Proposal for Development of a National Microwave Brightness-Temperature Standard*

James Randa+, Amanda E. Cox, David K. Walker
Electromagnetics Division, National Institute of Standards and Technology, 325 Broadway, Boulder, CO USA 80305-3328

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. We also review our recent work on development of a standard radiometer and on characterization of calibration targets.

Keywords: brightness temperature, microwave radiometry, radiometer calibration, remote sensing, standards

1. 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 why a national microwave brightness-temperature standard, based on fundamental physical quantities, is needed. 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 are the Consultative Committee on Electricity and Magnetism (CCEM) [3] and the Consultative Committee on Photometry and Radiometry [4].

The Electromagnetics Division of the U.S. National Institute of Standards and Technology (NIST) has taken initial steps toward developing a standard for brightness temperature at microwave frequencies [5 – 10]. The standard would comprise two components: a standard radiometer, traceable to primary noise standards, and a fully characterized

+randa@boulder.nist.gov; phone 1 303 497-3150; fax 1 303 497-5970; boulder.nist.gov/div818/81801/Noise

standard target. Several steps have been taken toward realizing the two separate standards. In the next section, we provide some background and describe our approach. Section 3 reviews our work on the standard-radiometer approach. In Section 4 we review our recent work on standard-target characterization and use. Section V presents a discussion and summary.

2. APPROACH

We use $B_f(\theta,\varphi)$ to denote the spectral brightness, defined as 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

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

where λ is the wavelength, and k is Boltzmann's constant. This differs from the conventional definition [11], 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. It also conforms to the common definition of noise temperature in terms of available power (rather than equivalent physical temperature of a passive blackbody source) in microwave circuits and systems, thus simplifying the treatment of the transition from incident brightness temperature to noise temperature input to the receiver.

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 [5,6]. 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. The antenna pattern can either be measured or calculated. It would be preferable to both measure and calculate the pattern, in order to check that the two methods yield the same results. The loss in the antenna is probably best obtained by calculation. Once the antenna characteristics are known, then if we measure the noise power delivered to the radiometer, we can calculate the incident power on the antenna, and therefore the brightness temperature.

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 having 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.

3. 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 [5]. The basic configuration is represented in Fig. 1. One of the NIST waveguide radiometers is calibrated in the usual manner with two primary

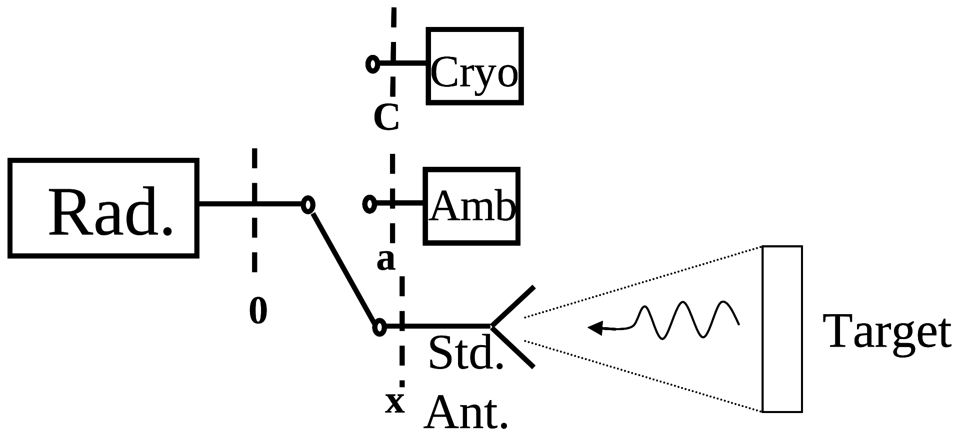

Fig. 1 Configuration for standard radiometer.

