Abstract—Downwelling radiative fluxes from inhomogeneous environments are not easy to quantify from the total measured signal contribution. We propose the use of a Lambertian reflector to assess this issue. Using ray tracing to extrapolate the bidirectional reflectance distribution function of a surface with high reflectivity in the microwave spectrum, we characterized a surface that acts as a near-Lambertian reflector at 37 GHz. After implementing such a plate using molded aluminum and getting its emissivity, we validated its Lambertian reflectance properties based on microwave surface-based radiometer measurements. This analysis also gives guidelines on how to make a Lambertian surface for different wavelengths in the microwave spectrum. Field experiments show the usefulness of such a Lambertian plate to estimate the downwelling contribution in ground-based radiometric measurements.

Index Terms—Downwelling brightness temperature, Lambertian reflector, passive microwave, ray tracing.

I. INTRODUCTION

Radiometric measurements are primarily dependent on the radiative physical properties of a specific target, e.g., its emissivity (ε) (or reflectivity). These measurements also depend on the properties of the sensor used, e.g., its frequency (wavelength) and incidence angle. For accurate radiometric measurements of a nonblackbody target (ε ≠ 1), it is necessary to isolate and quantify the contribution of the downwelling radiative fluxes emitted by the surrounding environment of the target reflected toward the radiometer. Field measurements are often made in complex environments where the contributions of the different emission sources surrounding the target are difficult to estimate.

Regardless of the observation angles, studies using passive microwave brightness temperatures (T_b) have to consider both sources of the measured T_b (T_b_measured), i.e., the emission by the surface itself (T_target * ε_target) and the portion of the downwelling radiative fluxes emitted by the surrounding environment (T_b Target) of the target reflected ((1 - ε_target)) toward the radiometer. Thus

\[ T_{\text{measured}} = T_{\text{target}} + (1 - \epsilon_{\text{target}}) T_{b_a} \]  

Measurements from surface-based radiometers (SBRs) are one of the cases where additional tools are needed to isolate the signal emitted by the target from all of the other sources in the integrated measurement of the sensor. For example, in the case of snow microwave emission studies, in which the snow emissivity allows the snow properties to be remotely characterized, the downwelling radiation from the sky or the forest canopy above the snow surface, reflected on the snow, significantly alters the retrieval if it is not corrected as the snow reflectance can be important. For example, assuming a typical snow emissivity ranging from 0.75 to 0.95 at 37 GHz and a downwelling T_a ranging from 30 K (for a clear sky) to 150 K (for the surrounding area), the error generated by neglecting T_a could vary from 1.5 K to up to 40 K, which is significant.

To isolate and quantify the downwelling radiative fluxes from the environment of the target, a Lambertian surface (LS) with a low emissivity (highest reflectivity) would be an ideal tool to discriminate the contribution of the environment from the target contribution. A radiometer is first used to measure a target Tb. Then, a Lambertian plate is placed over the target, and the Tb measurement of the Lambertian plate allows the retrieval of the integrated T_b_target [using (1) by replacing subscript target by LS]. In order to use the integrated T_b_a obtained by 63 the LS, target reflection or scattering must primarily have a Lambertian rather than a specular pattern. However, even if this is not the case, the integrated T_b_a obtained by the LS will still be a good approximation in an inhomogeneous environment (as demonstrated in Section IV).

We propose a Lambertian microwave surface in the form of an aluminum plate with a structure generating multiple reflections, i.e., a surface where the incident radiation will be reflected a great number of times, spreading the initial radiation in all directions. To help determine the appropriate surface to use, the following were done: 1) ray-tracing simulations were conducted to determine the surface properties needed; 2) a plate was created and characterized; and 3) field measurements were conducted on a reference bare soil surface measured under different surrounding environments to validate the use of such a Lambertian plate to retrieve the downwelling Tb.

II. RAY TRACING MODELING

A ray-tracing model has been implemented for this study 81 to select the geometric surface pattern that acts as a near-82 Lambertian reflector. A hemispherical grid was created from the duplication of icosahedron cells. This hemispherical grid, 84...
FIG. 1. Representation of the modeled surface of interest described by (2) with parameters $a = 3.4$ and $b = 3.5$.

which is composed of 2528 cells, was placed over the modeled surface and used to integrate the contribution by all reflected rays. Each triangular cell being identical to one another, the number of integrated rays in each cell is equivalent to a measured radiance. Twelve emission sources were used to characterize the reflection by the surface.

