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Development and Calibration of SMOS Reference Radiometer

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Abstract—Three flight models (FMs) of the reference radiometer of the Soil Moisture and Ocean Salinity (SMOS) mission have been developed and tested. SMOS is a joint mission of the European Space Agency, Centre National d’Etudes Spatiales of France, and Centre for the Development of Industrial Technology of Spain. The reference radiometer is a noise injection radiometer (NIR); the NIR subsystem FM has been developed by Elektrobit Microwave, Ltd., in collaboration with the Laboratory of Space Technology of Helsinki University of Technology, which has acted as a subcontractor. The NIR subsystem will be integrated into the Microwave Imaging Radiometer Using Aperture Synthesis (MIRAS) payload in 2006. MIRAS will be the sole instrument onboard the SMOS satellite. MIRAS has 66 total power receiver units (light and cost-effective front end) and three NIR units. The purpose of the NIR subsystem is 1) to provide precise measurement of the average brightness temperature scene for absolute calibration of the MIRAS image map, 2) to measure the noise temperature level of the internal active calibration sources of MIRAS [referred to as the calibration subsystem (CAS)], and 3) to form interferometer baselines, so-called mixed baselines, with the regular receiver units. The performance of the NIR is a decisive factor of overall MIRAS performance. In this paper, we present the design solutions for the NIR FMs, which enable the achievement of the mission goals set for the NIR subsystem. The results of the NIR test campaign, proving that the performance and environmental requirements are fulfilled, are also presented, and the outcome of the ground calibration campaign is analyzed. Furthermore, the orbital calibration scheme is depicted; the calibration scheme enables the NIR to measure its targets with precision.

Index Terms—Microwave Imaging Radiometer Using Aperture Synthesis (MIRAS), polarimetric radiometry, radiometry, Soil Moisture and Ocean Salinity (SMOS), synthetic aperture radimeters.

I. INTRODUCTION

L-BAND REMOTE sensing radiometers can be used to measure soil moisture [1] and sea surface salinity [2]. Both of these parameters are valuable in improving weather forecasting and climate monitoring. During the past few years, there has been a great interest in radiometric measurements in the protected L-band frequency range, 1400–1427 MHz. However, to obtain sufficient spatial resolution from space, a large antenna size is required. This is difficult using conventional real-aperture antennas. Therefore, aperture synthesis by means of interferometry is an attractive option.

In this paper, three flight models (FMs) of the reference radiometer of the synthetic aperture radiometer mission Soil Moisture and Ocean Salinity (SMOS) [3] have been designed, implemented and tested. SMOS is a joint mission of the European Space Agency (ESA), Centre National d’Etudes Spatiales of France, and Centre for the Development of Industrial Technology of Spain. Due to its architecture, the reference radiometer is referred to as the noise injection radiometer (NIR). The NIR subsystem FM has been developed by Elektrobit Microwave (EBM), Ltd., in collaboration with the Laboratory of Space Technology, Helsinki University of Technology (TKK); TKK has been the main subcontractor, being responsible for the tests, calibration, and field programmable gate array (FPGA) implementation. The engineering model of NIR is presented in [4] and the prototype in [5]. The calibration program of the NIR includes ground and orbital calibration, both vital for the performance of the instrument. The ground calibration was completed in spring 2006; the results are presented here.

The NIR subsystem, which consists of these three NIR units, will work as part of the Microwave Imaging Radiometer Using Aperture Synthesis (MIRAS) instrument [6], [7]. MIRAS is the sole instrument onboard the SMOS satellite; the prime contractor of MIRAS is European Aeronautic Defence and Space Company EADS N.V. (EADS)-Construcciones Aeronáuticas SA (CASA) Espacio de Spain. The main purposes of NIR are...
1) to provide precise measurement of the average brightness temperature scene for the absolute calibration of the MIRAS image map, 2) to measure the noise temperature level of the internal active calibration source (the calibration subsystem (CAS), [8]) for individual receiver calibration, and 3) to form interferometer baselines with the regular receiver units in the MIRAS array (so-called mixed baselines).

