Proposed Development of a National Standard for Microwave Brightness Temperature*

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***Abstract*—We review the advantages of a national standard for microwave brightness temperature and outline our proposed approach toward developing such a standard. The proposal is a combined standard that would comprise both a standard radiometer, traceable to primary noise standards, and a fully characterized standard target.**

Keywords-brightness temperature; microwave radiometry; radiometer calibration; remote sensing; standards

I. INTRODUCTION

There are currently no national standards for microwave brightness temperature, either at the U.S. National Institute of Standards and Technology (NIST) or elsewhere. Many realizations of microwave brightness-temperature standards exist in the form of heated or cooled calibration targets, but none is maintained as a national standard by a National Measurement Institute (NMI). This is in contrast to the visible and infrared (IR) portions of the spectrum, in which radiance standards exist—and have proven very useful [1]. There are many reasons to want a national microwave brightness-temperature standard based on fundamental physical quantities. It would provide a constant reference for comparison of different instruments over years or decades. Such a stable, accessible reference would benefit programs such as the National Polar-orbiting Operational Environmental Satellite System (NPOESS), which plans to launch multiple copies of the same instruments, as well as studies of long-term phenomena, such as climate monitoring.

A national standard would also provide a means for resolving disagreements between different instruments or programs, including instruments based on entirely different measurement parameters, since those other measurements should also be traceable to fundamental physical quantities. In this way, the standard would support the goals of merging data from multiple measurement systems from different nations, as will be necessary, for example, for the Global Earth Observation System of Systems (GEOSS). Furthermore, there is already an established international framework for harmonizing fundamental physical standards. The Meter Convention, through the International Committee for Weights and Measures (CIPM) and its consultative committees, and through the International Bureau of Weights and Measures (BIPM), defines the fundamental units and scales of the International System of Units (SI). The Consultative Committees (CCs) of the CIPM conduct international comparisons of national standards for the principal physical quantities. The results of these comparisons are compiled by the BIPM in a database that is publicly available [2]. Thus, not only is the set of fundamental units internally consistent, but the realizations of the standards at different NMIs are compared and kept consistent. The two relevant consultative committees for microwave radiometry would be the Consultative Committee on Electricity and Magnetism (CCEM) [3] and the Consultative Committee on Photometry and Radiometry [4].

II. APPROACH

We use $B_f(\theta,\varphi)$ to denote the spectral brightness, the power per unit area, solid angle, and frequency incident on (or emitted from) a surface. The definition of brightness temperature $T_B(\theta,\varphi)$ that we use is

$$T_B(\theta,\phi) \equiv \frac{\lambda^2 B_f(\theta,\phi)}{2k}, \tag{1}$$

where λ is the wavelength, and k is Boltzmann's constant. This differs from the conventional definition [5], in which (1) holds only in the Rayleigh-Jeans approximation, $kT<<hf$. We prefer (1) because it allows brightness temperatures to be added or integrated as powers, even when the Rayleigh-Jeans approximation does not apply.

We propose to develop a national standard for microwave brightness temperature. We have previously suggested a standard linked to fundamental noise standards, what might be called a "standard radiometer" approach [6, 7]. This standard consists of a NIST waveguide radiometer, calibrated with cryogenic primary noise standards, but with a characterized antenna connected at the measurement plane, where a diode noise source would normally be connected for measurement. Both the antenna pattern and the loss in the antenna must be known. Then, if the noise power delivered to the radiometer is measured, the incident power on the antenna, and therefore the brightness temperature, can be calculated.

An alternate approach would be to construct a "standard target," a well-characterized calibration target that would produce a known brightness temperature. Originally, we planned to use such a target to check the standard radiometer, and as a means of transferring the brightness-temperature standard to other users. However, we now propose using such a calibration target as a part of the full brightness-temperature standard. We would then have two independent realizations of absolute brightness temperature, each with its own full uncertainty analysis. The full standard would consist of a weighted average of the standard-radiometer value and the standard-target value for the brightness temperature. If the two individual standards had comparable uncertainties, the combined standard would have a significantly smaller uncertainty than either of the individual methods alone, and we would be more confident both in the standard and especially in the estimated uncertainty. (If one individual uncertainty were much smaller than the other, the combined standard would effectively reduce to the better standard with the other used as a check.) A second calibration target would be calibrated against this combined standard and would then be used to transfer the brightness-temperature standard to others, or the combined standard could be used to measure a customer's calibration target or radiometer at NIST.

Several steps have been taken toward realizing the two separate standards. In Section III we review the work on the standard-radiometer approach, and Section IV contains a brief outline of our recent work on standard-target characterization and use. Section V presents a discussion and summary.

