# Introducing calibration issues

Note for SMOS SAG[1]

30/11/2000

# 1General remarks

## 1.1Purpose

This document was made following a suggestion made during the 3rd SMOS SAG meeting. Its purpose is to initiate discussion on calibration issues. To achieve this goal the need for vicarious calibration is identified. Possible investigations are suggested together with foreseable difficulties. Some of the work /studies to be performed are then sketched.

## 1.2 What is calibration

In general terms, the purpose of calibration is to define a relationship, for a set of measured parameters $P_j$, between "uncalibrated" values $P_j$ and "calibrated" values $P'_j$ deemed to be the best estimates for actual values: $[P'_j,\dots] = F_j\ ([P_j, \dots])$. The $F_j$ relationships might be simply defined as a sequence of $[P'_j,\dots, P_j, \dots]$ vectors throughout the whole ranges considered for the measurements.

Most of the time however, **analytic** forms stipulated by parameters $k_m$, can be assumed for the $F_j$; then, the purpose of calibration is to determine the optimal $k_m$ for a set of functions: $[P'_j,\dots] = F_j\ ([P_j, \dots], k_m \dots)$;

In most cases, there is a **single** measured quantity P; often, also, F(P) is a **linear** function; in which case two $k_m$ parameters only (i.e. $k_0$, $k_1$) are needed. Total power radiometry (TPR) measurements offer a convenient (and relevant) illustration. Looking at this example however, one sees there are actually **two ways** to approach the calibration problem:

- The first one is based on an **approximate instrument model**; then, assuming that a quadratic detection law holds over the relevant range, a linear response curve actually results, with parameters ($k_0$, $k_1$) having well identified physical meanings, related to the noise figure and to the gain of the measuring device.
- Another way is to **ignore** any physical model and to assume that anyway, in a restricted range, the response curve can be assumed to be linear.

In the case of a TPR, the distinction is not immediately apparent, since the **basic** operation of this device is so simple (even though operating it correctly may require enormous care…). When using for example a couple of well known sources ("hot" and "cold" loads) in order to carry out an internal calibration, we actually consider the radiometer to be a "black box" with a linear response; at the same time we are aware that the meaningful instrument parameters, input noise and gain, will be provided by the calibration measurements However, in the case of interferometry, we shall have to keep this distinction in mind later on.

Losing hardly any generality, the "uncalibrated" data itself can be elaborated in such a way that P' does not differ much from P. This can be achieved by using, in order to compute P, approximate calibration data. Then the calibration formula reads: $P' = k_0 P + k_1$, where $k_0$ is close to unity and $k_1 << P$ over the relevant range of P values.

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[1] This is the initial version prepared par P. Waldteufel. It has benefitted from fruitful exchanges with Yann Kerr, Jacqueline Boutin and Chris Ruf.

## 1.3 Calibration versus validation

Let us consider the whole SMOS mission as aimed at providing measured values of physical quantities for various levels of elaboration. In our case typical levels are: visibility functions, brightness temperatures $T_B$, surface parameters such as soil moisture.

There are two ways of using external data available in addition to those 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 well known area is used to infer drifts of the instrument

In the second case, it may happen that external data are used for checking the consistency between those data and data provided by SMOS. We would speak then of **validation**.[2]

Therefore, the 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 based on time limited experiments. Actually cal and val data may have exactly the same nature: assuming for example 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 Summarizing the SMOS instrument and outputs.*

## 2.1 interferometric measurements, reconstruction

The SMOS basic sensor consists of many dozens of dual polarization radiometers. Antenna properties and receiver characteristics are made as identical as possible.

The signals yielded by those radiometers are used to compute time integrated, 1-bit correlation products, which are downlinked to Earth. From those, visibility functions are extracted; then the reconstruction yields a map of "**normalized**" $T_B$ $M_{Xi}(\Omega_i)$, $M_{Yi}(\Omega_i)$ on the antenna ports X and Y[3], for every solid angle direction $(\Omega_i)$ .

The reconstruction operator is basically a 2D inverse Fourier transform. However it is actually hugely complicated because it is necessary to account for intrument parameters which are specific of each receiving channel and each couple of receiving channels (baselines). In addition, a fringe washing correcting function (due to the finite instrument bandwidth) has to be introduced.

