NIST'S HIGH FREQUENCY METROLOGY PROGRAMS: CURRENT CAPABILITIES AND FUTURE DIRECTIONS[1]

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Abstract: Several core areas are covered by the NIST microwave metrology services. These include thermal noise, power, scattering-parameters (s-parameters), field strength and antenna parameters. The rapid change in technology and the current economic conditions have motivated us to re-examine our services and make changes where necessary. In this paper, we will examine the current state of the microwave measurement services at NIST, discuss what changes are happening to those services, and then give a glimpse of the future directions for the programs.

1.0 INTRODUCTION

The Electromagnetics Division of the Precision Measurement Laboratory of NIST carries out research and programs related to the areas of guided and free-field electromagnetic waves. The current (2010) frequency span covered is from 100 kHz to 750 GHz. One of the outcomes of Division research is the measurement services that are offered to our customers [1]. Our customers are made up of a very broad slice of the electronics industry. They include communications, manufacturers, aerospace, military, testing labs, government labs/agencies, and other National Metrology Institutes (NMIs); and we support many of our internal programs.
Recently, we have started to change some of our core metrology services. Many of our services are over 25 years old and have seen little change in those years. This is due primarily to those services being separated from active research efforts. An example of this is the type-N s-parameter service. While we have improved the measurement systems, the basic services are still those that were offered 25 years ago.

Technology is moving at a very rapid pace. Frequencies are being pushed much higher, and multi-tonal, differential, and other complex schemes are being used. Lifecycles on new technologies are getting shorter. To be able to meet the demand of the new technology, we need to continually update the services. Because we have a finite level of resources, presently, if we add something new, we must drop something else. This effect will also be seen in the changes in the services.

Current economic conditions have changed how we look at our services. We consider each device that comes through our labs as a unique device with different problems and results. Thus, there is no batch processing or assembly-line handling of the devices. Usually, each device we measure has its own eccentricities. We must work through these problems to get the best measurement possible. Some problems include: poor connectors, unstable connectors, connectors out-of-tolerance, unstable devices, complex measurement set-up, and many others. It takes time to deal with each of these. Current economic times require us to be financially responsible. The services must be focused to make sure that they do not become an unsustainable financial burden.

We are adopting a new philosophy regarding measurement services and research. Namely, measurement services will be one of the outcomes of an active research effort and are not a stand-alone project. This has a corollary change in that all services will now have a finite lifetime. This generally will be five years from the start of a service, but could be slightly more or less based on circumstances such as no developed industry support or high demand for continuation of the service. Once a service is deemed "mature", the technology and services will be transitioned to industry.

In the following sections, the present microwave services will be discussed. The status of the services in the core areas will be covered and any changes that are happening or about to happen will be discussed.

2.0 MEASUREMENT SERVICES – CONNECTORIZED SERVICES

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. Economic gains are realized through improvements in measurement accuracy. 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 gigahertz (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 gigahertz in 1.85 millimeter connectors. 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.

2.1 Thermal Noise

Noise is a limiting parameter in the performance of any electronic device or system. NIST noise-temperature measurements are performed on total-power radiometers, by means of two primary thermal noise standards, one of which is at ambient temperature and the other of which is at cryogenic (liquid nitrogen) temperature. For measurements at 30 MHz and 60 MHz, tunable coaxial standards are used. From 1 GHz to 12.4 GHz, coaxial standards are used, and for 12.4 GHz and above, waveguide/horn standards are used. The NIST radiometers are double-sideband, total-power radiometers [2].

Noise temperature measurements are available for single-port, coaxial and rectangular waveguide noise sources under conditions of continuous, unmodulated operation. Measurement results on devices submitted with adapters attached apply only to the combination of source plus adapter. For thermal noise, we provide calibration of coaxial noise standards at 30 MHz, 60 MHz, and from 1 GHz to 40 GHz. Waveguide standards are calibrated from 8.2 GHz to 65 GHz.

No reductions are presently anticipated in the thermal noise services. We have recently added the capability to measure noise parameters on low-noise amplifiers. The biggest change in this area is the addition of our work on brightness temperature standards to support remote sensing applications. This will be discussed in more detail later in this paper.

