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Identification of Spaceborne Microwave Radiometer Calibration Sites for Satellite Missions

Rüdiger, C.[1], **J.P. Walker**[1], **M. Allahmoradi**[1], **D. Barrett**[2], **J. Costelloe**[1], **R. Gurney**[3], **J. Hacker**[4], **Y.H. Kerr**[5], **E. Kim**[6], **J. Le Marshall**[7], **W. Lieff**[4], **A. Marks**[8], **S. Peischl**[1], **D. Ryu**[1] , **and N. Ye**[1]

[1] *Department of Civil and Environmental Engineering, The University of Melbourne, Parkville, Australia*
[2] *Sustainable Minerals Institute, The University of Queensland, Brisbane, Australia*
[3] *NERC Environmental Systems Science Center, University of Reading, Reading, United Kingdom*
[4] *Airborne Research Australia, Flinders University, Adelaide, Australia*
[5] *Biospheric Processes, CESBIO, Toulouse, France*
[6] *Hydrospheric and Biospheric Sciences Laboratory, NASA Goddard Space Flight Center, Greenbelt, United States*
[7] *Bureau of Meteorology Research Center, Bureau of Meteorology, Melbourne, Australia*
[8] *Environmental Observation and Landscape Science, CSIRO Land and Water, Canberra, Australia*
Email: crudiger@unimelb.edu.au

Abstract: The first dedicated soil moisture satellite mission will be the European Space Agency's Soil Moisture and Ocean Salinity (SMOS) mission. This satellite, scheduled for launch in the second half of 2009, has a new type of satellite design that is based on the radio-astronomy technique of simulating a large antenna from a number of smaller ones placed some distance apart. Because of its unique design and the fact it is sensing in a currently unutilized frequency range makes it critical that on-orbit calibration targets be included in the calibration strategy. Consequently, targets such as the Antarctic, cold oceans, tropical forests and deserts are being considered. However, the large footprint size of passive microwave observations means that large scale homogeneous regions must be identified for calibration purposes. Moreover, these sites must also be either stable through time or the temporal variation easily described by models. In order to satisfy the calibration accuracy required by SMOS for soil moisture retrieval, such sites should be characterized with a brightness temperature uncertainty of less than 4K.

A field experiment has been undertaken in November 2008 in the Australian Arid Zone to explore the suitability of three potential on-orbit calibration targets for SMOS. These sites were chosen for their assumed spatial homogeneity in terms of surface conditions (soil moisture and temperature, vegetation, soil type etc.), and consequently their expected microwave response. Each site covers an area of approximately 50km x 50km, being the approximate size of a satellite footprint. These sites include i) Wirringula Hills, a station to the north-east of Coober Pedy that is characterized by a dense cover of gibber; ii) Lake Eyre, characterized by a predominantly moist material under a layer of salt crust; and iii) Simpson Desert, characterized by sand dunes orientated in a north-south direction.

The data collected during this field campaign consists of both airborne and ground-based measurements. The airborne data includes passive microwave emissions obtained with an L-band airborne radiometer, thermal infrared observations, and optical data. The ground data collection consisted of surface soil moisture measurements at targeted locations along sections of the high-resolution flight tracks, and station measurements of soil moisture and temperature profiles to a depth of 40cm. Additionally, there were soil core samples to a depth of 2m, surface characterization and surface roughness measurements. The airborne data were collected at two different resolutions, 1km and 50m.

This paper presents the results from airborne observations made during this campaign, and discusses their significance in relation to the calibration of SMOS. Of the three study sites assessed, Wirringula Hills appears to be the most promising, having a spatial variability in brightness temperatures of less than 4K at H polarisation. In comparison, the Simpson Desert had a spatial variability of about 10K, and the moist region of Lake Eyre had a spatial variability of about 13K. Moreover, Lake Eyre was found to also have considerable spatial heterogeneity, making it unsuitable for calibration at the spatial resolution of SMOS.

