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Abstract: A plan is presented for developing a standard for brightness temperature at microwave frequencies, as well as two different methods for transferring this standard to the microwave remote-sensing community. The standard will be based on existing NIST waveguide and coaxial radiometers, which are calibrated with primary noise standards. The radiometers will be converted (reversibly) to standard remote-sensing radiometers by connecting characterized antennas to the plane at which the device under test is connected in normal use. The underlying theory and plans for implementation are presented. Once developed, the brightness-temperature standard and the method for comparison will allow microwave remote-sensing measurements to be traceable to the primary noise standards maintained by NIST.

Keywords: brightness temperature; microwave radiometry; remote sensing; standards; traceability

1. INTRODUCTION

Traceability of microwave remote-sensing measurements to primary physical standards offers a number of benefits, all deriving from the existence of a stable, common point of reference to which different measurements by different instruments at different times can be compared. Thus, for example, measurements from two different satellites could be meaningfully compared and reconciled if both were traceable to fundamental standards. If the standards are derived from basic physical principles, then they need not even be realized at the same laboratory. The remote-sensing instruments could be directly traceable to the realizations of the same fundamental physical quantity at the national measurement institutes of different countries. These different national standards are compared periodically through formal comparisons organized by the Consultative Committee on Electricity and Magnetism (CCEM) of the International Committee of Weights and Measures (CIPM). At least in principle, this would allow the comparison and reconciliation of data from U.S. and European satellites, for example. It would also provide a stable reference point that would allow the comparison of data from satellites flown years or decades apart, a critical issue for studying long-term phenomena such as climate change.

Without any clarification or specification, traceability to NIST can be a weak, almost nebulous, term in the context of remote sensing. It can refer to a single component or set of components, such as the temperature sensors in a calibration target, or a voltmeter used to read detector output; or it can refer to an entire instrument being calibrated against NIST standards, as is done at infrared, optical, and ultraviolet frequencies [1]. There are two key considerations we should bear in mind if we want to discuss traceability in a meaningful manner: (1) What is the physical quantity whose measurement is traceable? (2) What is the uncertainty associated with the traceability chain? These two questions are linked, of course. In the case of microwave remote sensing, for example, the physical quantity being measured is the received brightness temperature. The fact that the measurement of detector voltages or temperatures within the calibration target are NIST-traceable with some small uncertainty says nothing about the measured brightness temperature. The intervening steps from temperature within the target or detector voltage to brightness temperature are open to question; they must be verified and the uncertainties estimated. The more such steps there are, the larger the uncertainty becomes. In addition, each such step and the associated uncertainty between the traceable quantity (temperature within the target or voltage) and the ultimate measured quantity (brightness temperature) is open to question by doubters. The more that can be included within the traceability chain and the smaller the uncertainties, the better. This may all be obvious to some readers, but it is worth stating clearly at the outset since it underlies the approach and organization of this paper.

At present, NIST provides measurement services in two microwave areas that are relevant to remote-sensing radiometry. The Thermal Noise Metrology Project measures the noise temperature of customers' diode (or other) noise sources. In principle, these noise sources can then be used to measure the noise figure of a receiver or of a radiometer without its antenna. However, such partial traceability is often of little interest or use for remote-sensing radiometers. They serve a diagnostic or characterization purpose that can often be met adequately by other means. On the other hand, measurements of antenna pattern, offered by the Antenna Metrology Project, are very important. We shall see below that they are required in our plan to establish a brightness-temperature standard (as are the noise-temperature measurements), but they are also of interest in their own right. Even if the brightness temperature were known perfectly, it would still be necessary to know the scene to which that brightness temperature was to be attributed, and that requires knowledge of the antenna pattern. This paper will deal with the development of a brightness-temperature standard and the method to transfer it, but it should be remembered that the existing antenna-pattern measurement service constitutes a vital complement to a brightness-temperature standard.

In this paper we set out a plan to develop a link between microwave remote-sensing measurements and fundamental noise standards maintained by NIST. Such a link can be used to establish traceability for measurements of brightness temperature itself. NIST does not currently maintain standards for or perform measurements of brightness temperature at microwave frequencies. Therefore the first step in the plan must be to develop such a capability, which would integrate aspects of the antenna and noise measurement capabilities and standards already in place. Traceability would then be established by comparison to NIST brightness-temperature measurements or standards, as will be discussed later in this paper. The remainder of the paper is organized as follows. Section 2 reviews the theory underlying our approach to linking brightness-temperature measurements to noise standards. Section 3 outlines the plan for developing standard radiometers as standards for microwave brightness temperature and the approximate uncertainties that should be attainable. In Section 4 we discuss methods for comparing to those standards, and Section 5 is devoted to the summary and conclusions.