For the reconstruction, five approaches have been mentioned to the SMOS SAG: direct method, making use of phase/amplitude closure relationships, using external point sources, "clean" algorithm, "maximum entropy" method. For all five methods, the accuracy is yet to be assessed especially wrt realistic magnitudes and distribution.

Most probably a combination of methods will have to be used. This is all the more true since, in this list, 2 types of issues are actually considered together: one is the numerical method for dealing with the reconstruction (i.e. inverting the visibilities/ normalised $T_B$ relationship); this other one is measuring, or setting constraints upon, the parameters which are necessary to specify the reconstruction operator. The second range of considerations is close to calibration issues.

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[2] It may also happen that they are used for further scientific work by **combining** them with SMOS data.

[3] Concerning this notation, see the last item of section 5.

## 2.2 Total power measurement, brightness temperature mapping.

In addition to the interferometer, several (1 plus redundancies) total power radiometers (TPR) on board SMOS will provide total power measurements, i.e., quantitative measurements of $T_B$ integrated over the whole antenna pattern. That is, one obtains, as the (processed) output of one receiver, say for antenna port X, estimates of the brightnesss temperature $\langle T_X \rangle$ integrated over the antenna pattern.

For every direction $\Omega_j$ within the solid angle, the temperature values on the antenna port are obtained by multiplying the M fields (normalised $T_B$) by TPR data:

$T_{Xj}(\Omega_j) = \langle T_X \rangle$ x $M_{Xj}(\Omega_j)$

# *3 About on-board calibration*

## 3.1 The need for calibration

The parameters involved in the reconstruction process are many; they include sets of gain pattern coefficients. 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). Moreover all these physical parameters of the SMOS instrument are intermingled in the reconstruction process.

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. Such problems are likely to arise because:

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

The theroretical problems associated with 2D radiometric interferometry have been investigated in depth; therefore there is no reason to believe that we shall not know correctly the instrument response function. Specifications for before flight measurements are to be adressed during the industrial Phase A. This leaves us with the 3$^{rd}$ issue.

Without going into any detail, one can think of four reasons why the instrument parameters vary throughout the flight:

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

We are not too much concerned with random fluctuations on time scales shorter than the elementary integration time (for SMOS, circa 3 seconds), because they merge with other source of random errors and hopefully can be averaged out as well. We are, on the contrary, very much concerned with fluctuations on time scales ranging from this limit to the time interval bvetween calibration operations, and this is where short term stability requirements will have to be explicited. Still, by definition, calibration is unable to deal with such fluctuations.

The calibration, now, should correct for other errors. In this respect, it is worth stressing the possibility (case 4) of **systematic** variations on various time scales, due to the fact that the structure might undergo mechanical oscillations, and that thermal and mechanical constraints are likely to vary in a systematic way along the orbit, or with time of year, etc..

## 3.2 On board calibration subsystems and their shortcomings

Several calibration subsystems hare being considered for the SMOS interferometer. They involve noise injection (either correlated, or uncorrelated) and are meant to measure phase and modulus imbalances as well as offsets in the receivers.

A careful calibration subsystem is expected to be present for TPR.

This being said, the on board calibration subsystems have short comings, basically in 3 areas:

1. It is not warranted that on board calibration will reach the accuracy required for ocean measurements. Most of the figures quoted in the MIRAS pilot project are in the range of 0.5 K to 1 K, whereas the ocean requirements for accuracy are better than 0.1 K.
2. Parts of the instrument are outside the calibration loops. Specifically, what lies in front of the calibration switch, and includes the antenna characteritics and mismatch, as well as the consequence of coupling effects.
3. There may be a lack of reliability in the calibration subsystems themselves: this was illustrated in a recent analysis by C. Ruf concerning the aparent drift of one of the channels of the TOPEX radiometer.

These reasons, at least for items 2 & 3, are not SMOS specific at all, and they are acknowledged. For item 2, it is hoped either that the resign will reduce error sources to negligible levels, or that before flight measurements will keep their reliability throughout the flight.

All in all, however, this accounts for the need for external calibration.

