Recent Developments in Millimeter and Submillimeter Metrology at NIST[1]

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Abstract

The millimeter and submillimeter frequency ranges are becoming very important to today's electronics, security and communication industries. NIST has undertaken a research program to aggressively pursue this area. This paper discusses the millimeter/submillimeter activities in the Electromagnetics Division at NIST. We discuss the current status and the future directions of the programs.

1.0 Introduction

The millimeter wave band is defined as having a frequency range of 30 GHz to 300 GHz (wavelength of 10 mm to 1 mm) and the submillimeter wave/terahertz band a range of 300 GHz to 10 THz (wavelength of 1 mm to 30 µm). Currently there is much activity in these frequency ranges. Radio astronomy has used frequencies of 100 GHz and higher for many years, but has grown up somewhat isolated from the rest of the electronics industry. Frequencies below 1 THz are used currently for remote sensing measurements of the atmosphere and sea, largely because they offer good resolution, with better penetration through cloud cover than infrared detectors. These frequencies are less suited to communication applications because of high atmospheric absorption, but huge bandwidths are available with little competition and there is interest in using these frequencies for short range and highly-secure links. Frequencies of 100 GHz and higher are attractive for radar because it offers very good range resolution and because relatively small antennas can achieve good angular resolution. These systems are also attractive for small airborne radar and automotive radar for collision avoidance and adaptive cruise-control applications. While most of the aforementioned applications are becoming more important, the major driver for commercial interest in these frequencies has been the security market. Frequencies above 100 GHz will penetrate through clothing and other materials and the short wavelength results in small pixels and good image resolution. There are many chemicals that have resonances in these frequency ranges. Security applications at 100 GHz and higher are poised to increase rapidly.

Metrological support needs to be created to support these emerging areas. NIST's Electromagnetics Division is actively pursuing research related to the measurement of various quantities at these frequencies. The main areas of involvement are: antenna metrology, advanced communications, electromagnetic property of materials, noise parameters/brightness temperature standards, and scattering-parameter and power measurements.

2.0 Antenna Metrology

NIST's Antenna Metrology Program has for three decades served companies and government agencies seeking to maximize the efficiency of communications in terms of evaluation of the world's highest-performance antennas. Program physicists and engineers are leaders in testing key antenna performance characteristics used in some of the worlds' most sensitive applications, such as radar systems, aircraft communication and avionics, and satellites and spacecraft, which are vital for communications, weather prediction, and space science [1].

The Electromagnetics Division of NIST pioneered the near-field scanning technique, now the standard method for testing high-performance antennas designed to communicate across tens, thousands or even millions of kilometers, and continue to advance it both theoretically and experimentally. This technique measures an antenna's near-field at close distances (a few

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centimeters), then uses mathematical algorithms developed at NIST to determine/extrapolate the far-field. The 110 GHz antenna extrapolation range is shown in Figure 1. Near-field scanning allows for accurate assessment of the gain (the amount of power transmitted or received in the antenna's primary direction), polarization (the orientation of the electromagnetic field) and pattern (the angular distribution of transmitted or received energy) of antennas.

Figure 1. Millimeter wave extrapolation range.

Currently the NIST antenna program can make extrapolation gain measurements from 1.5 GHz to 110 GHz. This provides on-axis gain and polarization for antennas that are used as reference antennas on antenna ranges throughout the world. Typical gain accuracies are +/- 0.07 dB for most of this frequency range. The NIST antenna program also can make planar near-field (PNF) measurements up to 110 GHz. The planar method provides the forward hemisphere of the far field of the antenna under test. Sidelobes as low as -60 dB relative to peak have been successfully measured. This method is often used for measuring radar, remote sensing, and communications antennas.

Recently, we were able to obtain network analyzers and frequency extenders that cover a range up to 500 GHz. These units allow us to extend our extrapolation measurement capability to 500 GHz. This will be especially useful for remote sensing for climate-monitoring applications and will also be useful in the future for antenna applications requiring large bandwidths at millimeter wave frequencies. We also have started to perform material scattering measurements up to 500 GHz. We are currently performing bistatic radar scattering measurements to determine the properties of various substances that may be hidden (for example, weapons in clothing). Additionally, we are developing a spherical near-field (SNF) / probe pattern measurement capability to 220 GHz. This will be vital to support our remote sensing for climate monitoring project, especially at the 183 GHz (water vapor) and 118 GHz (oxygen) lines.