2. THEORY FOR STANDARD RADIOMETER

We plan to develop microwave brightness-temperature standards by (reversibly) converting the Noise Project's present radiometers, which are used to measure coaxial or waveguide noise sources, into standard remote-sensing radiometers that can then be used to link microwave remote-sensing radiometer measurements to primary thermal noise standards. This section sets out the general framework for doing so and indicates the particular antenna properties that must be determined in order link the remote-sensing measurements to the primary standards. For the most part, we follow the treatment in Chapter 4 of Ulaby, Moore, and Fung [2], except that we do not rely on the Rayleigh-Jeans approximation as they do. (This difference will be discussed below.)

The basic configuration of interest is shown in fig. 1. It is similar to the usual configuration [3] for measuring the noise temperature of a noise source except that an antenna replaces the noise source. The output noise temperature of the antenna (at plane x) can be measured in the same way as would the noise temperature of a noise source. We must then relate the noise temperature measured at plane x to the brightness temperature incident on the antenna. The brightness $B(\theta, \varphi)$ is the power per unit area and solid angle incident on (or emitted from) a surface, and the spectral brightness

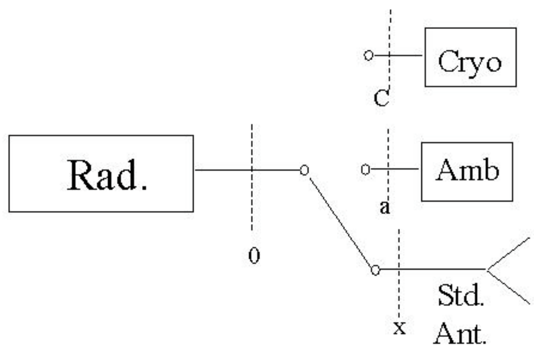

Fig. 1 Standard-radiometer configuration.

$B_f(\theta, \varphi)$ is the brightness per unit frequency. In terms of the spectral brightness, the differential power received by an antenna from differential solid angle $d\Omega$ in differential frequency interval df can be written as

$$dp = A_{eff} B_f(\theta,\phi) F_n(\theta,\phi) d\Omega df \quad , \tag{1}$$

where A_{eff} is the effective aperture area of the antenna, and $F_n(\theta,\varphi)$ is its normalized antenna pattern. This assumes that the polarization of the incident radiation is matched to the antenna. For unpolarized incident radiation the total power received in the frequency interval Δf is

$$P = \frac{1}{2} A_{eff} \int_{f}^{f+\Delta f} \int_{4\pi} B_f(\theta,\phi) F_n(\theta,\phi) d\Omega df \quad , \tag{2}$$

where the ½ arises from the average over incident polarization. In principle, of course, A_{eff} and F_n are also functions of frequency, but we assume that Δf is small enough that A_{eff} and F_n are effectively constant across the range of the frequency integration. From eq. (2) we can also identify the spectral power P_f received by the antenna ($P = \int P_f df$),

$$P_f = \frac{1}{2} A_{eff} \int_{4\pi} B_f(\theta,\phi) F_n(\theta,\phi) d\Omega \, . \tag{3}$$

To introduce the concept of brightness temperature, we consider the case of an antenna receiving radiation from an ideal black body. The spectral brightness emitted by an ideal black body at physical temperature T is uniform in all directions and is given by

$$B_f = \frac{2}{\lambda^2} \left(\frac{hf}{e^{hf/kT} - 1} \right) , \tag{4}$$

where h and k are Planck's and Boltzmann's constants, f is the frequency, and λ is the wavelength. For $hf/KT << 1$, this assumes the familiar Rayleigh-Jeans form,

$$B_f \approx \frac{2kT}{\lambda^2} \quad , \tag{5}$$

where T is the physical temperature of the ideal black body.