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 at 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 $\bar{T}_{BG} = T_a$, and (2) and (3) can be combined to yield

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

Equation (6) is the basic equation for our standard-radiometer measurements. It expresses the average incident brightness temperature $\bar{T}_T$ 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 $\bar{T}_T$ 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 [5]. 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 [11]) were performed for several separation distances between horn and target. For each distance, the "beam efficiency" η_{AT} was computed from the measured antenna pattern and the target geometry. The loss in the antenna was computed numerically from the dimensions and conductivity of the standard-gain horn. The brightness temperature measured using (6) was then compared to the brightness temperature computed from the temperature and approximate emissivity of the target. The results are shown in Fig. 2. In addition to the results for the heated target, Fig. 2 also shows two points obtained with the target at ambient temperature, which were measured as a check. The agreement is good or fair at all separation distances except the largest (about 5 m), where alignment problems may occur. Unfortunately, subsequent measurements on a different target were not successful, and the next task will be to resolve the problems that arose in those measurements.

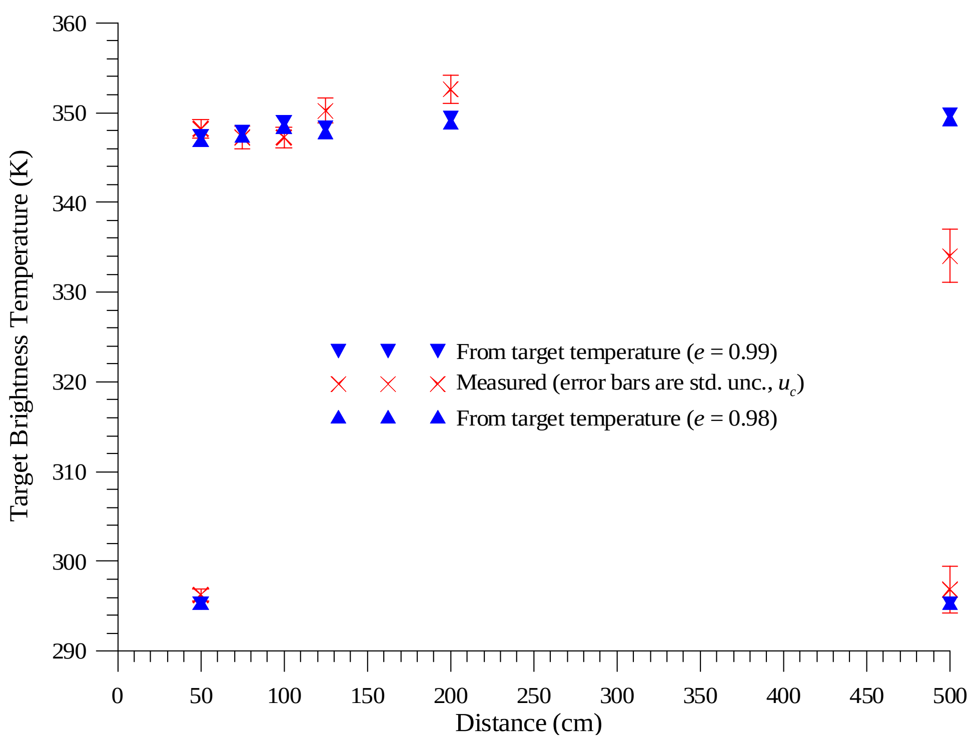

Fig. 2 Measured and predicted brightness temperatures vs. separation distance.

4. 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 both 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) characteristics of calibration targets, including imaging of temperature distributions, and measurement of the electromagnetic properties of materials used in targets.

4.1 Proximity Effects

Proximity effects arise when the separation distance between the radiometer and calibration target is not large enough to neglect both the antenna-target interactions and any consequences of non far-field conditions. We have studied the effect of target reflectivity on the input reflection coefficient of the radiometer and the consequences for measurements of brightness temperature [7]. This effect is a particular concern when a radiometer is calibrated in a "close-coupled" configuration, with the calibration target inches from the antenna, but is then used to view very distant scenes. In such cases the mismatch factor between antenna and receiver can be different in the calibration configuration from its value when viewing the scene, and therefore the powers delivered to the receiver in the two cases can be different for the same incident brightness temperature. The effect can be significant (a few kelvins) for radiometers without front-end isolators. However, 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 [8], but this is a difficult problem, and much remains to be done. For the brightness-temperature standard, clarification is needed for the minimum separation distance to use between the calibration target and the antenna of the radiometer. We will continue to work on the theory, but until the theory produces reliable quantitative results, we will check that the separation distance is sufficient by varying the distance and verifying that the results are independent of distance, as was described above for the standard-radiometer.