## 3.3 Specific SMOS difficulties

What is SMOS specific is 3-fold:

1. Radiating elements used in the mission have a wide antenna patterns. The antenna pattern is about 70° for the half power gain, which would correspond to a typical size of about 1000 km for a 3 dB contour on the Earth surface when nadir looking. Actually, since the antenna axis will be tilted, the area seen by the radiometer will be much larger than that and might even extend (along track) up to the horizon line and beyond it into the sky. Moreover about half of the main beam integrated gain lies outside the 3 dB contour.
2. The instrument response function is enormously complex;
3. The accuracy requirements are very severe, at least for the measurements over the ocean, which correspond to the lower end of the TB bracket (60 150 K); for the warm end (150-300 K), requirements are less stringent.

# *4 Vicarious calibration discussion*

## 4.1 TPR calibration on Earth targets

Due to the wide antenna pattern of SMOS antennas (see above), there seems to be no hope to obtain ground truth data allowing to compute a $\langle T_B \rangle$ that might be compared accurately to the TPR measurements

Another possibility: use statistical methods similar to those developed by C. Ruf for the TOPEX radiometer.

Should one select homogeneous zones as much as possible (large ocean area, no islands )? The selection will be made naturally if looking at the lower end of the $T_B$ histogram.

In any case the **Faraday rotation** issue should be kept in mind (hence prefer the morning orbit, as a minimum)

Problem of the hot source: is there a hope to use the upper end of the $T_B$ histogram ? That might correspond to zones dominated by thick forests. However, assimilating thick forests to blackbodies is not proven (see work by Catherin Prigent over the Amazon basin).

Possibly for the hot source the accuracy of internal calibration for the TPR will prove adequate?

## 4.2 Interferometer calibration on restricted Earth targets

Let us assume that the response and noise of the TPR are known with small errors. Then the measured value for $\langle T' \rangle$ reads (we drop from now on the antenna port subscript):

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

Similarly, let us assume the response of the interferometer can be written in a linear form; then, for a given direction $\Omega_i$

$$M'(\Omega_i) \sim k_{0i}(\Omega_i) + k_{1i}(\Omega_i)\, T(\Omega_i) / \langle T_X \rangle + \Sigma_{j \neq i} [\, k_{0j}(\Omega_j) + k_{1j}(\Omega_j)\, T(\Omega_j) / \langle T \rangle \,]$$

The linearisation such as just written is a sensible hypothesis: basically, the reconstruction operator is a linear one. However, such as it is, it is hopeless. Therefore we are going to consider the possibility that this expression might be simplified by ignoring the "crossed" dependencies:

$$M'(\Omega_i) \sim k_{0i}(\Omega_i) + k_{1i}(\Omega_i)\, T(\Omega_i) / \langle T \rangle$$

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 $\langle T' \rangle$ and $M'(\Omega_i)$ yields:

$$T'(\Omega_i) = \langle T' \rangle \text{ x } M'(\Omega_i) \sim K_0\, k_{0i} + K_0\, k_{1i}\, T\,(\Omega_i) / \langle T_X \rangle + K_1\, k_{0i} \langle T \rangle + K_1\, k_{1i}\, T(\Omega_i)$$

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

Having an adequate number of measurements should allow to obtain a system from which coefficients K and k can be estimated.

Certainly the simplification hypothesis above is very bold. It is absolutely necessary to investigate, through simulations, whether it holds water (possibly for a restricted category of scenes), or whether other simplifying assumptions are permitted.

Another serious difficulty is linked with **random errors**. The accuracy of SMOS measurements for a given pixel on the FOV is poor, and a lot of averaging has to be carried out. Retrieving empirical calibration coefficients over the whole FOV might necessitate a long period. If one wants to bring random uncertainties down to a level compatible with the ocean accuracy requirements (about 0.03 K), several tenth of thousands of snapshot data have to be averaged.[4]

## 4.3 Vicarious calibration using visibilities

As just seen, calibrating the instrument on specific, restricted areas on the Earth surface is going to be quite difficult (which means in other words that such ground truth data would probably be better suited to **validation** purposes). The basic reason for this is that one has to go through the reconstruction process. For one thing, the resulting situation is that there is then a considerable distance between the instrument response as derived from physical modeling and the data involved in the calibration process (indeed, the few remarks here above in 1.2 were made in view of this situation!). For another one, a tremendous loss in radiometric sensitivity is undergone when doing so.

