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1 A method is presented for estimating the calibration error affecting L-band ground-based radiometers, using the sky as a cold source. In a first step, the optimum conditions to perform this calibration are limited by removing sky areas where large radiation contributors (Sun and Moon) are present. In the region thus selected, an accurate computation of the brightness temperature measured by the antenna is performed using available sky background temperature survey charts (radio continuum and hydrogen HI line) and integrating the sky temperature over the directional gain pattern of a representative radiometer L-band antenna. Contributions from rear lobe are not considered. After adding the atmospheric contribution, maps of the noise temperature and its error are produced for the region of interest. The best calibration orientation for a sky-looking radiometer at medium northern latitude would be 0° in azimuth (northward) and an elevation equal to the radiometer’s latitude. It is found that the computed total sky noise contribution is 6.6 K, with 24 hour variations of ±0.2 K and a maximum bias of ±0.6 K. The results are valid for the whole year, assuming low to moderate solar activity and no rain.


1. Introduction

1.1. Objectives

[2] In order to infer soil moisture from brightness temperature data obtained from spaceborne L-band (1400 MHz) radiometers, such as in the up-coming Soil Moisture and Ocean Salinity (SMOS) mission [Kerr, 1998], theories have to be developed in order to relate surface moisture to soil emissivity. In order to validate such theories, measurements are planned using radiometers that are either airborne or mounted on cranes. However, these radiometers must be calibrated very accurately, since the soil brightness temperature has to be known to within 1 K.

[3] The calibration of a radiometer is generally carried out by using two reference sources with widely separated levels, a hot one and a cold one. If the temperature of the hot source is close to the ambient temperature and that of the receiver, loss and mismatch temperature errors on a transmission line are negligible [Ulaby et al., 1981]. Accordingly, the antenna can be disconnected, and a load connected directly to the receiver can be used as the hot reference, with a very well known physical temperature (for example, to within ±0.1 K).

[4] To obtain a similar accuracy with a cold reference, lossy and mismatched components have to be taken into account, and therefore the calibration must involve the antenna, guides, and transitions, which requires the antenna to be aimed toward a cold source. The technique used for measuring absorbing loads cooled with liquid nitrogen, such as mentioned by Ulaby et al. [1981], is already known to be difficult to implement in the millimeter wavelength domain, because of changes in the reflection coefficient that are not easily eliminated when nitrogen evaporates. It also seems hardly applicable to antenna apertures of the order of 1 m such as those used in L band. Sky pointing used as the cold source seems to be easier to carry out if the radiometer and its antenna are mounted on an actuator or a gantry support to facilitate instrument tilting. Using a dedicated sky-pointing horn avoids having to tilt the main antenna upside-down, but this is not satisfactory since it does not correct errors caused by the antenna and its matching network.

[5] The purpose of the present work is to develop a sufficiently general method for determining the best
conditions to perform such a calibration and to report the corresponding values and accuracies of the sky as a cold source. In addition, to simplify the calibration procedure, the proposed method sets as a constraint to be independent of the time of day.

1.2. Organization of This Study

[6] Using the sky as a cold target requires (1) a good knowledge of the source and (2) pointing the antenna toward a stable and reliable sky region (i.e., without time variations). To reach this goal, the various L-band sky noise sources are reviewed, the strongest ones being considered as discs of uniform brightness. The characteristics of a radiometer antenna operated at medium latitude will then be described, and only an overview of the Earth’s contribution will be given, as this topic is actually outside the scope of the present work.

[7] In order to define the areas in the sky that are appropriate for radiometer calibration a first step consists in eliminating those areas where the main radiation contributors are present. Pointing directions of the antenna are determined for which these sources are liable to cause a temperature increase of more than 0.25 K on the antenna, at any given time of day for the year 2001. These regions of the sky will be rejected from the calibration procedure.

[8] In the remaining regions of the sky thus defined, in a second step, a more accurate computation of the temperature measured by the antenna is performed using available sky background temperature survey charts. After adding the atmospheric contribution, maps of the noise temperature and its error are shown for the region pointed to.

