NIST

National Institute of Standards and Technology

Technology Administration

U.S. Department of Commerce

NISTIR 6613

January 2002

Electronics and Electrical Engineering Laboratory

Radio-Frequency Technology Division

Programs, Activities, and Accomplishments

The Electronics and Electrical Engineering Laboratory

Through its technical laboratory research programs, the Electronics and Electrical Engineering Laboratory (EEEL) supports the U.S. electronics industry, its suppliers, and its customers by providing measurement technology needed to maintain and improve their competitive position. EEEL also provides support to the Federal government as needed to improve efficiency in technical operations, and cooperates with academia in the development and use of measurement methods and scientific data.

EEEL consists of six programmatic divisions and two matrix-managed offices:

Electricity Division

Semiconductor Electronics Division

Radio-Frequency Technology Division

Electromagnetic Technology Division

Optoelectronics Division

Magnetic Technology Division

Office of Microelectronics Programs

Office of Law Enforcement Standards

This document describes the technical programs of the Radio-Frequency Technology Division. Similar documents describing the other Divisions and Offices are available. Contact NIST/EEEL, 100 Bureau Drive, MS 8100, Gaithersburg, MD 20899-8100, Telephone: (301) 975-2220, On the Web: www.eeel.nist.gov

The Cover symbolizes the diverse programs of the Radio-Frequency Technology Division and the cross-section of industry that it serves. The programs range from the development of new metrology for microelectronics devices and circuits for radio and high-speed digital applications, to the precise characterization of electromagnetic fields, wireless systems, and antennas for radar and for satellite and terrestrial communications.

Electronics and Electrical
Engineering Laboratory

Radio-Frequency Technology Division

Programs, Activities, and Accomplishments

NISTIR 6613

January 2002

U.S. DEPARTMENT OF COMMERCE
Donald L. Evans, Secretary

Technology Administration
Phillip J. Bond, Under Secretary of Commerce for Technology

National Institute of Standards and Technology
Arden L. Bement, Jr., Director

Contents

Welcome

The Radio-Frequency Technology Division is a critical national resource for a wide range of customers. U.S. industry is the primary customer both for the Division's measurement services and for technical support on the test and measurement methodology necessary for research, product development, manufacturing, and international trade. The Division represents the U.S. in international measurement intercomparisons and standards development related to radio-frequency and microwave technology and electromagnetic fields. The Division also provides measurement services and expert technical support to other agencies of the Federal government to support their programs in domestic and international commerce, in national defense, in transportation and communication, in public health and safety, and in law enforcement.

This book will describe our many and diverse projects. However, before you begin I would like to briefly describe our mission, programs, and our organization.

Mission

To provide the national metrology base for characterization of the electromagnetic properties of components, materials, systems, and environments, throughout the radio spectrum.

Division Function

The Division:

Enhances national competitiveness by providing metrology resources to facilitate development and commercialization of a broad range of radio-frequency electronic and electromagnetic technologies;

Develops theory, techniques, systems, and standards for measurement of electromagnetic and other essential properties of components, materials, environments and systems throughout the radio spectrum;

Provides for national and international measurement harmony and formal traceability via calibration services, reference standards, and measurement intercomparisons; and

Disseminates research results via archival publications, conference presentations, workshops, courses, and external interactions. Programs typically address fundamental measurement problems that are of interest to a broad industrial cross-section and of sufficient difficulty that resources are generally not available elsewhere to solve them. Programs leverage internal resources with resources from other government agencies, industry and academia, and endeavor to meet the most critical industrial and governmental needs.

Our Technical Programs

The Division carries out a broad range of technical programs focused upon the precise realization and measurement of physical quantities throughout the radio spectrum. Key directions include: (a) the development of artifact reference standards, services and processes with which industry can maintain internationally recognized measurement traceability, (b) the advancement of technology through the development of new measurement techniques that are theoretically and experimentally sound as well as relevant and practical, (c) the assessment of total measurement uncertainties, and (d) the provision of expert technical support for national and international standards activities. We strive to perform leading-edge, high quality research in metrology that is responsive to national needs. The radio-frequency spectrum ranges from above audio to below the far-infrared. The programs range from measurements for microelectronics devices and circuits for radio and high-speed digital applications, to the characterization of electromagnetic fields, wireless systems, and antennas for radar, satellite, and terrestrial communications.

Division programs cover the following technical areas:

Fundamental Microwave Quantities
The Fundamental Microwave Quantities Program develops standards and methods for measuring impedance, scattering parameters, attenuation, power, voltage, and thermal noise, and provides essential measurement services to the nation.

High-Speed Microelectronics
The High-Speed Microelectronics Program develops on-wafer measurement techniques for characterizing microelectronic structures and devices in the radio-frequency spectrum.

Wireless Systems
The Wireless Systems Program has three thrusts: the characterization of the nonlinear properties of devices and circuits, the proactive development of standards for broadband wireless access, and the characterization of passive intermodulation products.

Electromagnetic Properties of Materials
The NIST Electromagnetic Properties of Materials Program develops theory and methods for measuring the dielectric and magnetic properties of bulk and thin-film materials throughout the radio spectrum.

Antenna and Antenna Systems
The Antenna and Antenna Systems Program develops theory and techniques for measuring the gain, pattern, and polarization of advanced antennas, for measuring the gain and noise of large antenna systems, and for analyzing radar cross-section measurement systems.

Electromagnetic Compatibility
The Electromagnetic Compatibility Program develops theory and methods for measuring electromagnetic field quantities and for characterizing the emissions and susceptibility of electronic devices and products.

Division Organization

The Division is organized into two Groups that are focused upon measurements for guided-wave technologies and free-space electromagnetic-field technologies. The Groups, and their managers are:

RADIO-FREQUENCY ELECTRONICS GROUP: Conducts theoretical and experimental research to develop basic metrology, special measurement techniques, and measurement standards necessary for advancing both conventional and microcircuit guided-wave technologies; for characterizing active and passive devices and networks; and providing measurement services for power, noise, impedance, material properties, and other basic quantities.

Group Leader: Robert Judish
Tel: 303-497-3380
Email: judish@boulder.nist.gov

RADIO-FREQUENCY FIELDS GROUP: Conducts theoretical and experimental research necessary for the accurate measurement of free-space electromagnetic field quantities; for characterization of antennas, probes and antenna systems; for development of effective methods for electromagnetic compatibility assessment; for measurement of radar cross section and radiated noise; and provides measurement services for essential parameters.

Acting Group Leader: Perry Wilson
Tel: 303-497-3406
email: pfw@boulder.nist.gov

The Division is also exploring new directions for the advancement of wireless technology via the proactive development of standards for broadband wireless access (BWA).

IEEE WIRELESS STANDARDS PROGRAM
Director: Roger Marks
Tel: 303-497-3037
email: marks@boulder.nist.gov

We hope that this collection of information will help in understanding the work of the Division and for making use of the technical capabilities and services that we provide for industry, government, and academia. We also invite you to visit our web site at: http://www.boulder.nist.gov/div813/. This site will provide you with more information on our projects as well as measurement-related software and publications that can be downloaded.

Dennis Friday
Chief, Radio-Frequency Technology Division
NIST, Boulder, CO
Tel: 303-497-3131
email: friday@boulder.nist.gov

Radio-Frequency Technology Division

*Ext.
3131 FRIDAY, Dennis S., Chief
3132 LYONS, Ruth Marie, Secretary
3037 MARKS, Roger, N-WEST

*Ext.
3813 BACHINSKI, Julie, Admin. Officer
3514 GLAZE, Terry, Admin. Asst.

Radio-Frequency Electronics Group (813.01)

3380 JUDISH, Robert M. (GL)
5755 RIVERA, Susie A., Secretary
5533 GROSVENOR, John H.

Power Standards
4133 CROWLEY, Thomas (PL)
3609 FREE, George
3264 ONDREJKA, Connie L.
3939 SHERWOOD, Glenn V.
3365 VORIS, Paul G.
5778 CLAGUE, Fred (GR)
4327 DUENAS JIMENEZ, Alejandro (FGR)

Network Analysis
3634 GINLEY, Ronald A. (PL)
5362 JUROSHEK, John R.
3210 LeGOLVAN, Denis X.
5249 MONKE, Ann F.
5231 PACKER, Marilyn

Noise Standards
3150 RANDA, James (PL)
3664 ACKS, Nathan (PREP)
5737 BILLINGER, Robert L.
3280 TERRELL, Leon (Andy)
5490 WALKER, David K.

Non-Linear Device Characterization
7212 DeGROOT, Donald C. (PL)
5089 GUPTA, K. C. (GR)
3596 JARGON, Jeffrey A.
3652 REMLEY, Kate

High-Speed Microelectronics
3138 WILLIAMS, Dylan (PL)
4254 ARZ, Uwe (FGR)
3015 MORGAN, Juanita M.
3997 KABOS, Pavel

Electromagnetic Properties of Materials
5621 BAKER-JARVIS, James R. (PL)
5852 GEYER, Richard G.
3656 JANEZIC, Michael D.
5491 KAISER, Raian K.
5752 RIDDLE, Bill F.

Measurement Services
3753/5284 DeLARA, Puanani L.

Radio-Frequency Fields Group (813.02)

3406 WILSON, Perry. (GL)
3321 HAAKINSON, Edit H., Secretary
3302 BASSETT, David N., Secretarial Aid

Near Fields Antenna Techniques
5702 CANALES, Seturnino
5873 FRANCIS, Michael H.
3863 GUERRIERI, Jeffrey J.
3471 MacREYNOLDS, Katherine
3927 STUBENRAUCH, Carl F. (GR)
3694 TAMURA, Douglas T.

Standard EM Fields and Transfer Probe Standards
3214 CAMELL, Dennis G.
3726 DOWNEY, Stephen (PREP)
5958 GROSVENOR, Chriss A.
3737 JOHNK, Robert T.
3756 MASTERSON, Keith D.
3737 VENEMAN, Jason (PREP)
3168 NOVOTNY, David
5305 WEIL, Claude
4140 ONDREJKA, Andy (GR)

EMC Measurements & Facilities
3142 BHOBE, Alpesh (FGR)
3141 FORNBERG, Pelle (PREP)
3472 HILL, David A. (GR)
6184 HOLLOWAY, Chris
5766 KOEPKE, Galen H.
5372 LADBURY, John

Antenna Systems Metrology
3603 MUTH, Lorant A.
3326 WITTMANN, Ronald C.

GL Group Leader
PL Project Leader
GR Guest Researcher
FGR Foreign Guest Researcher
PREP Professional Research Experience Program Student

*Tel. Numbers are (303) 497- extension shown

Fundamental Microwave Quantities

Power

Goals

Develop, maintain, and improve standards, systems, and methods for measuring power over the frequency range from 100 kHz to 400 GHz. Provide measurement services and support to U.S. industrial and government laboratories.

2.4 mm microwave calorimeter and detector

Customer Needs

A system's output power level is frequently the critical factor in the design, and ultimately the performance, of almost all RF and microwave equipment. Accurate measurements of power and voltage allow designers and users of measuring and test equipment to determine whether performance specifications are met. Inaccurate measurements lead to over-design of products, and hence, increased costs. Economic gains are realized through improvements in accuracy. In a broad range of industries, state-of-the-art calibration services are needed so that customers can maintain quality assurance programs in the manufacture and distribution of their products. The availability of these services allows the customers to be globally competitive. The increasing speed of the internet, wireless technology, and FCC regulations on interference are driving the need for power measurements above 110 GHz. High bit-rate digital communications require the broadband characterization of microwave and millimeter-wave signals into and out of optoelectronic components. This characterization requires broadband power measurements from dc to 400 GHz.

Technical Strategy

The microwave industry is rapidly expanding into higher frequencies. For coaxial transmission lines the highest-frequency power detectors available at NIST use the 2.4 mm diameter connector and work over a frequency range that includes 0.5 to 50 GHz. As industry moves to higher frequencies, an increasing part of our calibration services involves these detectors. The 2.4 mm detector is also used as a standard to provide calibration services in other, lower-frequency connector sizes. Improving the understanding, capability and reliability of these detectors is important. Several improvements are planned for our 2.4 mm power detectors. First, the efficiency measurement will be improved by measuring the properties of a new open-circuit and short-circuit version of the detectors. The time response of the detectors will be studied to better understand why the detectors work differently in the microcalorimeter than in a direct comparison power measurement system. Next, we will completely evaluate a set of new commercial detector mounts that have been obtained. Finally, a new detector chip, the heart of the 2.4 mm power detector, will be developed by NIST to guarantee having a supply of these detectors in the future as well as improving their thermal properties.