Keywords: *Soil Moisture, Remote Sensing, Microwave Radiometry, SMOS, Field Campaign*

1 INTRODUCTION

The European Space Agency (ESA) has scheduled the launch of its Soil Moisture and Ocean Salinity (SMOS; Kerr et al., 2001) mission for the second half of 2009; the first soil moisture dedicated mission at L-band. This satellite will provide global brightness temperature observations at better than 40km resolution with a repeat overpass approximately every three days at the equator. However, SMOS consists of a new type of satellite design, which uses synthetic aperture techniques similar to those used in radio-astronomy, to simulate the large antenna size required at L-band. One additional feature of this technique is that it also yields data at a range of incidence angles for each pixel in the swath. As each new satellite has its own individual technical specifications and retrieval algorithms, a post-launch commissioning phase of several months is required for validation and calibration purposes.

Because of the unique design of SMOS, it is especially important that this satellite be carefully calibrated using a range of techniques and targets. To demonstrate this point, the Advanced Microwave Scanning Radiometer for the Earth Observing system (AMSR-E), which used a traditional microwave sensing technique for frequencies higher than C-band, experienced a post-launch data release delay of several months due to a poor calibration accuracy. Initially, it was intended to perform on-board calibrations of AMSR-E with a two-point on-board calibration system, by providing a hot and cold load reference to the system. While the cold load involved looks at the deep space background temperature, the hot load was provided by an onboard reference target. However, this target experienced significant temperature gradients due to influences by the sun (Wentz et al., 2003). The problem was overcome by using thermal information from other radiometers in orbit at the time, but not without a significant delay.

As a consequence of the AMSR-E experience, a large number of studies have been undertaken to find ways to provide a suitable warm load target that is not on the spacecraft. Such targets include tropical forests (Ferrazzoli et al., 2002) Antarctica (Macelloni et al., 2006 & 2007), arid regions and various parts of the ocean (Burrage et al., 2008). Consequently, to avoid post-launch calibration problems with SMOS a more cautious approach is being pursued, by using a range of on-orbit calibration targets from cold to hot. Vicarious calibrations of the satellite instruments will take place over targets with presumed homogeneous and known surface emissions. For instance, the emissions from Dome-C in the Antarctic have been shown to be constant at about 190K (Macelloni et al., 2006). Moreover, emissions from the Amazonian forest appear to have only little variation at C-band and higher frequencies and are therefore relatively constant at 290K (Brown and Ruf, 2005), which may suggest that they could be used as calibration targets at L-band . Other calibration targets include the ice-free sea surfaces, as the salinity effect is minimal and their physical temperature is well known and very stable with low or well known winds, and possibly the Taklamakan Desert in China. Additionally, SMOS will make a deep space observation for one orbit every two weeks (to be confirmed after the commissioning phase). More detailed discussions of the SMOS calibration and validation can be found in Brown et al. (2008) and Delwart et al. (2008).

Currently a number of experiments and campaigns are being planned and/or undertaken in order to identify further appropriate sites, such as deserts and salt lakes, particularly in Central Australia, Bolivia and China. In November 2008, a field experiment took place in the Australian Arid Zone (Lake Eyre and Simpson Desert regions; Fig. 1) in order to identify potential SMOS calibration sites in a predominantly dry environment. The study sites of this campaign were chosen for homogeneous surface conditions (Fig. 2) and their hypothesized spatial homogeneity in their microwave response. Similarly, if a temporal variation exists, it needs to be easily characterized through in-situ observations. Airborne observations collected during this experiment include brightness temperatures in the same microwave spectrum as SMOS, thermal infrared measurements, and high-resolution photographs. The ground data acquisition provided roaming surface soil moisture and thermal infrared measurements, profile soil temperature and moisture at base stations located within the focus areas, and finally soil and rock samples. In this paper, only the brightness temperature observations are presented.