The proposed surface pattern, as shown in Fig. 1, can be defined by

$$z = \frac{a}{2} \left( \sin \frac{2\pi x}{b} + \cos \frac{2\pi y}{b} \right)$$

where the constant $a$ defines the amplitude of the peaks, and $b$ defines the distance between them. The ray-tracing approach was used to define the optimal ratio of $(a : b)$ giving an isotropic distribution of reflections. It appears that, from a great number of simulations using a large range of $(a : b)$ values, the ratio $a : b \approx 1$ seems to act as a near-Lambertian reflector.

The results in Fig. 2 show, apart from a backscattering area and very large angles, a near-Lambertian reflection pattern when the $a : b$ ratio is $(a = 3.5 : b = 3.5)$. We also show arbitrarily tested ratios such as $(a = 7.0 : b = 3.5)$ and $(a = 3.5 : b = 7.0)$. It is interesting to note that, when $a$ is larger than $b$, the dispersion of the reflected radiation is greater at low incident angles. On the contrary, when the gap is larger than the amplitude height, specular reflections occur, and it generates a pattern of reflected radiation mainly oriented toward the source.

That backscatter response from the LS can be avoided when using the LS by choosing an azimuthal configuration where the backscatter contribution is negligible.

Fig. 3 highlights a key characteristic of the plate showing that the contribution to the radiation at angles close to nadir mainly comes from rays that have undergone multiple reflections, allowing a more evenly spread radiation in all directions. Verification of multiple reflections has helped to better characterize the surface when the ratio approached the optimal $a : b \approx 1$ ratio.

### III. IN SITU VALIDATION

Afterward, an aluminum plate was created by duplication of a mold $(a = 3.4 : b = 3.5)$ using a standard industrial wet sand molding technique. Special attention was paid to the smoothness of the geometric surface pattern. The plate is 50 cm wide by 60 cm long. The size of the aluminium plate was carefully chosen to ensure that the measurement footprint with 124 respect to the antenna beamwidth and the distance of the antenna from the plate would always be inside the plate with good tolerances.

We thus conducted a series of field measurements to determine the emissivity of this plate and to validate its Lambertian properties. These measurements took place in the middle of...
The viewing angle of the radiometer was set at 30 different directions, testing the Lambertian nature of the plate. The wood panel is first vertically placed and then tilted at 60°, as illustrated in Fig. 4. Radiometers were oriented to measure toward the east. The orientation of the setup 1 consisted of positioning an emission source, a microwave absorber (Ecosorb) target at ambient temperature, and a laser mounted 20 cm for 19 GHz and 17 cm for 37 GHz. A laser mounted 5 cm away was used to ensure proper positioning of the source configuration at 90°. As illustrated in Fig. 4, the source configuration at 90° has a lower Tb for measurements at 60°. This can be explained by the fact that the wavelength (1.58 cm) is 20% of the total downwelling radiation from the sky nadir and hemispheric Tb are negligible at 37 GHz. These differences between the modeled NARR and measured Tb were negligible. The downwelling radiation (Tb↓) was modeled using the atmospheric model implemented in the Helsinki University of Technology snow emission model [9] driven with the atmospheric profile conditions derived from the North American Reanalysis (NARR) data. Tb measurements were previously calibrated using a configuration where the emission source is at a 90° azimuth angle (see dark-colored lines in Fig. 5), except for the Tb measured at V-Pol at an incident angle of 30° and the emission source at an azimuth angle of 90°. A difference of less than 3 K is measured for a 30° viewing angle, whereas this difference increases to about 4 K for measurements at 60°. Fig. 5 shows the measured plate Tb for the different experimental configurations at 37 GHz in both vertical (V-Pol) and horizontal (H-Pol) polarizations. For both observation configurations at 37 GHz, there is a slight variation of Tb (see Fig. 5), except for the Tb measured at V-Pol at an incident angle of 30° and the emission source at an azimuth angle of 90°. A difference of less than 3 K is measured for a 30° viewing angle, whereas this difference increases to about 4 K for measurements at 60°. Changing the angle of the source (see Fig. 5) shows some interesting results. The specular reflective area should have a lower Tb for a configuration where the emission source is at a 90° azimuth angle (see light-colored lines in Fig. 5). Instead, a Lambertian pattern was observed. A Tb slightly below was witnessed for the measurements collected in V-Pol (see dashed lines in Fig. 5). Fig. 6 gives the results at 19 GHz in both polarizations for a viewing angle of 60°.