Because of the approximate linear relationship between B_f and T for a black body, and because the physical temperature of the scene is typically the quantity of interest in microwave remote sensing, it is common to define and work with a "brightness temperature" T_B rather than the brightness itself. The definition most commonly used (but which we will *not* use) is what can be called the equivalent black-body definition, *i.e.*, the brightness temperature is the temperature of an ideal black body that would give rise to the observed brightness. Thus eq. (4) is used for any radiating body (not just an ideal black body), with T defining the brightness temperature. With this definition, the brightness temperature of a black body is equal to its physical temperature, but the relationship between B_f and T_B expressed by eq. (5) is valid only in the Rayleigh-Jeans approximation. This is rather inconvenient, as will become evident below. The alternative is to use eq. (5) to *define* T_B,

$$T_B(\theta,\phi) \equiv \frac{\lambda^2 B_f(\theta,\phi)}{2k}, \tag{6}$$

which we shall call the power definition. With the power definition, the correspondence between the brightness temperature and the physical temperature for an ideal black body is only approximate, but this definition is much more convenient for use in common equations. In this paper, we use the power definition of T_B, eq. (6). The relation between T_B and the physical temperature of an ideal black body is obtained by using eq. (4) for B_f in eq. (6). For a non-black body, with emissivity ε less than one, a factor of ε is inserted into the right side of eq. (4), and eq. (6) is unchanged.

Using eq. (6) in eq. (2) and assuming that Δf is small, we have

$$P = \frac{kA_{eff}\Delta f}{\lambda^2}\int_{4\pi} T_B(\theta,\phi)F_n(\theta,\phi)d\Omega\,. \tag{7}$$

(Had we adopted the equivalent black-body definition of the noise temperature, eq. (7) would be complicated by a Planck factor. Similarly, all the equations below in which temperatures are added—or integrated—depend on the power definition of the brightness temperature.) If we define the input antenna temperature $T_{A,in}$ by

$$T_{A,in} \equiv \frac{A_{eff}}{\lambda^2}\int_{4\pi} T_B(\theta,\phi)F_n(\theta,\phi)d\Omega\,, \tag{8}$$

then eq. (7) takes the familiar form for the available power from a passive impedance at noise temperature $T_{A,in}$,

$$P = kT_{A,in}\Delta f\,. \tag{9}$$

Thus the input antenna temperature $T_{A,in}$ is the noise temperature (defined as the available noise spectral power divided by Boltzmann's constant) at the input (aperture) plane of the antenna. Equations (8) and (9) are the sort of relationship that we need. They give the noise power delivered to the radiometer by the antenna in terms of the incident radiation and the antenna properties. Some work still remains to be done, however. Equation (8) for the input antenna temperature can be put in a more useful form by using the relationship between the (lossless) effective area and the maximum directivity D_0, $A_{eff} = \lambda^2 D_0/4\pi$. The maximum directivity is, in turn, related to the pattern solid angle Ω_p by $D_0 = 4\pi/ \Omega_p$, where

$$\Omega_p = \int_{4\pi} F_n(\theta,\phi)d\Omega \, . \tag{10}$$

The effective area can therefore be written as

$$A_{eff} = \frac{\lambda^2}{\Omega_p}, \tag{11}$$

and the input antenna temperature assumes the form

$$T_{A,in} = \frac{\int_{4\pi} T_B(\theta,\phi)F_n(\theta,\phi)d\Omega}{\Omega_p} \, . \tag{12}$$

Equation (12) represents the noise temperature at the antenna input plane, whereas the radiometer measures the noise temperature at the output of the antenna, plane x in fig. 1. The two are related by (see, e.g., Ref. [4])

$$T_{A,out} = \alpha T_{A,in} + (1-\alpha)T_a \, , \tag{13}$$

where α is the available power ratio between the antenna aperture and the output plane (plane x in fig. 1), and T_a is the noise temperature corresponding to the physical temperature of the antenna. T_a is given by

$$T_a = \frac{1}{k}\frac{hf}{\left(e^{hf/kT_{phys}} - 1\right)}, \tag{14}$$

where T_{phys} is the physical temperature of the antenna, which is assumed to be ambient temperature. Reference [2] (and virtually all of the remote-sensing community) does not worry about subtleties such as the distinction between available power ratio and efficiency (delivered power ratio). They use the efficiency η_l rather than the available power ratio α in eq. (13). They then identify η_l as the inverse of the “loss factor” L, $\eta_l = 1/L$. From our experience with adapters in noise measurements, this is a reasonable approximation, assuming low loss and good matching. Some care will be required in computing or measuring the loss, to ensure that the correct quantity is obtained, and differences between α and the quantity measured or calculated will need to be accounted for in the uncertainty analysis.