2. Sky Noise Sources in L-band

2.1. Radio Continuum and Discrete Sources

[9] The radio continuum covers in a relatively uniform way frequencies that are accessible to observation. The continuum is composed of a background radiation to which many small “bright” regions are superimposed,
due to emissions from discrete radiosources. The background radiation has a maximum spread toward the galactic center and a strong emission ribbon close to the galactic equator, with a strong maximum close to the galactic center.

Among the waves radiated as a continuum, those originating from most of the discrete sources and from certain parts of the radiating background have a partially plane polarization. The error induced by assuming that polarization is uniformly distributed amounts to a few percent when point-like areas are considered and becomes negligible when integrated over areas about 10 deg wide.

For the Northern Hemisphere, Reich and Reich [1986] published a survey of intensities measured by averaging powers obtained at two orthogonal polarizations, within a 20 MHz bandwidth centered at 1420 MHz and reduced to 18 MHz by means of a filter for rejecting the hydrogen HI emission line. The accuracy reported by the authors is 0.5 K. The data used in the present work are from the $5^\circ \times 5^\circ$ resolution finder chart (Figure 3 in Reich and Reich’s article) in galactic coordinates. Figure 1 gives an overview of this chart. For the purpose of the integration calculations described in section 5.1, where a sufficiently fine computation step is needed, this contour chart was digitized as a two-dimensional (2-D) map of $360 \times 180$ pixels, each with a size of $1^\circ \times 1^\circ$ in galactic coordinates.

The minimum level is observed near the galactic north pole (3.2 K). It should be noted that a portion of the southern sky hemisphere is missing from the available database, but this has no influence on the present study, as only radiometers in the Northern Hemisphere will be considered here.

2.2. Neutral Atomic Hydrogen Emission Line (HI)

The emission of neutral atomic hydrogen’s transition at 1420.406 MHz is conventionally known as the 21 cm HI line; its half-power spectral band ranges from 300 to 500 kHz. This radiation is nonpolarized.

In order to improve sensitivity, radiometers designed for moisture and salinity studies, which are
looking downward, utilize the 1400–1427 MHz allocated band to the fullest possible extent, and therefore it is not desirable to insert a rejection filter for sky calibration purposes only, even the more as the HI line contribution is minor, as will be shown in section 5.2.

[15] For the Northern Hemisphere, Hartmann and Burton [1997] published a chart of intensities measured over 5 years by means of the Netherlands Foundation for Research in Astronomy (NFRA) 25 m radiotelescope with an angular resolution of 0.5° in galactic coordinates. The accuracy reported by the authors is 2%, or 0.1 K. These data are available on a CD-ROM appended in Hartmann and Burton’s book. On the basis of this chart, integrated between \(-450\) km s\(^{-1}\) and \(+400\) km s\(^{-1}\), or in the bandwidth from \(-2.1\) MHz to \(+1.9\) MHz, the HI line contribution reduced to a 20 MHz band was computed. A simplified representation of this map is shown in Figure 2. A 2.6 K maximum is observed near the galactic center, with values of less than 0.5 K for angular distances greater than 10° away from the galactic equator.

2.3. Sun

[16] In the absence of solar eruptions the Sun’s radio emission is restricted to its visible disc (0.5° diameter) but is far from uniform. In L band the average temperature ranges from \(10^5\) to \(5 \times 10^5\) K [Krüger, 1979]. To be conservative, a \(5 \times 10^5\) K upper value distributed over a 0.5° diameter will be considered. It should be noted, however, that on a type IV burst during the maximum solar activity period, this temperature might increase by more than an order of magnitude.

2.4. Moon

[17] The Moon’s brightness temperature is considered to be uniform across a 0.5° disc. According to Hagfors [1970] the moon’s temperature \(T_m\) is given by

\[
T_m = T_0 + T_i \cos (\alpha - \varphi_i),
\]

where \(T_0 = 270\) K, \(T_i = 5\) K (maxima observed at the 21 cm wavelength), and \(\alpha\) and \(\varphi_i\) are the phase and the phase shift of the moon due to the thermal wave penetrating within lunar soil, respectively. For the present estimations the maximum value of 275 K will be assumed.

