SMOS In-Orbit External Calibration and Validation

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Abstract

SMOS is ESA’s second Earth Explorer mission with the objective of producing global maps of Soil Moisture and Ocean Salinity over the Earth. The launch date is expected in September 2007. The only instrument on-board SMOS is an L-band Microwave Imaging Radiometer with Aperture Synthesis (MIRAS).

This paper describes what is believed to be the optimum strategy to calibrate and validate MIRAS in-orbit using external targets. Central to the method are the flat target response and the flat target transformation of the Corbella equation. The paper includes the application of the technique to image reconstruction and some illustrative simulations.

Introduction

The Flat Target Transformation (FTT) has been derived based on the Corbella equation, which correctly describes how MIRAS works [1]. The proposed in-orbit calibration and validation approach is thus fully based on this equation. The main objective of the FTT is to minimize the impact of antenna errors, as they are outside the internal calibration loop.

In a markedly different way to the point target response method used to calibrate other imaging systems, the FTT is essentially based on measuring a flat (uniform) target as the cold sky near the galactic poles. The original motivation to deviate from the classical impulse response calibration resides on the fact that no emitters are allowed in the protected radio-frequency band of MIRAS.

The Corbella Equation

The fully-polarimetric Corbella equation of the visibility function \( V \) was derived in [2] and reads as follows:

\[
V_{ij}^{pq}(u,v) = 2k_B \sqrt{B_iB_j} \alpha_i\alpha_j \times \frac{1}{\sqrt{\Omega_i\Omega_j}} \int_{\xi^2+\eta^2 \leq 1} F_{n,i}^{\alpha}(-\xi,\eta) F_{n,j}^{\beta,*}(-\xi,\eta) T_{B\alpha\beta}(-\xi,\eta) - \delta_{\alpha\beta}T_r \overline{\tilde{r}_{ij}} \left( -\frac{u\xi + v\eta}{f_o} \right) e^{-j2\pi(u\xi + v\eta)} d\xi d\eta
\]

where \( p \) and \( q \) are the polarisations (in the antenna reference frame) that are selected in each of the two receivers \( i \) and \( j \) involved in the particular baseline, \((u,v)\) the baseline in wavelengths \((\lambda_o=c/f_o)\), \((\xi,\eta)\) the direction cosines, \( k_B = 1.38 \times 10^{-23} \text{ J/K} \) is the Boltzmann constant, \( B \) the equivalent noise bandwidth of the receiver, \( \alpha \) the peak voltage gain of the receiver (including antenna losses) –not to be confused with the polarisation superscript–, \( \Omega \) the solid angle of the corresponding antenna, \( F_{n\alpha,p} \) the normalised voltage antenna pattern in \( \alpha \) polarisation when \( p \) polarisation is selected, \( T_{B\alpha\beta} \) the brightness temperature in \( \alpha\beta \) polarisation, \( T_r \) the receiver physical temperature (assumed the same for all receivers), \( \tilde{r} \) the fringe-washing function and \( \delta_{\alpha\beta} \) the Kronecker delta.

Eq.1 assumes Einstein’s sum convention over the repeated \( \alpha \) and \( \beta \) indices, meaning implicit summation over them in the following example, where the same selected polarisation \( p \) is assumed in both receivers:

\[
\begin{align*}
F_{n,i}^{\alpha,p} F_{n,j}^{\beta,p,*} (T_{B\alpha\beta} - \delta_{\alpha\beta}T_r) \\
F_{n,i}^{\alpha,p} F_{n,j}^{\beta,p,*} (T_{B\alpha\beta} - \delta_{\alpha\beta}T_r) & = \\
F_{n,i}^{\alpha,p} F_{n,j}^{\beta,p,*} (T_{B\alpha\beta} - \delta_{\alpha\beta}T_r) + F_{n,i}^{\alpha,p} F_{n,j}^{\beta,p,*} (T_{B\alpha\beta} - \delta_{\alpha\beta}T_r)
\end{align*}
\]

where \( F_{np,p} \) and \( F_{np,q} \) are the co- and cross-polar normalised voltage antenna patterns respectively, when the \( p \) polarisation is selected.