The three field sites chosen for this experiment represent regions of large homogenous extent:

a) Lake Eyre: a large flat salt lake, assumed to have homogeneously saturated soil moisture conditions immediately beneath its surface, based on previous visits to accessible parts of the lake;

b) Simpson Desert: a sandy desert, with only little vegetation and few precipitation events per year, assumed to have homogeneously dry surface soil moisture conditions, based on our previous soil moisture measurements in the area;

c) Wirrangula Hills: a rocky (gibber) desert with rock surface coverage of up to 90% and almost no vegetation, assumed to have a microwave response that is dominated by the rock cover emission.

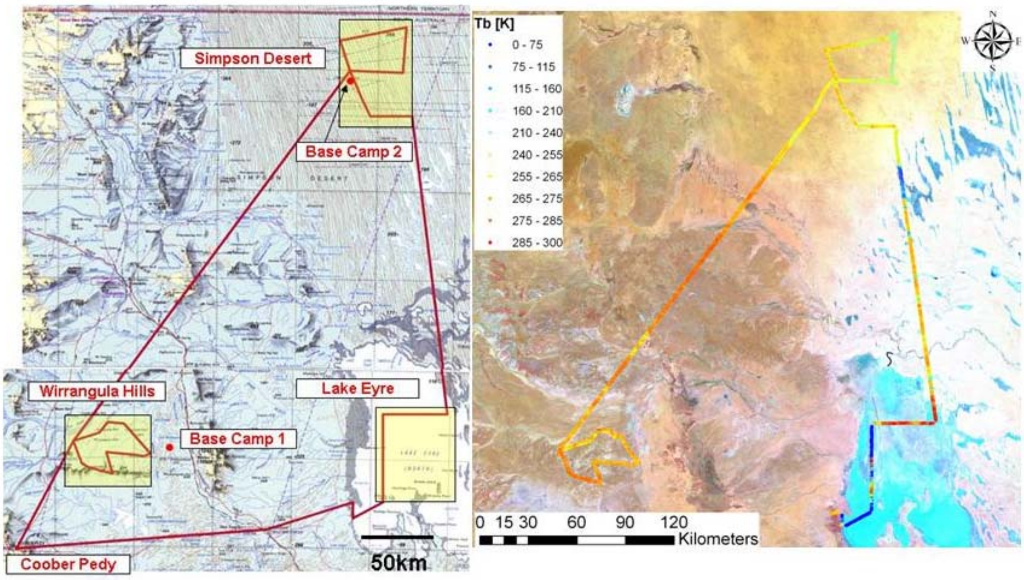


Figure 1. Overview of the three focus sites: Wirrangula Hills (gibber), Lake Eyre (salt lake), and the Simpson Desert (sandy desert) along with the corresponding LandSat false colour image. The red line on the left hand image shows the high-resolution and reconnaissance flights (50m), while the yellow boxes represent the low-resolution (1km) coverage. The data shown superimposed over the LandSat image (composite image of 2002) are the brightness temperature observations collected during the reconnaissance flight

Topographic effects across the sites should have only little impact on the hydrology and microwave response, as the areas of Wirrangula Hills and Lake Eyre are relatively flat (Fig. 2). The influence of the regular structure of dunes on the microwave signal may be studied with the high-resolution data set.

2. DATA

2.1. Airborne Data

The instruments carried onboard the aircraft during the campaign were the Polarimetric L-band Multibeam Radiometer (PLMR), six thermal infrared (TIR) sensors, a thermal imager, and a high resolution (21 MegaPixel) optical camera. The PLMR consists of six beams, each with a field of view of approximately 15°. The instrument was flown in the push-broom configuration, such that brightness temperature observations were made across the flight track at incidence angles of approximately ±7°, ±21°, and ±38° from nadir. The configuration of the six TIR sensors was such that the instruments field of view observed the same ground area as the six PLMR beams.