The observations made at 19 GHz (see Fig. 6) show that the reflection by the plate seems more specular than Lambertian since measurements with the source configuration at 180° (dark-colored lines) have higher Tb than those taken with the source configuration at 90° (light-colored lines). This can be explained by the fact that the wavelength (1.58 cm) is 20% higher than the minimum distances inside a gap for b = 3.5. A plate with properties similar to the one presented here is thus unable to reproduce a Lambertian reflection pattern at 19 GHz. Phenomena of surface roughness could also increase the specular nature of the plate.

<table>
<thead>
<tr>
<th>Source</th>
<th>19 GHz</th>
<th>37 GHz</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sky 0° NARR</td>
<td>7.0 K</td>
<td>14.8 K</td>
</tr>
<tr>
<td>Sky 0° Measured</td>
<td>9.4 K</td>
<td>8.9 K</td>
</tr>
<tr>
<td>Total Tb NARR</td>
<td>11.0 K</td>
<td>15.6 K</td>
</tr>
<tr>
<td>Sky 55° measured</td>
<td>15.4 K</td>
<td>14.4 K</td>
</tr>
<tr>
<td>Tbplate 60°</td>
<td>41.9 K</td>
<td>43.6 K</td>
</tr>
</tbody>
</table>

Table 1: Modeled and measured Tb from different sources.
We propose a simple approach to define the geometry of the plate depending on the wavelength (\(\lambda\)) to obtain a Lambertian pattern. To select the adequate \(a, b\) parameters, the minimum distance in a gap must be similar or slightly higher in size to the wavelength to allow a more homogeneous distribution of the incident radiation. This minimum distance in a gap can be expressed in a planar cut through the plate into the maximum peaks transect [see(3)] and another one in the maximum and minimum peaks transect [see (4)] when \(\Delta y_1\) and \(\Delta y_2\) tend to 0. Thus

\[
\Delta y_1 = a - a \cos \frac{\pi \lambda}{b} - \lambda \quad (3)
\]

\[
\Delta y_2 = 2a - 2a \cos \frac{\pi \lambda}{\sqrt{2b}} - \lambda. \quad (4)
\]

For example, \(a = 3.4\) and \(b = 3.5\) have a minimum distance in a gap lower than the wavelength in less than 2% of the vertical axis using \((\Delta y_1 + \Delta y_2)/2a\). To reproduce the Lambertian pattern observed at 37 GHz for 19-GHz measurements, the ratio \(\Delta y\) should be closer to \(a = b \geq 6.9\) cm.

**IV. SURFACE EMISSIVITY RETRIEVAL**

To demonstrate the efficiency of the proposed Lambertian plate, an experiment was set up to retrieve the emissivity of a dry homogeneous soil sample (Portland cement ASTM C150-2013) at 37 GHz, 55° incident angle, for different downwelling radiative fluxes. To perform the experiment, the radiometer, the soil sample, and the Lambertian plate were installed on a flatbed trailer to ensure that measurements were taken at the same angle and identical geometric conditions. In addition, four humidity and temperature sensors were placed in the soil sample, and a temperature sensor was used to keep track of the temperature of the plate before and after each radiometric measurement. These measurements show that the temperature and humidity of the soil sample remained constant during the experiment, which means that the emissivity of the soil remained constant for every site. At the Université de Sherbrooke campus, eight sites were chosen, four under low downwelling radiative fluxes (open space sites, S1 to S4 in Table II) and four under high downwelling radiative fluxes corresponding to coniferous and deciduous forest sites (S5 to S8 in Table II). These measurements were made on October 21, 2013, during the night under covered-sky conditions.