III. Review of Standard Radiometer

The standard-radiometer approach is based on linking the measured brightness temperature to primary noise standards through a characterized antenna. The approach was successfully tested and was reported in [7]. The basic configuration is represented in Fig. 1. One of the NIST waveguide radiometers is calibrated in the usual manner with two primary noise standards, one cryogenic and the other near ambient temperature. A standard (i.e., characterized) antenna is connected to the measurement plane (x in Fig. 1), where we would normally connect a noise source to be calibrated. From the noise temperature measured at plane x, T_x, we can compute the noise temperature at the antenna aperture, T_{in}, from

$$T_x = \alpha T_{in} + (1-\alpha) T_a , \tag{2}$$

where α is the available power ratio between the two planes (approximately equal to the inverse of the loss factor L), and T_a is the noise temperature corresponding to the physical temperature of the antenna, assumed to be ambient temperature. The noise temperature at the aperture can be broken into two separate contributions, one from the target, $\overline{T}_T$, and one from the background, $\overline{T}_{BG}$,

$$T_{in} = \eta_{AT} \overline{T}_T + (1-\eta_{AT}) \overline{T}_{BG} , \tag{3}$$

where η_{AT} is the fraction of the antenna pattern $F_n(\theta,\varphi)$ subtended by the target,

$$\eta_{AT} \equiv \frac{\int_{\text{target}} F_n(\theta,\phi) d\Omega}{\int_{4\pi} F_n(\theta,\phi) d\Omega} , \tag{4}$$

and where $\overline{T}_T$ and $\overline{T}_{BG}$ are defined by

$$\overline{T}_T \equiv \frac{\int_{\text{target}} T_B(\theta,\phi) F_n(\theta,\phi) d\Omega}{\int_{\text{target}} F_n(\theta,\phi) d\Omega} ,$$
$$\overline{T}_{BG} \equiv \frac{\int_{\text{other}} T_B(\theta,\phi) F_n(\theta,\phi) d\Omega}{\int_{\text{other}} F_n(\theta,\phi) d\Omega} , \tag{5}$$

where $T_B(\theta,\phi)$ is the incident brightness temperature.

To reduce the effect of the background, we need to control the environment in which the standard radiometer operates. We intend to use a shielded enclosure with absorptive walls, maintained at room temperature, which will also be the temperature of the antenna, T_a. Then $\overline{T}_{BG} = T_a$, and (2) and (3) can be combined to yield

$$\overline{T}_T = T_a + \frac{1}{\alpha \eta_{AT}} (T_x - T_a) . \tag{6}$$

Equation (6) is the basic equation for our standard-radiometer measurements. It expresses the average incident brightness temperature $\overline{T}_T$ received from the target in terms of the measured noise temperature T_x, the ambient temperature T_a, and the antenna properties α and η_{AT}. (Note that $\overline{T}_T$ will contain contributions not just from target emission, but also from background radiation scattered by the target.)

This approach was demonstrated using measurements performed in an anechoic chamber [7]. The NIST Antenna Metrology Project measured the antenna pattern of a standard-gain horn on their near-field range. The horn was connected to a NIST waveguide radiometer, and measurements of a heated target (borrowed from the NOAA Ground-Based Scanning Radiometer, GSR [8]) were performed for several separation distances between horn and target. The measured brightness temperature was compared to the brightness temperature computed from the temperature and approximate emissivity of the target. The results are shown in Fig. 2. The agreement is good or fair at all separation distances except the largest (about 5 m), where alignment problems may occur. Unfortunately,

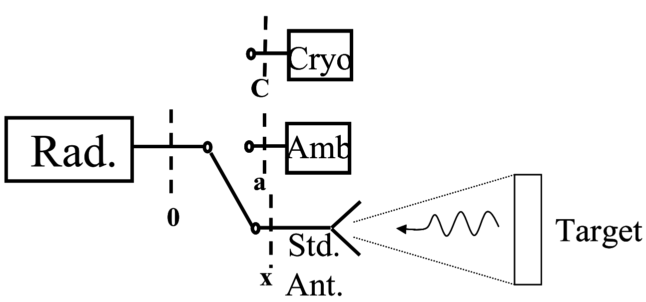

Fig. 1 Configuration for standard radiometer.

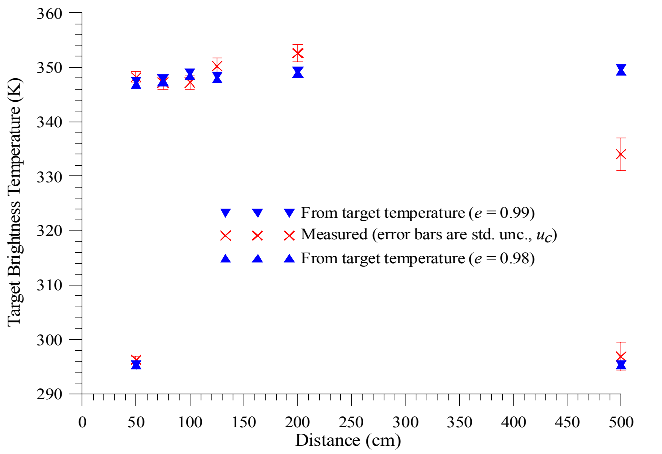

Fig. 2 Measured and predicted brightness temperatures vs. separation distance.

subsequent measurements on a different target were not successful, and the next order of business will be to resolve the problems that arose in those measurements.

