SMOS: Calibration issues

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1. General remarks

1.1 Purpose

In this document we will consider calibration as the operation by which the signal measured by the instrument is transformed into a "top of the atmosphere" brightness temperature for any pixel in the useful field of view. Of course an accuracy figure is attached to the calibration procedure. In general calibration allows assessing the biases and removing them. There is thus a temporal aspect to be addressed as well.
Validation is somewhat different as it corresponds to a procedure established to verify the accuracy of the retrieved geophysical parameter with respect to the actual value. Validation is consequently subsequent to calibration and requires a different approach even thought the two operations ("Cal-Val") are linked.

To perform calibration several operations are requested in the case of SMOS. The first one is performed by the instrument itself mainly through hardware (very often called"on-board calibration"). The second one is typical of SMOS and relates to the interferometry concept itself. Finally, in some cases a third step is reuired. It is very often called "vicarious calibration" and requires well-known targets and should not be confused with "validation". The issues linked to vicarious calibration are quite general to almost any remote sensing mission. In the case of SMOS, what makes this issue particularly important is that accuracy requirements on ocean measurements are so severe that there are probably no hopes of meeting them based on internal calibration procedures only.

1.2 Formulating the calibration problem

An experimental device is characterized by its response function F. If M is a number yielded by the instrument (and in the general case some data processing):

$M = F(Pi\ldots, Qj\ldots)$

Where the Pi are the input physical parameters (brightness temperatures), and Qi are the parameters of the observing system (i.e. instrument characteristics and viewing conditions). The first step is thus to assess the functional form for F (the direct transfer function), in terms of the Pi and Qj, (measurements before launch and subsequent monitoring during flight), and to implement the inverse transform in order to retrieve the parameters Pi:

$Pi = F^{-1}(M, Qj\ldots)$

Then, a logical attitude consists of defining the calibration operation as aimed at providing values for the Qj parameters with the accuracy necessary in order to achieve the required accuracy over the Pi quantities.

These remarks seem evident. Indeed the on-board calibration system proposed for the SMOS instrument aims at exactly that: estimating gains, noise levels, phase shifts and the like. However the perspective is bound to change when considering calibration using vicarious sources. The reason for this is that, in the internal calibration, one refers explicitely to the **direct** transfer function, implying an accurate modelling of the instrument (which is not a simple one…). When adressing external calibration, one has to refer to the **inverse** transfer function. In the SMOS case, F^{-1} is so complicated that it may turn out, at least in a first step, that it is not manageable to adress directly the problem of measuring the Qj. The most natural thing to do then will be to assume an **approximate** form for F^{-1}, simpler than the actual one. Then the aim will be to measure a set of "empirical" parameters Q'j , which characterize the approximate transfer function; the task of relating the Q'j to the actual Qj becomes a step to be considered later and separately.

1.2 Calibration versus validation

Let us consider the whole SMOS mission as aimed at providing measured values of physical quantities for various degrees of elaboration. In our case typical levels are: brightness temperatures T_B, surface parameters such as soil moisture. There are two ways of using external data available in addition to data provided by the instrument: either such external data are entered in the processing of SMOS data, or they are not.

In the first case, we shall speak of calibration data. For instance Sea surface salinity of a welkl knwon area is used to inferdrifts of the instrument

In the second case, it may happen either that data are used for validation (if there is a possible comparison between external and internal values which are expected to be the same) of a geophysical retrieval scheme, or that they are used for further scientific work by combining them with SMOS data. We would speak then of validation.

Therefore this distinction between calibrartion and validation does not depend on the nature of the data (their level of elaboration), but only on the purpose to which they are used. It can only be expected that calibration is carried out continuously while validation will be more time limited experiments Actually cal and val data may have exactly the same nature: assuming we have a set of T_B, there is nothing to forbid us to select half of this set for calibration purpose and then use the other half for validation.

In what follows we consider data to be used for calibration purposes. But there is no difference, until we decide how to use them.