3.0 Millimeter Wave Metrology for Wireless Communications

The Wireless Systems Metrology Program supports the growing wireless industry by developing methods to test the operation and functionality of wireless devices in the presence of various types of distortion. The Wireless Systems Metrology Program is also concerned with the impact of nonlinear distortion on the transmission of wireless signals, which can be especially severe for new wideband modulated signal transmissions. Accurately measuring distortion behavior of nonlinear radio-frequency devices is a key element in understanding how the device will perform once it is incorporated into a system. Even under weakly nonlinear conditions, low-noise devices such as those used in receiver front ends will exhibit nonlinear behavior that includes harmonic generation and intermodulation distortion. This program has studied problems that commonly arise in performing and interpreting nonlinear measurements, such as power and wave-based representations, and the effects of terminating impedance on intermodulation distortion. Researchers are also working to develop traceability to fundamental parameters such as power and electric field [2].

Another aspect of the program is concerned with “spectrum crunch”, which refers to the increased demand for radio-frequency spectrum that has recently arisen from the use of wireless devices such as mobile phones. In particular, smart phones use several times the bandwidth of traditional cellular phones. As recently noted by the Cellular Telecommunication Industry Association, 3 % of wireless smart-phone customers now use 40% of total available wireless bandwidth. Use of the millimeter wave spectrum holds promise for helping to alleviate the spectrum crunch, either through the direct use of spectrum for wireless, or through transferring existing services to these bands. Toward this end, the U.S. FCC has recently allocated spectrum at frequencies in the 70, 80, and 90 GHz range that is thirty times the total cellular bandwidth available today. At the same time, semiconductor processing advancements have, for the first time, enabled inexpensive silicon chips that operate above 50 GHz.

In anticipation of the use of millimeter wave frequency bands for wireless communication, we have initiated development of metrology that focuses on key wireless-system parameters, including antenna efficiency, free-field radiated-power measurements, modulated-signal distortion parameters such as adjacent channel power ratio and error vector magnitude, and harmonic distortion, which can occur well above 100 GHz for systems with center frequencies in the tens of gigahertz. We are currently developing a calibrated modulated signal source that can be used as a transfer standard by those developing transmitters, receivers, and test instrumentation in the millimeter wave frequency bands. The source will be traceable to NIST’s electro-optic sampling system through high-speed sampling oscilloscope measurements.

4.0 Electromagnetic Properties of Materials

The Electromagnetic Properties of Materials (EPM) project covers the measurement of the fundamental electrical properties of materials from bulk to nanoscale and from 1 MHz to 0.3 THz. Understanding the interaction of microwaves with materials and the electrical properties of materials is very important to the development of new electronics and medical technologies. The emphasis for the project is on measurement methods for substrates, thin films, liquids, biological materials, and artificial materials. This includes measurement fixtures, analysis of those fixtures, and the development of related measurement theory and techniques. One example of this is the split-cylinder measurement system, shown in Figure 2. This system was originally proposed by Gordon Kent and then greatly improved at NIST and adopted by a commercial manufacturer [3]. The program advances the state of the art by introducing advanced concepts based on the underlying physics that govern the nature and properties of the materials.

Figure 2. Commercialized version of NIST’s split-cylinder test fixture.

Recently, the EPM Project has extended its capability for permittivity and permeability measurements into the millimeter range, reaching frequencies over 110 GHz. We have developed and extended our capabilities to measure materials through the insertion of materials into waveguides. This has been done in WR 28 (26.5 – 40 GHz), WR 22 (33-50 GHz), WR 15 (50-75 GHz), and WR 10 (75 – 110 GHz) waveguides (Figure 3). These measurements are presently used to support our Infrastructure Corrosion Studies project and our Climate Change projects. For our waveguide approach the scattering parameters are measured in each band; then, NIST-developed theory and software are used to de-embed the parameters of the material in the waveguide fixture. We can measure powdered versions of materials by embedding them in a low-loss material such as beeswax. For solid materials the sample must be machined to fit snuggly in the waveguide shim. We use air-gap correction formulas developed at NIST to correct for systematic effects of small gaps between the material and the fixture.

Figure 3. Waveguide shims that are to be loaded with material samples.

Other systems that have been improved include our Fabry-Perot system, which has been extended to 110 GHz for the measurement of thin-film materials. Additionally, we are developing the capability to make free-space material measurements (Figure 4). For this system, samples are placed between microwave focusing lenses and the permeability and permittivity of the sample can be determined. The upper frequency limit of the system will be pushed to at least 500 GHz as we refine the system hardware and software.