4.2 Target Temperature Characteristics

Calibration targets are designed to approximate blackbody sources over the frequencies of interest. The microwave brightness temperature available to the radiometer from the calibration source is a function of the physical temperature of the target and its emissivity. The physical temperature of the target is typically measured by temperature sensors embedded in the target substrate, and a weighted average of the sensors, along with the emissivity value, is used to calculate the effective brightness temperature during the calibration of sensor data. In some targets, temperature gradients can exist both across the target face and between the heated (or cooled) substrate and the surface viewed by the radiometer. These gradients can give rise to large uncertainties with respect to the brightness temperature received at the radiometer aperture, thus affecting its calibration and the accuracy of the data products derived from the instrument. In order to develop a method to better characterize calibration target properties, we explored ways to observe and quantify these thermal gradients [9]. The techniques we developed have the potential benefit of providing much insight into the performance of microwave calibration targets. These methods can provide detailed information on the relationship between the observed target surface and the temperature monitoring devices. The measurements can quantify the temperature gradients existing within the target, and they can provide a detailed image of the overall target thermal characteristics.

Using a typical microwave calibration target and the infrared calibration facilities available at our Gaithersburg, MD location, we calibrated portions of the microwave target with respect to the embedded platinum resistance thermistors (PRTs) and imaged the target using two different thermal-imaging arrays. To measure the infrared brightness temperature, we viewed the target with the NIST Thermal-infrared Transfer Radiometer (TXR) [13]. The TXR was developed for use in intercomparisons and scale verifications of sources used to calibrate thermal-infrared (TIR) channels. The TXR is a liquid-nitrogen-cooled filter radiometer with two channels at 5 and 10 μm with a 1 μm wide bandpass. The absolute calibration of the TXR radiance scale is traceable via an on-board infrared blackbody to a NIST high-accuracy infrared cavity radiometer, the Water Bath Blackbody (WBBB) [14]. The TXR has a field of view of 30 milliradians and was positioned to view approximately one pyramid of the microwave target structure at a time.

Two different infrared imaging cameras were used to observe the heated microwave target. Both cameras read array values out to a computer file and allow image capture. One of the imagers uses a liquid nitrogen cooled 320 x 256 InSb array, and has a spectral bandpass from 2 µm to about 5.5 µm. The other imager uses an uncooled 320 x 240 microbolometer array, and has a spectral bandpass from 7 µm to 13 µm. The imaging arrays provide information on the thermal gradients that occur across the face of the target. Both of these imagers viewed the target with a spatial resolution sufficient to resolve intra-pyramid brightness temperature gradients with several pyramids in the full field of view.

TXR data indicated gradient across the face of the target of approximately 1.25 K over a distance of 10 cm. Figure 3 shows an IR image of a portion of the microwave target. The geometric structure can be seen in this image; both the tips of the pyramids and the valleys between them are visible in this image. The lighter dots correspond to the lower temperature of the tips of the pyramids (the target is heated at the base). The linear features of the valleys can be seen between the pyramids. The blue vertical line right of center and the blue horizontal region at the bottom of the image are artifacts of the imager and should be ignored. The image also shows that for this particular target and temperature, there is not a large gradient across the face of the target.