2. SMOS measurements

The SMOS sensor consists of about 80 dual polarization radiometers, with antennas which are as identical as possible (and well characterised individually), and set along identical orientations for each polarization. Note the copolar pattern of the antennas is very broad: about 70° for the half power gain, which corresponds to a typical area about 5000 km wide on the Earth surface. Actually, since the antenna axis will be tilted, the area seen by the radiometer will be much larger than that and extend (along track) up to the horizon line.

Considering the SMOS system, two categories of biases needing calibration can be identified.

1. The first one is related to the "absolute" value of the brightness temperature measured. The concept relies on the use of total power radiometers. For this topic, the classical methods can be used (calibration of the radiometer).
2. The second one corresponds to the relative errors in the reconstructed map of brightness temperatures. They are related to phase ands amplitude errors, correlator's offsets, pointing errors, etc.. They are specific to the interferometry concept.

2.1 Total power

Among the radiometers located on the instrument, several (1 plus redundancies) are total power radiometers which will provide total power measurements, i.e., quantitative measurements of temperatures integrated over the whole antenna pattern. That is, one obtains, as the (processed) output of one receiver, say for antenna port X[1]:

$$\langle A_X \rangle \sim S_X \; (N_X + \langle T_X \rangle)$$

S_X is a radiometer transfer coefficient (slope), **assuming a linear response** within the operating range; N_X will correspond to an equivalent input noise temperature.

The radiative temperatures on the antenna port $\langle T_X \rangle$, $\langle T_Y \rangle$ are related to the field of upwelling britghness temperatures T_H , T_V:

$$\begin{pmatrix} \langle T_X \rangle \\ \langle T_Y \rangle \end{pmatrix} = \iint_{\Omega} [\Gamma][\Psi] \begin{pmatrix} \langle T_H \rangle \\ \langle T_V \rangle \end{pmatrix} d\Omega$$

Where:

- Ω is the solid angle ;
- T_H, T_V are the upwelling radiative temperatures reaching the radiometer[2];
- The coefficients in the $[\Gamma]$ matrix, which depend on Ω, are gain pattern functions;
- The coefficients of the $[\Psi]$ matrix depend on Ω and the antenna tilting angle; they characterize the geometrical transformation from upwelling radiated fields to fields collected on the antenna ports.

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And hence the radiometric temperature:

$$\langle T_X \rangle = \langle A_X \rangle \; / \; S_X \; - N_X$$

Note that if the beam were narrow, this equation would reduce to: $A_{0X} \sim N_X + S_X \; T_H$, with T_H being the upwelling T_H on the axis. However, as we know, this is far to be the case

One can seen that calibrating the total power radiometer amounts to estimating the N and S pairs of coefficients, leaving aside for the time being the matter of pattern and angle coefficients.

2.2 Interferogram

Most of the radiometers are used to compute 1-bit correlation products, from which visibility functions are extracted; then the reconstruction yields a map of "**normalized**" brightness temperatures in the solid angle $M_X(\Omega)$, $M_Y(\Omega)$ on the antenna ports.

The parameters involved in the reconstruction process are many; they include sets of gain pattern coefficients similar to the Γ coefficients above (but dependant upon each antenna in the interferometer). They involve many error sources: linked either to the channel (channel errors) or to the pairs of channels used to build the correlation products (baseline errors). Moerover all these physical parameters of the SMOS instrument are intermingled in the reconstruction process.

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[1] Here we have written an equation for one of the (X,Y) antenna ports ; the expression fort the Y port would be similar

[2] Note that Faraday rotation will occur between the surface and the sensor

2.3 Obtaining target brightness temperatures

For every solid angle, the temperature values on the antenna port are obtained by multipying the M fields (normalised TB) by total power radiometer data:

$T_X(\Omega) = \langle T_X \rangle$ x $M_X(\Omega)$

Here we meet a potential difficulty, linked to the matrix for geometrical field transformation $[\Psi]$. Is it allowed to apply this transformation from the $T_{X,Y}(\Omega)$ to the $T_{H,V}(\Omega)$ **after** the reconstruction, in a separate step ? Or does one have to account for the $[\Psi]$ matrix in the reconstruction process itself?