There is an increasing demand for millimeter-wave calibration services, particularly at frequencies above 50 GHz. This demand is being driven to a large extent by the high-bit-rate digital systems that are currently being developed for optical-fiber communications systems and the Internet. Since these systems use pulsed signals instead of pure continuous wave, wide-band frequency coverage is needed in order to properly characterize the system. Although the existing WR-10 waveguide microcalorimeter and transfer standards can operate over the frequency range from 75 to 110 GHz, our WR-10 measurements have been limited to a narrow frequency range because of our WR-10 signal source. A backward-wave oscillator capable of producing greater than 10 mW from 75 to 110 GHz has recently been purchased and will be used to make measurements over the full waveguide band. We will next characterize the WR-10 transfer-standard power detector using the microcalo-

Technical Contact:
Tom Crowley
Ron Ginley

Staff-Years (FY 2001):
3.0 Professional
4.5 Technician
1.0 Guest Researcher

Funding Sources:
NIST (20%)
Other (80%)

rimeter over the full WR-10 waveguide band. We will then develop a system to measure the effective efficiency of commercial detectors and optical-fiber detectors. This will be either a direct-comparison power measurement system or a single six-port network analyzer system and will use the backward-wave oscillator as its source.

Due to the increasing speed of circuitry and communications, the high-frequency content of digital signals, as well as FCC regulations on harmonic emissions from radar and transmission devices, there is a need for power measurements above 110 GHz. Digital signals pose constraints on measurements that are different from those of sinusoidal signals. Because circuits are becoming more integrated on a single chip, on-wafer power measurements are needed. An approach for meeting these needs will be developed. Extension of traditional measurement techniques, as well as completely new approaches, will be investigated.

Type N coaxial power detectors are widely used as standards in industry and constitute a large fraction of our calibration service workload. Maintaining the integrity of the Type N calorimeter and transfer-standard capabilities is essential. A new set of bolometric transfer standards will be produced and evaluated. We will also design and construct an improved Type N calorimeter.

The Department of Defense Primary Standards Laboratories have looked to NIST for guidance on microwave metrology issues and for ways to improve their measurement capabilities. One of the major problems facing the Department of Defense Primary Standards Laboratories is the development of a database for storing and verifying scattering parameter and power measurements. We will complete the development of an online software package for storing and verifying scattering parameter and power measurements for the Army Primary Standards Laboratory. The software package will also be made available to the Air Force and Navy Primary Standard Laboratories.

The direct-comparison systems have made available many new or improved power measurement capabilities. It is very important to document and certify these new calibration capabilities. In order to do this a complete uncertainty analysis must be completed for each capability of the system.

We will complete documentation for all the capabilities of the NIST direct comparison systems.

Accomplishments

■ Construction of a WR-42 calorimeter was completed. Its correction factor was measured, uncertainties were determined, and two new bolometer detectors were characterized.

■ A better understanding of the operation of the 2.4 mm coaxial power detector was obtained by studying its temporal response. Components with a slow-time scale response due to thermal effects are different when the detector is measured in the microcalorimeter from when it is operated in the direct-comparison system. The detector's efficiency correction factor was modified to more accurately reflect the detector's behavior when used in the direct-comparison system. New short-circuit and open-circuit versions of the detector that better match the thermal characteristics of the primary-standard detector have been obtained. Measurements with them will allow further improvement in the efficiency measurement and uncertainty evaluation.

■ Developed a new calibration service for 2.92 mm power detectors. The new service uses the NIST direct-comparison system, calibrated adapters and the 2.4 mm thin film power detectors. The 2.92 mm calibration service covers a frequency range of 0.05 GHz to 40 GHz. Previously no measurement capability in this connector size existed.

■ We participated in a key international comparison in coaxial power measurements with 3.5 mm connectors that cover the frequency range of 0.05 GHz to 26.5 GHz. The comparison is on going and will evaluate the measurement equivalency of at least 10 national measurement laboratories.

■ Direct-Comparison Systems have been built for the Air Force and Army Primary Standards Laboratories. They will be delivered to the military in early part of 2002. The systems are duplicates of the NIST system and are capable of power measurements using 2.4, 2.92, 3.5, 7 mm and Type-N connectors.

■ A WR-10 backward-wave oscillator that produces an output signal of over 10 mW from 75 to 110 GHz has been purchased. Initial calibration of WR-10 bolometer detectors has begun.

■ During November 2000, NIST delivered a Type N coaxial microcalorimeter to the Productivity and Standards Board (PSB) in Singapore. In June and July of 2001, an informal comparison of that calorimeter and an older model calorimeter was performed using two NIST bolometer detectors that had been previously purchased by PSB. The agreement between the two was within the expanded uncertainty at all 41 frequencies measured.

■ The ac-dc difference of NIST primary thermal voltage converter standards has been reevaluated, the measurement system has been modified, and the reported calibration uncertainty has been reduced by a minimum of 50 % over the frequency range 30 kHz-100 MHz for voltages between 0.45 volts and 100 volts.

FY Outputs

Calibrations

Calibrated 203 devices for customers that generated an income of $403,000.

Recent Publications

Juroshek, J. R.; NIST 0.05-50 GHz Direct Comparison Power Calibration System; Proc., Conf. on Prec. Electromagn. Meas., 14-19 May 2000, Sydney, Australia, pp. 166-167; May 2000

Allen, J. W.; The Switched Coupler Measurement System for High Power RF Calibrations; NIST TN 1510; July 1999

Allen, J. W.; Clague, F. R.; Larsen, N. T.; Weidman, M. P; The NIST Microwave Power Standards in Waveguide; NIST TN 1511; February 1999

Allen, J. W.; NIST's Switched Coupler High Power Measurement Service; Proc., Meas. Sci. Conf., 28-29 January 1999, Anaheim, CA, pp. 116-119; January 1999

Juroshek, J. R.; A Direct Calibration Method for Measuring Equivalent Source Mismatch; Microwave J., pp. 106-118; October 1997

Fundamental Microwave Quantities

Scattering Parameters and Impedance

Technical Contact:
Ron Ginley

Staff-Years (FY 2001):
0.5 Professional
2.0 Technician

Funding Sources:
NIST (30%)
Other (70%)

Goals

Provide traceability for microwave measurements in scattering parameters, impedance, and attenuation. Support the microwave industry by developing standards and new measurement techniques. Develop methods for assessing and verifying the accuracy of vector network analyzers.

Commercial vector network analyzer

Customer Needs

Vector network analyzers (VNAs) are the single most important instrument in the microwave industry. These instruments are commonly found on production lines, in calibration laboratories, and in research laboratories. VNAs are typically calibrated daily, and the accuracy of their measurements can vary significantly after calibration depending on the operator's skill, the quality of the calibration standards, and the condition of the test ports. The microwave industry needs cost-effective techniques to monitor and verify the accuracy of VNA measurements. In addition, industry requires validation of techniques and procedures that they develop. NIST supports these needs by providing consultations on measurement techniques and uncertainty characterization. We also offer an extensive array of measurement services that allow VNA users to establish and gain confidence in their capability.

Technical Strategy

There is an increasing demand for millimeter-wave calibration services, particularly at frequencies above 50 GHz. This demand is largely driven by the high-bit-rate digital systems that are currently being developed for optical-fiber communications systems and the Internet. NIST needs to develop improved and more cost-effective services in scattering parameters and power to support those needs. We plan to expand our cabilities in s-parameters to full-band frequency coverage in WR-15 (50-75 GHz) and WR-10 (75-110 GHz).

New connectors are being developed for instrumentation and cables, as the communications industry applications move higher frequencies. Support is needed for these new connector interfaces. In the next couple of years we will add calibration services in currently unsupported coaxial connector sizes (i.e. 1.85 mm, 1.0 mm, SMA and 75 ohm).

The Department of Defense's calibration and standards laboratories require state-of-the art systems to support their measurement capability. Historically, NIST has provided them with dual six-port VNAs for scattering parameter measurements and direct-comparison systems for power calibrations. NIST will continue to aggressively support the calibration activities of the Air Force, Army, and Navy Primary Standards Laboratories. We are improving the design of the NIST System 3 six-port system (18-40 GHz) and will develop an upgrade based on the new design. We also plan to completely refurbish the Navy System 3 dual six-port VNA.

The Department of Defense looks to NIST for guidance on microwave metrology issues and for ways to improve methods for evaluating measurement data and for validating the calibration of complex instrumentation. Complex databases for storing and verifying measurements of scattering parameters and power are required. We are currently developing a software package for the Military Laboratories for storing and verifying scattering-parameter measurements. In addition, we are developing processes to analyze data in the database and apply the results to uncertainty component calculations. In 2003, we will complete the development of an online software package to be used for storing and verifying measurements of scattering parameters by NIST and the Army Primary Standards Laboratory for. Additionally, we will analyze our check-standard data and determine long-term calibration uncertainty components.

Many of our customers have the same measurement capabilities and uncertainties as we have. This has caused us to look at different ways to support the VNA systems in industry. One of these methods has been the NIST Measurement Comparison Program (NIST MCP) established last year. This program is rapidly being accepted in industry as a way to verify VNA performance and uncertainties. We will procure and evaluate more NIST MCP kits for each connector type covered (Type-N, 7, 3.5, 2.92, and 2.4 mm). We will also develop methods that allow customers to obtain preliminary NIST MCP data online.

Making highly accurate measurements on VNAs are very difficult because of the requirement for airline standards, precision test ports and advanced measurement techniques. The difficulty and cost in obtaining airline standards and precision test ports forces most VNA users to use less accurate calibration methods. We are considering ways to improve some of these calibration methods and bring their accuracy close to that of airline based calibrations. These enhanced calibration techniques would also provide a means for VNA users to reduce costs of measurements on their systems. In 2003, we will develop software to convert measured data of calibration standards obtained from airline-based calibrations into the device model parameters used in the SOLT (short-open-load-through) and SOL (short-open-load) calibration techniques. In the following year we will develop software to use measured data of calibration standards directly in SOLT and SOL calibrations or use the measured data to obtain enhanced models of the calibration devices. Finally, we will develop techniques for evaluating calibration devices used in the LRM (line-reflect-match) calibration technique.

An important component in validating the s-parameter capabilities at NIST is participation in international comparisons. These comparisons help NIST to ensure that its s-parameter capabilities are comparable to those of other national measurement institutes. This relationship insures that the users of NIST calibration services will be able to compete in the international market. We plan to participate in a key international comparisons of attenuation in Type-N and s-parameters in 3.5 mm within the next year.

Accomplishments

- Completed the upgrade of the Army Primary Standards Laboratory's System 1 Dual Six-port System (100 kHz to 1 GHz). The system will be delivered to the Army by the end of the first quarter of FY'02.

- Performed many special reflection coefficient measurements of digital oscilloscope modules and photodetectors to support work being done in the Optoelectronics Division.

FY Outputs

Calibrations

Calibrated 128 devices for customers that generated an income of $125,000.

Recent Publications

Ginley, R. A.; Microwave Network Analyzers: A Discussion of Verification Methods; Cal Lab, pp. 22-25; October 1999

Judish, R. M.; Splett, J.; Robust Statistical Analysis of Vector Network Analyzer Intercomparisons; Proc., IEEE Instrum. Meas. Tech. Conf., 24-26 May 1999, Venice, Italy, pp. 1320-1324; May 1999

Ginley, R. A.; Microwave Network Analyzers - A Discussion of Verification Methods; Proc., Meas. Sci. Conf., 28-29 January 1999, Anaheim, CA, pp. 120-125; January 1999

Juroshek, J. R.; Wang, C. M.; McCabe, G. P.; Statistical Analysis of Network Analyzer Measurements; Cal Lab; May/June 1998

Jargon, J. A.; Revised Uncertainty of the NIST 30 MHz Phase Shifter Measurement Service; Proc., Meas. Sci. Conf., 5-6 February 1998, Pasadena, CA; February 1998

Fundamental Microwave Quantities

Noise

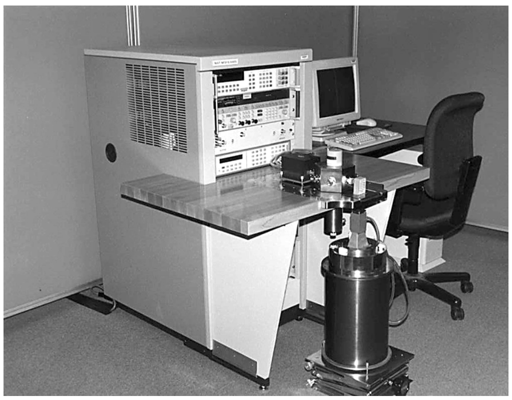
Technical Contact:
Jim Randa

Staff-Years (FY 2001):
2.5 Professional
2.0 Technician

Funding Sources:
NIST (60%)
Other (40%)

Goals

Develop methods for very accurate measurements of thermal noise; provide support for such measurements in the communications and electronics industries, as well as for other government agencies.



Noise figure radiometer and cryogenic standard

Customer Needs

Noise is a crucial consideration in designing or assessing the performance of virtually any electronic device or system that involves detection or processing of a signal. This includes communications systems, such as cellular phones and home entertainment systems, as well as systems with internal signal detection and processing, such as guidance and tracking systems or electronic test equipment. The global market for microwave and millimeter-wave devices in these areas is huge and growing. Important trends that must be addressed include the utilization of higher frequencies, the growing importance of low-noise amplifiers, the demand for and lack of repeatable and traceable on-wafer noise-measurement techniques, and the perpetual quest for faster, less expensive measurements. The two most important noise-related technical parameters requested by industry are the noise temperature of a one-port source and the noise figure of an amplifier.