2.2 Scattering-Parameters

S-parameters have presented a particular problem in determining our support path. S-parameter measurements are required for accurate measurements in all of the other microwave disciplines. The accuracy of s-parameter measurements is directly related to the calibration of the vector network analyzers (**VNAs**) used for measurements. The traceability of the calibration standards is usually through dimensional methods. The s-parameter measurements made at NIST are not generally used for establishing traceability to the SI, but instead are used to verify whether the day-to-day calibrations (or error reduction process) on the VNAs have been done correctly. In other words our measurements have been used by our external customers to bolster confidence in their entire measurement process. This function can be met by many other facilities [3]. Thus, we have essentially discontinued all of our artifact-based, legacy, s-parameter measurement services as of October, 2009. We still maintain all of the capabilities that we have had to support internal projects and will perform these measurements for an outside agency if the need exists.

We have replaced the old services with two new programs. Both of these follow the measurement comparison approach. First we have several sets of devices in the type-N, 7 mm, 3.5 mm, 2.92 mm, and 2.4 mm connector sizes that are used for comparison of a lab's measurement to NIST's measurements of the same devices. Customers receive plots of their measurements against NIST's and the difference of their measurements from NIST's with the NIST uncertainties identified. The second approach replaces the kits of fixed devices with one of the new electronic calibration units that are now available. This new program that has been recently developed utilizes the electronic calibration devices as the comparison artifacts and gives all of the comparative results from the fixed-devices approach. It also compares VNA calibrations based on data from the customer and NIST and returns a single figure-of-merit on how good the customer's calibration is, referenced to the NIST calibration [4]. This program is presently based on 1.85 mm electronic calibration devices, but will be expanding to the 2.4 mm and type-N connector sizes in the next year. Additionally, the program is presently based on customers measuring NIST-owned units. The program will be changed so that customer-owned units will also be supported.

One more change to the s-parameter services is the addition of a 1.85 mm connector capability. We now support full 10 MHz to 67 GHz measurements of customer devices. Yes, this is a return to the artifact-based type of service. This has been done to supply customers with a capability they may not have or do not have the resources to establish. As 1.85 mm connectors become more prevalent, this service will be transitioned to industry in about four to five years. Support for 1.0 mm connectors is also under development.

2.3 Microwave Power

An electronic system's output power level is frequently the critical factor in the design, and ultimately the performance, of RF and microwave equipment. The primary power standards used at NIST are the NIST-designed micro calorimeters. The calorimeters are used to calibrate the effective efficiency of our primary transfer standards, which are thermistor-type power detectors. Currently we have Type-N and 2.4 mm coaxial calorimeters and WR-42, 28, 22, 15 and 10 waveguide calorimeters. Other coaxial sizes are measured through the use of calibrated adapters. Customer devices are measured on direct comparison systems or the six-port automatic network analyzer systems [5].

The availability of primary transfer standards is becoming the most significant problem for the power measurement services. Many of our standards are no longer available. Waveguide standards above WR-28 are no longer produced. Other of our primary transfer standards are built around parts that are either very scarce or totally nonexistent. We are taking several different approaches to deal with this problem. First, we are working actively with several different manufacturers who are coming up with new designs for power detectors that will be useable in our calorimeters. Second, we are re-engineering the design for the calorimeters so that they can be used with a broader range of devices. The older design could be used only with special detectors designed for use in the calorimeter. The new calorimeter design will allow for use of commercial detectors meeting minimal specifications to be measured. Additionally, the new calorimeters are also designed to be used in a dry calorimeter mode as a primary transfer standard. A WR-15 calorimeter has been built and the correction factor and uncertainty analysis is almost complete. A new type-N design that is in the construction phase is also being pursued and some early analysis has been completed.

The measurement of type-N power devices currently makes up approximately 70 % of the NIST power services. When the new type-N calorimeter is completed, the type-N services will change. Presently we try to measure any standard that anyone sends in to us. This is very time-consuming, and many of these devices do not need the accuracy of a NIST measurement. With the new type-N calorimeters, we will shift to measuring only standards that are at the primary transfer standard level. Essentially we will calibrate the primary transfer standards for the top tier of calibration labs and then they will disseminate the calibrations to the rest of industry. This change is expected to happen by the end of 2011.

We have also just established the capability and measurement services for 1.85 mm connector power measurements. Traceability will be established to our 2.4 mm primary transfer standards below 40 GHz and to waveguide standards from 40 GHz to 67 GHz. At the time of writing, late 2010, the first customer devices for this new service are in our lab to be measured.