In the antenna measurement mode, the NIR measures the so-called modified Stokes parameters in brightness temperature, which are defined under the Rayleigh–Jeans approximation as [9]

$$\mathbf{T} = \left[ \frac{T_v}{T_h} \frac{T_3}{T_4} \right]$$

$$= \frac{\lambda^2}{k_B \eta B} \left[ \frac{\langle |E_v|^2 \rangle}{\langle |E_h|^2 \rangle} \frac{2 \Re \{\langle E_v E_h^* \rangle\}}{2 \Im \{\langle E_v E_h^* \rangle\}} \right]$$

(1)

$$= \frac{T_v}{T_h} \frac{2 \sqrt{T_v T_h} \Re \{V\}}{2 \sqrt{T_v T_h} m \Im \{V\}}$$

(2)

where $T_v$, $T_h$, $T_3$, and $T_4$ are the brightness temperatures of the vertically and horizontally polarized radiation and third and fourth Stokes parameter, respectively; $\lambda$ is the wavelength; $k_B$ is Boltzmann’s constant; $\eta$ is the impedance of the medium; $B$ is the bandwidth; $E_v$ and $E_h$ are the vertically and horizontally polarized electric fields, and $V$ is the denormalized correlation between the horizontal and vertical channels. The brackets (expectation operators) stand for the infinite time average.

As the NIR will be the absolute reference for the MIRAS measurements, its performance is of paramount importance to the mission. The challenges in the measurements are the facts that there is only one accurate external target (cold sky), the individual antennas have a wide field of view, the physical temperature of the NIR is not actively stabilized, and certain calibration parameters cannot be measured in orbit, but on ground only.

In addition to the on-ground characterization, the test campaign of the NIR FM included environmental acceptance and qualification tests [vibration, thermal vacuum, and electromagnetic compatibility (EMC) tests]. One NIR unit was tested according to qualification test limits, whereas the other two were tested according to acceptance-test limits.

### II. Reference Radiometer

The NIR has a set of requirements that are based on the SMOS mission requirements. Table I lists some of the key performance parameters. Especially noteworthy is the requirement for stability; 0.02 K/$^\circ$C is a very stringent value, considering the absence of an active thermal stabilization system at subsystem level, as well as the budgetary and schedule constraints set for the development. In the following sections, the hardware of the NIR is described and the operation is discussed in detail.

#### A. Hardware

An NIR FM consists of 1) two radiometer receivers, one for vertical and one for horizontal polarization, 2) a controller, and 3) four phase-stable low-loss RF cables that connect the controller to the receivers. The controller incorporates an antenna that receives the target noise. The NIR receivers, light and cost-effective front end (LICEF), are almost identical to the other receivers of MIRAS and have been manufactured by MIER Telecomunicaciones, Spain. Also, the antenna is identical to those of the other antennas of MIRAS (manufactured by RYMSA, Spain). Both antenna and receivers are provided by the main contractor as customer furnished equipment. Fig. 1 shows a schematic diagram of the placement of the NIR in the payload.

The functions of the controller are to 1) inject reference noise into the two receiver chains, 2) regulate the amount of the injected noise to keep the system balanced with antenna temperature or with the calibration noise from CAS, and 3) control the switches of NIR (Dicke switches of the receivers and the noise switches of the controller) according to the selected operation mode. A photograph of the controller is presented in Fig. 2. Due to practical reasons, the engineering model is shown; the FM looks the same. A schematic diagram of the V-channel of the NIR is presented in Fig. 3. The basic blocks of the controller are bias circuitry, which generates the required voltages and provides EMC protection (omitted in the figure), two noise injection circuitries and couplers (for vertical and horizontal polarization channels), and an FPGA circuitry, which controls the noise injection circuitry and frontend switches of the NIR receivers.

In Fig. 3, 1B/2L stands for 1-bit/2-level digital output for the correlator of MIRAS, used to retrieve the third and fourth Stokes parameters or to form correlations for mixed baselines.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Receiver noise temperature</td>
<td>275 K</td>
</tr>
<tr>
<td>Resolution, H and V</td>
<td>0.25 K</td>
</tr>
<tr>
<td>Resolution, 3 and 4</td>
<td>0.55 K</td>
</tr>
<tr>
<td>Stability</td>
<td>0.2 K/$^\circ$C</td>
</tr>
<tr>
<td>Stability (with compensation)</td>
<td>0.02 K/$^\circ$C</td>
</tr>
<tr>
<td>Channel isolation</td>
<td>&gt; 40 dB</td>
</tr>
</tbody>
</table>