Figure 2. Surface conditions at Wirrungula Hills (left), Lake Eyre (centre) and Simpson Desert (right).

Table 1. Overview of the four flights showing the areas flown and the data collected with the airborne instruments and on the ground. The statistics are standard deviations of the brightness temperatures observed over the areas at high (50m) and low (1km) resolution. For the Simpson Desert and Lake Eyre, those are presented separately for the "wet" and "dry" sections of the focus areas.

Site	**Surface Type**	**Measurements airborne / in-situ**	**Date**	**Tb std. dev.**
Reconnaissance (all three sites)	salt lake (LE) gibber (WH) sandy desert (SD)	PLMR, thermal IR / thermal IR, profile soil moisture and temperature	09 November 2008	only high-res.: 12.6 / 10.4 (LE – wet/dry) 5.2 (WH) 10.1 (SD)
Lake Eyre	salt lake	PLMR, thermal IR / profile soil temperature, surface soil moisture	10 November 2008	high-res. (wet/dry): 16.1 / 15.6 low-res. (wet/dry): 13.2 / 19.6
Wirrangula Hills	gibber	PLMR, thermal IR, photography / thermal IR, profile soil moisture and temperature, surface soil moisture, deep core samples	12 November 2008	high-res.: 4.1 low-res.: 3.3
Simpson Desert	sandy desert		14/15 November 2008	high-res. (wet/dry): 8.6 / 9.8 low-res. (wet/dry): 9.5 / 8.7

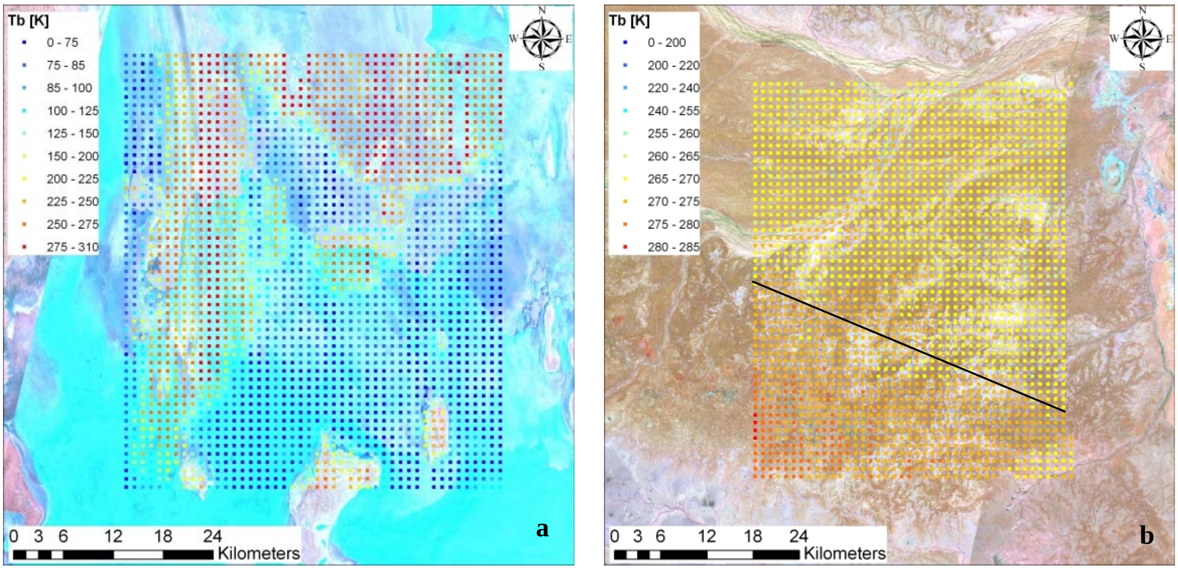
The airborne data were collected at both high- and low-resolution. The low-resolution flight covered a full SMOS pixel (i.e., ~50km x 50km) at 1km resolution, while the high-resolution flights covered local areas along pre-defined flight paths at 50m resolution. A general overview of the flight dates and observations collected is presented in Table 1. The regional flights were timed such that they would be centred on the 6am SMOS overpass time (e.g. 4am to 8am). An exception was the reconnaissance flight, which took place in the afternoon. This reconnaissance flight covered the high-resolution area across the three focus sites (Fig. 1). The data collected during the reconnaissance flight were used to identify areas of interest for the ground data collection, which was to be undertaken coincident with over-flights on the following flight days.