Technical Strategy

We are pursuing new work in three general areas: traditional noise-temperature measurements, characterization of amplifier noise characteristics, and on-wafer noise measurements. In traditional (connectorized) noise-temperature measurements, the goal is to cover the frequency range from 8.2 GHz to 65 GHz for waveguide sources, and 30 MHz, 60 MHz, and 1 GHz to 50 GHz for coaxial sources. Concurrently, redesign of systems and test procedures is reducing the time required for such measurements, thereby reducing the costs to our customers.

The second general thrust of the project is in amplifier noise-parameter measurements. The long-term goals in this area are to improve techniques for measurement of noise parameters of amplifiers (especially low-noise amplifiers), to develop measurement capability for noise parameters of amplifiers with coaxial connectors from 1 to at least 12 GHz, and to provide a means for industry to access this capability, either through measurement comparisons or a measurement service.

The third area of new work is noise measurements on a wafer or substrate. We are currently developing on-wafer noise sources suitable for use in interlaboratory comparisons of noise-temperature measurements, and as the noise parameter work progresses, it will be extended to measurements of noise parameters of on-wafer amplifiers and devices.

Accomplishments

- An investigation of noise-parameters for multiport amplifiers, particularly differential amplifiers, was completed. Such amplifiers are receiving increased attention because of their widespread use in cell phones and other applications in the low-GHz range. The work suggested a framework for parameterizing the noise characteristics of such amplifiers, defined appropriate noise figures for them, and outlined measurement procedures for the noise figures in two practical examples. This work is documented in two papers, one presented at the 55th ARFTG Conference in June 2000 and the other which was published in IEEE Trans. MTT in October, 2001.

- A program was written to simulate general amplifier noise-parameter measurements with known underlying uncertainties. The simulator will be used to test analytical software, to compare different measurement strategies, and to perform Monte Carlo evaluation of uncertainties in the noise-parameter measurement service once the service is developed. The simulator was used with W. Wiatr's analytical program to evaluate uncertainties in a common noise-parameter measurement method. The results were reported in a paper presented at the British Electromagnetic Measurements Conference in November 2001, and in a paper to be submitted to the IEE Proceedings.

FY Outputs

Calibrations

Calibrated 9 devices for customers that generated an income of $50,000.

Recent Publications

J. Randa and W. Wiatr, "Noise-parameter uncertainties from Monte Carlo simulations," Conference Digest of British Electromagnetic Measurements Conference (BEMC-2001); Harrogate, UK, November 2001.

J. Randa, "Noise characterization of multiport amplifiers," IEEE Trans. Microwave Theory & Techniques, to be published (October, 2001)

J. Randa, L.P. Dunleavy, and L.A. Terrell, "Stability measurements on noise sources," IEEE Trans. Instrum. Meas., vol. 50, no. 2, pp. 368–372 (2001)

J. Randa, F. -Im. Buchholz, T. Colard, D. Schubert, M. Sinclair, J. Rice, and G. Williams "International comparison: Noise temperature of coaxial (GPC-7) sources," Metrologia, vol. 37, (2000)

C. Grosvenor, J. Randa, and R.L. Billinger, "NFRad"Review of the new NIST noise measurement system," 55th RFTG Conference Digest, pp. 135-44; Boston, MA, (June 2000)

J. Randa, "Multiport noise characterization and differential amplifiers," 55th ARFTG Conference Digest, pp. 106-115; Boston, MA (June 2000)

J. Randa, L.P. Dunleavy, and L.A. Terrell, "Noise-source stability measurements," 2000 Conference on Precision Electromagnetic Measurements Digest (Sydney, Australia), pp. 445-446 (May 2000)

C. Grosvenor, J. Randa, and R.L. Billinger, "Design and testing of NFRad-A new noise measurement system," NIST Tech. Note 1518 (March 2000)

J. Randa, W. Wiatr, and R.L. Billinger, "Comparison of adapter characterization methods," IEEE Trans. Microwave Theory & Techniques, vol. 47, no. 12, pp. 2613-2620 (1999)

J. Randa, R.L. Billinger, and J.L. Rice, "On-wafer measurements of noise temperature," IEEE Trans. Instrum. Meas., vol. 48, no. 6, pp. 1259-1269 (1999)

W. Wiatr, J. Randa, and R.L. Billinger, "Comparison of methods for adapter characterization," 1999 IEEE MTT-S International Microwave Symposium Digest (Anaheim, CA), pp. 1881-1884 (1999)

J. Randa, F. -Im. Buchholz, T. Colard, D. Schubert, M. Sinclair, J. Rice, and G. Williams, "International comparison of thermal noise-temperature measurements at 2, 4, and 12 GHz," IEEE Trans. Instrum. Meas., vol. 48, no. 2, pp. 174-177 (1999)

L. Dunleavy, J. Randa, D. Walker, R. Billinger, and J. Rice, "Characterization and applications of on-wafer diode noise sources," IEEE Trans. Microwave Theory & Techniques, MTT-46, pp. 2620-2628 (1998)

J. Randa, F. -Im. Buchholz, T. Colard, D. Schubert, M. Sinclair, J. Rice, and G. Williams, "International comparison of noise-temperature measurements at 2, 4, and 12 GHz," Conference Digest, 1998 Conference on Precision Electromagnetic Measurements (Washington, DC), pp. 615-616 (1998)

J. Randa, D. Walker, L. Dunleavy, R. Billinger, and J. Rice, "Characterization of on-wafer diode noise sources," 51st ARFTG Conference Digest, pp. 53-61, Baltimore, MD (1998)

J. Randa, "Uncertainties in NIST noise-temperature measurements," NIST Tech. Note 1502, (March, 1998)

High-Speed Microelectronics

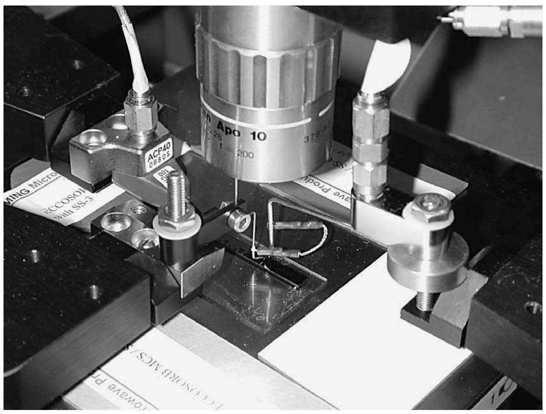
Technical Contact:
Dylan Williams

Staff-Years (FY 2001):
2 Professional
1.0 Technician
1.5 Guest Researcher

Funding Sources:
NIST (80%)
Other (20%)

Goals

Support the microwave, telecommunications and computing industries through research and development of high-frequency on-wafer metrology. The goal of the project is to develop electrical metrology for new 40 GB/s optical links, 30 to 100 GHz wireless systems, and high-speed microprocessors by establishing accurate on-wafer waveform and frequency-domain metrology to 200 GHz.



Test of a commercial high-impedance probe for performing non-invasive on-wafer waveform measurements

Customer Needs

The rapid advance in the speed of modern telecommunications and computing systems drives this project. The explosion of optical and wireless telecommunications is fueling the demand for microwave and radio-frequency microelectronics, and advances in the silicon industry continue to drive the size of digital circuits down and their clock rates up to microwave frequencies. Characterizing signal integrity in a microprocessor with a 2 GHz clock rate requires at least 10 GHz of calibrated measurement bandwidth on lossy silicon substrates. Limited available bandwidth is pushing wireless systems into the millimeter-wave region of 30 to 100 GHz. New 40 GB/s optical links require electrical metrology to 200 GHz. These extraordinary advances in technology require new high-speed frequency-domain and waveform measurements. However, current commercial sampling oscilloscopes are limited to a 50 GHz bandwidth, and current broadband single-sweep network analyzers are limited to 110 GHz.

Technical Strategy

Coaxial connectors pose insurmountable economic hurdles for high-speed telecommunications and computing. This project focuses on the only feasible alternative: developing high-speed, on-wafer time-domain and frequency-domain metrology for highly integrated structures, differentail transmission lines, on-wafer devices, and signal-integrity measurements. Due to their inherent high-speed and calculable systematic errors, electro-optic sampling systems play a central role in attaining high-frequency traceability for the project. We are using commercial oscilloscopes to establish both accurate connectorized and on-wafer frequency-domain, signal-integrity, and waveform metrology to 50 GHz, using electro-optic sampling systems to break the 50 GHz waveform measurement barrier, and are working on the 110 GHz frequency-domain network analysis barrier.

We have already successfully applied frequency-domain mismatch corrections to electro-optic sampling systems. This collaborative effort with the Optoelectronics Division has allowed us to characterize the phase and magnitude response of photodetectors and verify the "nose-to-nose" oscilloscope calibration to 30 GHz. This work has also set the foundation for 110 GHz photodetector and waveform measurements.

We are also developing techniques for performing noninvasive on-wafer waveform measurements for signal-integrity characterization in digital silicon ICs. We are developing calibration procedures for systems like those shown in the figure on the left. We plan to apply calibrated oscilloscopes to measure waveforms in fast, differential-coupled silicon interconnect structures.

We are also working to establish traceability of absolute electrical phase to electro-optic sampling systems to 40 GHz. This will lay the groundwork for verifying the 3-mixer calibration important to characterizing up and down-converters used in high-frequency wireless communication systems, and for a variety of direct calibrated microwave signal measurements. Eventually we hope to extend functional test of wireless communications components to 110 GHz.

We also plan to perform electro-optical on-wafer waveform measurements to 110 GHz. We will collaborate with the Optoelectronics Division to apply these to the characterization of 10, 20, and 40 GB/s telecommunications components. We will extend our on-wafer frequency-domain and waveform measurement capability to 200 GHz, which we will apply in a collaborative effort to the testing of 80 GB/s telecommunications components.

Accomplishments

- Built an on-wafer electro-optic waveform sampling system that features several hundred GHz of measurement bandwidth and calculable systematic errors.

- Compared waveform measurements performed on our newly constructed electro-optic sampling system to oscilloscope measurements, and verified the nose-to-nose calibration to 30 GHz.

- Developed a frequency-domain method of characterizing high-impedance probes suitable for performing noninvasive on-wafer waveform and signal-integrity measurements.

- Developed an accurate method of measuring the characteristic impedance of a transmission line fabricated on lossy silicon substrates and an accurate on-wafer calibration using this method.

- Developed instrumentation and methods for accurately and completely characterizing small printed coupled lines.

- Developed a causal microwave circuit theory whose voltages and currents reproduce the temporal behavior of the actual electric and magnetic fields in the circuit. The new causal theory does this by linking the time and frequency domains. This fixes all of the remaining free parameters of conventional microwave circuit theory

- Characterized low-k dielectrics fabricated at SEMATECH using transmission-line methods developed at NIST. Measurements from different line geometries agreed to within 5 % up to 40 GHz. The work involved tight collaboration between NIST and International SEMATECH (ISMT). The test structures were designed at NIST, the samples were fabricated at ISMT, the electrical measurements and data analysis were performed at NIST, and the physical measurements and electromagnetic analysis were performed at ISMT.

FY Outputs

Software

MultiCal measurement software implementing the multiline TRL calibration.

Four-port measurement software for performing orthogonal two-port, three-port, and four-port measurement with in-line calibrations and inexpensive hardware.

Characteristic impedance of silicon transmission lines software designed to accurately determine the characteristic impedance of transmission lines fabricated on silicon substrates.

CausalCat Software: For computing causal characteristic-impedance magnitude from the phase of the integral of the Poynting vector over the guide cross section.