3. Radiometer

[18] The measurement site selected by the SMOS group for long-term moisture studies is the Fauga site (1.294°E, 43.386°N, height 187 m) near Toulouse, France. A gantry support for the L-band radiometer will allow antenna movements within a vertical plane with an orientation that will be determined according to the conclusions of the present study.

3.1. Characteristics of the Main Antenna Lobe

[19] A survey has shown that at the time of writing there were about 10 L-band ground radiometers in the world, with aperture sizes ranging from 0.5 to 1.3 m. Steerable antennas with larger dimensions are too bulky.
for convenient use, and smaller dimensions entail a too large ground illuminated area. In the present case, the antenna under development was chosen in the upper part of this dimension range.

[20] The main lobe of this antenna has an axis-symmetric pattern with a total half-power beam width of 15°. A parabolic approximation for the antenna horn radiation pattern is applicable to pattern levels from 0 to −35 dB. The first sidelobes are approximated as a flat level of −35 dB extending from ±26° to ±40°. For off-axis angles greater than ±40° the antenna pattern level is assumed to be negligible. This assumption is equivalent to neglecting the effect of ground for sky-pointing L-band radiometers at the time of their calibration. This issue is briefly analyzed in section 3.2.

3.2. Rear Lobe Characteristics and Ground Contribution

[21] Ground noise is detected from the antenna rear lobe and possibly sidelobes, according to the antenna tilt angle. Assuming that the amount of energy picked up from the ground at 300 K represents a 1% portion of the total energy received by the antenna, the contribution of ground would be 3 K. However, a value smaller than 1% can only be obtained with an antenna having very low rear lobes (>50 dB). For such an antenna a totally unobstructed aperture is mandatory (i.e., horn or offset antenna feed).

[22] In order to know the whole antenna pattern, nearfield measurements are required because rear lobe farfield measurements would be much too faint to be detected. To show how difficult this method is to implement, reference can be made to its application in the case of a microwave antenna. Breinhjerg and Lemanczyk [1990] describe the measurement of a radiation pattern using a Microwave Remote Sensing and Communications (RESCOM) radiometer having a small-beam-width antenna (1.9°). (RESCOM is a subsidiary of the Danish research and development department of ERICSSON; this radiometer was first developed at the Danish company ELEKTRONIKCENTRALEN). Measurements carried out with this offset feed and square aperture (0.65 m × 0.65 m) antenna at a 5.6 m distance, and a 0.5° angular separation between measurement points, amount to a total of 259,920 data points, or 20 hours for each polarization. Specialized software allowed the E and H plane patterns (Figure 3), as well as the pattern contribution from the lower or ground hemisphere shown.
in Figure 4, to be derived. For an L-band antenna, determining the antenna pattern, although it requires fewer points, is much more difficult to implement because of the larger antenna size.

[23] Theoretical calculations suggest that because of the wider lobe of L-band antennas the contribution of rear lobes will be larger than for the microwave case shown in Figure 4. In addition, as shown in this figure the minimum pattern contribution from the ground hemisphere is reached at elevations greater than 40°. In the same manner, this angle, which represents the elevation at which the ground contribution is minimum, will be known by determining this curve in L band.

4. Determination of the Sky Region Best Suited for Calibrations

[24] For the calibration to be independent of the time of day, the Sun and the Moon are considered as the strongest perturbing sources. In this section, we first determine what the distance must be from the axis of given antenna beams to each of these two sources for the perturbation to be less than a given threshold. From these distances the least perturbed sky region is derived over a whole year.

[25] In Table 1, four different antenna beam widths have been considered, from 15° to 40°, which correspond to the 1.3 m to 0.5 m antenna dimension range mentioned previously. For each beam width the Sun and Moon temperatures seen by the antenna are reported in column 4. Column 5 gives the beam gain at the off-axis angle required for reducing the noise contribution below the above-mentioned threshold, here chosen to be a small value of 0.25 K (this threshold value is half the accuracy of available continuum data). Column 6 gives this off-axis angle. It can be noticed that for beam widths greater than 15° the detected Moon temperature is smaller than this threshold.