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**Fig. 1.** Schematic diagram of an NIR unit onboard MIRAS. One NIR radiometer consists of two LICEF units, phase-stable low-loss cables, a controller, and an antenna that is identical to those in the regular LICEF-units.
B. Operation of Reference Radiometer

The NIR operates by injecting (or adding) a known and constant amplitude noise temperature pulse to the antenna signal. The level of the combined antenna signal and the injected noise is adjusted to achieve a balance with respect to a reference (or Dicke) load. This adjustment is accomplished by adjusting the length of the pulse. Both Dicke half cycles being balanced, the method removes the effect of the receiver gain and offset variations. The length of the noise injection pulse is then proportional to the antenna temperature \[ T_A \]. The amount of the injected noise is controlled by the FPGA, i.e., the feedback loop is controlled digitally. The control is based on the calculation of the noise difference between the two Dicke half cycles, and adjusting the change of the noise injection level based on this. One great benefit of this method is the fact that there is practically no possibility of the control loop starting to oscillate. Fig. 4 presents a schematic diagram of the power detector output of one receiver in NIR-A mode; this demonstrates how the noise injection balances the input of the radiometer.

The NIR has several operational modes for measuring the antenna and CAS noise temperature and for calibration. The antenna temperature is measured using a noise injection mode called NIR-A mode and the CAS noise level is measured using a noise injection mode called NIR-R mode. Also, total power modes are used, for example, for solving the receiver noise temperature. Table II lists the operational modes of the NIR. For the measurement of the receiver noise temperature, two modes are used: one has the intermediate frequency (IF) attenuator ON and the other has it OFF in order to apply the so-called four-point method (explained in for example [12]).

The equations for NIR operation are presented in the following two sections. The model for the calibration of the front end of the NIR follows the principle of the theory of the radiative transfer, i.e., \[ T' = \frac{T}{L} + \left(1 - \frac{1}{L}\right) T_{\text{phys}} \] (3)
where $T$ is the input noise temperature of a passive network, $T'$ is the output noise temperature, $T_{\text{phys}}$ is the physical temperature of the loss $L$, which is the loss causing the equivalent noise temperature of the passive network. This is defined at the input of the network as [11], [13], [14]

$$T_e = (L - 1)T_{\text{phys}} = \left( 1 - \frac{|S_{22}|^2}{|S_{21}|^2} - 1 \right) T_{\text{phys}}$$  \hspace{1cm} (4)

where $S$ refers to the scattering parameters of the network. This yields for the relation between the loss parameter and the scattering parameters

$$L = 1 - \frac{|S_{22}|^2}{|S_{21}|^2}.$$  \hspace{1cm} (5)

This definition is used for the loss $L$ in the subsequent sections (as opposed to using $S_{21}$ directly) in order to take the matching of the components into account.

In order to solve the antenna temperature, the front end and the antenna is divided in sections, as shown in Fig. 3. This is done to account for the facts that the noise injection level $T_{NA}$ needs to determined in the calibration, and that the controller, cables, and receivers are located in different thermal environments, as can be seen in Fig. 1. The equations are derived in a way similar to the ones for the prototype presented in [5].

1) Antenna Measurement: The NIR is calibrated by solving the calibration parameters $A$ and $B$ in order to solve the antenna temperature from the following equation:

$$T_A = A T_A + B.$$  \hspace{1cm} (6)

The parameter $A$ is defined as

$$A = -L_1 L_2 T_{NA}$$  \hspace{1cm} (7)

where $L_1$ is the loss of the antenna patch and $L_2$ is the loss of the intermediate layer of the antenna. The parameter $B$ is defined as

$$B = L_1 L_2 (L_{NC} L_A L_{DA} (T_{pu} - T_{t2}) - T_{t1})$$  \hspace{1cm} (8)

where $L_{NC}$ is the insertion loss of the coupler (including the connections inside the NIR Controller); $L_A$ is the loss of the cable between the coupler and the receiver; $L_{DA}$ is the loss of the Dicke switch; $T_{pu}$ is the physical temperature of the internal reference load; $T_{t2}$ is the thermal noise of the path from the coupler to the output of the Dicke switch and $T_{t1}$ is the thermal noise of the antenna defined as follows:

$$T_{t1} = \left( 1 - \frac{1}{L_1} \right) T_{p7} \left( 1 - \frac{1}{L_2} \right) T_{p6}$$  \hspace{1cm} (9)