The input antenna temperature of eq. (12) integrates over the full 4π solid angle. It therefore includes contributions from both the main beam and any side lobes, as well as from both the target of interest and any background radiation. In common remote-sensing applications, the solid-angle integration is separated into an integration over the main lobe plus an integration over everything else. Thus the main beam *defines* the target of interest. In our case, we will be viewing a calibration target, which may intercept only a part of the main beam, or it may intercept more of the pattern than just the main lobe. We wish to separate the calibration-target component of the brightness temperature from everything else. We therefore separate $T_{A,in}$ into two parts, one containing the integration over the solid angle subtended by the target of interest, and the other containing the rest of the 4π solid angle. We do this for both the input antenna temperature and for the pattern solid angle, eq. (10), and we define a target contribution T_T and a background contribution T_{BG} to $T_{A,in}$,

$$T_{A,in} = T_T + T_{BG}$$

$$T_T = \frac{\int\limits_{\text{target}} T_B(\theta,\phi) F_n(\theta,\phi) d\Omega}{\Omega_p} \tag{15}$$

$$T_{BG} = \frac{\int\limits_{\text{other}} T_B(\theta,\phi) F_n(\theta,\phi) d\Omega}{\Omega_p} \ .$$

If we further define an "antenna-target efficiency" η_{AT},

$$\eta_{AT} \equiv \frac{\int\limits_{\text{target}} F_n(\theta,\phi) d\Omega}{\Omega_p} , \tag{16}$$

we can write

$$T_{A,in} = \eta_{AT} \overline{T_T} + (1-\eta_{AT}) \overline{T_{BG}} , \tag{17}$$

where

$$\overline{T_T} = \frac{\int\limits_{\text{target}} T_B(\theta,\phi) F_n(\theta,\phi) d\Omega}{\int\limits_{\text{target}} F_n(\theta,\phi) d\Omega}$$

$$\overline{T_{BG}} = \frac{\int\limits_{\text{other}} T_B(\theta,\phi) F_n(\theta,\phi) d\Omega}{\int\limits_{\text{other}} F_n(\theta,\phi) d\Omega} \ . \tag{18}$$

In eq. (17), $\overline{T_T}$ is the incident brightness temperature averaged over the portion of the antenna pattern corresponding to the target solid angle, which is the quantity of interest for the standard radiometer. The antenna-target efficiency η_{AT} is the fraction of the full antenna pattern that is subtended by the target of interest. The quantity $\overline{T_{BG}}$ is the average brightness temperature from directions other than the target.

We can use eq. (17) in eq. (13) to obtain an equation for $\overline{T_T}$ in terms of measured quantities,

$$\overline{T_T} = \frac{1}{\alpha \eta_{AT}} T_{A,out} - \frac{(1-\eta_{AT})}{\eta_{AT}} \overline{T_{BG}} - \frac{(1-\alpha)}{\alpha \eta_{AT}} T_a \ . \tag{19}$$

To control the effect of $\overline{T_{BG}}$ in eq. (7), we need to control the environment in which the standard radiometer operates. We intend to use an enclosure with absorptive walls, maintained at room temperature, which will also be the temperature of the antenna, T_a. In that case, $\overline{T_{BG}} = T_a$, and eq. (7) becomes

$$\overline{T_T} = T_a + \frac{1}{\alpha\eta_{AT}}\left(T_{A,out} - T_a\right). \tag{20}$$

Equation (20) is the desired result for our standard-radiometer measurements. It allows us to determine $\overline{T_T}$, the average incident brightness temperature received from the target, in terms of $T_{A,out}$, α, η_{AT}, and T_a. In eq. (20) $T_{A,out}$ is the noise temperature at the output of the antenna, measured by the radiometer; α is the available power ratio between the antenna aperture and its output, approximately equal to $1/L$; η_{AT} is the antenna-target efficiency, defined in eq. (16) and determined from the normalized antenna pattern; and T_a is the noise temperature corresponding to the physical temperature of the antenna and the enclosure.