Recent Publications

Williams, D. F.; Arz, U.; Grabinski, H. “Characteristic-Impedance Measurement Error on Lossy Substrates.” IEEE Microwave and Wireless Components Letters, Vol. 11, No. 7, pp. 299-301 July 2001

Cramer, N.; Walker, D. K. “Modeling Coplanar Waveguide Structures Constructed of Ferromagnetic Metal.” Dig. 2001 IEEE MTT-S Symp., 20-25 May 2001, Phoenix, AZ, pp. 483-486, May 2001

Williams, D. F.; Hale, P. D.; Clement, T. S.; Morgan, J. M. “Calibrating Electro-Optic Sampling Systems.” Dig. IEEE Microwave Theory Tech. Intl. Symp., 20-25 May 2001, Phoenix, AZ, pp. 1527-1530 May 2001

Williams, D. F.; Alpert, B. K. “Causality and Waveguide.” Circuit Theory IEEE Trans. Microwave Theory Tech., Vol. 49, No. 4, pp. 615-623 April 2001

Hale, P. D.; Clement, T. S.; Williams, D. F. “Measuring Frequency Response of high-Speed Optical Receivers Requires Microwave Measurements.” SPIE's OE Mag., p. 56 March 2001

Walker, D. K.; Williams, D. F.; Padilla, A.; Arz, U.; Grabinski, H. “Four-Port Microwave Measurement System Speeds On-Wafer Calibration and Test.”, Microwave Journal, pp. 148-154 March 2001

Arz, U.; Williams, D. F.; Walker, D. K.; Rogers, J. E.; Rudack, M.; Treytner, D.; Grabinski, H.; Characterization Of Asymmetric Coupled Cmos Line; Dig. IEEE Microwave Theory Tech. Intl. Symp., 11-16 June 2000, Boston, Ma, pp. 609-612; June 2000

Wiatr, W.; Walker, D. K.; Williams, D. F.; Coplanar-Waveguide-To-Micro-Strip Transition Model; Dig., IEEE Microwave Theory Tech. Intl. Symp., 11-16 June 2000, Boston, Ma, pp. 1797-1799; June 2000

Araz, U.; Grabinski, H.; Williams, D. F.; Influence Of The Substrate Resistivity On The Broadband Characteristics Of Silicon Transmission Lines; Proc., 54th Auto. Rf Tech. Group Conf., 2-3 Dec. 1999, Atlanta, Ga, pp. 58-63; December 1999

Kaiser, R. F.; Williams, D. F.; Sources Of Error In Coplanar Waveguide Trl Calibrations; Proc., 54th Auto. RF Tech. Group Conf., 2-3 Dec. 1999, Atlanta, Ga, pp. 75-80; December 1999

Jargon, J. A.; Marks, R. B.; Rytting, D. K.; Characterizing Lumped-Element Calibrations For Four-Sampler Vector Network Analyzers; IEEE Trans. Microwave Theory Tech., Vol. 47, No. 10, pp.2008-2012; October 1999

Williams, D. F.; Alpert, B. K.; A Causal Microwave Circuit Theory And Its Implications; Proc., URSI General Assembly, Toronto, Canada, 13-21 August 1999, P. 142; August 1999

Williams, D. F.; DeGroot, D. C.; Electrical Measurements For Electronic Interconnections At NIST; Proc., URSI General Assembly, Toronto, Canada, 13-21 August 1999, P. 31; August 1999;

Williams, D. F.; Alpert, B. K.; Characteristic Impedance, Power And Causality; IEEE Microwave Guided Wave Lett., Vol. 9, No. 5, pp. 181-182; May 1999

Williams, D. F.; Alpert, B. K.; Characteristic Impedance, Causality, And Microwave Circuit Theory; Proc., IEEE Sig. Propagation Interconnects Workshop, 19-21 May 1999, Titisee-Neustadt, Germany, pp. 1-2; May 1999

Williams, D. F.; Walker, D. K.; 0.1-10 GHz Cmos Voltage Standard; Proc., IEEE Sig. Propagation Interconnects Workshop, 19-21 May 1999, Titisee-Neustadt, Germany; May 1999

Williams, D. F.; Metal-Insulator-Semiconductor Transmission Lines; IEEE Trans. Microwave Theory Tech., Vol. 47, No. 2, pp. 176-181; February 1999

DeGroot, D. C.; Williams, D. F.; National Institute Of Standards And Technology Programs In Electrical Measurements For Electronic Interconnections; Proc., Electrical Performance Of Electronic Packaging., 25-28 October 1998, West Point, NY, pp. 45-49; October 1998

Marks, R. B.; On-Wafer Millimeter-Wave Characterization; Proc., European Gaas' 98 Symp., 5-6 October 1998, Amsterdam, The Netherlands, pp 21-26; October 1998

Williams, D. F.; High Frequency Limitations Of The JEDEC 123 Guideline; Proc., Electrical Performance Of Electronic Packaging., 25-28 October 1998, West Point, NY, pp 45-49; October 1998

Marks, R. B.; Jargon, J. A.; Rytting, D. K.; Accuracy Of Lumped-Element Calibrations For Four-Sampler Vector Network Analyzers; Dig., IEEE MTT Intl. Symp., 7-12 June 1998, Baltimore, Md, pp. 1487-1490; June 1998

Walker, D. K.; Williams, D. F.; Comparison Of Solr And Trl Calibrations; Dig., 51st Auto. Rf Tech. Group Conf., 7-12 June 1998, Baltimore, Md, pp. 83-87; June 1998

Williams, D. F.; Arz, U.; Grabinski, H.; Accurate Characteristic Impedance Measurement On Silicon; Dig., '98 IEEE MTT, Intl. Microwave Symp., 7-12 June 1998, Baltimore, Md, pp. 1917-1920; June 1998

Williams, D. F.; Walker, D. K.; Lumped-Element Impedance Standards; Dig., 51st Auto. Rf Tech. Group Conf., 7-12 June 1998, Baltimore, Md, pp. 91-93; June 1998

Williams, D. F.; Metal-Insulator-Semiconductor Transmission Line Model; Dig., 51st Auto. Rf Tech. Group Conf., 7-12 June 1998, Baltimore, Md, pp. 65-71; June 1998

Williams, D. F.; Walker, D. K.; In-Line Multiport Calibration; Dig., 51st Auto. Rf Tech. Group Conf., 7-12 June 1998, Baltimore, Md, pp. 88-90; June 1998

Milanovic, V.; Ozgur, M.; DeGroot, D. C.; Jargon, J. A.; Gaitan, M.; Zaghloul, M.; Characterization Of Broad-Band Transmission For Coplanar Waveguides On Cmos Silicon Substrates; IEEE Trans. Microwave Theory Tech., Vol. 46, No. 5, pp. 632-640 ; May 1998

DeGroot, D. C.; Jargon, J. A.; Rf And Microwave Device Measurements Using A Digital Sampling Oscilloscope; Instrum. Newsletter, Vol. 9, No. 4, pp. T1-4; December 1997

DeGroot, D. C.; Marks, R. B.; Jargon, J. A.; A Method For Comparing Vector Network Analyzers; Dig., Auto. Rf Tech. Group Conf., 4-5 December 1997, Portland, Or, pp. 107-114; December 1997

Marks, R. B.; Formulations Of The Basic Vector Network Analyzer Error Model Including Switch Terms; Dig., Auto. Rf Tech. Group Conf., 4-5 December 1997, Portland, Or, pp. 115-126; December 1997

Williams, D. F.; Walker, D. K.; Series-Resistor Calibration; Dig., Auto. Rf Tech. Group Conf., 4-5 December 1997, Portland, Or, pp. 131-137; December 1997

Williams, D. F.; Janezic, M.D.; Ralston, A.; Quasi-Tem Model For Coplanar Waveguide On Silicon; Dig., Electrical Performance Of Electronic Packaging Conf., 27-29 October 1997, San Jose, Ca, pp. 225-228; October 1997

Wireless Systems

Nonlinear Device Characterization

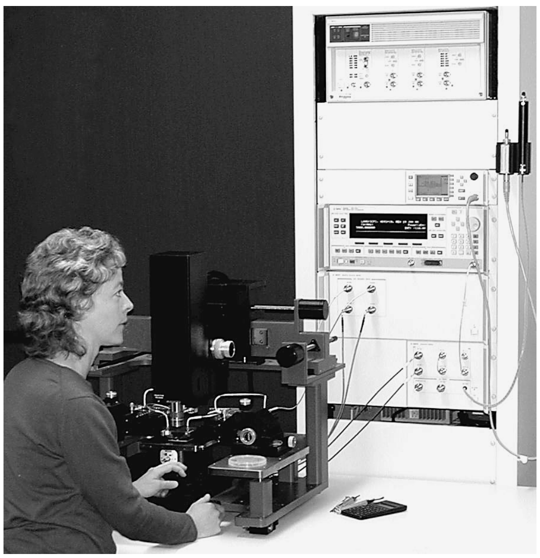
Technical Contact:
Don DeGroot

Staff-Years (FY 2001):
3.0 Professional
0.4 Guest Researcher

Funding Sources:
NIST (90%)
Other (10%)

Goals

Develop and support general methods of characterizing nonlinear components, circuits, and systems used in digital wireless communications; refine and transfer these methods through interactions with industrial research and development laboratories.



Dr. Kate Remley performs large-signal measurements of an RF power amplifier using the Nonlinear Network Measurement System

Customer Needs

Radio-frequency measurements are applied extensively in the deployment of commercial wireless communication systems. They are crucial to all stages of system development, from device modeling to circuit design and system performance characterization. NIST's RF and microwave measurement teams are addressing the critical need for accurate measurements of nonlinear electrical networks and supporting industrial standards development.

Technical Strategy

The Nonlinear Device Characterization (NDC) Project is developing and verifying measurement-based descriptions of devices, circuits, and systems that contain nonlinear elements. The RF power amplifier is a key nonlinear component with which engineers are currently contending. Industrial experts estimate that the RF power amplifiers account for 60-70 % of base station costs and 20-30 % of the total wireless link cost. Traditional microwave circuit design has relied on the ability to cascade circuit elements through simple linear operations and transformations, but engineers lose the ability to predict circuit performance across operating environments, or states, when their circuits include a nonlinear element. Presently, there is a critical need for fundamental RF measurement techniques to develop and validate nonlinear models and commonly applied figures of merit. Contributions in this area will significantly improve design-cycle efficiency and trade between manufacturers, and will eventually facilitate improvements in communications through the full incorporation of nonlinear models at the system design level.

The NDC Project recently acquired and established a new measurement facility known as the Nonlinear Network Measurement System (NNMS). The system provides the most general approach to measuring large-signal responses. It is a stimulus-response network analyzer that supplies periodic signals, and then acquires broadband incident and reflection waveforms at the device under test. The NIST facility will be used as a reference system in measurement and model comparisons. The project team is developing accurate calibration and measurement techniques for the NNMS, including validation of the Nose-to-Nose calibration technique, a practical and available method of measuring the phase relations of components in signals with 50 GHz bandwidths. The project team is now refining the statement of measurement uncertainty in the Nose-to-Nose method and will apply it to NNMS measurements.

The Nonlinear Network Measurement System is being applied first to canonical circuits to compare general measurements with predictions made by circuit simulators and new behavioral models. We have applied these techniques to identify stable verification circuits that will be used in NIST-sponsored interlaboratory comparisons. Second, the measurement system is being applied to develop and verify artificial neural network (ANN) models for nonlinear circuits being developed in cooperation with the University of Colorado. NNMS data will be used to train ANN models, to verify circuit operation and model predictions, and to validate a circuit optimization approach.

The NDC Project has also started to examine the link between nonlinear circuit descriptions and system performance simulations. Through collaborations with NIST's broadband standards development effort, members of the NDC Project will assemble a measurement system to test the performance of communication links.

Plans are underway with the University of Colorado to establish a Joint Research Center for Nonlinear Electronics in Wireless at Radio Frequencies (newRF). This Center, funded by industrial members, will support graduate research projects. The graduate research assistants and CU faculty will work with NIST staff on the newRF projects. The Center will increase the effectiveness of the NIST facilities while developing a new class of technical professionals who have the skills required by industry.

Accomplishments

■ Expanded numerical simulations of the Nose-to-Nose calibrations as the basis for an initial uncertainty statement. There are no other methods of identifying the error terms due to the internal sampling electronics used by the Nose-to-Nose calibration. The simulator-based sensitivity study gives us the basis for a first-level uncertainty bound for this calibration.

■ Adapted Multiline TRL Calibration for NNMS and included it in Agilent software, with Agilent collaborators. All users of current and future NNMS instruments will have access to the NIST reference calibration in their daily measurements.

■ Added modulated signal capabilities to NIST NNMS. Demonstrated modulated signal measurements on an example commercial amplifier. Conducted multiple modulation calibrations to study instrument repeatability. NIST can now use the NNMS to characterize circuits using two-tone and multi-tone signals, and then compare these to commonly used figures of merit. Agilent now has better repeatability data for their instrument.

■ Designed interlaboratory comparison for nonlinear network analyzer users. Designed and fabricated prototype verification circuits. Formulated initial comparison method and measures. Performed initial comparisons between Agilent NNMS (Belgium) and NIST NNMS. Users of NNMS and related instruments (MTA, custom scope-based network analyzers) will gain assurance in their ability to identify nonlinear input-output transfer functions.

■ Developed nonlinear models for verification devices. Developed and applied conventional compact diode models. Developed frequency-domain behavioral modeling strategy with University of Colorado. Developed time-domain behavioral models with guest researcher from K. U. Leuven. The interlaboratory comparison of nonlinear network analyzers requires models since we do not have a generalized nonlinear parameter to use. The models can accurately represent the nonlinear transfer function of the verification circuits over the state-space that we characterize them, allowing participants to find the differences between their measurements and our model predictions.

■ Developed early metrics for comparing data from nonlinear circuit characterizations. We are forming tools that can easily summarize differences found in the multidimensional data sets common to nonlinear measurements and modeling. The metrics will be used immediately in NIST model and measurement comparisons.

