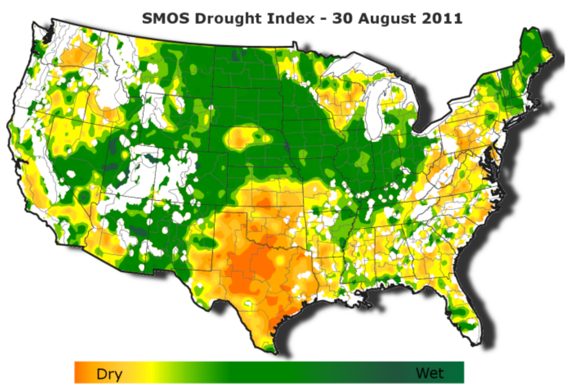

Figure 11 : SMOS drought index over the USA for August 2011 (Albitar et al., 2012).

4. Conclusion

SMOS was a new approach to new measurements. The challenge of building, before launch, retrieval algorithms with experience of neither L-Band measurements, nor synthetic aperture radiometer or even soil moisture/ sea surface salinity, proved to be successfully taken up.
After more than two years in operation and 2.5 years in orbit, the results are outstanding. For soil moisture, one of the main goals of the mission, results are very good for the homogeneous, low vegetation, targets. Good results are also starting to emerge over forested areas. Outstanding results have been obtained over the oceans, which remain challenging. The main issue encountered was the RFI pollution but things are also improving in this domain.
Based upon this success, the next challenge will be twofolds. First, to keep on improving the accuracy and the validity domain of the retrieval algorithms (extending over more and more surface types). Secondly, to keep on developing new products and new research venues (cryopshere is one obvious target) and implement them, as briefly suggested in this paper.
SMOS also demonstrated the need for absolute estimates of surface variables. For soil moisture for instance, change detection may have demonstrated its usefulness, but to really use the information one needs absolute values which can currently only be obtained from low frequency radiometry.
It is with this requirement in mind, together with the need for a higher sensitivity (for ocean applications) or higher spatial resolution (for coastal studies and soil moisture) that we are currently working on the SMOSNEXT concept. SMOS data is available from ESA (levels 1 and 2) and from CATDS (levels 3 and 4).

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References

WMO, 2006. Systematic observation requirements for satellite-based products for climate. Technical document. World Meteorological Organisation.

Albitar, A., Kerr, Y.H., Merlin, O., Richaume, P., Sahoo, A., Wood, E.F., 2012. Evaluation of SMOS Soil Moisture products over continental US using the SCAN/SNOTEL network. IEEE Transactions on Geoscience and Remote Sensing 50(5), 1572–1586.

Alory, G., Maes, C., Delcroix, T., Reul, N., Illig, S., 2012. Seasonal dynamics of sea surface salinity off Panama: The Far Eastern Pacific fresh pool. Journal of Geophysical Research 117, C04028.

Berthon, L., Mialon, A., Bitar, A. Al, Cabot, F., Kerr, Y., 2012. SMOS CATDS level 3 Soil Moisture products. In: EGU General Assembly. EGU, Vienna, Austria, 22–27 April 2012.

Boutin, J., Martin, N., Yin, X., Font, J., Reul, N., Spurgeon, P., 2012. First Assessment of SMOS Data Over Open Ocean: Part II–Sea Surface Salinity. IEEE Transactions on Geoscience and Remote Sensing 50(5), 1662–1675.

Cabot, F., Anterrieu, E., Picard, G., Macelloni, G., Kerr, Y., 2012. Validating SMOS brightness temperatures over land. In: Microad, 12th Specialist Meeting on Microwave Radiometry and Remote Sensing of the Environment. Frascati, Italy, 5-9 March 2012.

Ferranti, L., Viterbo, P., 2006. The European summer of 2003: Sensitivity to soil water initial conditions. Journal of Climate 19(15), 3659–3680.

Jackson, T.J., Bindlish, R., Cosh, M., Zhaoa, T., Starks, P.J., Bosch, D.D., Seyfried, M., Moran, M.S., Goodrich, D., Kerr, Y., Leroux, D., 2012. Validation of Soil Moisture and Ocean Salinity (SMOS) Soil Moisture over Watershed Networks in the U.S. IEEE Transactions on Geoscience and Remote Sensing 50(5), 1530–1543 .

Kaleschke, L., Tian-Kunze, X., Maaß, N., Mäkynen, M., Drusch, M., 2012. Sea ice thickness retrieval from SMOS brightness temperatures during the Arctic freeze-up period. Geophysical Research Letters 39, L05501.