3.0 MEASUREMENT SERVICES – FREE FIELD

Antenna systems are a key link between many electronics systems and the world. The performance of precision antennas plays a key role in many very sensitive applications including radar, aircraft, satellites, and spacecraft used for communications, weather prediction, space science and others. By precisely determining the characteristics of antennas, the size, weight and cost of these systems can be optimized. The Radio-Frequency Fields Group of NIST conducts theoretical and experimental research necessary for the accurate measurement of free-space electromagnetic field quantities; the characterization of antennas, probes, and antenna systems; the development of effective methods for electromagnetic compatibility assessment; the measurement of radar cross section and radiated noise; and providing measurement services for essential parameters. Measurement services conducted by the Group are field strength by use of a TEM cell, field strength by use of an anechoic chamber, and on-axis antenna gain and polarization by use of an extrapolation range.

3.1 Field Strength

This program generates reference electromagnetic (EM) fields and uses these for accurate calibration of EM probes. Accurate EM field measurements are needed to characterize our wireless world and ensure that (a) the valuable electromagnetic spectrum is optimally used, (b) electronic systems are compatible and are not sources or victims of EM interference, and (c) people are not exposed to hazardous fields. As instrumentation and electronics achieve higher clock rates, EM field parameter metrology is needed at ever higher frequencies. The program is working to extend current methods and facilities to higher frequencies and to develop new test methods to increase accuracy and reduce measurement costs.

Industry requires EM field measurement capabilities and transfer probes that are traceable to NIST in order to meet multinational compliance requirements and reduce barriers to worldwide acceptance of U.S. products. We address these needs with the following [6]:

Reference Fields – Well defined EM reference fields are necessary for the calibration of antennas and probes. They are also needed for research and development to increase measurement accuracy and spectral range; as will be necessary to support the future needs of U.S. industry and private test laboratories.

Field Probes – Accurate field probes are needed by government and industry to define EM field levels. U.S. defense and homeland security agencies rely heavily on EM systems for sensors and strategic communication. New probes need to be developed for an ever-expanding range of EM environments.

Probe Calibrations – Field probe calibrations are costly. Techniques to reduce calibration costs are needed, especially for applications that require multiple probes and frequent recalibration.

Field strength is measured in TEM cells or in the NIST EM Anechoic Chamber. We do have an Open Area Test Site and the capability to measure dipoles, log-periodics, monopoles, and loop antennas there; however, this is a rarely used capability and is not offered as a routine measurement service.

3.11 TEM Cell

Transverse electromagnetic (TEM) transmission line cells are used to establish standard electromagnetic fields in a waveguide environment. Their application has become wide spread because of their versatility, measurement accuracy, and ease of operation [7]. The NIST TEM cells are used to calibrate electrically small antennas and antenna systems used for electromagnetic field probes in the frequency range of 10 kHz to 300 MHz.

3.12 Anechoic Chamber

Microwave anechoic chambers are currently in use for a variety of indoor antenna measurements, electromagnetic interference (EMI) measurements, and electromagnetic compatibility (EMC) measurements. The prime requirement is that an appropriate transmitting antenna at one location within the chamber generates a known field throughout a volume of the chamber having dimensions sufficient to perform antenna measurements. This volume is frequently referred to as the “quiet zone”, and its reflectivity level will determine the performance of the anechoic chamber [7]. Services are currently available for power density from 200 MHz to 450 MHz by means of open-ended waveguides to generate the standard electromagnetic fields and from 450 MHz to 46 GHz by use of pyramidal horns.

3.2 On-axis Antenna Gain and Polarization by Use of an Extrapolation Range

Measurements of an antenna’s near-field at close distances (a few centimeters) are used to define the far-field response through the use of mathematical algorithms developed at NIST. 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 operating at frequencies from 1.5 GHz to 110 GHz. Project scientists have recently completed the development of a dynamic laser-based, antenna-probe tracking system with probe-position correction algorithms. This enables the use of existing planar near-field scanning ranges at much higher frequencies than previously attainable, thereby extending the life of some of the nation's key antenna-testing infrastructure. Such higher frequencies hold significant promise in the areas of medical and security imaging and radiometer systems for improved weather and climate prediction.

4.0 FUTURE DIRECTIONS

The core metrology capability of the Electromagnetics Division is becoming closely tied to on-going research efforts. There are many new directions that are being investigated that we are very excited about. The areas of research include remote sensing standards, metrology for nanoscale devices, electromagnetic (EM) properties of materials, high-frequency systems above 110 GHz, wireless systems metrology, antenna measurements to 500 GHz, and improved testing facilities for antenna/fields evaluation.