■ Developed generalized approach to measurement-based frequency-domain models of nonlinear circuits. Demonstrated Artificial Neural Network Models to define and obtain nonlinear large-signal scattering parameters. This approach may prove useful in improving the efficiency of nonlinear circuit design. It is the only definition of a nonlinear scattering parameter that does not assume linearization at some point.

■ Concluded second phase of PIM measurement comparison. Participants have determined how well their measurements compared to ensemble averages for characterizations of a verification device with ultra-low passive intermodulation.

FY Outputs

Software

TDNACal: software designed for calibrated time-domain network analysis measurements.

Recent Publications

K. A. Remley, D. C. DeGroot, J. A. Jargon, and K. C. Gupta, "A method to compare vector nonlinear network analyzers," 2001 IEEE MTT-S Internat. Microwave Symp. Dig., pp. 1667-1670, May 21-24, 2001.

K. A. Remley, D. F. Williams, D. C. DeGroot, J. Verspecht, and J. Kerley, "Effects of nonlinear diode junction capacitance on the nose-to-nose calibration," IEEE Microwave Wireless Comp. Lett., vol. 11, no. 5, pp. 196-198, , 2001.

J. A. Jargon and K. C. Gupta, "Artificial neural network modeling for improved coaxial line-reflect-match calibrations," Internat. J. RF Microwave Computer-Aided Eng., vol. 11, no. 1, pp. 33-37, Jan., 2001.

D. F. Williams and K. A. Remley, "Analytic sampling-circuit model," IEEE Trans. Microwave Theory Techn., vol. 49, no. 6, pp. 1013-1019, 2001.

J. A. Jargon, "Measurement Comparison of a Low-Intermodulation Termination for the U.S. Wireless Industry," NIST Technical Note 1521, Jul. 2001.

J. A. Jargon and K. C. Gupta, "Artificial neural network modeling for improved on-wafer line-reflect-match calibrations," 31st European Microwave Conf. Dig., Sep., 2001.

J. A. Jargon, P. Kirby, K. C. Gupta, L. Dunleavy, and T. Weller, "Modeling Load Variations with Artificial Neural Networks to Improve On-Wafer OSLT Calibrations," 56th ARFTG Conf. Dig., pp. 76-88, Boulder, CO, Nov. 2000.

J. A. Jargon, K. C. Gupta, and D. C. DeGroot, "Artificial neural network modeling for improved on-wafer OSLT calibration standards," Int. J. RF Microwave Computer-Aided Engin., vol. 10, no. 5, pp. 319-328, Sep., 2000

L. Rouault, B. Verbaere, D. DeGroot, D. LeGolvan, and R. Marks, "Measurements and models of a power amplifier suitable for 802.16.1," IEEE 802.16.1 p-00, Sep. 13, 2000

P. D. Hale, T. S. Clement, K. S. Coakley, C. M. Wang, D. C. DeGroot, and A. P. Verdoni, "Estimating the magnitude and phase response of a 50 GHz sampling oscilloscope using the "Nose-to-Nose" method," 55th ARFTG Conf. Dig., pp. 35-42, June 13, 2000

D. C. DeGroot, P. D. Hale, M. Vanden Bossche, F. Verbeyst, and J. Verspecht, "Analysis of interconnection networks and mismatch in the Nose-to-Nose calibration," 55th ARFTG Conf. Dig., pp. 116-121, June 16, 2000

K. A. Remley, D. F. Williams, and D. C. DeGroot, "Realistic sampling-circuit model for a Nose-to-Nose simulation," 2000 IEEE MTT-S Int. Microwave Symp. Dig., June 11-16, 2000

J. A. Jargon and D. C. DeGroot, "NIST unveils status of PIM testing," Microwaves & RF, pp. 78-81, Jan., 2000

Williams, D. F.; Remley, K. A.; Nose-To-Nose Response Of A 20 GHz Sampling Circuit; Proc., 54th Auto. RF Tech. Group Conf., 2-3 Dec. 1999, Atlanta, Ga, pp. 64-70; December 1999

D. C. DeGroot, K. L. Reed, And J. A. Jargon, "Equivalent Circuit Models For Coaxial Oslt Standards," 54th ARFTG Conf. Dig., pp. 103-115, Dec. 3-4, 1999

Jargon, J. A.; DeGroot, D. C.; Comparison Of Passive Intermodulation Measurements For The U. S. Wireless Industry; NIST TN 1515; October 1999

Jargon, J. A.; DeGroot, D. C.; Reed, K. L.; NIST Passive Intermodulation Measurement Comparison For Wireless Base-Station Equipment; Dig., Auto. RF Tech. Group Conf. 3-4 December 1998, Rohnert Park, Ca, pp. 128-139; December 1998

Wireless Systems

Standards for Broadband Wireless Access

Technical Contact:
Roger Marks

Staff-Years (FY 2001):
1.0 professional

Funding Sources:
NIST (100%)

Goals

Accelerate the development of the broadband wireless communications industry by leading and facilitating the open development of accredited, consensus technical standards for worldwide use.

Customer Needs

With the start of U.S. auctions in 1994, the radio spectrum has been moving into private hands. This spectrum is only minimally unregulated. Innovation has brought new technology to market but, without widely supported standards, costs remain unnecessarily high, exports are stifled, and the benefits of new technology fail to fully flow down to the consumer.

Technical Strategy

This project gives NIST a proactive role in the development of technically-superior standards for wireless communications. Its current focus is on fixed broadband wireless access systems that have the potential to provide competitive alternative connections to Internet, voice, and video networks for residential and business sites worldwide. Spectrum for these services is in private hands, but the wide scale deployment of systems awaits standardization.

History and Progress of Standardization Effort

The project effort has been directed toward establishing and leading a global industry effort in broadband wireless access standardization. The project began when project leader Roger Marks launched a web site and newsletter (currently with over 850 subscribers) in April 1998. At a Kickoff Meeting in August 1998, he suggested that, based on his research, the most appropriate organization with which to pursue standardization would be the LAN/MAN [Local/Metropolitan Area Networks] Standards Committee of the Institute of Electrical and Electronics Engineers, Inc. (IEEE), a nonprofit technical professional society. The IEEE, through its accredited Standards Association, supports an open process for the development of global standards. The committee, informally known as IEEE 802, has become the world's primary (and virtually only) developer of standards for computer networking; its 802.3 Ethernet and 802.11 Wireless LAN standards are ubiquitous. The IEEE 802.16 Working Group on Broadband Wireless Access arose from this endeavor, and Marks has remained Chair. The group has 163 Voting Members, and over 700 people from over 15 countries have attended one of the group's 15 bimonthly sessions.

September 2001 saw the publication of the first of the Group's standards: IEEE Standard 802.16.2 ("Coexistence of Fixed Broadband Wireless Access Systems"). The group has also completed and is awaiting final approval of its core project: IEEE Draft P802.16 ("Air Interface for Fixed Broadband Wireless Access Systems"). Marks served as Technical Editor for both of these documents and chaired the subgroup that developed P802.16.

While the P802.16 air interface is specific to 10-66 GHz systems, the group is developing enhancements to expand the applicability to 2-11 GHz in both licensed and unlicensed bands. An additional project is developing enhancements to 802.16.2.

In accordance with IEEE 802 rules, Marks, as Working Group Chair, decides the Group's procedural issues while the Group makes the technical decisions. He also maintains the 802.16 web site, which handled requests for over 2.8 million files in the year 2000.

Marks is working to ensure that the 802.16 standards are successful worldwide. He interacts with regional and international standardization organizations to promote the use of 802.16 outputs.

In August 2001, upon invitation of the Chinese government Marks visited Beijing to keynote a conference whose single topic was the applicability of 802.16 standards as Chinese national standards. The attendance of 240 people include 100 government officials and 80 representatives of telecommunication operators.

Marks also plays a role in broader issues of open standardization. He helped to organize the 2001 IEEE Conference on Standards and Innovation in Information Technology and presented a paper there on government roles in standardization.

Wireless System Characterization Facility

One goal of the wireless system characterization facility is to support standardization by providing unbiased measurement results. Another is to apply system-level measurement results to challenging component-level characterization issues, particularly for nonlinear components. The project has acquired the instrumentation for a unique characterization laboratory integrated with the facilities of the Nonlinear Device Characterization project.

FY Outputs

Standards

Marks, R. B. (Technical Editor); IEEE Standard 802.16.2-2001: IEEE Recommended Practice for Local and Metropolitan Area Networks—Coexistence of Fixed Broadband Wireless Access Systems, September 10, 2001.

Marks, R. B. (Technical Editor); IEEE Draft P802.16/D5-2001: IEEE Draft Standard for Local and Metropolitan Area Networks—Part 16: Air Interface for Fixed Broadband Wireless Access Systems, October 18, 2001.

Recent Publications

Marks, R. B., Gifford, I. C., and O'Hara, B.; Standards in IEEE 802 Unleash the Wireless Internet, IEEE Microwave Magazine 2, pp. 46-56, June 2001.

Marks, R. B.; IEEE Standardization for the Wireless Engineer, IEEE Microwave Magazine 2, pp. 16-26, June 2001.

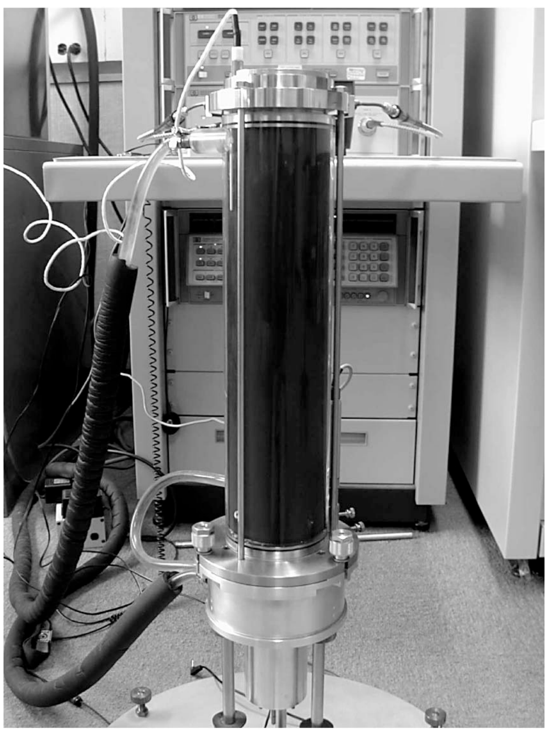
Marks, R. B.; IEEE Takes on Broadband Wireless, EE Times 1169, pp. 78,106, and 108, June 4, 2001.

Marks, R. B. and Hebner, R. E.; Government Activity to Increase Benefits from the Global Standards System, 2001 IEEE Conference on Standards and Innovation in Information Technology (Boulder, Colorado, USA, 3-5 October 2001).

Electromagnetic Properties of Materials

Goals

Develop, improve, and analyze measurement methods, uncertainties, and theory for the characterization of the complex permittivity and permeability of dielectric and magnetic materials in the RF and microwave spectrum, as a function of temperature and bias fields. We plan to extend measurement capability to higher frequencies and a broader range of temperature, and to develop new methods for thin films and on-chip measurement of permittivity. We also plan to develop models for underlying relaxation phenomena that occur in dielectric and magnetic materials. Finally, we will provide measurement services, become active on standards committees, and develop Standard Reference Materials (SRMs).



Cylindrical Cavity Resonator

Customer Needs

The trend in microelectronic applications is toward higher frequencies, variable temperatures, and thinner materials. Substrate-based components employing thin films form the basis for microelectronic circuitry. Substrate electronic materials are used in printed wiring boards (PWB), low-temperature cofired ceramics (LTCC), CPU chips, and microwave components. Industry requires new measurement methods, with well-characterized uncertainties, at microwave and millimeter frequencies and over variable temperatures. Knowledge of temperature-dependent dielectric and loss properties of ceramics, substrates, and crystals are crucial in the wireless and time-standards arena at microwave and millimeter frequencies. For example, computer-based design methods require very accurate data on the dielectric and magnetic properties of these materials over wide frequency and temperature ranges. Various applications require composite dielectrics that emulate the human body's electrical properties for testing metal detectors and analyzing electromagnetic interference (EMI) of implant medical devices. Liquid permittivity measurements are needed to support biotechnology research. To support the evolving microelectronics industry, methods for characterizing metamaterial properties will be necessary for the development of novel new technologies. On-chip, microscale-to-nanoscale permittivity measurements are important for the microelectronic industry. Dielectric reference materials are needed to provide measurement traceability to NIST and measurement intercomparisons provide assessments of the quality of material characterization. An understanding of loss mechanisms in low-loss crystals is important in interpreting measurement results.

Technical Strategy

In response to needs in the microelectronics industry, we are developing accurate methods for measuring the dielectric properties of thin-films using transmission-line and resonator methods. Using the previously developed on-wafer transmission-line model, we will extend measurements of thin films to frequencies above 40 GHz.