Kerr, Y., Njoku, E.G., 1990. A semi empirical model for interpreting microwave emission from semi-arid land surfaces as seen from space. IEEE Transactions on Geoscience and Remote Sensing 28(3), 384–393.

Kerr, Y., Waldteufel, P., Richaume, P., Wigneron, J.P., Ferrazzoli, P., Mahmoodi, A., Al Bitar, A., Cabot, F., Gruhier, C., Juglea, S., Leroux, D., Mialon, A., Delwart, S., 2012. The SMOS Soil Moisture Retrieval Algorithm. IEEE Transactions on Geoscience and Remote Sensing 50(5), 1384–1403.

Kerr, Y., Waldteufel, P., Wigneron, J.P., Delwart, S., Cabot, F., Boutin, J., Escorihuela, M.J., Font, J., Reul, N., Gruhier, S., Juglea, S.E., Drinkwater, M.R., Hahne, A., Martin-Neira, M., Mecklenburg, S., 2010. The SMOS Mission: New Tool for Monitoring Key Elements of the Global Water Cycle. Proceedings of the IEEE 98(5), 666–687.

Kerr, Y., Waldteufel, P., Wigneron, J.P., Martinuzzi, J.M., Font, J., Berger, M., 2001. Soil moisture retrieval from space: The Soil Moisture and Ocean Salinity (SMOS) mission. IEEE Transactions on Geoscience and Remote Sensing 39(8), 1729–1735.

Merlin, O., Al Bitar, A., Walker, J.P., Kerr, Y., 2010. An improved algorithm for disaggregating microwave-derived soil moisture based on red, near-infrared and thermal-infrared data. Remote Sensing of Environment 114(10), 2305–2316.

Merlin, O., Duchemin, B., Hagolle, O., Jacob, F., Coudert, B., Chehbouni, G., Dedieu, G., Garatuza, J., Kerr, Y., 2010. Disaggregation of MODIS surface temperature over an agricultural area using a time series of Formosat-2 images. Remote Sensing of Environment 114(11), 2500–2512.

Mialon, A., Coret, L., Kerr, Y. H., Secherre, F., Wigneron, J.-P., 2008. Flagging the Topographic Impact on the SMOS Signal. IEEE Transactions on Geoscience and Remote Sensing 46(3), 689–694.

Oliva, R., Daganzo, E., Kerr, Y., Mecklenburg, S., Nieto, S., Richaume, P., Gruhier, C., 2012. SMOS RF Interference Scenario: Status and Actions Taken to Improve the RFI Environment in the 1400-1427 MHz Passive Band. IEEE Transactions on Geoscience and Remote Sensing 50(5), 1427–1439.

Picard, G., Kerr, Y., Macelloni, G., Champollion, N., Fily, M., Cabot, F., Richaume, P., Brogioni, M., 2011. Spatial variations of L Band emissicities in Antarctica: first results from the SMOS mission. In : IEEE International Geoscience and Remote Sensing Symposium (IGARSS). IEEE, Vancouver, Canada, 24-29 July 2011.

Rahmoune, R., Ferrazoli, P., Kerr, Y., Richaume, P., 2012. Analysis of SMOS signatures over forests and application of L2 algorithm. IEEE Transactions on Geoscience and Remote Sensing, in press.

Reul, N., Tenerelli, J., Chapron, B., Vandemark, D., Quilfen, Y., Kerr, Y., 2012. SMOS satellite L-band radiometer: A new capability for ocean surface remote sensing in hurricanes. Journal of Geophysical Research 117, C02006.

Rudiger, C., Walker, J.P., Kerr, Y., 2011. On the Airborne Spatial Coverage Requirement for Microwave Satellite Validation. IEEE Geoscience and Remote Sensing Letters 8(4), 824–828.

Schmugge, T., Gloersen, P., Wilheit, T.T., Geiger, F., 1974. Remote sensing of soil moisture with microwave radiometers. Journal of Geophysical Research 79(2), 317–323.

Silvestrin, P., Berger, M., Kerr, Y., Font, J., 2001. ESA's Second Earth Explorer Opportunity Mission: The soil Moisture and Ocean salinity Mission - SMOS. IEEE Geoscience and Remote Sensing Newsletter(118), 11–14.

Slominska, E., Marczewski, W., Slominski, J., 2012. SMOS over Antarctica - a short story of massive iceberg. In: EGU General Assembly. EGU, Vienna, Austria, 22–27 April 2012.

Thomann, G.C., 1976. Experimental results of the remote sensing of sea surface salinity at 21-cm wavelength. IEEE Transactions on Geosciences Electronics 14(3), 198–214.