Right now the answer is not completely clear. Pending clarification, we consider that the level of data where calibration operation using actual observations may be carried out is the level of radiative temperatures on the antenna port $T_{X,Y}(\Omega)$. The reason for this is that it is always possible on one hand to apply the reconstruction limited to the $T_{X,Y}(\Omega)$ values; on the second hand to build TX,Y(Ω) values from observed $T_{H,V}(\Omega)$ values. Of course this is only a first step.

2.5 How it will be done with SMOS

In summary, the onboard calibration will have to be designed to monitor system inperfections so as to eliminate the biases. The main sources of error due to the hardware are:

1. the antenna inperfections: non similarities, position and pointing, oscillations of the arms, antenna voltage ripples (phase and amplitude), cross polarisation;
2. the receivers' errors which can be attibuted to a receiver: amplitude,in-phase, quadrature errors, noise injection network errors;
3. the receivers' errors which cannot be attributed to a receiver: phase and amplitude errors,;
4. other baseline errors: offesets in correlators,

The design ogf the instrument should be directed towards accounting and minimising these errors to achieve a good calibration.

For the reconstruction errors, several approaches are investigated. Oviously problems to deal with are closely linked to some of those expressed above. Five methods are currently considered.

1. The first to come to mind is the direct method where a very good knowledge of all the error sources are well known 'antenna patterns, phase amplitude and UV plane unbalance) From this knowldge a conjugate phasor function can be build for the real system. This method is obviously difficult to achieve and accuracy is very dependent on the actual knwoledge of the system.
2. The second one relies on the phase/amplitude closure (based on the baseline redundancies).
3. The third one relies on imaging a known point source of adequate level (as many point sources as possible to measure visibility) to assess unbalance. The problem with this methods is that, working in a protected band does not allow to have artificial point sources.
4. The pseudo "clean algorithm": it relies on a source composed of point sources in a uniform background. Through iterations, the background /brightest point are scales to be repklaced by a clean synthesised beam
5. The "maximum enthropy" method: with a scene model the image giving the maximum entropy and fitting the knwon visibility is reconstructed

For all the five methods, the accuracy is yet to be assessed especially wrt realistic magnitudes and distribution. Most probably a set of methods will have to be used.

In conclusion one can see that the SMOS system by itself will not be able to perform a real calibration for the interferometry part. It will be necessary to use vicarious sources to be able to reach the mission objectives. To identify suitable point sources (islands?) will probably require a specific study.

3. Measurement errors

Before going further, it is useful to review briefly random and systematic measurement errors.

3.1 Random errors

Total power radiometer: a "snapshot" measurement will suffer an uncertainty ΔA due to radiometric sensitivity, that is

$$\Delta\langle T_X\rangle \;\tilde{}\; (N + \langle T_X\rangle) / \mathrm{sqrt}(\beta\ \tau)$$

Assuming a bandwidth β=20 MHz, a snapshot integration time $\tau = 0.3$ s, a noise temperature N = 180 K, the signal temperature = 200K yields ΔA ˜ 0.16 K

Interferometric data: the **order of magnitude** of the radiometric uncertainty due to the C factor over the "denormalized" T_B values A x C is the product of the total power radiometer error by the number of elementary radiometers, which is about 80. There is some reduction (by a factor of about 2) due to apodization over the reconstructed T_B map, in such a way that for a snapshot this resulting uncertainty is of the order of 0.16 x 80 / 2 # 6 K (near the antenna axis).

Therefore the relative uncertainty due to the total power radiometer in the A x a product is negligible.

3.2 The rationale for accuracy requirements

The accuracy requirement for SMOS is mainly driven by the salinity retrieval requirements. It is known that the sensitivity of the T_B to the surface salinity is of the order of 1 K for 3 PSU. Therefore reaching the GODAE requirements calls for an accuracy on the T_B of about 0.03 K.