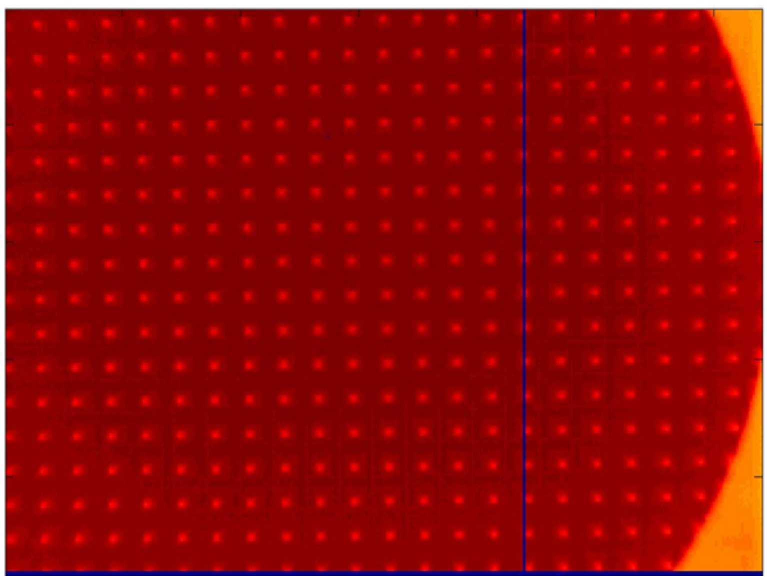

Fig. 3 Infrared image of the microwave calibration target.

We have shown that we can quantify the temperature gradients in the target, including those between the PRT and the radiating surface and between one area on the target and another. The infrared imagery gives a display of these gradients over a larger physical scale than does the TXR data. Both of these methods contribute to a greater understanding of the overall target performance and in the future can be used to fully characterize a calibration source.

Future work includes relating data from specific target positions to data from PRTs embedded at different depths within the target base and studying the z-direction dependence (if any) for the distance between the TXR and the target. Work is underway to achieve an absolute calibration of the imagery data from both infrared cameras.

4.3 Electromagnetic Properties of Target Materials

There are numerous microwave absorbing materials on the market designed for a wide variety of applications. These materials cover a broad range of performance characteristics that are not always well understood or well publicized. The electromagnetic properties of microwave absorbers are often frequency dependent, and in many cases are used at frequencies for which they were not initially designed or for which the properties have yet to be measured. A user of one of these materials may have to make certain assumptions about the material performance and, in the case of modeling performance across a range of frequencies, may have to interpolate or extrapolate from the information provided.

Calibration targets are typically constructed of a thermally-conductive substrate coated with microwave absorbing material to provide a near blackbody radiator at the frequencies of interest. The overall emissivity of a target depends on the electromagnetic properties of the surface material, the thickness of the material relative to the frequency at which it is observed, and the geometry of the target surface. Estimates of the emissivity are often made from reflectivity measurements. Emissivity values can also be derived from a knowledge of the electromagnetic properties of the materials used, but there is currently no widely accepted standard method for determining the emissivity of a microwave calibration target.

To carefully characterize the electromagnetic properties of absorber materials incorporated in calibration targets, we have collected, from various manufacturers, a number of different samples that could be measured in waveguide. Using the transmission/reflection (T/R) method [15] for measuring the relative permittivity and permeability, we have measured various absorber material samples in a series of rectangular waveguide fixtures at frequencies ranging from 8 to 18 GHz. In this method, the relative permittivity and permeability of the sample are calculated from the measured S-parameters of a sample-loaded waveguide and the dimensions of both the sample and waveguide fixture. These bands were chosen because they contain common frequencies at which microwave remote sensing radiometers operate and represented a natural extension of existing NIST capability. We chose to use waveguides rather than coaxial transmission lines for ease of sample preparation and to allow future extension of the measurements to 26.5 GHz or higher. Preliminary measurements for these materials have been presented in [10]. In Figs. 4 and 5 we present the results of a ferrous-doped epoxy sample for two waveguide bands.