3. PLAN FOR STANDARD RADIOMETER

If eq. (20) is to be used to characterize a radiometer, the two antenna properties we need are α, which is the available power ratio between the antenna aperture and its output, approximately equal to the inverse of the loss factor $1/L$, and η_{AT}, which is the antenna-target efficiency. Ohmic losses are best determined by calculation, using any of a number of software packages. For common, commercial standard-gain horns the ohmic losses are found to be less than 0.03 dB with the worst-case conductivity (at about 20 GHz). However, the uncertainty in the electrical conductivity is the major uncertainty in determining the ohmic losses. The normal practice is to neglect the ohmic loss and include an additional uncertainty of 0.03 dB to account for its neglect [5]. A possible alternative method would be to measure the gain and the directivity of the antenna by two independent methods and to obtain the loss from the ratio of gain to directivity. However, a preliminary estimate indicates that it would have uncertainties comparable to those in the calculational method. (It could still be useful as a check.)

The antenna-target efficiency η_{AT} is defined in eq. (16). To determine it, we must measure the antenna pattern over all angles for which the normalized antenna pattern $F_n(\theta,\varphi)$ is not negligible. NIST pioneered the use of near-field scanning for antenna-pattern measurements [6] and continues to maintain and use several near-field ranges for this purpose. The frequency range covered is currently 2 GHz to 75 GHz, but the upper limit will be extended to 110 GHz in the very near future. The antenna group is currently conducting an experiment to determine how well they can measure the pattern of a standard-gain horn. These measurements will allow us to estimate the uncertainty with which η_{AT} can be determined.

From the standpoint of noise measurements, the framework developed in Section 2 requires only a measurement of the noise temperature at the input plane to the receiver section of the radiometer. This corresponds to the input plane for the coaxial and waveguide radiometers that NIST has built and with which NIST has been measuring the noise temperature of noise sources for several decades. Current capability includes two discrete points at low frequency (30 MHz and 60 MHz) and continuous coverage from 1

GHz to 65 GHz. Cryogenic coaxial standards [7] are used up to 12.4 GHz, and cryogenic waveguide-horn standards [8] are used above 12.4 GHz. The typical uncertainty in the noise temperature measured at the input plane depends on the frequency and the noise temperature being measured. For the typical 10 000 K diode noise source that NIST measures, the standard (1-sigma) uncertainty is about 0.4 % or 0.5 % for frequencies up to about 20 or 25 GHz, and it increases to around 0.9 % at 65 GHz. For noise temperatures in the 200 K to 300 K range, however, the uncertainties are considerably smaller, approximately 0.3 K at 20 or 25 GHz.

Because we do not normally measure noise temperatures in the 200 K to 300 K range, we thought it prudent to test whether our uncertainty estimates were reliable. To do so, we designed and constructed a variable noise source whose noise temperature is known and can be varied in a range around ambient temperature (296 K). The noise temperature was then measured, and the measured and predicted noise temperatures were compared. This was done on our coaxial radiometer for frequencies from 2 GHz to 12 GHz, for noise temperatures from 263 K to about 320 K, with very good results [9]. We conclude that our uncertainty estimates are approximately correct (at least for this radiometer) and that we can measure noise temperatures around 250 K to 300 K with a standard uncertainty of about 0.3 K.

The final component in using eq. (20) as the basis for a standard radiometer is to control the environment, so that $\overline{T}_{BG} = T_a$. For this purpose, we plan to use the standard radiometer in a chamber that would exclude outside radiation and present a uniform background radiation at T_a = 296 K. A preliminary sketch of such a chamber is shown in fig. 2. It is similar to a radio-frequency (RF) anechoic chamber, with metal (probably aluminum) exterior walls, lined on the inside with RF absorber. A major difference from an RF anechoic chamber is the temperature control that is required. We expect to house the chamber within a temperature-controlled room to maintain the outer walls at the desired temperature. Fans will be used to circulate the air, preventing the development of hot or cold spots, and an array of thermistors will be embedded in the walls to monitor the temperature. A positioning table or assembly will be located near the back wall, suitably shielded with absorber to obscure the electronics behind it. The required precision and sophistication (and concomitant cost) of the positioner is not clear at this time. The size of the chamber will require some study. We want the target to be in the far field of the antenna, and we want the chamber to be usable down to about 18 GHz. If the common antenna far-field criterion of $2d^2/\lambda$ is used, the chamber would need to be only about a quarter meter long, which is conveniently small. However, for some purposes [10], the far-field criterion for a standard-gain horn is about $32(d^2/\lambda)$, which would require a chamber length of about 4 m. Clearly, this issue must be addressed before chamber design and cost estimates can be done. The NIST waveguide radiometers and cryogenic standards are already kept on carts and can be rolled into position at the front of the chamber. The size of the opening at the front of the chamber will be determined by a compromise between shielding and air circulation. If necessary, it would be simple to design shielded air vents for placement in the walls.