where $T_{p7}$ is the physical temperature of the antenna patch and $T_{p6}$ is the physical temperature of the intermediate layer of the antenna, and

$$T_{t2} = \left( 1 - \frac{1}{L_{NC}} \right) \frac{T_{p3}}{L_A L_{DA}} + \left( 1 - \frac{1}{L_A} \right) \frac{T_{cab}}{L_{DA}} + \left( 1 - \frac{1}{L_{DA}} \right) T_{pU}$$  \hspace{1cm} (10)

where $T_{p3}$ is the physical temperature of the coupler and $T_{cab}$ is the physical temperature of the cable between the coupler and the receiver approximated with

$$T_{cab} = \frac{T_{p3} + T_{pU}}{2}.$$  \hspace{1cm} (11)

The level of the noise injection is determined by measuring a known target, $T_{A0}$, which is the cold sky in the case of the NIR, yielding

$$T_{NA} = \frac{1}{L_1 L_2} \left( \frac{B - T_{A0}}{\tau_A} \right).$$  \hspace{1cm} (12)

The third and fourth Stokes parameters are solved using the following equation:

$$T_3 = 2 \sqrt{\hat{T}_{Ax} \hat{T}_{Ah} \Re \{ \hat{V} \}}$$  \hspace{1cm} (13)

$$T_4 = 2 \sqrt{\hat{T}_{Ax} \hat{T}_{Ah} \Im \{ \hat{V} \}}$$  \hspace{1cm} (14)

where $\hat{T}_{Ax}$ and $\hat{T}_{Ah}$ are linearity corrected (see Section III-B) vertical and horizontal antenna brightness temperatures and $\hat{V}$ is the amplitude-corrected (the effect of the receiver noise removed) correlation coefficient. See [5] for details of the amplitude correction in the case of the NIR.

2) CAS Measurement: CAS measurement is calibrated by determining the calibration parameters $A_R$ and $B_R$. The CAS output noise temperature is solved as follows:

$$T_{CAS} = A_R T_R + B_R$$  \hspace{1cm} (15)

where $\tau_R$ is the length of the noise injection in the CAS measurement mode (NIR-R mode). The calibration parameter $A_R$ is written as

$$A_R = \frac{T_{NR} L_{DC}}{L_R}$$  \hspace{1cm} (16)

where $T_{NR}$ is the level of the noise injection; $L_{DC}$ and $L_{DR}$ are the loss of the Dicke switch in CAS measurement and noise injection positions, respectively, and $L_R$ is the loss of the cable.
Fig. 5. Calibration flow of the reference radiometer. The black rectangles depict measurements, gray ellipses depict the solving of intermediate parameters, black ellipses depict the solving of the end products, and the gray circles with dashed lines depict the application of the ground calibration values. Certain operational modes are mentioned in the black rectangles; NIR-A mode for solving the noise injection level for antenna measurement (and for solving antenna temperature), NIR-AR mode for solving the noise injection level for CAS measurement, LICEF-LC and LICEF-LC2 modes for measuring the CAS so that the IF-attenuator of the receiver is OFF and ON, respectively, LICEF-LA for measuring the antenna temperature in total power mode and LICEF-LU for measuring the uncorrelated load.

through which the noise is injected. The calibration parameter $B_R$ is written as

$$ B_R = \frac{T_{p3} L_{DC}}{L_R L_{DR}} + T_{i3} $$

(17)

where $T_{p3}$ is the physical temperature of the reference load used in the NIR-R mode and

$$ T_{i3} = \left(1 - \frac{1}{L_R}\right) \frac{L_{DC}}{L_{DR}} T_{cab} + \left(1 - \frac{L_{DC}}{L_{DR}}\right) T_{pU}. $$

(18)

The noise injection level is determined by measuring a known target, cold sky in the case of the NIR, in the so-called NIR-AR mode, which can be formulated as

$$ T_{NR} = \frac{L_R L_{DR}}{\tau_{AR}} \left( T_{ANA} - \frac{T_{p3}}{L_R L_{DR}} - T_{i3} \right) $$

(19)

where $T_{ANA}$ is the noise level in the antenna channel during noise injection and $\tau_{AR}$ is the length of the noise injection in the NIR-AR mode.