The brightness temperature data presented in this paper have been corrected to a reference time of 6am and reference incidence angle of 38deg, and filtered for data with an aircraft roll of more than 2.5°. The data were temporally corrected for diurnal changes in the effective soil temperature using the 6am temperature observed at 2.5cm at the base station as a reference (assuming its representativeness for the whole area – assumption to be verified during a second field experiment), and the ratio between the temperature at 6am to that measured at any other time (in Kelvin) as a scaling factor. The angular correction was performed by assuming that the ratio between the brightness temperature means of the different beams was spatially constant. Consequently, multiplying the observation at any one location with this ratio transfers the brightness temperature of the original beam to the reference beam. The data were finally binned onto a regular grid with a resolution of 1km, averaging all available observations within each pixel.

2.2. Ground-based Data

Ground data were collected for forward modelling (not presented here) and understanding of spatial variability in observed brightness temperature. Moreover, the forward modelling will serve as validation of the radiative transfer model and demonstrate the ability to predict the temporal response of the calibration site. The results from this analysis will be the topic of a future study, however, the ground data collected are briefly described here for completeness.

The ground-based measurements included base stations with temperature sensors installed at depths of 2.5, 5, 15, 25, and 40cm, soil moisture sensors at the surface (0-6 cm) and at 25cm depth, and a thermal infrared sensor for the skin surface temperatures. Additionally, surface soil moisture measurements were made for target transects of ~1km in length and 300m in width, using the Hydraprobe Data Acquisition System. Moreover, gravimetric soil moisture samples were taken for probe calibration, rock fraction samples and



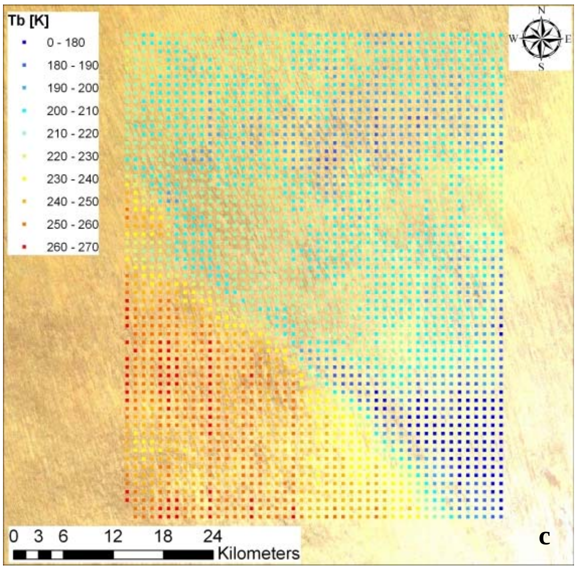


Figure 3. Horizontally polarised brightness temperatures binned onto a regular grid of 1km resolution for a) Lake Eyre (10 Nov), b) Wirrangula Hills (12 Nov), and c) Simpson Desert (15 Nov).

roughness measurements were made for surface characterization, and soil core samples together with temperature and moisture measurements were made to a depth of approximately 2m for a better understanding of the microwave penetration depth. Soil cores were primarily taken in order to obtain the deeper soil moisture and temperature profile. Furthermore, previous studies undertaken in the Sahara showed that microwave signatures may be emitted from subsoil layers of more than 10's of metres (Prigent et al., 1999). In the case of the Simpson Desert it was found that a densely compacted soil layer exists at about 2m, which limits the observation depth to the profile above this layer. The surface roughness was determined, with a roughness board across 2m long transects oriented in north-south and east-west directions.