The Corbella equation fully describes the behaviour of an aperture synthesis microwave radiometer as MIRAS and predicts that antenna errors are critical since they scale with the temperature contrast (difference) between the brightness temperature of the target and the receivers physical temperature. Ocean salinity retrieval in SMOS is thus challenging.
MIRAS Flat Target Response

A flat target is defined as follows: one which is completely unpolarised, with the same brightness temperature in every direction and constant over time. Excellent realisations of such reference flat targets at the spatial resolution of MIRAS are the cold sky near the galactic poles and the absorber wall of an EMC anechoic chamber that is at a known physical temperature. In the case of the cold sky around the galactic Pole [3]

\[
\begin{align*}
T_P^v &= T_P^h = 3.5 \text{ K} \\
T_P^{vh} &= T_P^{hv} = 0 \text{ K}
\end{align*}
\]

The visibility function of a flat target at \(T_o\) can be derived from Eq.1:

\[
V^{pq}_{ij}(u, v; T_o - T_r) = (T_o - T_r) \left(\frac{\bar{T}_P}{\bar{T}_o} - 1\right) V^{\alpha\alpha,pq}_{ij}(u, v)
\]

where

\[
V^{\alpha\alpha,pq}_{ij}(u, v; 1) = \frac{1}{\sqrt{\Omega_i \Omega_j}} \int_{\xi^2 + \eta^2 \leq 1} \frac{1}{\sqrt{1 - \xi^2 - \eta^2}} \tilde{r}_{ij}(\xi, \eta) e^{-j2\pi(u\xi + v\eta)} d\xi d\eta
\]

will be called the flat target response of the instrument from now on.

Flat Target Transformation

The impact of antenna errors would be minimized if, in the Corbella equation, the receiver temperature were replaced by the average temperature of the scene, that is:

\[
\tilde{V}^{pq}_{ij}(u, v) = 2k_B \beta B_{ij} \alpha_i \alpha_j \times \frac{1}{\sqrt{\Omega_i \Omega_j}} \times \int_{\xi^2 + \eta^2 \leq 1} F^{\alpha \beta}_{n,i}(\xi, \eta) F^{\alpha \beta}_{n,j}(\xi, \eta) \frac{\bar{T}_P^\beta(\xi, \eta)}{\sqrt{1 - \xi^2 - \eta^2}} \tilde{r}_{ij}(\xi, \eta) e^{-j2\pi(u\xi + v\eta)} d\xi d\eta
\]

The FTT achieves this objective through the following transformation

\[
\tilde{V}^{pq}_{ij}(u, v) = V^{pq}_{ij}(u, v) - \Delta V^{pq}_{ij}(u, v)
\]

where

\[
\begin{align*}
\Delta V^{xx}_{ij}(u, v) &\approx \frac{\bar{T}_P^x - T_r}{T_P^x - T_r} V^{xx}_{ij}(u, v; T_P - T_r') \\
\Delta V^{yy}_{ij}(u, v) &\approx \frac{\bar{T}_P^y - T_r}{T_P^y - T_r} V^{yy}_{ij}(u, v; T_P - T_r') \\
\Delta V^{xy}_{ij}(u, v) &\approx \frac{\bar{T}_P^{x+y} - T_r}{T_P^{x+y} - T_r} V^{xy}_{ij}(u, v; T_P - T_r') \\
\Delta V^{yx}_{ij}(u, v) &\approx \frac{\bar{T}_P^{x+y} - T_r}{T_P^{x+y} - T_r} V^{yx}_{ij}(u, v; T_P - T_r')
\end{align*}
\]

The FTT consists therefore in subtracting a scaled version of the visibilities acquired when looking to the flat cold sky from the ones measured during normal operation.
FTT-based Image Reconstruction Including the Alias Regions

According to Eq.7 the visibilities of the observed scene \( V_{ij}^{pq}(u, v) \) can be split in two parts: the FTT-transformed visibilities \( V_{ij}^{pq}(u, v) \) plus the scaled visibilities of the galactic pole \( \Delta V_{ij}^{pq}(u, v) \). The visibilities of the galactic pole are expressed in terms of the flat target response in Eq.4. This allows to cancel the brightness temperature (brightness temperature multiplied by the antenna patterns over the obliquity factor) can be recovered as follows:

\[
T^{pq}(\xi, \eta) = IR\left[V_{ij}^{pq}(u, v)\right] + T_r \cdot IR\left[V_{ij}^{\alpha \alpha, pq}(u, v; 1)\right]
= IR\left[V_{ij}^{pq}(u, v)\right] + IR\left[\Delta V_{ij}^{pq}(u, v)\right] + T_r \cdot IR\left[V_{ij}^{\alpha \alpha, pq}(u, v; 1)\right]
= IR\left[V_{ij}^{pq}(u, v)\right] + IR\left[\bar{T}_B - T_r\right] \cdot IR\left[V_{ij}^{\alpha \alpha, pq}(u, v; 1)\right] + T_r \cdot IR\left[V_{ij}^{\alpha \alpha, pq}(u, v; 1)\right]
\]

(9)

Due to the linearity of the image reconstruction operator, the images of the two parts can be reconstructed separately and only added after reconstruction in the image domain. The reconstruction of the first part, the FTT-transformed visibilities, is insensitive to errors in the knowledge of the instrument antenna pattern due to the small remaining difference temperature. On the other side this lack of knowledge would result in significant errors when attempting to reconstruct the flat target response of the galactic pole.