III. CALIBRATION OF REFERENCE RADIOMETER

A. Calibration Approach

The calibration approach for the reference radiometer includes two steps; 1) certain parameters are characterized on the ground and 2) these parameters are applied during orbital calibration, which is carried out frequently. The orbital calibration is based on the measurement of the cold sky, which has a well-known brightness temperature level. The cold sky is measured during the external calibration procedure of the SMOS, in which the entire satellite is pointed to the cold sky for a period of about half an orbit. Fig. 5 shows a block diagram of the orbital calibration of the NIR. In the figure, black rectangles depict measurements in the various modes of the targets. The key measurements (cold sky in the NIR-A and NIR-AR modes) are shown at the top of Fig. 5. These measurements are made in order to determine the noise injection levels $T_{NA}$ and $T_{NR}$.

This process involves ground calibration parameters, which are depicted in the figure with gray circles with dashed lines. The black ellipses indicate the solving of the end products: fully polarimetric antenna temperature, CAS noise level and correlations for the mixed baselines (which are not discussed in detail in this paper). These steps also include the application of ground calibration parameters.

Furthermore, there are measurements in the LICEF-LC and LICEF-LC2 modes, which measure the two levels of CAS (with IF-attenuator OFF and ON, respectively, in order to apply the four-point method) for the receiver noise temperature and phase imbalance measurements. The measurement of the cold sky is also performed in the LICEF-LA mode. This is for determining the so-called Corbella correlation, which is due to the finite isolation between the channels over antenna [15]. Finally, there
The equivalent noise temperature and receiver noise temperature are specified to be 35 dB at the frequency band. The applied absorber material (with 25-cm pyramids), which is better than 30 dB, based on the reflection coefficient of the connecting cable [10]. The return loss of the antenna targets is estimated when the cable is measured and compensated for using the loss of the connecting cable [10]. The cold coaxial load is cooled down with liquid nitrogen and the temperature distribution in the connecting cable. The return loss of the coaxial loads is measured to determine the residual correlation offset. Each of these steps also include the application of the ground calibration parameters.

The following parameters were solved during the on-ground characterization: 1) antenna and front-end loss, 2) the phase imbalance between V- and H-channels (or V–H phase imbalance) of the antenna and front end, 3) nonlinearity correction, and 4) the temperature dependence of the noise injection level. These parameters are applied during orbital calibration when the level of the noise injection, receiver noise temperature and V–H phase imbalance of the channels are solved. After this, the correction for the nonlinearity is applied to the measured level of brightness temperature. The calibration of the mixed baselines is out of the scope of this paper.

B. Ground Characterization Principles

1) Loss Parameters: In order to solve the loss of the different sections of the front end, the receiver noise temperature is measured in two planes; in the incoming plane and in the outgoing plane of this particular section of the front end. See Fig. 6 for clarification.

For the measurement of the receiver noise temperature, ambient and cold loads are used; either matched coaxial loads or reference antenna targets, depending on the type of the section under study. The return loss of the coaxial loads is measured to be over 30 dB. The cold coaxial load is cooled down with liquid nitrogen and the temperature distribution in the connecting cable is measured and compensated for using the loss of the cable [10]. The return loss of the antenna targets is estimated to be better than 30 dB, based on the reflection coefficient of the applied absorber material (with 25-cm pyramids), which is specified to be 35 dB at the frequency band.

The loss is solved as follows using the definition for the equivalent noise temperature and receiver noise temperature [11]:

\[ T_{\text{rec2}} = T_e + LT_{\text{rec1}} = (L - 1)T_{\text{phys}} + T_{\text{rec1}} \]  \hspace{1cm} (20)

yielding

\[ L = \frac{T_{\text{rec2}} + T_{\text{phys}}}{T_{\text{rec1}} + T_{\text{phys}}} \]  \hspace{1cm} (21)

where \( L \) is the loss, \( T_{\text{rec2}} \) and \( T_{\text{rec1}} \) are the receiver noise temperatures with and without the loss in front of the receiver, respectively, and \( T_{\text{phys}} \) is the physical temperature of the loss element.