3. RESULTS AND DISCUSSIONS

Lake Eyre was hypothesized to represent a smooth and wet target having a homogeneous microwave response at mid-range brightness temperature, with the northern part of the Lake Eyre peninsula included to provide a land contrast. While the roughness measurements supported the smooth surface assumption (root mean square roughness of 1.35mm), the brightness temperature data showed unexpected results. The data suggest that the surface conditions of Lake Eyre are characterized according to two main types of response, brightness temperatures similar to those over land and a low brightness temperature response similar to that hypothesised (Fig. 3a). However, even the low brightness temperature response was lower than expected (mean value around 80K at H polarization), most likely due to the hyper-saline conditions that exist in the lake soil water. Moreover, the variability of brightness temperature across this low brightness temperature area is about 13K. The reason for this bi-modal response is not entirely clear, as access to Lake Eyre is very restricted without using a helicopter. However, the high brightness temperatures in the western and northern parts of the study region coincide with the areas receiving flood water from the Warburton and Cooper Creeks and the Diamantina River. The warm "tongue" in the north and west is the Warburton Groove, which receives the first flood water. As the flood waters enter Lake Eyre, sediments carried with the floods are deposited in this area. This apparently leads to a contrast in surface conditions, with potentially dry silt deposits in the north and moist hyper-saline conditions with a salt crust in the south. The only possible access to Lake Eyre from the west is via the Anna Creek Public Access Road (see Fig. 1), where it was found that the ground water level is immediately below the lake’s surface, explaining the low brightness temperatures for this area.

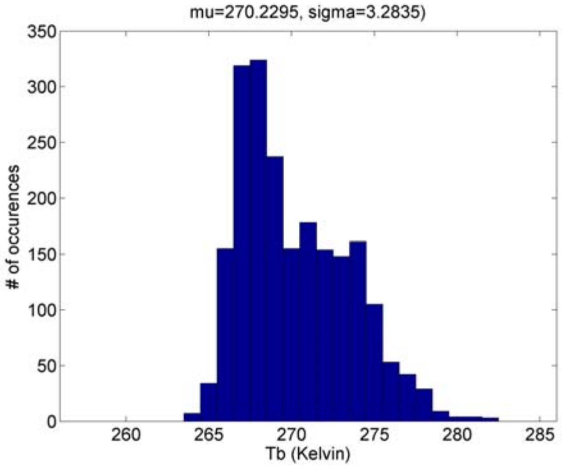


Figure 4. Frequency histogram of the gridded low-resolution brightness temperature data at Wirrangula Hill (12 November). The mean (mu) and standard deviation (sigma) are also given.

The brightness temperature data obtained over the gibber areas of Wirrangula Hills showed a low variability in their brightness temperature response (3.3K; Fig. 3b and Fig. 4). This variability is within the requirements for a SMOS Cal/Val site (which is equivalent to the radiometric noise of the instrument of 2-4K; Kerr and Waldteufel, 2003). Moreover, the small brightness temperature gradient from the north-east to the south-west is possibly explained by the occurrence of a precipitation event that passed through the northern part of the focus area five days prior to the flight. The spatial variability in the brightness temperature observations is further reduced when separating the Wirrangula Hills observations into “wet” and “dry” (or radiometrically cool and warm) conditions. In this case, the variability of the brightness temperature to the north of the black line on Fig. 3b is 2.0K and to the south of the black line is 2.8K. Additionally, the high-resolution flight yielded a variability of 4.1K (5.2K during the reconnaissance flight).