[26] For identifying the least perturbed region the positions of the Sun and Moon were computed using ephemerid calculation software developed in BASIC by

<table>
<thead>
<tr>
<th>Antenna Beam Width</th>
<th>Source</th>
<th>Temperature</th>
<th>Antenna Temperature When Pointing Toward Source</th>
<th>Beam Gain for a 0.25 K Noise Contribution</th>
<th>Offset for a 0.25 K Noise Contribution</th>
</tr>
</thead>
<tbody>
<tr>
<td>15°</td>
<td>Sun</td>
<td>500,000 K</td>
<td>555 K</td>
<td>-33 dB</td>
<td>25°</td>
</tr>
<tr>
<td></td>
<td>Moon</td>
<td>275 K</td>
<td>0.3K</td>
<td>-1 dB</td>
<td>4°</td>
</tr>
<tr>
<td>20°</td>
<td>Sun</td>
<td>500,000 K</td>
<td>312 K</td>
<td>-31 dB</td>
<td>32°</td>
</tr>
<tr>
<td></td>
<td>Moon</td>
<td>275 K</td>
<td>0.2 K</td>
<td>Na</td>
<td>Na</td>
</tr>
<tr>
<td>30°</td>
<td>Sun</td>
<td>500,000 K</td>
<td>139 K</td>
<td>-33 dB</td>
<td>45°</td>
</tr>
<tr>
<td></td>
<td>Moon</td>
<td>275 K</td>
<td>0.1 K</td>
<td>Na</td>
<td>Na</td>
</tr>
<tr>
<td>40°</td>
<td>Sun</td>
<td>500,000 K</td>
<td>78 K</td>
<td>-25 dB</td>
<td>58°</td>
</tr>
<tr>
<td></td>
<td>Moon</td>
<td>275 K</td>
<td>&lt;0.1 K</td>
<td>Na</td>
<td>Na</td>
</tr>
</tbody>
</table>

Here, Na, not applicable.

Figure 5. Outer boundaries of the region of the sky least perturbed by the Sun and Moon, in local horizontal coordinates, for antenna aperture angles of 15°, 20°, 30°, and 40°.
Bouigue [1996] and imported to the MATLAB computing environment. These computations were done with steps of 1 hour for a whole year (2001), yielding 8760 possible values for each analyzed direction of the sky. These directions are defined in local horizontal coordinates by a grid of 5° × 5° resolution over 360° in azimuth and 90° in altitude. Each time the analyzed direction is at an angle smaller than the one given in column 6 of Table 1, it is rejected. For a given antenna aperture the least perturbed region of the sky, or quiet region, is then found as the one encompassing all non-rejected directions.

Figure 5 shows the boundaries of the obtained regions for the four antenna beam widths chosen here. These regions are centered on a point of azimuth 0° and of same altitude as the radiometer’s latitude (43.386° in our case), i.e., the celestial north. It can be noticed that for the smallest antenna considered here (40° aperture) the size of the quiet region is restricted to a few degrees from the north celestial pole, while for the 15° beam width considered in the remainder of this work a much larger area is available for sky-pointing radiometer calibrations all year long.

5. Noise Level Detected in the Quiet Region

We now analyze more finely what the exact value of the equivalent cold load of a radiometer pointed to any direction in the circumpolar region defined above is and assess its stability or accuracy. The two radiation contributors considered in this determination are the radio continuum and the hydrogen HI line.

5.1. Computation of the Noise Level Detected by the Antenna

For that purpose, an array of circumpolar directions centered on the celestial north is chosen and scanned. In the local reference frame these directions range from −40 to +40° with 5° steps in azimuth and from 40° to 90° with 5° steps in altitude. The sky temperature seen by the antenna pattern is computed at each of the 17 × 11 = 181 different orientations thus defined. The 40° minimum altitude corresponds to the ±40° extension of the antenna pattern model chosen for this analysis (see section 3.1). Of course, the method presented here is also applicable to any given antenna pattern.