The soil emissivities in Table II were calculated using (1) with an emissivity of 0.095 for the Lambertian plate as defined by the \(\text{in situ}\) validation. Mean soil emissivity, supposed to remain constant even under different environments, is 0.781 with a standard deviation of 0.038 in horizontal polarization and 0.913 in vertical polarization with a standard deviation of 0.006. In vertical polarization, the use of the Lambertian plate allowed the characterization of the soil emissivity with very small variation margin by quantifying and removing the contribution of the surrounding environment, regardless of the downwelling contribution sources. In horizontal polarization, the soil emissivity can be estimated, but a 0.121 variation in the Lambertian emissivity is present, mainly in the forested sites. This variation could be caused by specular reflections of the downwelling emissions on the soil surface, which is not measured by the Lambertian aluminum plate.

Horizontal polarization measurements indicate that it might be more useful to measure both integrated \(T_b\) and specular \(T_b\) to access if the surface has a Lambertian or a specular reflection pattern. Regarding only the specular contribution, even measurements of a small footprint with a small beamwidth antenna come from a much larger environment footprint. To get that exact footprint contribution, the antenna should be directly pointed at the environment footprint, upside down from the previous measurement, placing it underground. A smaller 270 footprint could be measured by pointing at the specular angle. The problem with this technique is the enormous variations in measured \(T_b\) by slightly moving the antenna while keeping the same inclination and orientation (we refer to this problem as case P). A worst case P scenario would be the following: doing measurements in a forest where trees could conceal their own contribution or measurements of normally concealed trees while moving the antenna, thus rendering an inadequate integration of the radiative fluxes. Regarding the footprint, surfaces are rarely perfectly plane. Contributions from different angles other than the specular angle from the antenna make the use of a Lambertian reflector more adequate than a specular reflector.

### Table II

<table>
<thead>
<tr>
<th>Site</th>
<th>(T_b) H-Pol (K)</th>
<th>(T_b) V-Pol (K)</th>
<th>(T) (K)</th>
<th>Soil (\epsilon)</th>
</tr>
</thead>
<tbody>
<tr>
<td>S1</td>
<td>47.9</td>
<td>230.3</td>
<td>47.4</td>
<td>265.2</td>
</tr>
<tr>
<td>S2</td>
<td>52.9</td>
<td>233.3</td>
<td>50.4</td>
<td>265.4</td>
</tr>
<tr>
<td>S3</td>
<td>54.9</td>
<td>236.2</td>
<td>50.9</td>
<td>265.7</td>
</tr>
<tr>
<td>S4</td>
<td>64.2</td>
<td>234.9</td>
<td>66.4</td>
<td>266.7</td>
</tr>
<tr>
<td>S5</td>
<td>107.7</td>
<td>237.9</td>
<td>112.3</td>
<td>269.7</td>
</tr>
<tr>
<td>S6</td>
<td>135.7</td>
<td>243.4</td>
<td>139.8</td>
<td>272.1</td>
</tr>
<tr>
<td>S7</td>
<td>178.7</td>
<td>270.4</td>
<td>173.0</td>
<td>277.6</td>
</tr>
<tr>
<td>S8</td>
<td>205.1</td>
<td>264.5</td>
<td>205.3</td>
<td>279.1</td>
</tr>
</tbody>
</table>

The problem with this technique is the enormous variations in measured \(T_b\) by slightly moving the antenna while keeping the same inclination and orientation (we refer to this problem as case P). A worst case P scenario would be the following: doing measurements in a forest where trees could conceal their own contribution or measurements of normally concealed trees while moving the antenna, thus rendering an inadequate integration of the radiative fluxes. Regarding the footprint, surfaces are rarely perfectly plane. Contributions from different angles other than the specular angle from the antenna make the use of a Lambertian reflector more adequate than a specular reflector.
contribution $T_b$ from an inhomogeneous environment seems to be a better way to approximate the downwelling contribution to the signal. The target reflection characteristics depend on the electromagnetic frequency used for the measurements. It is important to choose an LS with the adequate geometry and to determine the target reflection characteristics when selecting whether to use the LS with or without a specular reflector.

V. CONCLUSION

This study has demonstrated that it is possible to determine a plate pattern that acts as a near-Lambertian surface. A protocol was also suggested to implement such plates for different wavelengths in the microwave spectrum. A plate was created with an available mold, and its Lambertian properties were validated at 37 GHz with in situ experiments. This experiment showed that regardless of the surrounding environment, radiometric measurements of the created plate were able to measure the integrated hemispherical downwelling contribution of the area. Such a tool will greatly improve the accuracy of ground-based microwave radiometric measurements in complex environments such as in the Canadian boreal forest.

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REFERENCES