Considering now correlation products, the second drawback disappears: the random error on a "snapshot" correlation product is quite small. The first drawback is considerably diminished, since each correlation product is associated with a well defined baseline, allowing at least some connection between measured values and the physical instrument parameters.

Obviously, difficulties are to be expected when using correlation products. Probably, it has never been done in Earth remote sensing; therefore here a whole new field opens.

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[4] It should be remembered that in the measurement itself this high figure is achieved by extending the snapshot duration, then combining several tens of data with various incidence angles, then space averaging (over 200 x 200 km areas), then time averaging (several orbits)

The vicarious physical quantities (or properties) to be used in the calibration process are visibility functions, which basically represent the spatial structure of the $T_B$ field for the scales (and orientations) specified by the relevant interferometric baselines. For an homogeneous scene at ground level, the overall spatial structure would be dominated by the incidence angle dependancy (with some ripples due to windowing effects). That would affect the short beselines.

What about inhomogeneous scenes (and large baselines)? Most likely, it will be very difficult to obtain the corresponding information over a full field of view area, therefore looking for the stationarity of statistical data properties like in the TOPEX radiometer case seems the best bet. But in the TOPEX case the main underlying assumption was the stationarity of minimum ocean temperatures. What can be said about the stationarity of brightness temperature spatial structures?

The next problem consists in relating the calibration data to instrument characteristics. On the one hand, we will have expected, probably statistical, properties of the visibility function; on the other hand, we will have SMOS measured correlation products. Most instrument characteristics, both for channel and baseline properties, are involved in this comparison. It remains to determine how either separate information (with respect to these various system paramters) can be extracted from the comparison, or global calibration properties can be built in a meaningful way.

## 4.3 The deep sky

According to platform engineers, there is a possibility to turn the satellite upside-down once in a while (possibly as often as once a month or so), and thus to point the antenna toward the deep sky.

The possible use of this configuration for calibration purposes certainly deserves investigation (such an investigation is part of the industrial Phase A). Its interest has nevertheless to be established as it is not obvious. In the SMOS bandwidth, sky is cold but by no means an homogeneous source. Furthermore, the random uncertainty considerations are still with us (i.e.: untertaking a calibration over a restricted area in the field of view will require a lot of integrating time).

Also, the sun contribution has to be looked into.

# *5 concluding remarks*

As might be expected, the output of this note consists more of question marks and delineating future work than answers.

1. Among the preparatory work to carry out with in mind vicarious calibration, there ought to be on emphasis on simulation. Several kind of simulations are needed; representative scenes in the space of visibility functions, climatological analysis of simulated scenes…

   In another domain, it is important to assess as well as possible systematic error sources due to thermal and mechanical variation throughout the flight.

2. We should reanalyse the role of internal calibration. This must wait until we are better able to assess the performance of external calibration, but as the work goes along we should be able to better define the respective roles. For example, in the TOPEX case studied by Chris Ruf, the result was to understand what went wrong, and it turned out that the problem actually came from a long term drift in a component associated with the internal calibration subsystem. After understanding this and correcting for the drift, it became possible again to rely on the internal calibration.

   Therefore one might think of vicarious calibration as a way to check the internal calibration. What complicates matters for SMOS is that we are not sure to which extent the internal calibration system will be able to achieve performances in line with science requirements over the ocean. Certainly, at the present time we are still less sure about vicarious calibration, so the discussion must wait.

3. In any case, calibrations will not provide data over very short time periods. Therefore the need for excellent short term stability is still crucial. In this respect, note that the short term stability of the TOPEX radiometer channels was of the order of 0.25 K r.m.s.

4. Throughout the note, we have "bypassed" the fact that signals collected by the SMOS antenna (subscript X, Y) are linked to upwelling signals ($T_H$, $T_V$) by a complicated relationship which involves both geometrical and antenna pattern factors. The collected fields are combinations of upwelling horizontal and vertical fields. This step (which is not yet completely sorted out) introduces a further complication in processing SMOS data, and in the vicarious calibration operations as well.