The PWB and LTCC industries need to characterize the permittivity of substrates. We will further develop wideband, variable-temperature metrology. We will extend the capability of our Fabry-Perot measurement system to include variable temperatures, and complete the model development of the split-post resonator. We will measure a wide spectrum of ceramic materials that are commonly used in the electronics industry, as a function of temperature and publish a journal paper. We will continue to support the LTCC Working Group through measurement assistance.

Technical Contact:
Jim Baker-Jarvis

Staff-Years (FY 2001):
5.0 Professional

Funding Sources:
NIST (40%)
Other (60%)

To satisfy needs in the health care and metal detector industries, we will characterize materials that mimic the electrical properties of the human body. Through funding from the Justice Department, we will develop measurement metrology on composite phantom materials.

In order to support the biotechnology industry, we will improve our liquid measurement metrology. We will perform an in-house intercomparison between the liquid measurement methods we have developed over the years.

To support the emerging microelectronic composite materials technologies, we will develop measurement metrology on metamaterials and develop an on-wafer material that has negative permittivity and permeability at 60 to 70 GHz.

To support the microelectronics industry in on-chip dielectric measurements metrology, we will develop atomic-force microscopy methods in collaboration with Division 816 for use as localized nanoscale permittivity measurement methods. We will organize a conference workshop session on these methods.

We will support the development of standards by attending and contributing to standards committee meetings. To satisfy a need to understand and summarize the physics of high-frequency losses in dielectrics we will test crystals over wide temperature and frequency ranges and compare the measured losses to expressions in the solid-state literature.

Accomplishments

■ Measurements of low-k dielectrics were made using International SEMATECH supplied wafers and NIST-developed transmission line methods. A paper summarizing the method is in press in IEEE MTT.

■ For DARPA we developed a new cavity thin-film measurement method. The method is based on measurement of a substrate, with and without a film attached. The method was tested on a film of barium strontium titanate film on a substrate of lanthanum aluminate.

■ Measurements were made on thin films supplied by Jan Obrzut of Polymers Division of MSEL using a split-post resonator method. A mode-match model for a thin film fixture that Jan Obrzut of MSEL is using was developed. Measurements were also made for Army Research Lab thin films they supplied.

■ Technical Note 1520 was completed summarizing the LTCC substrate high-frequency measurement technology. This Technical Note will also serve as a traceability reference guide for our special test measurement services. This was a collaborative effort with the Electricity Division of EEEL and the Ceramics Division of MSEL.

■ We collaborated with the Ceramics Division of MSEL in the LTCC Working Group by performing substrate measurements.

■ We worked closely with Ferro Corporation, Heraerus, and Dupont to measure commonly used LTCC materials and to solve an outstanding problem in metal-loss determination. This work resulted in transfer of measurement technology, software, and fixtures to industry.

■ We developed synthetic materials that emulate the conductivity of human body tissues. This work, funded by the Justice Department for use in modeling metal detectors performance. We developed well-characterized phantom materials over a frequency range of 100 Hz to 10 MHz. Three candidate materials were studied; two were liquid of mixtures of salts and low-conductivity liquids, and the other was a semi-solid, carbon black in silicone.

■ A method for the simultaneous measurement of the permeability and conductivity of bulk metals from 1000 Hz to 1 MHz was developed. The permeability measurement uses a toroid of metal sample wound with wire. A system for variable temperature measurements was developed. A study of the temperature-dependence of the permittivity for a number of commonly used plastics was performed and the results are in press in IEEE Transactions Dielectrics and Electrical Insulation.

■ In FY 2001, the fabrication and measurement of SRM materials were performed. In addition, a repeatability study, uncertainty analysis, and measurement assurance plan were completed. A constitutive theory for simultaneous magnetic and electric driving fields was developed from first principles.

Recent Publications

Baker-Jarvis, J. R. ; Janezic, M. D. ; Riddle, B. F. ; Holloway, C. L. ; Paulter, N. G. ; Blendell, J. E. Dielectric and Conductor-Loss Characterization and measurements on Electronic Packaging Materials NIST TN 1520, July 2001

Haugan, T.; Wong-Ng, W.; Cook, L. P.; Geyer, R. G. ; Brown, H. J.; Swartzendruber, L.; Kaduk, J. “Development of Low Cost (Sr, Ca)$_3$Al$_2$O$_6$ Dielectrics for Bi$_2$Sr$_2$CaCu$_2$O$_{8+}$. Applications” IEEE Trans. Applied Superconductivity, Vol. 11, No. 1, pp. 3305-3308 March 2001

Baker-Jarvis, J. R.; A Generalized Dielectric Polarization Evolution Equation; IEEE Trans. Dielectr. Electr. Insul., Vol. 7, No. 3, pp. 374-386; June 2000

Jones, C. A.; Grosvenor, J. H.; Weil, C. M.; Rf Material Characterization Using A Large-Diameter (76.8 Mm) Coaxial Air Line; Proc., Intl. Microwave Conf. Mikon, 22-24 May 2000, Warsaw, Poland, Vol. 1, pp. 417-420; May 2000

Krupka, J.; Baker-Jarvis, J. R Geyer, R. G.; Measurements Of The Complex Permittivity Of Single-Crystal And Ceramic Strontium Titanate At Microwave Frequencies And Cryogenic Temperatures; Proc., Intl. Microwave Conf. Mikon, 15 May 2000, Warsaw, Poland, Vol. 1, pp. 301-304; May 2000

Baker-Jarvis, J. R.; Riddle, B. F.;, Dielectric Measurements Of Substrates And Packaging Materials; Proc., Intl. Conf. on High Density Interconnect And System Packaging, 26-28 April 2000, Denver, Co, pp. 177-181; April 2000

Synowczynski, J.; Dewing, G.; Geyer, R. G.; Acceptor Doping Of Barium Strontium Titanate And Magnesium Oxide Composites; Proc., Am. Ceram. Soc., 25-28 April 2000, Indianapolis, In, pp. 241-259; April 2000

Jones, C. A.; Grosvenor, J. H.; Weil, C. M.; Rf Material Characterization Using A Large-Diameter (76.8 Mm) Coaxial Air Line; NIST TN 1517; February 2000

Geyer, R. G.; Complex Permittivity And Permeability Of Ferrite Ceramics At Microwave Frequencies; Trans. Am. Ceram. Soc., Vol. 100, pp. 195-215; 1999

Geyer, R. G.; Kabos, P.; Magnetic Switching; Wiley Encyclopedia Of Electrical And Electronics Engineering, Vol. 12, pp. 179-191; 1999

Holloway, C. L.; Baker-Jarvis, J. R.; Johnk, R. T.; Geyer, R. G.; Electromagnetic Ferrite Tile Absorber; Wiley Encyclopedia Of Electrical And Electronics Engineering, Vol. 6, pp. 429-440; 1999

Krupka, J.; Derzakowski, K.; Tobar, M.; Hartnett, J. G.; Geyer, R. G.; Complex Permittivity Of Some Ultra-Low Loss Crystals At Cryogenic Temperature; Meas. Sci. Tech. J., Vol. 10, pp. 387-392; October 1999

Harnett, J. G.; Tobar, M. E.; Mann, A. G.; Invanov, E. N.; Krupka, J.; Geyer, R. G.; Frequency-Temperature Compensation In Ti3+ And Ti4+ Doped Sapphire Whispering Gallery Mode Resonators; IEEE Trans. Ultrasonics, Ferroelectrics, And Frequency Control, Vol. 46, No. 4, pp. 993-999; July 1999

Baker-Jarvis, J. R.; Riddle, B. F.; Young, A.; Ion Dynamics Near Charged Electrodes With Excluded Volume Effect; IEEE Trans. Dielectr. Electr. Insulation, Vol. 6, No. 2, pp. 226-235; April 1999

Baker-Jarvis, J. R.; Riddle, B. F.; Janezic, M. D.; Dielectric And Magnetic Properties Of Printed Wiring Boards And Other Substrate Materials; NIST TN 1512; March 1999

Janezic, M. D.; Jargon, J. A.; Complex Permittivity From Propagation Constant Measurements; IEEE Microwave Guided Wave Lett., Vol. 9, No. 2, pp. 76-78; February 1999

Baker-Jarvis, J. R.; Jones, C. A.; Riddle, B. F.; Electrical Properties And Dielectric Relaxation Of DNA In Solution; NIST TN 1509; November 1998

Weil, C. M.; Janezic, M. D.; Jones, C. A.; Vanzura, E. J.; Measurement Intercomparisons Of Dielectric And Magnetic Material Characterization; Proc., Conf. On Prec. Electromagn. Meas., 6-10 July 1998, Washington, DC, pp. 481-482; July 1998

Geyer, R. G.; Jones, C. A.; Krupka, J.; Microwave Characterization Of Dielectric Ceramics For Wireless Communiucations; Advances In Dielectric Ceramic Materials, Vol. 88, pp. 75-91; May 1998

Geyer, R. G.; Jones, C. A.; Krupka, J.; Complex Permeability Measurements Of Ferrite Ceramics Used In Wireless Communications; Advances In Dielectric Ceramic Materials, Vol. 88, pp. 93-113; May 1998

Geyer, R. C.; Baker-Jarvis, J. R.; Vanderah, T. A.; Mantese, J. F; Complex Permittivity And Permeability Estimation Of Composite Electroceramics; Advances In Dielectric Ceramic Materials, Vol. 88, pp. 115-129; May 1998

Krupka, J.; Weil, C. M.; Recent Advances In Metrology For The Electromagnetic Characterization Of Bulk Materials At Microwave Frequencies; Proc., Mixon Xii, Intl. Microwave Conf., 20-22 May 1998, Krakow, Poland, pp. 243-253; May 1998

Baker-Jarvis, J. R.; Jones, C. A.; Janezic, M. D.; Shielded Open-Circuited Sample Holder For Dielectric Measurements Of Solids And Liquids; IEEE Trans. Instrum. Meas., Vol. 47, No. 2, pp. 338-344; April 1998

Janezic, M. D.; Baker-Jarvis, J. R.; Full-Wave Analysis Of A Split-Cylinder Resonator For Nondesructive Permittivity Measurements; IEEE Trans. Microwave Theory Tech., Vol. 47, No. 10, pp. 2014-2020; October 1999

Antenna and Antenna Systems

Antenna Measurement Theory and Application Systems

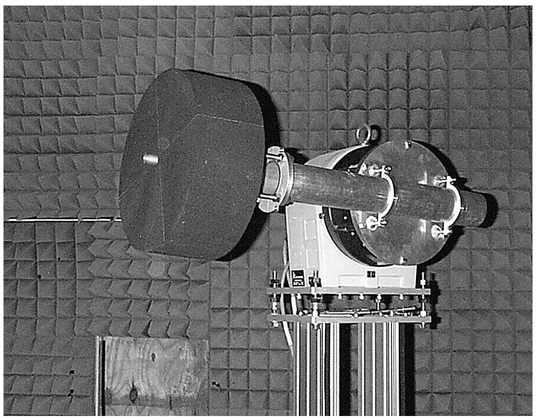
Technical Contact:
Mike Francis

Staff-Years (FY 2001):
3.0 Professional
1.0 Technician

Funding Sources:
NIST (70%)
Other (30%)

Goals

Develop, refine, and extend measurement techniques to meet current requirements and to anticipate future needs for accurate antenna characterization.



Setup for a quiet-zone scan. In an actual measurement the exposed metal on the rotator and tower would be covered with microwave absorber. The probe is just visible in the left center, slightly beyond the end of the absorber.

Customer Needs

Microwave antenna hardware continues to become more sophisticated and NIST is tasked with providing correspondingly sophisticated measurement support. Current demands include:

Improved accuracy: High-performance systems, especially those that are satellite-based, require maintenance of tighter tolerances.

Higher frequencies: Millimeter-wave applications up to 500 GHz have been proposed. NIST routinely receives requests for measurements above 75 GHz (near the current limit of support.)

Low-sidelobe antennas: Military and commercial communications applications increasingly require sidelobe levels of 50 dB below peak, or better, a range where measurement by standard techniques is difficult.

Complex phased-array antennas: Large, often electronically-steerable phased arrays require special diagnostic tests to ensure full functionality.

In situ and remote measurements: Many systems cannot be simply transported to a measurement laboratory. Robust techniques are needed for on-site testing.

Production-line evaluation: Techniques are required that emphasize speed and economy, possibly at the expense of the ultimate accuracy.

Evaluation of anechoic chambers and compact ranges: A number of widely used measurement systems rely on establishing a well-characterized test field. Near-field methods can be used to evaluate and analyze the quality of these test fields.

Technical Strategy

NIST must expand its frequency coverage for antenna calibrations to meet the demands of government and industry. We will upgrade special test services to include the band 75 to 110 GHz and upgrade services to include the band 110 to 170 GHz.

To ensure accuracy, we need to determine the quality of the incident field in the quiet zone of compact or far-field ranges. We will complete sample measurements of a known target to introduce sources of non-ideal fields and verify that they can be detected.