Figure 4. Free-field test system for material measurements.

The characterization of the interface between fields and materials will be a critical task for any device, material or metrology development from nanoscale to larger scales. Areas to be addressed over the next 5 to 10 years will include developing measurement systems and techniques at frequencies approaching 1 terahertz, defining theoretical concepts, and developing the optimum measurement tools to extend electromagnetic metrology and reference materials to the nanoscale and eventually to the atomic scale. We will develop quantitative electromagnetic measurements of thin-film electronic materials, liquids, biomaterials, and other advanced materials over a wide range of experimental conditions including size, frequency, temperature, and magnetic fields. We are trying to anticipate years in advance the measurement needs of industry in nondestructive substrate measurements, microfluidics, thin-film characterization, and near-field probing techniques.

5.0 Noise/Brightness Temperature/Remote Sensing

Microwave radiometers are a critical part of space-based sensor suites that make global observations of the Earth's atmosphere, land, and oceans. Microwave sensors contribute to such measurements as atmospheric moisture profiles, sea-surface wind speed and direction, sea-surface temperature, soil moisture, and sea-ice characterization. As climate measurements increasingly call for environmental data records that span years or even decades, and rely on data from multiple instruments on multiple platforms spanning different operational time periods, the need for rigorously and independently validated traceability to the International System of Units (SI), is also increased. There are currently no national standards for microwave brightness temperature, either in the U.S. or elsewhere. Many realizations of microwave brightness temperature standards exist in the form of heated or cooled calibration targets, but none of these are 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 [4].

There are many reasons why a national microwave-brightness temperature standard that is based on fundamental physical quantities is needed. It would provide a constant reference for comparing different instruments over a long time. It would provide a means for resolving differences between different instruments or programs including instruments based on entirely different measurement parameters. This would work because the measurements would be traceable back to fundamental physical quantities and it would support the goals of merging data from multiple measurement systems from different nations.

The Fundamental Guided Wave Metrology Program and the Antenna Metrology Project at NIST are engaged in an effort to improve calibration methods and tools for microwave remote-sensing radiometry. A principal component of this effort is the development of a standard for brightness temperature at microwave frequencies, as well as two different methods for transferring this standard to the microwave remote-sensing community. NIST already has a battery of microwave radiometers that measure noise temperature at a coaxial or waveguide reference plane. The radiometers are converted (reversibly) to standard remote-sensing radiometers by connecting characterized antennas to the reference plane at which the device under test is connected in normal use. 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. A proposed measurement set up is shown in Figure 5. Figure 6 shows a calibration target (on the right side of the photo) and a calibrated antenna and receiver (on the left side) that is connected to the noise radiometer.

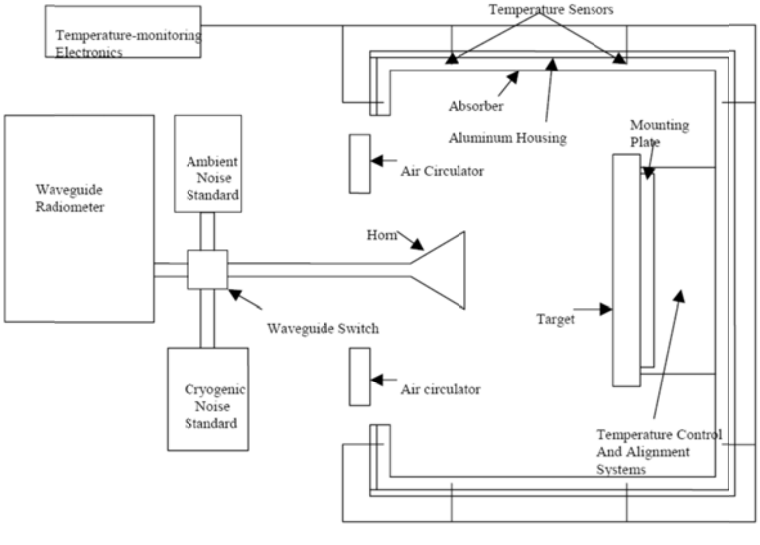

Figure 5. Schematic of the proposed brightness temperature calibration system.