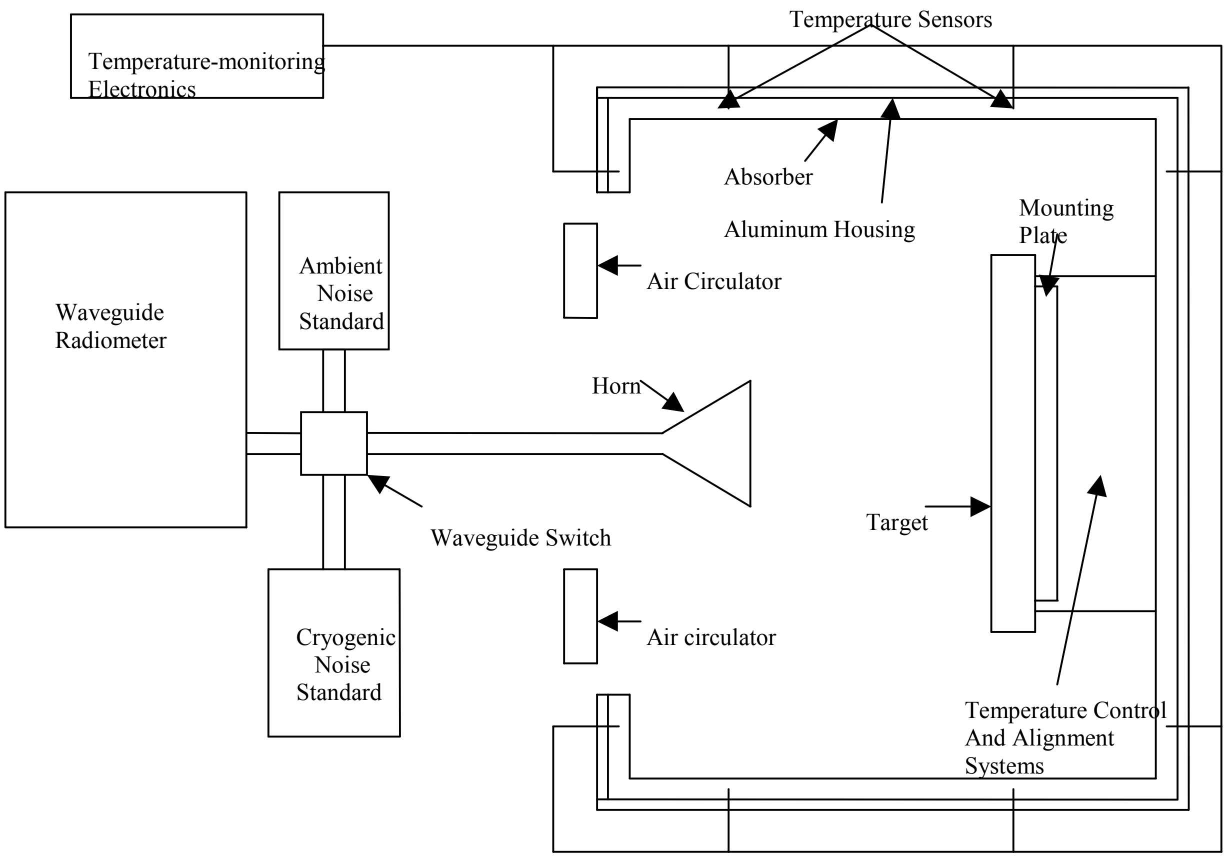

Figure 2. Preliminary sketch of chamber for standard radiometer.