4.1 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 measurements such 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 periods, the need for rigorously and independently validated traceability to the 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 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 do exist and have proven very useful. NIST is now pursuing a combined microwave brightness temperature standard that would comprise both a standard radiometer, traceable to primary noise standards, and a fully characterized standard target.

4.2 Nanoscale Device Metrology

Integrated electronics are rapidly shrinking in size, becoming much more complex, and operating at higher frequencies. Soon, the current designs of electronics based on CMOS technology will no longer be able to meet the upcoming challenges. The next generation of electronics has not yet been developed. We are developing the metrology tools that will allow the companies that are going to develop this next generation to be able to make the right choices in directions.

We are developing a set of scanning technologies that will be able to look at device characteristics and their interactions with microwave signals at nanoscale resolutions. Tools include rf scanning tunneling microscopes and broadband atomic force microscopes. Examples of the first-of-their-kind work that is being carried out include (a) creating a calibration scheme to quantitatively determine the doping density of semiconductor materials, and (b) being able to quantitatively look at the *in-situ* carrier generation due to photovoltaic activity.

4.3 EM Properties of Materials

The functioning of all of modern electronics relies on the EM properties of the materials that are used to construct these devices. New materials are being created with a development cycle of less than six months. These new materials are being used to support smaller, faster and more complex electronic devices. It is imperative to know the EM properties of these materials so that the devices will function properly and be as efficient as possible. Our work in the area of EM properties of materials spans several different areas. The definitions of permittivity and permeability are well defined down to resolutions of millimeters. What happens as the size scale continues to shrink? Answering this question is one of our main research areas. Essentially, how the definition and determination of these quantities change as one goes from the macro-scale to the nano-scale to the meso-scale. Additional efforts in this area include looking at RF characteristics of nano-volumes of fluids and developing and measuring the responses of metamaterials.

4.4 Fundamental Metrology above 110 GHz

The need for accurate measurements above 110 GHz is here. Transistors have been developed that operate in the range of 600 GHz. Homeland security systems are being developed that take advantage of these high frequencies. Imaging systems for space applications make use of these low terahertz signals. No National Metrology Institute has developed the metrology support needed in power, s-parameters, or noise above 110 GHz.

We have started to investigate the calibration of VNAs at these high frequencies. Initially, we are investigating systems that are based on waveguide bands. We are determining the proper calibration technique and calibration standards that should be used to calibrate high-frequency VNAs. We have found that these VNAs are capable of making very good measurements in this area, but the calibration standards are severely limiting the accuracy of the measurements. After completing this work, we will expand our investigations to high-frequency, on-wafer systems. We will also develop capabilities in power and noise above 110 GHz.

4.5 Wireless Systems Metrology

The Wireless Systems Metrology Program develops ways to measure complex telecommunication signals used by industry, public safety (rescue workers), and government. The project develops methods to measure communication and data signals, and to imitate complex environments where reliable reception may be a problem; this includes multipath distortion, ranging from a line-of-sight environment (low-multipath) to a pure Rayleigh environment (high-multipath). Applications include developing tests to evaluate the effects of interference on wireless communications used in factories for the control of robots, methods to measure cellular telephone fields, test facilities for evaluating search and rescue communications, and robot communications [5].

4.6 Antenna Metrology

The need for the precise calibration of antenna parameters is growing. New applications such as climate change monitoring, telecommunication and space science rely on knowing the precise characteristics of the antennas used for measurements and communications. To support these needs, measurement capabilities to 500 GHz are being developed. These include on-axis measurement services and extending the near-field probe and planar near-field measurements to 500 GHz.

4.7 Improved Antenna Testing Facilities

Two areas are being investigated for improved antenna testing facilities. The co-conical field generation system is a large-volume system that has been developed to be used to calibrate and test small antennas, sensors, and probes [5]. Normal TEM cells are limited by geometrical constraints to operate below 1 gigahertz. The new closed-cell, co-conical geometry system can be used to test devices up to 45 gigahertz. We have also recently added a new reverberation chamber and are developing new evaluation techniques and uses for the chamber to support many of our electromagnetic field research areas.

CONCLUSION

The measurement services of the Electromagnetics Division of NIST are changing. The availability of resources and the current economic environment have made it necessary to streamline or even eliminate some of our services. By tying the services to active research efforts, the services do have a strong future. There are many upcoming programs that will add new and exciting capabilities.

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