Measurements, especially at millimeter-wave frequencies, often require probe-positioning tolerances that are difficult to maintain. The position of the probe can be accurately tracked with a laser interferometer. This tracking information can be used efficiently to correct measurement results for probe-position errors. We will adapt probe position-correction software (that has been completed for planar near-field scanning) for application to spherical near-field scanning.

One of the larger sources of error in near-field measurements is multiple interactions between the probe and test antenna. Although this effect is included in the general theory, there is currently no practical compensation method. We will complete a study on compensation for multiple-interaction errors, possibly involving a simplified scattering model for electrically small probes.

In planar near-field scanning, measurements are theoretically required over an infinite plane. In practice, the need to truncate leads to pattern-prediction errors that can be especially serious for broad-beam antennas. There are several promising methods for reducing truncation errors. We will complete a study on the reduction of truncation errors using maximum-entropy methods and/or representations by prolate spheroidal functions.

The near-field extrapolation method, developed at NIST, is one of the more accurate ways of characterizing the on-axis gain and polarization properties of antennas. Further improvement is still possible, however and we will extend the extrapolation software to take full advantage of phase information and to analyze the conditioning of the algorithm.

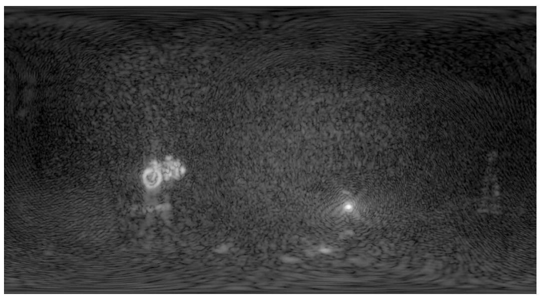


Image of measurement laboratory at 16 GHz, focused on bicycle (left) and also showing illuminating source horn (center), ladder (right), and undesired room sources (lower center).

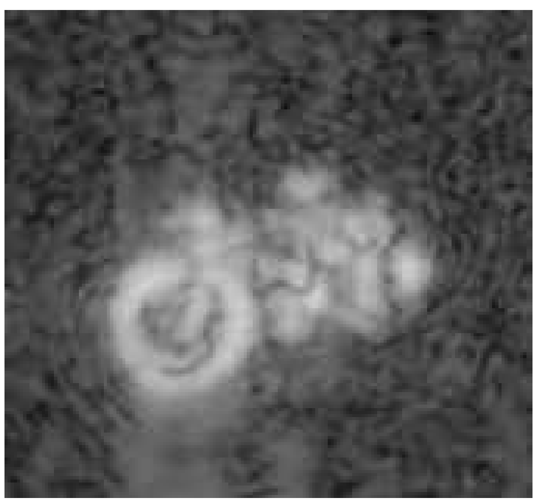
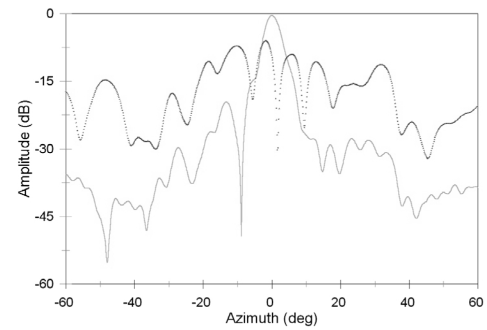


Image with bicycle portion enlarged.

Large, high-performance antennas, especially those deployed in space, require calibration to ensure optimum performance. By 2003, we will develop a method for remotely calibrating large antennas.



Antenna pattern (solid line) and the result of a simulated measurement (dashed line) where random probe position errors on the order of a wavelength have been introduced (normal measurement spacing is ½ wavelength). NIST software permits accurate, efficient recovery of the original pattern. The corrected result is not distinguishable from the original on the scale of this plot.

Accomplishments

■ Quiet-zone measurement data have been acquired. Detailed effects caused by a bicycle a ladder, and some unwanted scattering sources in the range are apparent in the photo on the left. Quiet-zone evaluation software is complete.

■ A 3D probe position-error correction scheme has been developed and published for planar near-field scanning applications. Software is available to the public.

■ We acquired millimeter-wave receiver and signal sources for antenna measurements in the 75 to 110 GHz frequency range.

FY Outputs

External Recognition

■ Mike Francis was elected President of the Antenna Measurement Techniques Association (AMTA) for the year 2000. AMTA is an international organization with a membership of about 400 scientists and engineers.

Short Courses

■ NIST and the Georgia Institute of Technology annually offer an introductory course on antenna measurements. Every other year NIST presents an in-depth technical course restricted to near-field methods that were pioneered at NIST.

Software

■ Currently available for planar, cylindrical, and spherical scanning applications. Probe position-correction software is available for the planar methods. Quiet-zone evaluation and imaging programs should be available soon.

Recent Publications

Wittmann, R. C.; Francis, M. H.; “Test-Chamber Imaging Using Spherical Near-Field Scanning,” Proc. Antenna Meas. Tech. Assoc., Oct. 2001.

Guerrieri, J. R.; Canales, S.; “Alignment procedure for field evaluation measurements on a spherical surface,” Proc. Antenna Meas. Tech. Assoc., pp. 2–7, Oct. 1999

Newell, A. C.; “Error analysis techniques for planar near-field measurements,” IEEE Trans. Antennas Propagat., vol. AP-36, pp. 754–768, May 1998

Wittmann, R. C.; Alpert, B. K.; Francis, M.H.; “Near-field antenna measurements using nonideal measurement locations,” IEEE Trans. Antennas Propagat., vol. AP-46, pp. 716–722, May 1998

Stubenrauch, C. F.; MacReynolds, K.; Norgard, J. D.; Seifert, M.; Cormack, R. H.; “Microwave far-field patterns determined from infrared holograms,” Proc. Antenna Meas. Tech. Assoc., pp. 125–130, Nov. 1997

Wittmann, R. C.; Black, D. N.; “Quiet-zone evaluation using a spherical synthetic aperture radar,” Proc. Antenna Meas. Tech. Assoc., pp. 406–410, Sept. 1996

Antenna and Antenna Systems

Metrology for Antenna, Wireless and Space Systems

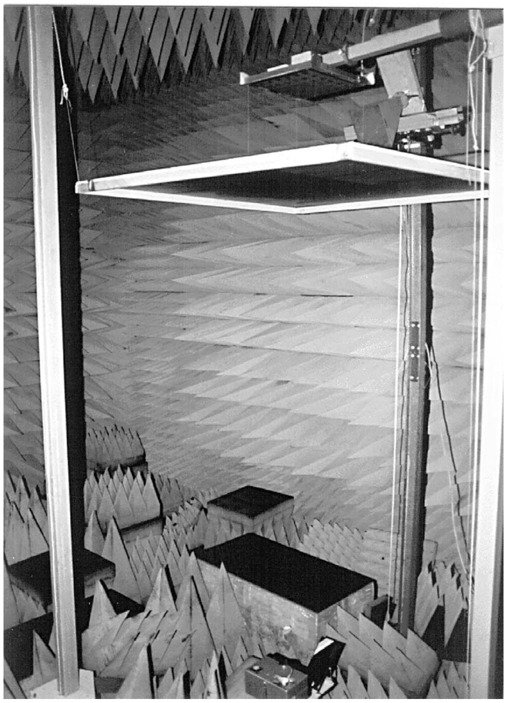
Technical Contact:
Katherine MacReynolds

Staff-Years (FY 2001):
1.0 Professional
1.0 Contractor
1.0 Student

Funding Sources:
NIST (70%)
Other (30%)

Goals

Maintain and develop the standards, methods, and instrumentation for measuring critical performance parameters of earth terminal, satellite, and other critical antenna systems, such as those associated with public safety.



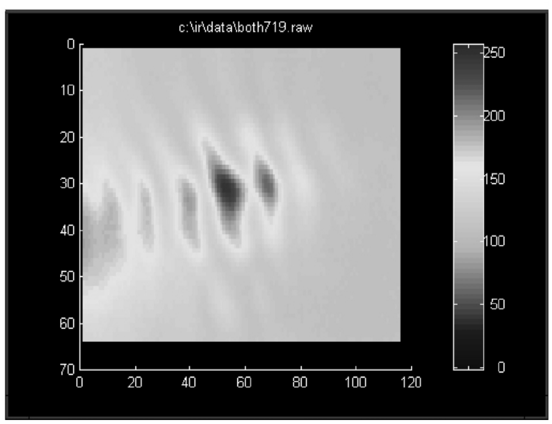
Set-up for thermal imaging holography measurements. The large rectangular object is the resistive screen; the test antenna is in the upper center, the reference horn is in the upper right, and the infrared camera is in the lower center of the picture.

Customer Needs

Satellite communication is a finely tuned technology requiring accurate measurements of antenna gain, noise temperature, G/T (system gain divided by system temperature), and EIRP (effective isotropic radiated power) to ensure optimum performance. Ground stations and test ranges that monitor the performance of commercial and government satellites require traceability to NIST standards. Measured satellite performance is used to determine incentive-clause payments to satellite contractors or charges billed to users or lessees so the results produced at these facilities must be of the highest accuracy. New capabilities are needed to support anticipated technologies, such as anticollision radars. NIST traceability is also required by law-enforcement agencies to ensure the accuracy of their speed measurement devices — down-the-road radar, across-the-road radar, and lidar.

Technical Strategy

NIST currently maintains antenna measurement standards and capabilities for frequencies from 1.5 to 75 GHz. Some automobile anticollision radars will operate at frequencies from 76 to 77 GHz and aircraft anticollision radars will operate at frequencies from 94 to 96 GHz. We will define anticollision radar system testing requirements and evaluate existing metrology for system parameter measurements. We will develop metrology and artifact standards for automobile anticollision radars. Finally, we will develop metrology and artifact standards for aircraft anticollision radars.

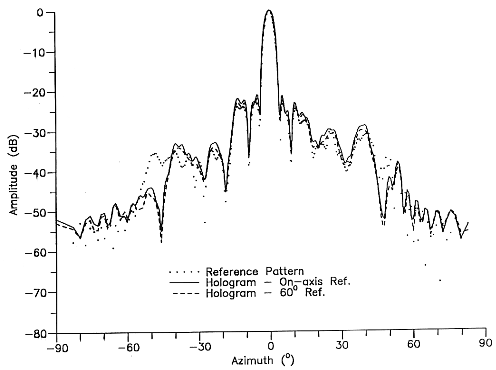


Thermal image of the near-field interference pattern of a microstrip antenna and standard gain horn.

Antenna systems are often tested in indoor laboratory environments. The outdoor environment in which they operate has additional sources of noise and may add to the system noise temperature. To accurately predict the performance of antenna systems in their operating environment, based on their performance in the laboratory, we need to predict the noise due to sources in the operating environment. We will determine the

G/T of an antenna both indoors and outdoors and evaluate the ability to predict outdoor performance from indoor measurement.

Large antenna systems cannot be evaluated in an indoor laboratory environment. A method is needed to evaluate large antenna systems in situ. We will develop thermal holographic methods for diagnostics of large antenna systems.



Comparison of the far field as determined by conventional near-field methods (dotted line) and from thermal imaged holograms (dashed and solid lines).

To ensure the accuracy of speed-measuring devices used by police, the International Association of Chiefs of Police (IACP) must have adequate test equipment. We will develop and provide prototype across-the-road radar speed simulators.

We will provide a working lidar speed-simulator system to be used at an IACP laboratory to be established at the University of North Florida.

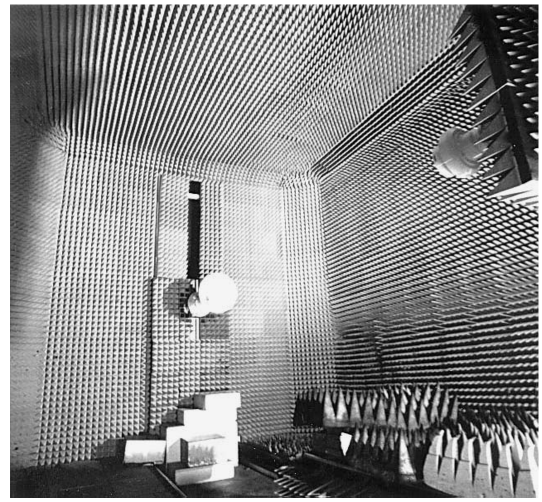
Accomplishments

■ Developed the theory of using infra-red/microwave holography for transmitting antenna measurements in collaboration with the University of Colorado, Colorado Springs (UCCS). As part of this effort, NIST performed tests and analyses on a small 4 x 4-element array and a 1.2 m dish operating at 4 GHz.

■ Established a program to provide support for the IACP testing program for traffic speed-measurement devices including down-the-road radar, across-the-road radar, and lidar.

■ Completed and tested a prototype across-the-road radar speed simulator for use in IACP test laboratories.

■ Evaluated software developed under a Small Business Innovative Research grant that predicts outdoor antenna system performance from indoor measurements.



