Standards Development For Remote Sensing at Microwave and Terahetz Frequencies

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Abstract The Noise Project in the Electromagnetics Division of the National Institute of Standards and Technology (NIST) has proposed the development of standards for microwave brightness temperature for use in remote-sensing applications such as The standards would be based on existing satellite-based weather observations. fundamental standards for electromagnetic noise in waveguide systems. The connection to brightness temperature, which is a radiated quantity, would be made by means of a well characterized antenna. A heated calibration target would be used to supplement the basic standard, either as a check or to reduce the uncertainty by a redundant measurement. We have performed preliminary measurements at 26 GHz that demonstrate the feasibility of the proposed standard. A parallel effort is in progress for terahertz frequencies. For terahertz noise we are building a heated target to be used as a noise standard, since we did not already have fundamental noise standards for such high frequencies. This standard will be used with a terahertz radiometer. The radiometer is based on a receiver that uses a hot-electron bolometer (HEB) mixer that is coupled to the radiation by a quasi-optical adapter. We expect to perform terahertz noise measurements with the system by the end of the year.

Keywords microwave radiometer microwave remote sensing microwave standards terahertz noise terahertz radiometer terahertz standards

1. INTRODUCTION

Remote sensing at microwave and terahertz frequencies has practical applications of enormous importance. Among the most important microwave applications are weather and climate monitoring. Water and oxygen emission lines make microwave frequencies important for measurements of sea surface temperature, sea surface wind, soil moisture, ice cover, atmospheric water vapor profile, and pressure and temperature sounding. Microwaves can also be used to "see" through clouds and measure what would be obscured from visible detection. Terahertz frequencies have important security applications, as do millimeter waves; but biomedical imaging and spectroscopic applications, such as cancer detection, may well prove to be even more important.

Despite their great importance, there is no national standard either for microwave brightness temperature (which is the radiated quantity that is detected in passive microwave remote sensing) or for terahertz brightness temperature or radiance, or even for terahertz noise. Radiance standards exist and have proven very useful for visible and infrared (IR) frequencies ^[1], but there are no equivalent standards for microwave or This is understandable for terahertz frequencies, where the terahertz frequencies. supporting technology is still being actively developed. For the microwave range, however, the necessary technology has been mature for decades, and waveguide and coaxial noise standards and measurements have been commonplace since the 1970s, but the extension to the radiated case has not been made (for national standards). In part this has been due to the extensive success of microwave remote sensing even in the absence of national standards. For relative measurements-such as cloud cover, ice cover, and many sounding applications—an *absolute* standard is not necessary. For applications where an absolute standard is necessary, individual groups have built or purchased their own calibration standards, have used celestial references (e.g., cold space) when possible, or have used some form of "vicarious" calibration, using a terrestrial target whose brightness temperature is known or can be inferred from other information. This other information can come from *in situ* temperature measurements, such as an array of earth based thermometers in a region viewed by a satellite based radiometer, from measurements by another satellite radiometer, or other means. The successes of microwave remote sensing attest to the sufficiency of these approaches in many cases. However, there have also been cases in which problems could have been avoided and in which other or better measurements could have been made, had a national standard been available.

Recent developments have greatly increased the need for fundamental physical standards for microwave brightness temperature that would be recognized and accepted nationally and internationally. One driving force is the inexorable push for smaller uncertainties. Microwave radiometers currently being built have specifications for uncertainties below 0.5 K. Achieving such small uncertainties will require special care in the calibration (as well as in other aspects), and convincing others that such uncertainties have been achieved will require (or be greatly facilitated by) an accepted reference source, i.e., a standard. The second recent development is the growing importance of combining and comparing data from different instruments. This may take the form of comparing results from two different microwave instruments measuring at the same time and location, combining or reconciling data from a microwave instrument with that from an infrared instrument, or investigating trends in data over very long time periods. These require a standard that is based on fundamental physical principles (in order to harmonize with instruments that may be calibrated in entirely different manners) and that is very stable over very long time periods. Thus, as uncertainty requirements become more demanding, as data from different instruments are more commonly combined or compared, as the possibility looms of gaps between replacement instruments, and as the importance of precise monitoring of long-term trends is (finally) recognized, the need for accurate, very stable standards tied to fundamental physical principles becomes increasingly apparent.

Over the past few years, the Electromagnetics Division of NIST has taken some steps toward developing standards for remote sensing at both microwave and terahertz frequencies, and this talk will review that work. For microwave frequencies, we have suggested a plan for developing national microwave brightness-temperature standards that would be linked to our fundamental noise standards ^[2]. More recently, we have suggested supplementing such a standard radiometer with a standard target ^[3, 4], and have also done work to characterize important properties of calibration targets ^[5-8]. For the terahertz range, we are developing a radiometer and noise standard ^[9]. Because the coupling of the standard to the radiometer is through a quasi-optical adapter, and the transmission is radiative, this is in fact a brightness-temperature or radiance standard.