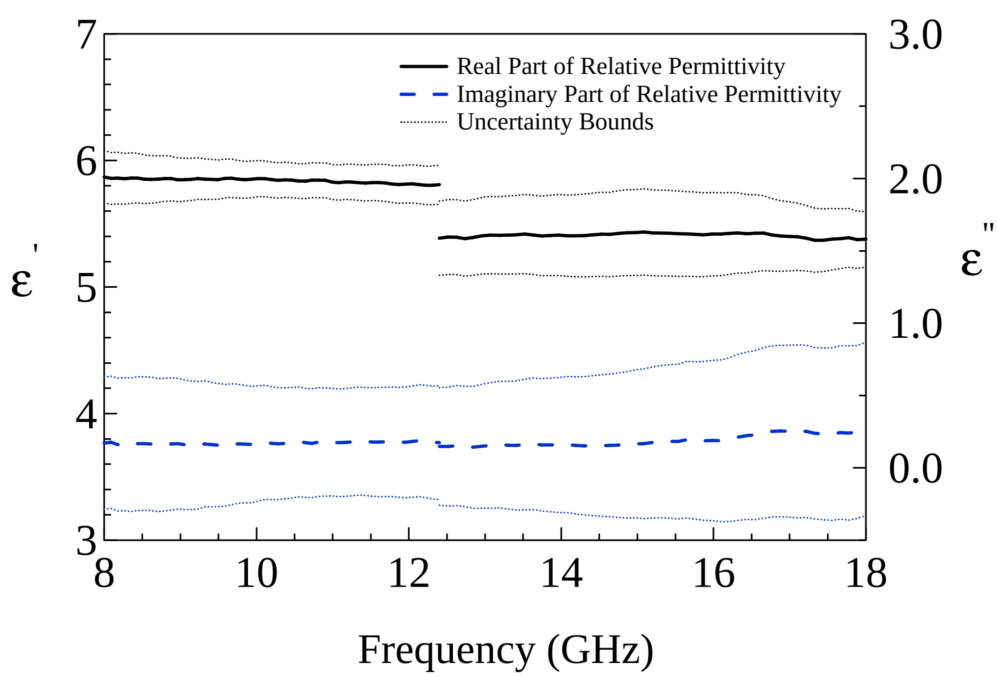

Fig. 4 Complex permittivity for ferrous-doped epoxy.

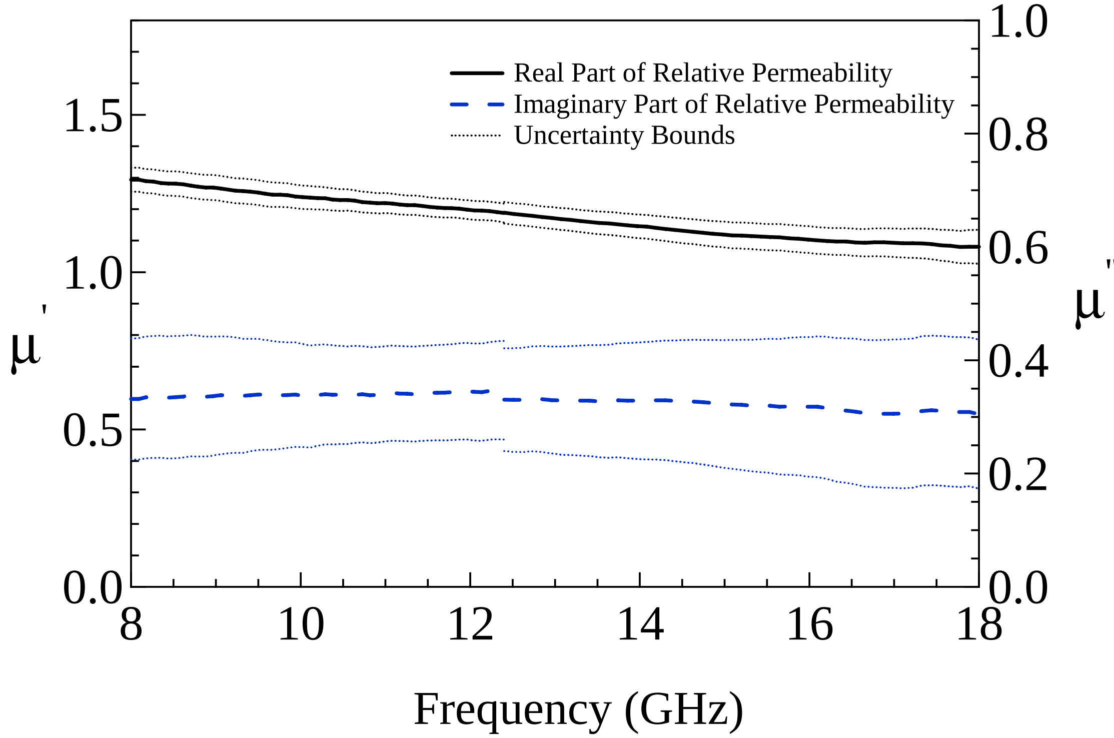

Fig. 5 Complex permeability for ferrous-doped epoxy.