The final flight was over the Simpson Desert (Fig. 3c). Unfortunately a significant precipitation event occurred over the north-eastern part of the focus area during the night of the 14th November, and continued throughout the flight on the morning of the 15th November. Due to the extreme remote location of this site and the distance from the operations airport, the aircrew was not aware of this unlikely rain event until arriving in the study area. Consequently, the brightness temperature response is bi-modal (Fig. 5). For the purpose of testing the hypothesis of a spatially homogenous brightness temperature response under dry conditions, it was assumed that no rainfall occurred in the south western part of the study site. However, the variability in brightness temperature for this area was 9.5K, which is still higher than that obtained for Wirringula Hills, and well beyond the SMOS target requirement of 4K. To check the possibility that these results were affected by small amounts of rainfall across the south-western part, the brightness temperature variability was compared with that from the initial reconnaissance flight, which had a variability of 10.1K.

4. CONCLUSIONS

This study has shown that the Wirrangula Hills area represents a possible warm on-orbit calibration target for SMOS, with an observed spatial variability of less than 4K. This value represents the SMOS requirement for sensor calibration accuracy. Such a warm calibration target will complement the proposed on-orbit calibration targets for colder temperatures, such as Dome-C in Antartica and the Atlantic Ocean off New Foundland.

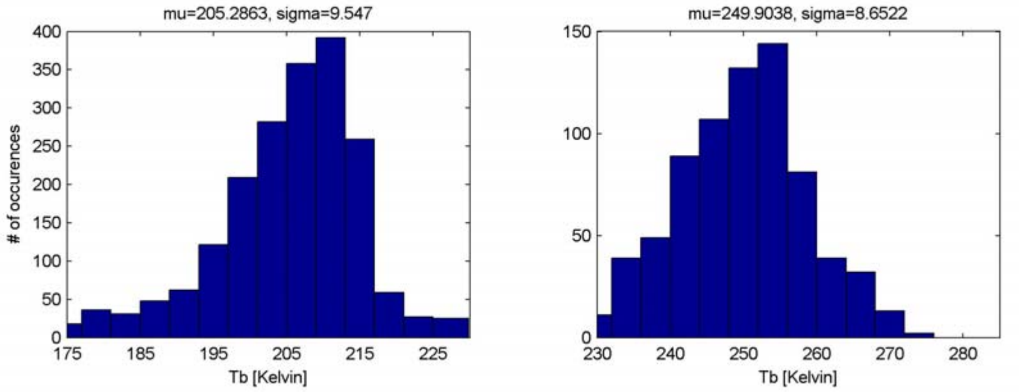


Figure 5. Frequency histogram of the gridded low-resolution brightness temperature data observed over the Simpson Desert (15 November). The mean (mu) and standard deviation (sigma) are also given.

Lake Eyre is not a suitable target, due to its extreme bi-modal response at the spatial scale of a SMOS pixel. Moreover, even the hypothesized response from the moist salty areas of the lake had a brightness temperature variability of approximately 13K, which is more than three times that of the Wirrangula Hills site. Likewise the dry conditions of the Simpson Desert had a spatial brightness temperature variability of approximately 10K, being more than twice that of the Wirringula Hills site. Nevertheless, if the spatial variability were consistent and its mean constant throughout the seasons, the Simpson Desert may still be useful for warm target calibrations.

In order to confirm the spatial homogeneity of the Wirringula Hills site and the assumptions in relation to rainfall across the Simpson Desert, it is proposed that flights across these two regions be repeated during the winter of 2009, which is also likely to coincide with the post-launch calibration of SMOS. Consequently, these flights would be timed to coincide with SMOS overpasses. Moreover, to understand the temporal variation of these sites, in-situ soil moisture and temperature stations will be installed across the Wirringula Hills site in May. The proposed in-situ stations will provide the forward model input variables required to simulate the brightness temperature emissions from the surface. These modelled brightness temperatures can then be used for comparison with and subsequent calibration of the brightness temperatures observed by SMOS during its overpass of the site.

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