The next section of this paper gives an overview of our work on microwave brightness-temperature standards development; Section 3 reviews our work on the terahertz radiometer and standard; and Section 4 contains a brief conclusion.

2. MICROWAVE BRIGHTNESS-TEMPERATURE STANDARDS

2.1 Standard Radiometer

We have proposed a microwave brightness-temperature standard that would be traceable to our fundamental thermal-noise standards ^[2]. The basic idea is illustrated in Fig. 1. One of the NIST waveguide radiometers ^[10], which is usually used to calibrate diode or gas-tube noise sources, is calibrated in the usual way, by use of our cryogenic primary noise standard for that waveguide band ^[11, 12] and an ambient standard incorporated into the radiometer. The radiometer measures noise temperature at plane x, where the noise source would be connected in normal operation. For the brightness-temperature standard, we instead connect a characterized antenna at the measurement plane. The characteristics of the antenna that we need to know are its antenna pattern, the loss in the antenna, and the reflection coefficient at plane x (looking toward the antenna, from the radiometer). With a characterized antenna, the brightness temperature incident on the antenna can be computed from the noise temperature measured at plane x ^[2],

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



Fig. 1 Configuration for standard radiometer.

where \overline{T}_T is the average incident brightness temperature received from the target, T_x is the measured noise temperature, T_a is the ambient temperature, α is the available power ratio of the antenna (approximately equal to the inverse of the loss), and η_{AT} is the fraction of the antenna's pattern that is subtended by the target. Thus, we would have a standard radiometer, which could be used to measure, and therefore calibrate, calibration targets for use by other laboratories. The calibration performed in this manner would be traceable to our fundamental noise standards. Such calibrations would have to occur in a well controlled environment to insure that we could properly account for radiation from sources other than the target under test. We envision an arrangement such as that shown in Fig. 2, in which the antenna of the standard radiometer protrudes into a temperature controlled chamber that houses the target under test. The walls of the chamber will be covered with radio frequency absorbing material (emissivity near unity), and their temperature would be monitored by an array of thermometers. The air would be circulated to prevent formation of hot spots around the target.

We have not yet built such a chamber, but we have performed preliminary measurements to demonstrate the feasibility of our approach ^[2]. A standard-gain horn antenna was attached to our WR-42 (18 – 26.5 GHz) radiometer, and we measured the brightness temperature from a heated calibration target mounted on a cart in the NIST anechoic chamber. The antenna pattern of a standard-gain horn had been previously measured on the NIST near-field range, its loss was calculated, and its reflection coefficient was measured (in the actual measurement configuration). We then measured the brightness temperature of a heated target as a function of distance from the antenna, using eq. (1), with η_{AT} computed from the measured antenna pattern and the target geometry and separation distance. The measured brightness temperature should be independent of the separation distance. Fig. 3 shows the results as a function of separation distance and compares the results to the brightness temperature obtained from



Fig. 2 Preliminary sketch of chamber for standard radiometer.



Fig. 3 Measured and predicted brightness temperatures vs. separation distance.

the physical temperature of the target, measured by embedded thermometers. The results are very good, except at the largest distance, where we think alignment error may be causing the problem. The measurement uncertainties were estimated to be about 1 K at the closer distances. With additional care, we believe the uncertainty could be reduced to 0.5 K or below.

2.2 Standard Target and Hybrid Standard

Most microwave remote-sensing radiometers are calibrated with a heated (or in some cases cooled) calibration target. A standard target could also be used as a microwave brightness-temperature standard, and we have suggested combining that approach with the standard radiometer of the previous section to develop a hybrid standard ^[3, 4] that would be a weighted sum of the results from the two approaches. Use of a heated calibration target as a brightness-temperature standard requires a thorough understanding of its properties. We have taken some steps to improve characterization methods for calibration targets. In particular, we have done work on three problems: transverse temperature gradients in the target, electromagnetic characterization of the target material, and effects of using the target in close proximity to the radiometer.

Calibration targets have their temperatures sensed at only a few locations on the target; it is therefore important to know how the temperature varies across the face of the target, and it is also important to know the temperature difference between the point at which the temperature is sensed (in the volume of the target) and the surface of the target, which is what is sensed by the remote radiometer. Both these issues can be addressed by

infrared imaging of the target surface ^[5]. Fig. 4 shows an infrared image of the surface of a heated calibration target, clearly showing an array of relatively cold spots corresponding to the tips of the pyramids on the target surface. While Fig. 4 shows the relative temperature distribution, the absolute surface temperature can be determined if the infrared emissivity of the surface is known and the infrared imager has an absolute calibration. This would then reveal any differences between surface temperature and the temperatures measured by the embedded thermometers.