The computation consists in integrating, in the antenna’s reference frame, the contributions of the radio continuum and HI hydrogen line over the antenna pattern. For each off-axis angle θ and azimuth direction ϕ taken in a plane perpendicular to the beam axis, and at a given time t, the temperature \( T_{\text{int}}(\theta, \phi, t) \) that would be measured by the antenna for a boresight of elevation EL and azimuth AZ, in local...
horizontal coordinates, is given by the following integral:

\[
T_{\text{int}}(EL, AZ, t) = \frac{1}{4\pi} \int_{0}^{2\pi} \int_{0}^{\pi} g(\theta, \phi) T(EL, AZ, t, \theta, \phi) \sin \theta \, d\theta \, d\phi,
\]

where \( g(\theta, \phi) \) is the antenna gain.

[31] The sky temperature distribution \( T(EL, AZ, t, \theta, \phi) \) for the sky portion corresponding to the antenna bore-sight is derived from either of the sky temperature charts shown in Figures 1 and 2 (each comprising 360 pixels in galactic longitude and 180 pixels in galactic latitude) after several geometrical transformations. These transformations map pixels in the initial galactic coordinates of the charts into ones in the target reference frame of the antenna. The integration is done numerically with a \( 1^\circ \times 1^\circ \) resolution in the \( (\theta, \phi) \) antenna coordinates.

[32] To assess how both contributors vary as the Earth rotates over the day, the integration is repeated at different times \( t \) over a 24 hour period, with steps of one half hour, thus leading to a series of 48 estimates for each of the individual antenna pointing directions.

[33] For each of the 181 analysis directions, only the maximum and minimum values, \( T_M \) and \( T_m \), are kept among the 48 integration results. From these two values, \( (T_M + T_m)/2 \), referred to as the intermediate value, and the maximum deviation \( (T_M - T_m)/2 \) relative to this intermediate value are then computed.

5.2. Analysis of the Integration Results

[34] The radio continuum and discrete source contributions are shown as contour lines in local horizontal coordinates (Figure 6). The intermediate values are shown in Figure 6a, and the maximum deviation is shown in Figure 6b. Figure 7 shows, with the same presentation, the contribution of neutral atomic hydrogen. Figures 8a and 8b are the contour lines of the intermediate values and maximum deviations, respectively, for the combined radio continuum and HI line, namely, the overall sky background contribution, excluding Sun and Moon.

[35] Since the contribution of ground is considered as negligible in the 40\(^\circ\) to 90\(^\circ\) elevation range analyzed here, the integration result in the exact north celestial pole direction does not vary as the Earth rotates, at least not in the Toulouse region for which this analysis is performed because of the axis-symmetrical shape of the antenna pattern.

[36] Thus, for the radio continuum, the 3.55 K value (Figure 6a) obtained in the celestial north pointing direction is stable, and the bias error is that given by Reich and Reich’s [1986] charts, i.e., 0.5 K. Farther away from the north, 24 hour variations increase (Figure 6b).
They can reach values as high as ±1 K at zenith, whereas the intermediate value slightly increases to 4.2 K.

As to the HI line, the obtained intermediate value of about 0.1 K is also stable for the same reason, and the bias error is that of Hartmann and Burton’s [1997] charts, reduced to the 20 MHz band, or 0.02 K. When the deviation increases from the north, the 24 hour variations increase. They reach ±0.34 K at zenith. A similar behavior is observed for the intermediate value.

For the overall background contribution the 3.6 K value obtained in the celestial north pointing direction is also stable, and the dominant bias error is that of the radio continuum. Farther from the north, 24 hour variations increase. They can be as high as ±1.2 K at zenith, whereas the intermediate value slightly increases to 4.6 K.

5.3. Atmospheric Contribution

5.3.1. Atmospheric contribution at zenith.

Atmospheric attenuation, without hydrometeors, is small at frequencies close to 1.4 GHz. In order to estimate its variability a series of simulations was carried out using the “LIEBE 93” code [Liebe et al., 1993].

On the one hand, molecular oxygen induces, for realistic temperature and pressure ranges, a total attenuation at nadir of about 0.06 dB, which corresponds to a radiometer temperature contribution of the order of 2 K.

The variation range induced by variations in surface pressure $P_s$ is on the order of 0.1 K; because of the accuracy of pressure measurements the corresponding RMS error is negligible. An increase in temperature causes a decrease in the attenuation cross section but, at the same time, induces an increase in the layer’s effective temperature, and both effects compensate each other significantly. Overall, assuming an adiabatic profile, the variation range observed for surface temperatures ranging from 0°C to 30°C is close to 0.1 K. Because of errors in the temperature profile shape it seems reasonable to assume an RMS error of about 0.02 K.