In Figs. 4 and 5 we show results for the complex permittivity and permeability of the ferrite-loaded, epoxy absorber material. For the complex permeability (Fig. 5), we see good agreement between the two waveguide bands. However, we see some discrepancy in the complex permittivity results. The samples for each band were machined from different lots, and there is a possibility that there is a slight batch-to-batch variation of the material properties. The air gap between the sample and waveguide differs for each band and the correction becomes more critical as frequency increases; we plan to investigate this discrepancy further. The results for the lower frequency band are consistent, within defined uncertainties, with those measured during previous tests for the same sample.

The results from these measurements can be used to better characterize passive microwave radiometer calibration targets as well as absorber for other applications. Measurements of more samples of varying absorber characteristics are planned. Several more samples have been obtained for measurement, including ferrous-doped epoxy samples of multiple absorber concentrations, carbon-loaded closed-cell foam, and other types of foam materials. We now have waveguide test fixtures to make measurements up to 26.5 GHz; this is useful since our standard radiometer measurements have been made in this frequency range.

5. 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 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, we estimate 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, we can safely assume that the uncertainty in the combined standard would be no larger than that of the standard radiometer, and could be somewhat smaller.

REFERENCES

1. J. P. Rice and B. C. Johnson, "NIST activities in support of space-based radiometric remote sensing," *Proc. SPIE* 4450, 108 – 126 (2001).
2. http://kcdb.bipm.org/
3. http://www.bipm.org/en/committees/cc/ccem/
4. http://www.bipm.org/en/committees/cc/ccpr/
5. J. Randa, A.E. Cox, D.K. Walker, M. Francis, J. Guerrieri, and K. MacReynolds, "Standard radiometers and targets for microwave remote sensing," *IGARSS 2004 Conference Digest*, paper 2TU_30_10, Anchorage, AK (Sept. 2004).
6. J. Randa, A.E. Cox, and D.K. Walker, "Proposed development of a national standard for microwave brightness temperature," *2006 IEEE International Geoscience and Remote Sensing Symposium Digest*, to be published, Denver, CO (August 2006).
7. J. Randa, D.K. Walker, A.E. Cox, and R.L. Billinger, "Errors resulting from the reflectivity or calibration targets," *IEEE Trans. Geosci. Remote Sens.* 43 (1), 50 – 58 (Jan. 2005).
8. R.C. Wittmann, A.E. Cox, and R.H. Direen, "Proximity effects in the calibration of microwave radiometers," *Proceedings of the 2005 Antenna Measurement Techniques Association Symposium (AMTA 2005)*, 333 – 336, Newport, RI (Nov. 2005).
9. A.E. Cox, J.J. O'Connell, and J.P. Rice, "Initial results from the infrared calibration and infrared imaging of a microwave calibration target," *2006 IEEE International Geoscience and Remote Sensing Symposium Digest*, to be published, Denver, CO (August 2006).
10. A.E. Cox and M.D. Janezic, "Preliminary studies of electromagnetic properties of microwave absorbing materials used in calibration targets," *2006 IEEE International Geoscience and Remote Sensing Symposium Digest*, to be published, Denver, CO (August 2006).
11. F. Ulaby, R. Moore, and A. Fung, *Microwave Remote Sensing: Fundamentals and Radiometry, Vol. 1*, Norwood, MA, Artech House (1981).
12. NOAA Environmental Technology Laboratory, Ground-Based Scanning Radiometer, http://www.etl.noaa.gov/technology/gsr/
13. B.C. Johnson and J.P. Rice, "The NIST EOS Thermal-Infrared Transfer Radiometer," *Metrologia* 35(4), 505 – 509 (1998).
14. J.B. Fowler, "A Third Generation Water Bath Based Blackbody Source," *J. Res. NIST* 100(5), 591 – 599 (1995).
15. J. Baker-Jarvis, M. Janezic, J. Grosvenor, and R. Geyer, "Transmission/Reflection and Short-Circuit Line Methods for Measuring Permittivity and Permeability," *NIST Technical Note* 1355-R (1993).

Proceedings of the SPIE, Vol. 6301, 630105 (Sept. 1, 2006)