Fortunately the image of the flat target response does not need to be obtained from the measured visibilities of the galactic pole but can be obtained by simulation without requiring precise knowledge of the instrument.

The image of the flat target response of the real instrument \( V_{ij}^{\alpha \alpha, pq}(u, v; 1) \) with the ideal image reconstruction operator is the same as the image of the flat target response visibilities simulated with an ideal instrument \( V_{ij}^{\alpha \alpha, pq, IDEAL}(u, v; 1) \) that were reconstructed with an Inverse Hexagonal Fourier Transform:

\[
IR_{IDEAL}\left[V_{ij}^{pq, pq}(u, v; 1)\right] = IHFT\left[V_{ij}^{pq, pq, IDEAL}(u, v; 1)\right]
\]

(10)

This is due to the fact that the IHFT is the ideal image reconstruction operator for the ideal instrument. Therefore Eq.(9), when expanded for the different polarizations, gives

\[
T^{xx}(\xi, \eta) = IR\left[V_{ij}^{xx}(u, v) - \frac{T_B^{xx}}{T_p - T_r} V_{ij}^{xx}(u, v; T_p T_r)\right] + \bar{T}_B^{xx} \cdot IHFT\left[V_{ij}^{yx, xx, IDEAL}(u, v; 1)\right] + \bar{T}_B^{yy} \cdot IHFT\left[V_{ij}^{yx, yy, IDEAL}(u, v; 1)\right]
\]

(11a)

\[
T^{yy}(\xi, \eta) = IR\left[V_{ij}^{yy}(u, v) - \frac{T_B^{yy}}{T_p - T_r} V_{ij}^{yy}(u, v; T_p T_r)\right] + \bar{T}_B^{xx} \cdot IHFT\left[V_{ij}^{yx, yy, IDEAL}(u, v; 1)\right] + \bar{T}_B^{yy} \cdot IHFT\left[V_{ij}^{yx, yy, IDEAL}(u, v; 1)\right]
\]

(11b)

\[
T^{xy}(\xi, \eta) = IR\left[V_{ij}^{xy}(u, v) - \frac{T_B^{xx} + T_B^{yy}}{2(T_p - T_r)} V_{ij}^{xy}(u, v; T_p T_r)\right] + \bar{T}_B^{xx} \cdot IHFT\left[V_{ij}^{yx, xy, IDEAL}(u, v; 1)\right] + \bar{T}_B^{yy} \cdot IHFT\left[V_{ij}^{yx, xy, IDEAL}(u, v; 1)\right]
\]

(11c)

\[
T^{yx}(\xi, \eta) = IR\left[V_{ij}^{yx}(u, v) - \frac{T_B^{xx} + T_B^{yy}}{2(T_p - T_r)} V_{ij}^{yx}(u, v; T_p T_r)\right] + \bar{T}_B^{xx} \cdot IHFT\left[V_{ij}^{yx, yx, IDEAL}(u, v; 1)\right] + \bar{T}_B^{yy} \cdot IHFT\left[V_{ij}^{yx, yx, IDEAL}(u, v; 1)\right]
\]

(11d)
Demonstration of the FTT Using the SMOS End-to-End Simulator

The following simulations demonstrate that the FTT reduces the noise in the retrieved images. For this, the SEPS simulator developed for ESA by the Department of Signal Theory and Telecommunications of UPC (Spain) has been used on an ocean scene.

The first step in the FTT process is the measurement of the cold sky visibilities. The visibilities of the sky measurement are then subtracted from the measured ocean visibilities scaled with the scaling factor following Eq.8. After inversion of these FTT-visibilities the ideal-instrument image of the sky and a flat target are added back. The resulting brightness temperature image for the X-polarization is shown below in Figure 1.

![Figure 1: Brightness temperature of the ocean scenario at X-polarization – with FTT (LEFT) and without (RIGHT)](image)

The statistical analysis of the figures above confirm an improvement factor (noise reduction in the image due to antenna errors) between 3 and 5 due to the FTT.

Conclusion

This paper has presented what is believed to be the optimum method of external calibration for MIRAS. The method consists in the flat target transformation of the fully polarimetric Corbella equation. This technique minimises the impact of system errors, in particular antenna pattern errors, in the measured correlations. It only requires cold sky views near the galactic poles, from time to time along the mission.

The paper has described the correct method of applying the FTT to the image reconstruction data processing, where the generation of the flat target response is used within the processing without requiring a precise knowledge of instrument deviations.

The performance of the FTT has been SEPS-simulated with noise reduction factors around 4 over ocean. The improvement is limited to a factor about 2 in the alias regions. Additional research indicate that the FTT could be applied in more sophisticated ways.

REFERENCES