The principal disadvantage of such a chamber is the lack of a capability for thermal-vacuum (TV) testing. Space-based radiometers operate in a vacuum, and although the temperature is controlled, it is not likely to be 296 K. Since the heat transfer mechanisms depend on the surrounding atmosphere, the thermal properties of a calibration target will be different in a TV chamber from those in the proposed "ambient" chamber. It is therefore desireable to test under the anticipated operating conditions, i.e., in a TV chamber. At this time, however, such a facility appears to be beyond the anticipated resources of NIST. The next section includes a suggestion for how we can compensate for the lack of a TV environment for the proposed brightness-temperature standard. There are also possible ways to mitigate the effects. For example, one significant factor in the possible difference between behavior in a TV chamber and in an ambient chamber is that in a TV chamber there is virtually no convective heat transfer, whereas in an ambient chamber there is. The effect of this difference can be minimized by fitting a styrofoam cover over the front surface of the target, to eliminate its thermal contact with the surrounding atmosphere.

To estimate the uncertainty achievable with a standard radiometer, we refer to eq. (20). We expect to be able to control T_a to within about 0.2 K. As we noted above, $T_{A,out}$ can be measured with a standard uncertainty of about 0.3 K up to about 26 GHz. The uncertainty in α for a standard-gain horn will be about 0.5 %. We do not yet know the uncertainty in η_{AT}. If it can be kept to about the same as that in α, we should be able to achieve a standard uncertainty in $\overline{T_T}$ of about 0.3 K to 0.8 K for $\overline{T_T}$ between 200 K and 300 K, at frequencies up to about 26 GHz.

4. BRIGHTNESS-TEMPERATURE STANDARD AND TRANSFER

The standard radiometer(s) discussed above will constitute a standard for brightness temperature, linking measurements of it to primary noise standards. For it to be useful, however, there must be a means for others to compare to this standard. One way would be for outside parties to send their calibration targets to NIST, where the targets could be measured by the standard radiometers in the NIST ambient chamber. It would also be very useful for NIST to have a transportable transfer standard, which could be measured by the customer's radiometer at the customer's facility. For this purpose, we plan to develop a standard calibration target, in addition to the standard radiometers. Its temperature will be monitored by several thermistors, so that it will constitute a brightness-temperature standard in its own right, but it also will be measured by the standard radiometers, thereby providing a check of both the standard target and the radiometers. This standard calibration target will be designed for use in TV chambers, so that it can be used in the same facilities that are used for pre-launch testing of a customer's radiometer and its calibration targets. An integral part of the development and design of the NIST standard target will be the development of methods for testing and characterizing such targets. In particular, we will attempt to develop test methods for detecting thermal gradients within the target (infrared imaging) and for measuring reflectivity or emissivity of the target.

Assuming both standard radiometers and a transportable standard target are developed, there will be a number of strategies available for establishing traceability through comparison to a NIST brightness-temperature standard. In the NIST chamber, a customer's calibration target could be measured directly with a NIST standard radiometer, thereby linking its brightness temperature to primary noise standards (under ambient conditions). A customer's radiometer (within size limitations) could also be measured in the NIST chamber and compared directly to the NIST standard radiometer by measuring the same target with both radiometers. The standard target could also be measured at a customer's facility, either under ambient conditions or in a TV chamber. A comparison between the performance of the NIST standard target in the NIST ambient chamber and in a TV chamber could be done if a portable radiometer was available. The standard target could then be measured by the same radiometer in both the ambient chamber and in a TV chamber. It would also be measured with the NIST standard radiometer in the ambient chamber. This would provide a link of the portable radiometer to the NIST standard radiometer, an opportunity that could be attractive enough to induce the owner of a portable radiometer to participate in such a comparison.

5. SUMMARY

We plan to develop standards for microwave brightness temperature for the frequency range 18 to 65 GHz, starting with the WR-42 (18 to 26.5 GHz) band. This will be done by connecting characterized antennas to the measurement ports of existing NIST waveguide radiometers, which are calibrated against primary noise standards. Thus the brightness temperature standard will be tied to the primary noise standards. A chamber will be constructed to provide a controlled (but not TV) environment for using these radiometers. At the lowest frequencies, we anticipate a standard uncertainty of about 0.3 K to 0.8 K in the brightness temperature for temperatures in the 200 K to 300 K range. In parallel, we plan to develop a portable standard calibration target, which will be suitable for use in a TV environment. The portable standard calibration target will be cross-checked with the standard radiometers. The standards will enable the measurement of customers' radiometers or targets at NIST at ambient temperature and pressure or measurement of the NIST standard target at a customer's facility under either ambient or thermal-vacuum conditions.

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