For a heated target to be used as a microwave brightness-temperature standard, its emissivity at microwave frequencies needs to be known. As yet there is no widely accepted measurement method with known uncertainties for measuring the target emissivity, but some work has been done to measure the dielectric properties of a material commonly used in calibration targets ^[6].

When a microwave brightness-temperature standard is used, either a standard radiometer or a standard target, the target should be in the far field of the radiometer's antenna, but in satellite-borne radiometers it is not uncommon for the calibration target to be in close proximity to the antenna. Depending on the reflectivity of the target, this can have a significant effect on the match between the antenna and the rest of the radiometer [7]. Also, if the target is in the near field of the antenna, the antenna response is different from what is represented by its far field pattern. Much work remains to be done on this issue, but there are indications that the effect can be significant ^[8].



Fig. 4 Infrared image of the microwave calibration target.

3. TERAHERTZ NOISE STANDARDS

3.1 Terahertz Radiometer

The terahertz radiometer that we will use ^[9] is based on a detector and receiver that were developed for terahertz imaging applications ^[13]. The general configuration is shown in Fig. 5. The incident terahertz radiation and the beam from the LO source are combined by a thin mylar beam splitter. In the figure the incident terahertz radiation is shown coming from a LN₂ load; the final system will use a variable temperature heated target that is currently under construction. The LO is a commercial harmonic multiplier source that can provide hundreds of microwatts of power at our operating frequency of 850 GHz. The LO beam and the terahertz "signal" are directed through a quartz window into the cryocooler. Inside the cryocooler, they impinge on the silicon lens of the quasioptical adapter, as shown in Fig. 6. The silicon elliptical lens (4 mm diameter) focuses the radiation on the terahertz antenna located at the second focus of the elliptical lens. A monolithic twin-slot antenna with a bandwidth of about 10 % is used. The antenna structure was fabricated from an e-beam-evaporated Ti/Au film by use of a lift-off step. We currently use UV lithographic techniques. A hot-electron bolometer (HEB) mixer is fabricated at the terminals of the antenna, with an IF filter line from the mixer output to a low-noise amplifier (LNA). HEBs offer many advantages: they have very low noise temperatures, almost within an order of magnitude of the quantum noise limit; they can operate over the entire terahertz range; they have very small parasitic reactance; and they can be matched to the antenna impedance by varying the geometry of the HEB device.



Fig. 5 Full system for terahertz noise measurements.



Fig. 6 Quasi-optical adapter.

The MMIC LNA also has extremely low noise. Its noise temperature was measured and was found to be below 5.5 K over the entire 1 GHz to 11 GHz frequency range, with a minimum value of 2.3 K \pm 0.3 K at 7 GHz [14]. The entire receiver (quasi-optical adapter, antenna, HEB mixer, LNA) is integrated into a single receiver block, as shown in Fig. 7. The IF output from the receiver can be chosen anywhere in the range 0.5 GHz – 5 GHz and is read by a diode detector and power meter. The noise temperature of the entire system has been measured to be better than 1800 K (at 850 GHz). The system shown has



Fig. 7 Integration of quasi-optical adapter, HEB mixer, and MMIC LNA into receiver block.

been constructed and thoroughly tested in a liquid-helium cryostat. It is now being assembled and tested in a mechanical cryocooler.

A key element of the full radiometer system is the blackbody source that will be used to calibrate the system, represented by "LN₂ Load" in Fig. 5. We are in the final stages of instrumenting a basic version of such a standard. It consists of a sheet of ribbed rubber material glued to a copper plate 61 cm square. The back of the plate has copper tubing soldered to it, and heated oil is pumped through the tubing to heat the plate and therefore the ribbed rubber material that covers the radiating surface. The temperature of the oil can be varied from 50 °C to 250 °C. The temperature of the radiating surface will be monitored with thermistors, and we will use the terahertz imaging system to evaluate lateral uniformity. The emissivity will be estimated from measurements of the total reflectance, to be performed by the NIST Physics Laboratory. We expect the first measurements with the entire calibrated system to be performed in late 2007.

4. SUMMARY

We have presented an overview of work at NIST on developing standards for remote sensing radiometry at both microwave and terahertz frequencies. The terahertz work is progressing, and we expect the initial measurements, traceable to our blackbody standard, to be made late this year. The work on a microwave brightness-temperature standard has been interrupted. It will be resumed if funding becomes available.

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International Conference on Measurement and Metrology (ICMM-2007) General Reports, pp. 33 - 42 Beijing, China 5 - 7 September, 2007