As just indicated, the random uncertainty over a snapshot T_B measurement is of the order of 6 K or more. This uncertainty can be reduced by:

A factor of 5 due to preintegration over 3 seconds for each polarization (dwell time 20 km).
A factor of about 30 due to the multiangular diversity
A factor of 50 for space integration (5 across track for mean 40 km pixel size, 20 along track for 10 independent 20 km long samples)
A factor of 4 for time integration (orbits)

Globally, one has about 30 000 independent samples, allowing to bring the 6 K random uncertainty down to 0.035 K. Therefore we are close to the GODAE specifications. This is less optimistic than initially estimated in the COP-16 SMOS proposal to ESA, because it turns out that the current design option makes it very difficult to bring the basic noise figure of the receivers down to values given in COP-16.

In view of the performances to be hoped for concerning random uncertainties, it is consistent to require comparable performances for systematic errors; this is the purpose of the calibration efforts.

3.3 Source of inaccuracies

If the response function were perfectly known, and the values of parameters entering it were also perfectly known and stable, there would be no calibration problems. Problems arise because:

The response function may not be perfectly known;
The parameters are not perfectly measured before the flight;
These parameters vary during the flight

This 3rd issue deserves some further consideration. Without going into any detail, one can think of four reasons the instrument parameters vary:

Random fluctuations;
Slow drifts due to aging;
Sharp variations due to "events" (failures, energetic particles…)
Systematic variations.

While we are not too much concerned with random fluctuations (because they merge with other source of random errors and hopefully can be averaged out as well, even though this certainly deserves further investigation), the calibration should correct for other errors. In this respect, it is worth stressing the possibility of systematic variations, due to the fact that thermal and mechanical cosntraints are likely to vary in a systematic way along the orbit.

If the picture seems grim so far, there are also some reasons for optimism: carefully designed space borne radiometers (see ERS1) show a very steady and stable response with time.

It is also worthwhile to separate the different sources of biases as a function of their time scales.

1. The short time scale is mainly linked to the high freqeuncy evolution of the system (receivers, oscillations of the structure etc..).
2. The medium scale which corresponds to an orbit and is mainly linked to thermal cycle constraints and has a repetitivity (i.e. can be seasonal)
3. The long-term evolution, which corresponds to, trends (aging of the components for instance).

Point 1 should be addressed through on board calibration, point 2 through calibration and possibly modelling from previous data and vicarious calibration. Point three can probably be only addresssed with use of vicarious calibration.

4. Limitations for calibration using vicarious sources

We will now address the specific issues linked to vicarious calibration. We consider targets on the Earth surface. The idea of looking at the deep sky background has been evaluated. It is certainly feasible with the spacecraft, but it seems that the background unformity might not be optimal. A specific study might be required

So on the Earth the basic situation is that the target will be small with respect to the whole antenna pattern: thus, it will amount to a small number of SMOS pixels.

4.1 Error on the set of SMOS data

Random errors. In order to detect 0.03 K, one must have 30 000 independent samples. Removing the factor of about 30 provided by angular diversity and the factor of 5 due extending from the snapshot to 1.5 seconds (2 polarisations in 3s), this leaves 200 independent data. The specification is at least the same as for the measurement. One should in addition beware of pointing errors..

Systematic biases: if the calibration targets are for various locations along the orbit

4.2 Errors on calibration data sets

It is very likely that (at least) random errors will also be present in the calibration set, in which case the necessary number of data will be higher.

The **accuracy of calibration data** also has to be considered. We have the actual physical values at the surface (with some uncertainty) and must reconstruct Tb through modelling with the required accuracy. It is thus necessary to know perfectly well the direct model. It is also necessary to separate random and systematic errors (in the modelling as well). Finally, one must be aware that, especially when looking at extended targets, the required accuracy makes it necessary to account for contributions from the atmosphere, the ionosphere, and, in addition, to account for smearing effects on incidence angles in SMOS data.