2) Phase Parameters: Two separate setups are needed for solving the V–H phase imbalance of the front end and the antenna. The difference of the phases of the correlations measured with the two setups yields the V–H phase imbalance of the front end. See Fig. 7 for clarification. The V–H phase imbalance of the section in front of the receivers can be solved as

\[ \Delta \Theta = \arg(\mu_2) - \arg(\mu_1) \]  \hspace{1cm} (22)

where \( \Delta \Theta \) is the V–H phase imbalance of the front-end section (between plane 1 and plane 2), and \( \mu_2 \) and \( \mu_1 \) are the correlations measured with and without the front-end section, respectively. Note that, in order for this formulation to work, either the correlations \( \mu_1 \) and \( \mu_2 \) have to be measured using the same source or the correlations have to be in-phase calibrated (see, for example, [5]).

A correlated noise source connected to the two receivers of the radiometer can be used for the measurement when the antenna is not included. However, when the antenna is included, the measurement of the V–H phase imbalance on this plane is more complicated. The so-called dual-angle method can be used for this [16]. The idea of this method is to measure linearly polarized correlated noise at two different angles, which are at 90° separation and at a 45° angle with respect to the polarization plane of the antenna of the radiometer. The method comes down to the following equation:

\[ \Theta = \arctan \left( \frac{3m(M_{-45}) - 3m(M_{+45})}{\Re{M_{-45}} - \Re{M_{+45}}} \right) \]  \hspace{1cm} (23)

where \( \Theta \) is the V–H phase imbalance and \( M_{-45} \) and \( M_{+45} \) are the quadrature-corrected (see, for example, [5]) correlations obtained at −45° and +45° angles with respect to the electric field of the transmitted field, respectively.

3) Nonlinearity Correction: There are two sources of error that are taken into account in the so-called nonlinearity correction. The first is the nonlinearity of the detector of the receiver and the second is the fact that the coupling of the directional coupler is assumed to be an ideal adder in the equations of operation. To this end, the technique presented in [17], and modified by Vilaseca from Mier Comunicaciones, Spain, [18] is applied here to the case of a NIR.

Fig. 8 shows a schematic diagram of the measurement setup used in this technique. The idea is to add a constant amount of noise on top of a noise level that can be varied. The benefit of this method is the fact that the only critical parameter for the accuracy of the measurement is the stability of the added noise, which is achieved relatively easily.
The linear and quadratic correction is applied to the antenna temperature as follows:

\[ \hat{T}_A = T_A + T_{\text{lin}} \]  

where \( \hat{T}_A \) is the corrected antenna temperature, \( T_A \) is the antenna temperature before the correction is applied, and

\[ T_{\text{lin}} = c(T_A - T_0) + d(T_A - T_0)^2 \]  

in which \( c \) is the linear correction term, \( d \) is the quadratic term and \( T_0 \) is the antenna temperature during calibration.

Using (6) and (25), the length of noise injection can be written as

\[ \tau_{\text{OFF}} = \left[ \hat{T}_A - B - c(T_A - T_0) - d(T_A - T_0)^2 \right] \frac{1}{A} \]  

where \( \tau_{\text{OFF}} \) is the length of the noise injection when the additional noise is off. When the additional noise is on the length of the noise injection is written as

\[ \tau_{\text{ON}} = \left[ \hat{T}_A - B - c(T_A + \Delta T - T_0) + d(T_A + \Delta T - T_0)^2 \right] \frac{1}{A} \]  

in which \( \Delta T \) is the amount of the additional noise.

Now, the difference between the situations when the noise injection is on and off can be solved. This equation allows us to write the difference in the form of a straight line

\[ \Delta T = \tau_{\text{OFF}} - \tau_{\text{ON}} \]

\[ = \frac{2d\Delta T}{A} (T_A - T_0) + \frac{1}{A}(d\Delta T + c - 1) \]

\[ = k_1(T_A - T_0) + k_2 \]

where \( k_1 \) and \( k_2 \) are the slope and offset of the line, respectively. Now, using these coefficients the parameters \( c \) and \( d \) can be solved

\[ c = \frac{A}{\Delta T}k_2 - d\Delta T + 1 \]  

and

\[ d = \frac{1}{2\Delta T}k_1. \]

The slope of the line \( k_1 \) determines the quadratic term, and parameters \( k_1 \) and \( k_2 \) together determine the linear term. Note that \( A \) is actually the level of the noise injection, and that its changes cause only second-order uncertainty to the correction. A similar set of equations is derived for the CAS measurement.