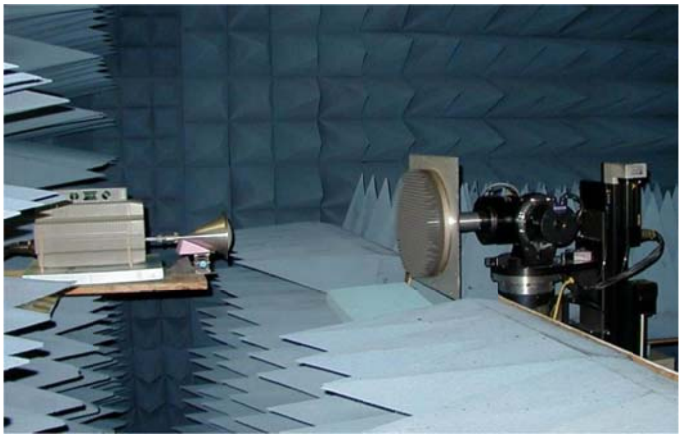

Figure 6. Test set up showing brightness temperature target and calibrated antenna that is connected to a radiometer system.

We are developing this capability initially in well-established waveguide bands. Initial work has been in the WR-42 (18-26.5 GHz) and WR-28 (26.5-40 GHz) bands. We will be extending the coverage up to approximately 200 GHz in order to cover 183 GHz. The 183.31 GHz water-vapor line is one of the most important spectroscopic lines for remote sensing of the Earth's atmosphere. This line is utilized by a wide variety of instruments that measure water vapor for atmospheric studies and weather prediction, including instruments at the surface, on high-altitude research aircraft, and on satellites.

6.0 Scattering-parameter/Power

The science of microwave measurements is expanding in many different directions. There is a constant push to use higher frequencies. Signals are becoming much more complex and include modulation effects, multiport/differential signals, complex waveforms, and other unusual signal schemes. On-wafer measurements are in greater demand. These new requirements are dictated by the needs of the telecommunication, computing, defense/security, and general electronics communities. Our work looks at the fundamental metrology problems for scattering-parameter and power. We provide a large range of state-of-the-art microwave measurements, theoretical developments, measurement techniques, and standards for customers. We have traditional measurement services that cover from 100 kHz to 110 GHz through many different microwave connector sizes [5] and we are developing similar capabilities up to 1.1 THz.

Our services provide the fundamental microwave properties that customers rely on to establish the critical factors in design and performance of RF and microwave equipment. Our customers also establish traceability to the SI through our measurements. The verification of calibrations and measurement processes on commonly used microwave measurement systems is of paramount importance to our customers. We support this through our measurements and the measurement techniques that we make available.

New requirements are dictated by the needs of many of the sectors of the electronics industry. The telecommunication and computing communities, for example, are approaching data rates of 100 gigabits per second, which will require support up to 500 GHz (for third and fifth harmonics) as well as modulated-signal power, waveform analysis, and other parameters. Oscilloscope/pulse applications need s-parameter and power measurement support above 50 GHz in 1.85 millimeter connectors, which we have just made available. Molecular resonance measurements for chemical identification will need precision measurement support in the 500 GHz to 700 GHz range. Remote sensing will require measurements of unprecedented accuracy. New imaging systems will require support in many different microwave parameter areas.

We are evaluating vector network analyzer (VNA) capabilities, and calibration and measurement methodologies when used at these high frequencies [6]. A detailed analysis of our multiline TRL calibrations at submillimeter wave frequencies led us to conclude that their measurement error is limited by systematic bias introduced primarily by misalignment of the flanges and calibration shims (E-plane and H-plane displacements), and that this error cannot be reduced by averaging. We then showed that TSM (Thru-Short-Match) calibrations based on precision loads and TS(RO) (Thru-Short-Radiating Open) calibrations based on radiating open-ended test ports reduce transverse displacements significantly, and provide attractive alternatives with greater accuracy.

We verified the accuracy of the TSM and TS(RO) calibrations by developing a full uncertainty analysis that captures all of the errors for rectangular waveguide interfaces [6]. We showed not only that the uncertainty analysis provides reasonable estimates of the accuracy of these calibrations, but that it provides a systematic way of setting weights in optimal TSM(RO) calibrations based on both load and radiating open standards.

We have developed different tools to try to minimize connector-based errors such as the rail system shown in Figure 7. This system greatly reduces the stress on the flanges and improves repeatability.