4.3 Field of view issues

We come now to what seems to be a major difficulty. For the absolute calibration, we have to rely on the total power radiometer calibration. The factor due to the total power radiometer includes the integration of brightness temperatures over a very large solid angle (representing about 1000 km), when data available for calibration will be specific of a (comparatively) small area, the size of a few smos pixel. There will never be (unless perhaps considering the deep sky) an adequate set of experimental data to calibrate the total power radiometer. The oceans are not uniform and/or well known over such a large extent (the spatial correlation for salinity is expected to be of the order of a few hundred kilometres, the influence of wind and temperature will also be significant, and rain cells are bound top be present). Over land it is not possible to find such atrgets. The only possible solution currently considered is the antarctic polar ice cap where relatively large uniform areas can be found. The size would be similar to that found over the oceans but with less perturbating factors (wind, spatial variations, isotropy, atmosphere and rain). Such an area would also be observed more often. One should also bear in mind that long term calibration with ground targets requires addressing the climatic evolution issue.

5. Linear approach

5.1 Formulation

Let us assume that the response and noise of the TPR are known with small errors. Then the measured value for $\langle T'_X \rangle$:

$$\langle T'_X \rangle = K_0 + K_1 \langle T_X \rangle$$

Similarly, let us assume the response of the interferometer can be written in a linear form:

$$M'_X(\Omega) \sim k_0(\Omega) + k_1(\Omega) \; T_X(\Omega) / \langle T_X \rangle$$

The linearisation is a bold hypothesis. However, it may not be hopeless to assume that over a small range the variations of the system parameters result in a linear variation (keeping in mind that the reconstruction process is basically linear).

Introducing the ratio to the radiometric temperature integrated over the whole pattern is another hypothesis. Still, this seems consistent with the way the whole pattern temperature is used.

In these formulas, the K_0, $k_0(\Omega)$ are assumed to be small, K_1, $k_1(\Omega)$ are assumed to be close to unity.

Combining both yields:

$$T'_X(\Omega) = \langle T'_X \rangle \text{ x } M'_X(\Omega)$$

$$= K_0\, k_0 + K_0\, k_1\, T_X / \langle T_X \rangle + K_1\, k_0 \langle T_X \rangle + K_1\, k_1\, C$$

Here we can neglect the 1rst term, and use the measured values in terms 2 and 3 since they are assumed small. Therefore, we obtain a linear formula where the integrated temperature for the whole field has been eliminated.

5.2 Operation

The calibration data set provides us with measurements, which allow us to compute "true" T_X values for specific locations in the FOV (i.e. W values). The associated SMOS measurements provides corresponding $T'_X(\Omega)$ values. The calibration consists in estimating the k coefficients.

However, staying with the estimation of random errors indicated above, there is no way of estimating the directional coefficients, because the random error on each indicvidual measurement will be too high.

Also, there is the matter of systematic variations along the orbit.

Hence 3 steps:

1. Try to obtain K0 and K1, assuming errors on the k0 and k1 are simply random and add to the noise, therefore the k0=0, the k1=1. In this step try to achieve calibrations over several targets spread over latitudes.
2. From various targets, test the systematic variation along the orbit.
3. Finally adress the problem of calibrating the k0 and k1. This will take several monthes of data…

6. Conclusion

This document intends to be a first step towards the definition of a calibration procedure for SMOS. It is intended thus to be a working document open for discussions. It seems that for achieving a good calibration we will have to work on several levels, which are unfortunately closely interelated with all the complexity it will entail.

The first point is the instrument calibration itself with both the hardware (i.e.antenna +receivers) and interferometry. This will not be sufficient and vicarious calibration will be required as well, leading to specific issues as explained above (targets, temporal variations, modelling). These issues can only be addressed through further studies and use of the end to end simulator.

The second point is related to the protocole for vicarious calibration. The issues are linked to the choice of suitable targets (i.e, size, stability and knowledge) and corresponding time scales. If long-term stability could probably be addressed with use of time/space averages (with the caveat of climatic trends) short-term stability will have to be derived (requiring being able to simulate the orbit cycling).

The third point is the distinction between absolute and relative calibration. The first one requires a large target to be viewed (and known) and very good total power radiometers. Relative calibration will require a good knowledge and modelling of the instrument (errors in receivers will translate into errors in Tbs) and of the reconstruction. It will be necessary to use long-term calibration here as well (random errors precludes the use of "single shot" acquistions).