4) Temperature Dependency of Noise Injection: A study of the temperature sensitivity of the reference radiometer’s prototype is presented in [10]. Some results for the engineering model are presented in [19]. The results showed that the fit of a linear correction model to the data points was very good (i.e., low scatter and good repeatability). The applied linear model accounts also for all the changes of loss and matching of every component correcting the fixed-loss model. Several correction models (with respect to the fixed-loss model) were studied with the prototype [10], which took the temperature changes of different components into account independently. The results showed that the model based only on the temperature of the noise source was as accurate as the models based on several measured temperatures.

The correction model is acquired by measuring a known noise source connected to the antenna output plane (which excludes the antenna from the measurement) while the physical temperature of the NIR is cycled. Additionally, the effect of the antenna and its connection is modeled in orbit during the commissioning phase of the mission. However, their effect is expected to be very small, or even negligible.

IV. GROUND CALIBRATION RESULTS

A. Antenna and Front-End Loss

Table III lists the loss parameters of the antenna and the connection between the antenna output planes and the input planes of the LICEF-units. For comparison, the loss was also measured with a vector network analyzer (VNA), also shown in Table III. The accuracy of the VNA measurement is specified to be 0.05 dB for normal range measurements, but for this kind of low-loss measurements it is worse than that; however, the accuracy of the radiometric characterization measurement is in the order of 0.01 dB. However, the results of Table III show very similar values (within 0.02 dB) for every other channel except H-channel of NIR-3 (0.06 dB). The result shows that the radiometric measurement also accounts for the matching of the front end, which is critical.

In general, the front-end losses show very similar results for the V- and H-channels; the only exception is NIR-3, which shows a small (0.10 dB) difference. A potential explanation...
for the loss imbalance of NIR-3 is the manufacturing process, which includes many manual steps. These are prone to small variations, which can lead to imbalance if summed up.

B. Antenna and Front-End Phase Imbalance

Table IV shows the V–H phase imbalance of the front end (between antenna output plane and input plane of LICEF-units) and of the antenna for nominal and redundant correlations. For comparison, the V–H phase imbalance of the front end was also measured with a VNA showing very similar results. However, the phase measurement accuracy of the VNA measurement is worse than the accuracy of the characterization measurement that uses correlations.

The results for NIR-1 and NIR-2 V–H phase imbalance are relatively equal, but the result for NIR-3 is different. A potential explanation lies in the manual manufacturing processes, as was the case in the front-end loss differences. The fact that the loss imbalance in NIR-3 is significant can explain the different V–H phase imbalance as well.

C. Nonlinearity Correction

Table V presents the nonlinearity correction parameters for all three NIR units. V- and H-channels have a systematic difference, which is explained by the different layout of the channels. Fig. 9 shows the nonlinearity correction for V- and H-channels of NIR-1 as an example. A calibration target of about 120 K, which is the output noise temperature of the coaxial reference load used in the measurement, is assumed. The correction is, at maximum only slightly over 1 K, V- and H-channels having very similar curves.

Fig. 10 shows examples of the fitted lines of (28) with slope of $k_1$ and offset of $k_2$ for V- and H-channels of NIR-1. The deviations from the line are small, indicating the reliability of the method.

D. Temperature Dependency of Noise Injection

The thermal cycling consisted of at least two cycles ranging from $+10 \degree$ C to $+40 \degree$ C, which is the operational range of the subsystem, for each unit. The results showed that the temperature dependence of the antenna and reference noise injection of both channels of all units is under 0.1%/\degree C. Due to the fact that the noise injection length (expressed as a fraction of the half of the Dicke cycle) is typically 10% to 40%, the effect of the noise injection variation on the measured antenna temperature is in

\begin{table}[h]
\centering
\caption{Nonlinearity Correction for the Antenna Measurement}
\begin{tabular}{|c|c|c|c|}
\hline
\multicolumn{2}{|c|}{c (10^{-5})} & \multicolumn{2}{|c|}{d (10^{-5})} \\
\hline
NIR-1 V & 4.69 & -2.74 & \\
NIR-1 H & 7.29 & -4.28 & \\
NIR-2 V & 4.30 & -2.47 & \\
NIR-2 H & 10.4 & -6.09 & \\
NIR-3 V & 4.86 & -2.92 & \\
NIR-3 H & 8.34 & -5.01 & \\
\hline
\end{tabular}
\end{table}