On the other hand, water vapor induces an attenuation that never exceeds, in a tropical saturated atmosphere, 0.003 dB at nadir, which corresponds to a maximum contribution of 0.05 K. Even if the humidity profile is not well known, the resulting error will not exceed 0.02 K.

Under these conditions, variations of the atmospheric contribution $T_a$ to the radiative temperature at nadir can be represented on the basis of simple approximations. For example, the following formula can be suggested:

$$T_a \approx 1.97 + 0.14(P_s - 1000)/40 - 0.1 \frac{T_s}{30} + 0.04 \frac{H}{100}(T_s - 20)/50,$$

with $P_s$ being surface pressure (hectopascals), $H$ being mean relative humidity (percentage), and $T_s$ being surface
temperature ($^\circ$C). Accordingly, the accuracy of this estimation is of the order of 0.03 K.

[44] Finally, the cross sections themselves are not perfectly known; errors estimated in this respect are 5\% for oxygen and 10 to 15\% for water vapor. Formula (3) provides an estimation of $T_a$ with an accuracy of about 0.03 K and a possible bias error of 0.1 K.

[45] For the present application (standard atmosphere) it will be assumed that $T_a = 2.0$ K with a bias error of 0.1 K and a daily variation of $\pm \Delta T_a = 0.1$ K corresponding to temperature and pressure variations of 30$^\circ$C and 14 hPa, respectively. The pressure and temperature measurements at ground level allow this variation to be reduced.

### 5.3.2. Atmospheric contribution as a function of pointing elevation.

[46] For a homogeneous plane atmosphere a common approximation for the atmospheric layer thickness at an angular altitude $\alpha$ (in local horizontal coordinates) is given by

$$h(\alpha) = h(\pi/2) / \sin \alpha.$$  

This leads to the following altitude dependence of the atmospheric temperature $T_{at}$:

$$T_{at} = T_a / \sin \alpha,$$

$$\Delta T_{at} = \Delta T_a / \sin \alpha.$$  

### 5.4. Noise Budget

[47] Contributions of the overall sky background and atmosphere have been summed together. The values of the brightness temperature thus obtained are shown on a sky chart in horizontal coordinates (Figure 9). Intermediate values are given in Figure 9a, and 24 hour deviations are given in Figure 9bb.

[48] The calibration of a ground-based radiometer using the sky background noise in the frequency band allocated to L-band passive radio astronomy (1400 to 1427 MHz) is possible (that is, not perturbed by the Sun or Moon) in a pointing direction approximately centered on the celestial north. For a medium latitude ($\approx 45^\circ$) radiometer equipped with a 15$^\circ$ beam width antenna having zero gain for off-axis directions greater than $\pm 40^\circ$, the temperature detected in this celestial north direction is 6.6 K and is affected by small 24 hour variations (less than $\pm 0.2$ K) that can be reduced if the atmospheric contribution is estimated from local temperature and pressure measurements. The bias error, which is the sum of bias errors in Reich and Reich’s [1986] survey and the atmospheric contribution, is $\pm 0.6$ K. Pointing altitudes greater than this lead to a slightly lower temperature. Twenty-four hour variations increase steeply up to $\pm 1.4$ K at 90$^\circ$ altitude.

[49] It should be recalled that these results do not take into account ground effects. They are valid for the whole year and any polarization and were obtained on the basis of the following assumptions: weak to moderate solar activity (no type IV bursts), no rain, and first antenna sidelobes better than $-35$ dB.
6. Conclusion

A method has been presented to determine the values of the sky brightness temperature as detected by an L-band radiometer antenna and used as the cold source in its calibration. The position and extent of the region of the sky least perturbed by the Sun and Moon are first found for various antenna apertures. Within this region the method then provides exact values of the cold source and its accuracy as well as possible variations due to Earth rotation and the presence of the atmosphere. The latter derivation, although performed for a specific antenna of 15° beam width (among the smallest possible for L-band ground-looking radiometers), can be recalculated using any other known antenna pattern.

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