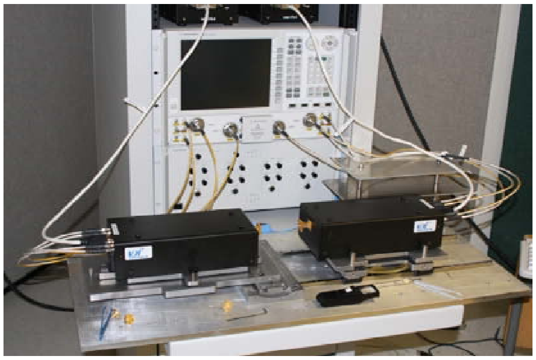

Figure 7. The rail system constrains the movement of the extension heads and cables.

The systematic error caused by the shim/flange and flange/flange displacement is shown in Figure 8. Here we see that the error is zero only when the two apertures are perfectly aligned, otherwise there is a positive error that is much greater for the shim/flange displacement than it is for the flange/flange displacement. This indicates that the standard LRL (Line-Reflect-Line) calibration approach, which is reliant on shims, is much less effective than the other approaches tried. We have done this work primarily in the WR-1.5 band (500-750 GHz) and will extend it to WR-1 (750 GHz – 1.1 THz) when we obtain WR-1 extension heads for our VNA.

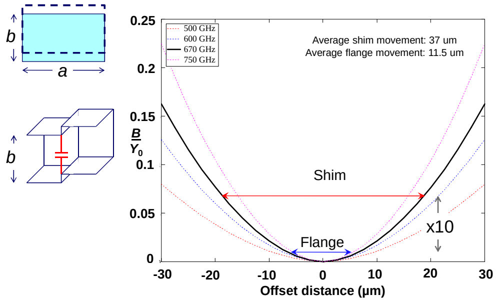

Figure 8. Normalized admittance created by lateral displacement of two waveguide interfaces in a WM-380 (WR 1.5) calibration. The figure shows that the effect of the shim-to-flange displacements is approximately ten times larger than the effects of flange-to-flange displacements.

We also investigated the effect of better precision test ports. Figure 9 illustrates the improvement obtained in the measurement of the reflection coefficients of a long section of rectangular waveguide when we used a TS(RO) calibration and our precision test ports, compared to a TSM calibration with standard test ports. The occasional "spikes" in the curves corrected by the TS(RO) calibration shown in Figure 9 are consistent with the sharp variations in the reflection coefficient of radiating opens due to reflections off the alignment pins.

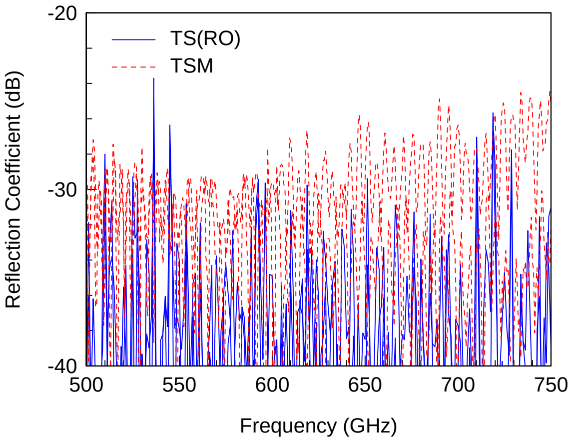

Figure 9. Comparison of measurements of a long rectangular-waveguide section calibrated by TSM with standard test ports and TS(RO) with precision test ports.

The development of power capabilities above 110 GHz is very difficult to do correctly. While we can simply scale the approach that we have used at lower frequencies involving calorimeters and primary transfer standards, this probably is not the best way to proceed above 110 GHz. Primarily, we need to decide the best method to be used to establish power traceability to the SI in the range of 110 GHz to the low terahertz region. We are investigating several possibilities. These possibilities are looking at establishing traceability through mechanisms that are much different than the current established ones. We are just in the beginning phase of the search and evaluation of potential technologies, and have not identified any one technology that meets our requirements.

7.0 Conclusion

Applications in many different branches of science require metrological solutions in the millimeter and submillimeter wave frequency ranges. There are many opportunities for metrology at frequencies above 110 GHz and up to the low terahertz area. NIST is actively pursuing research in many areas to meet these needs. The status and future of NIST's Electromagnetics Division's antenna, millimeter wave for wireless communications, electromagnetic properties of materials, noise/brightness temperature/remote sensing, and s-parameter/power programs have been discussed.

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