\begin{table}[h]
\centering
\caption{V–H Phase Imbalance (for Nominal and Redundant Correlations) of the Antennas and the Front-End Connections}
\begin{tabular}{|c|c|c|c|c|}
\hline
\multicolumn{5}{|c|}{\textbf{Receiver Plane}} \\
\multicolumn{2}{|c|}{Nominal} & \multicolumn{2}{|c|}{Antenna Plane} & \multicolumn{2}{|c|}{Difference} \\
\multicolumn{2}{|c|}{(Redundant)} & \multicolumn{2}{|c|}{(Redundant)} & \multicolumn{2}{|c|}{Nominal} \\
\multicolumn{2}{|c|}{\Theta [\text{deg}]} & \multicolumn{2}{|c|}{\Theta [\text{deg}]} & \multicolumn{2}{|c|}{(Redundant)} \\
\hline
NIR-1 & -49.7 (-49.3) & -38.0 (-37.6) & 11.7 (11.7) & \\
NIR-2 & -49.3 (-49.3) & -41.9 (-40.3) & 7.4 (8.0) & \\
NIR-3 & -29.1 (-30.2) & -11.1 (-11.3) & 18.0 (18.9) & \\
\hline
\end{tabular}
\end{table}
the order of 0.025%/°C. This can be reduced further by a factor of 5 to 10 using the linear model for the variation of the noise injection level with temperature.

Furthermore, it is important to note that the temperature variation in the orbit is expected to be less than the operational range. Based on the payload level thermodynamical simulations carried out by EADS-CASA Espacio, Spain, the thermal variation of the antenna patch, during one orbit, is around 15 °C, that of the controller and the intermediate layer of the antenna is around 2 °C and that of the LICEF units is around 1 °C. Also, the thermal gradient is expected to be very constant between the different components.

E. Calibration Experiment With Engineering Model

An experiment to validate the calibration approach was conducted with the engineering model using the sky and a cold antenna target as references. During the experiment sky was clear, and the sun in the horizon. The cold target was an absorber load cooled down with liquid nitrogen.

First, the calibration was performed by a measurement of the sky, and then the cold load was measured in order to compare the measurement result to the predicted brightness temperature. During the experiment, the temperature of the NIR varied strongly, and also the gradient between the components changed dramatically, which is not representative for the in-orbit case. For this reason, a dedicated thermal model was used in the analysis of the results.

Fig. 11 shows the results of the experiment for both V- and H-channels. The down arrow shows the calibration epoch and the up arrow shows the epoch during which the cold load temperature is determined.

The jumps in the plot are due to the positioning of the radiometer. The obtained cold load values are 77.6 K for the V-channel and 77.9 K for the H-channel. These values correspond well to the predicted values, as the brightness temperature of sky is assumed to be 6.6 K and the temperature of the liquid nitrogen is 77.35 K. This result shows that the concept of the calibration, i.e., one reference target with characterization of the front end, works.

V. Performance Summary

Table VI summarizes the performance of NIR FM. The noise temperature and radiometric resolution values are within the requirements in all cases. Also, the design of the coupler was very successful; very high isolation could be combined with extremely low loss and small size (10 × 10 × 1.3 mm). Furthermore, the isolation between orthogonal channels (vertical and horizontal) is very high. Note, however, that the presented figure does not include the cross-coupling of the antenna.

The stability as a function of the physical temperature does not satisfy the requirement in the cases of NIR-1 and NIR-3. However, the presented values are estimates and the measurement situation was not entirely representative. Furthermore, in the measurement the units were cycled between 10 °C to 40 °C relatively rapidly; in the orbit the thermal fluctuation of the units is, based on the simulations, around 2 °C per orbit (excluding antenna patch surface, which experiences greater excursion). Thus, the performance is considered satisfying in this respect also.

VI. Conclusion

The FMs of the NIR subsystem (reference radiometers) of SMOS have been designed, manufactured, tested, and characterized. The key performance parameters were retrieved, a ground calibration campaign was conducted and the units passed the environmental acceptance and qualification tests. In most cases, the measured performance parameters met the original requirements set for the NIR subsystem of SMOS. The only exception was the stability with varying physical temperature; it proved to be challenging to fulfill this stringent requirement under the budgetary and schedule constraints of the project. However, the modeling of the behavior with temperature and the application of software correction improve the stability. The retrieved ground calibration results will be used for the in-orbit calibration of the NIR and MIRAS. The in-orbit calibration was also designed to include the appropriate steps to fulfill the measurement purposes of the NIR.
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REFERENCES


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