IV. Standard Target

Heated or cooled targets are routinely used to calibrate microwave remote-sensing radiometers. If a calibration target is to be used as a national standard (or part of such a standard) for brightness temperature, it is essential that the characteristics of the target and the method for using it are well understood and that the associated uncertainties are assessed. We therefore have worked to improve target characterization. In particular, we have studied or are studying proximity effects in the use of calibration targets, infrared (IR) imaging of temperature distributions in calibration targets, and measurement of the electromagnetic properties of materials used in targets.

Proximity effects arise when the separation distance between radiometer and calibration target is not large enough to neglect the antenna-target interactions. We have studied the effect of target reflectivity on the input reflection coefficient of the radiometer and the consequences for measurements of brightness temperature [9]. Such effects can be significant (a few kelvins) for radiometers without front-end isolators, but all the radiometers that we will use in the brightness-temperature standard will have front-end isolators, and so this effect will be negligible. The other possible proximity effect is due to the fact that the calibration target may not be in the far field of the radiometer's antenna. Initial work indicates that this may be an important effect [10], but this is a difficult problem, and much remains to be done.

The physical temperature of a calibration target is usually monitored by several thermometers (usually platinum resistance thermometers, PRTs) embedded in the target material from the back. Because the PRTs measure the temperature within the material rather than on the actual target surface, and because only a limited number of PRTs are used, questions arise about differences between the bulk and surface temperatures, and about longitudinal variations from center to edge of the target or from tips to valleys of the array of pyramids on the target surface. In a paper presented at this conference [11], Cox, O'Connell, and Rice report initial results of IR imaging measurements of a heated microwave calibration target. An IR image of part of the target is shown in Fig. 3. The salient feature of the image is a regular array of light colored dots, corresponding to the tips of the pyramids, and indicating that they are at a lower temperature than the rest of the target. The image also indicates that in this case there is not a large difference between the temperature at the target center and at the edge. In principle, the absolute surface temperature can also be determined, if the IR emissivity of the material is known. Analysis of this issue is in progress.

To use a calibration target as a primary standard, it is also necessary to know its emissivity, in addition to its physical temperature. The overall emissivity of a target depends on both the composition and the geometry of the surface. There is currently no single, generally accepted way to determine the target emissivity. In principle, the emissivity can either be measured or computed from the electromagnetic properties of the material(s) and the geometry of the surface. Part of the NIST standard-target effort is to measure the permeability and permittivity of materials commonly used in target construction. Preliminary results on ferrous-doped epoxy and carbon-loaded closed-cell foam have been reported at this conference [12].

V. Summary

We have argued the need for a national standard for microwave brightness temperature and have suggested development of a combined standard, which would comprise both a standard radiometer and a standard calibration target. The standard-radiometer component of the brightness-temperature standard would establish traceability to the NIST primary noise standards. The standard-target component would reduce the uncertainty of the combined standard to some extent (which would depend on the uncertainty achieved by the standard target), and it would provide a valuable check or confirmation of the standard radiometer.

The standard target would also facilitate transfer of the brightness-temperature scale to other users. Some of the most important uses of calibration targets are in thermal vacuum (TV) chambers. The combined standard would be realized in a thermally stable chamber, but not in a TV environment. Customers' targets could be calibrated under ambient conditions in this chamber. To transfer the standard to a customer's facility, a transfer-standard calibration target would

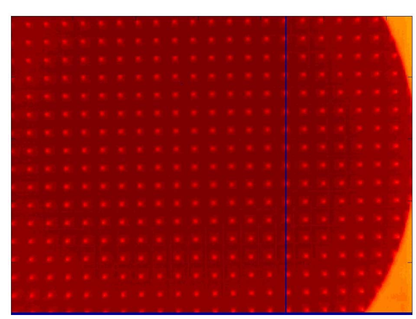

Fig. 3 Infrared image of a microwave calibration target.

be used. This transfer standard would be similar in design to the standard target used in the combined standard and would have an uncertainty quite close to that of the combined standard. It could be used at a customer's facility, either under ambient conditions or in a TV chamber.

NIST currently has waveguide radiometers and primary noise standards covering the 12.4 GHz – 65 GHz frequency range. We would expect the brightness-temperature standard to be developed first for 18 GHz – 26.5 GHz and then for other bands up to 65 GHz. At the lower end of the anticipated frequency range, it was estimated that the standard target by itself can achieve uncertainties of 0.3 K to 0.8 K for brightness temperatures between 200 K and 300 K [7]. The uncertainty achieved by the combined standard would depend on the uncertainty in the combined target, which we cannot yet estimate reliably. However, it is safe to assume that the uncertainty in the combined standard would be no larger than that from the standard radiometer, and could be somewhat smaller.

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