The NIST probe pattern range with the fixed probe located near the center of the photo and the moving probe located on the moving tower in the upper right of the photo.

FY Outputs

Calibrations

Completed measurements for Space Systems Loral on two dual-port circularly polarized probes for on-axis gain, polarization and patterns. One probe was in the WR-42 band (18-26.5 GHz) and one probe was in the WR-28 band (26.5–30 GHz). These probes will be used as near-field reference probes for measuring communication satellite antennas.

Completed measurements for Space Systems Loral on a dual-port linearly polarized probe in WR-28 at 30 GHz for on-axis gain, polarization and patterns.

Completed measurements for EMS Technologies on two WR-42 (18 – 26.5 GHz) pyramidal horns for on-axis gain at ten frequencies, plus stepped gain.

Completed measurements for TRW Space and Electronics for on-axis gain at eight frequencies on a WR-42 (18–26.5 GHz) horn lens antenna and a WR-28 (265–40 GHz) horn lens antenna.

Completed measurements for Primary Standards Lab on a WR-22 (33–50 GHz) dual-port linearly polarized probe at three frequencies for on-axis gain, polarization, and patterns.

Completed measurements for Space Systems Loral of a dual-port linearly polarized and dual-port circularly polarized probe in WR-187 (3.95–5.85 GHz) for on-axis gain at three frequencies and stepped gain over the band limits.

Completed measurements for Tobyhanna Army Depot on a right circularly polarized probe in WR-430 band (1.7–2.6 GHz) at one frequency for on-axis gain. Performed gain and pattern tests on a PASS subarray for Tobyhana Army Depot.

External Recognition

NIST, along with Ball Aerospace, hosted the 2001 AMTA Symposium in Denver, CO October 21-26, 2001.

Katie MacReynolds received the EEEL Measurement Service Award at the 2001 NRC Panel Meeting for her contributions to, and leadership of, antenna calibration services.

The Antenna Measurement Techniques Association (AMTA) presented the 2001 Distinguished Achievement Award to Allen Newell and David Kerns, both retired NIST employees, for the development of the planar near-field measurement technique.

Software

Planar Near-Field Library

Cylindrical Near-Field Library

Spherical Near-Field Library

Atmospheric Attenuation Library

Recent Publications

MacReynolds, K. and Francis, M.H., “Antenna Gain Measurements: The Three-Antenna Extrapolation Method,” Proceedings of the Antenna Measurement Techniques Association, pp. 370-375, October 1999

Ondrejka, A.R. and Johnk, R.T., “Portable Calibrator for Across-the-Road Radar Systems,” NIST Tech. Note 1398, May 1998

Antenna and Antenna Systems

Metrology for Radar Cross Section Systems

Technical Contact:
Lorant A. Muth

Staff-Years (FY 2001):
2.0 Professional

Funding Sources:
NIST (10%)
Other (90%)

Goals

Assist the DoD and industrial radar cross section (RCS) measurement ranges on creating and implementing a National DoD Quality Assurance Program to ensure high quality RCS calibrations and measurements with stated uncertainties.

The basic cylinder set used to calibrate static RCS measurement systems in the frequency range of 2-18 GHz. The cylinders are made of aluminum, and are manufactured to a tolerance of ±0.0127 cm.

Customer Needs

RCS measurements on complex targets, such as aircraft, ships, missiles, are made at different types of RCS measurement ranges such as, a compact range (indoor static), an outdoor static or an outdoor dynamic facility. Measurements taken at various ranges on the same targets must agree with each other within stated uncertainties to increase confidence in RCS measurements industry wide. Although the sources of uncertainty are well known, a comprehensive determination of the magnitudes of uncertainties in RCS calibrations and measurements has yet to be accomplished at any of the government or industrial ranges. Such studies are needed at every RCS measurement range, if the U.S. RCS industry is to maintain its world leadership well into the new millennium. To satisfy this requirement we need to establish well-formulated procedures that measurement ranges can use to determine their uncertainties.

Technical Strategy

The complex measurement systems and measurement practices at RCS ranges should be documented uniformly throughout industry to enable meaningful comparison of capabilities and important range-to-range differences. The framework of an RCS Range Book, in the context of a DoD RCS Self-Certification Program, has been proposed to ensure community wide compliance. A DoD Demonstration Project is in progress to assess the feasibility and usefulness of such a program.

A thorough technical analysis of the currently followed measurement procedures is essential to reveal areas of strength and weaknesses, and to foster appropriate improvements.

Currently, the following areas of research in RCS measurement technology could be beneficial:

(1) The set of calibration artifacts used by industry ought to be enhanced to assess and improve calibration accuracy.

(2) Defendable range specific uncertainty analyses are needed throughout the RCS industry.

(3) An RCS interlaboratory comparison program and the corresponding technology needs to be developed to enhance confidence in our uncertainty analysis, in the calibration of RCS artifacts, and in the measurements on unknown targets.

Project activities will include the following: Conclude the RCS Range Book reviews for the DoD Demonstration Project in support of the National DoD RCS Range Certification Program. Provide in-depth comments to improve on the procedures used at the RCS measurement ranges. Also, continue the RCS Range Book reviews for industry, and make appropriate recommendations for improvements in RCS calibration and measurement procedures. In addition, work closely with selected RCS ranges to develop detailed procedures for determining RCS calibration and measurement uncertainty. Develop and publish an uncertainty analysis both for monostatic and bistatic RCS measurements at the selected facilities. Develop an expanded set of RCS calibration artifacts to be able to calibrate the system at various signal levels of interest, and conduct an interlaboratory comparison study to assess the results. Fully assess the technical merit and deficiencies of existing calibration and measurement procedures, data-analysis techniques and uncertainty analysis. Publish recommendations for improvements in measurement procedures. Further explore known problems in areas of dynamic sphere calibration, polarimetric calibration, etc. Organize the annual RCS Certification Meeting at NIST, Boulder to provide a forum for the RCS community to discuss procedural and technical issues.

Accomplishments

■ We have reviewed 6 major government RCS measurement ranges during the first 2 years of the project. RCS range personnel gave presentations at NIST, Boulder to the RF Fields group over a period of 3 days to examine range calibration and measurement procedures, instrumentation, documentation and uncertainty analysis procedures. NIST and the personnel of each RCS measurement range performed preliminary uncertainty analyses jointly.

■ We have published a general framework for RCS uncertainty analysis (NISTIR 5019) to stimulate interest in RCS uncertainty analysis at RCS measurement ranges. The work was disseminated to the RCS community at conferences and via direct communication. We have collaborated with personnel of the Naval Air Warfare Center, Aircraft Division at Patuxent River, MD to examine in-depth the uncertainties in dynamic sphere calibrations. As a result, the uncertainties on dynamic ranges are much better understood, but more work is needed for a complete analysis.

■ We have collaborated with personnel of the Naval Command, Control and Ocean Surveillance Center, San Diego, CA to examine in-depth the uncertainties in dynamic RCS measurements made on naval ships. The preliminary uncertainty analysis for this range has been published in a NISTIR (see Publications). Several improvements in the calibration procedures have been recommended and adopted as a result of this study.

■ We have noted several areas for improvement in the dynamic sphere calibration procedures. The calibration data exhibited unexplained large variations and contained frequency components that indicated significant electromagnetic interference from unknown sources. Minor modifications to the instrumentation removed the unwanted frequencies. However, large variations in the amplitude of calibration data remained, which indicate possible pointing problems in the radar tracking system. This research is still ongoing today.

■ The RCS ranges reported less than satisfactory results with existing polarimetric calibration procedures. We developed a more robust calibration procedure wherein full polarimetric data is obtained using a dihedral rotating around the line-of-sight to the radar. The new procedure allows one to improve the signal-to-noise ratio, and check for alignment problems by exploiting the symmetry properties of the dihedral. Diffraction effects can also be minimized by properly shaping the edges and sides of the dihedral. The presence of unwanted spatial harmonics can indicate problems with the radar. A full uncertainty analysis still needs to be developed for this procedure. We are working with several of the RCS ranges to further study this technique.

■ The RCS community has adopted a basic cylinder calibration set (see figure) to test the calibration integrity of monostatic RCS systems. Computed radar cross sections for the cylinder set have been obtained. These four cylinders have been measured at a number of government and industrial measurement ranges. We have consistently found that measurements agreed with the theoretical RCS to less than 0.5 dB. We have shown that such comparisons demonstrate good repeatability; however, we need more robust independent measurement procedures to determine the measurement uncertainties.

■ The DoD Demonstration Project has been established to explore the feasibility and cost of a National DoD RCS Self-Certification Program. Three DoD measurement facilities have undertaken to develop their RCS Range Books, which contain the full documentation of range procedures, as outlined in the ANSII Z-540 standards document. These Range Books have been submitted to an RCS Certification Review Committee for examination and comments. Three Review Committees have been established, and the AFRL, Pax River and NRTF Range Books have been submitted for review.

■ We have organized an annual RCS Certification Meeting for the last 5 years. The purpose of these meetings is to discuss procedural and technical criteria for a national DoD RCS self-certification program, to discuss known technical issues in RCS calibration and measurements, and to discuss progress on the DoD Demonstration Project. On the average, 60 representatives of government and industrial ranges have attended these meetings. In 1999 and 2000 we also had six foreign nationals from the UK and Canada attending. Feedback has been consistently positive.

■ The RCS community has adapted the ANSI Z540 standards document for use by RCS ranges. A Handbook for the Assurance of Radar Cross Section Measurements has been written to assist the RCS community to construct their Range Books.

Recent Publications

L. A. Muth, “Phase dependence in radar cross section measurements,” National Institute of Standards and Technology, NIST TN 1522, 2001.

L. A. Muth, “An assessment of the NIST RCS project,” Proc. Antenna Meas. Tech. Assoc., Philadelphia, PA, p. 375, 16 - 20 Oct. 2000.

L. A. Muth, “Uncertainties in dynamic sphere radar cross section data,” Proc. Antenna Meas. Tech. Assoc., Philadelphia, PA, pp. 382 - 386, 16 - 20 Oct. 2000.

L. A. Muth, "Radar cross section calibration errors and uncertainties," Proc. Antenna Meas. Tech. Assoc., Monterey Bay, CA, pp. 115 - 119, 4 - 8 Oct. 1999.

L. A. Muth, R. Johnk, and D. Novotny, "Errors and uncertainties in Radar Cross Section Measurements," Proc. Nat. Conf. Stand. Lab., Charlotte, NC, pp. 276 - 280, July 1999.

J. P. Skinner, B. M. Kent, R. C. Wittmann, D. L. Mensa, and D. J. Andersh, "Normalization and interpretation of radar images," IEEE Trans. Antennas Propagat., Apr. 1998.

J. Sorgnit, P. Mora, L. A. Muth, and R. C. Wittmann, "Uncertainty analysis procedures for dynamic radar cross section measurements at the Atlantic Test Range," National Institute of Standards and Technology, NISTIR 5073, Feb. 1998.

L. A. Muth, R. C. Wittmann, and B. M. Kent, "Interlaboratory comparisons in radar cross section measurements," Proc. Antenna Meas. Tech. Assoc., Boston, MA, pp. 297 - 302, 17-21 Nov. 1997.

B. M. Kent, and L. A. Muth, "Establishing a common RCS range documentation standard based on ANSI/NCSL Z-540-1994-1 and ISO Guide 25," Proc. Antenna Meas. Tech. Assoc., Boston, MA, pp. 291 - 296, 17 - 21 Nov. 1997.

L. A. Muth, R. C. Wittmann, and B. M. Kent, "Measurement assurance and certification of radar cross section measurements," Proc. Natl. Conf. Stand. Labs., Atlanta, GA, pp. 555 - 566, 27 - 31 July 1997.

L. A. Muth, and R. C. Wittmann, "Calibration of polarimetric radar systems," Proc. IEEE Intl. Symp. Antennas Propagat. Soc., Montreal, Canada, pp. 830 - 833, 14 - 18 July 1997.

M. J. Prickett, R. A. Bloomfield, G. A. Kinzel, R. C. Wittmann, and L. A. Muth, "Uncertainty analysis for NRaD radar cross section easurements," National Institute of Standards andTechnology, NISTIR 5061, April 1997.

L. A. Muth, R. C. Wittmann, and W. Parnell, "Polarimetric calibration of nonreciprocal radar systems," Proc. Antenna Meas. Tech. Assoc., Seattle, WA, pp. 389 - 393, 30 Sept. - 4 Oct. 1996.

L. A. Muth, R. C. Wittmann, B. M. Kent, and J. D. Tuttle, "Radar cross section range characterization," Proc. Antenna Meas. Tech. Assoc., Seattle, WA, pp. 267 - 272, 30 Sept.- 4 Oct. 1996.

L. A. Muth, R. L. Lewis, and R. C. Wittmann, "Polarimetric calibration of reciprocal-antenna radars," Proc. Antenna Meas. Tech. Assoc., Williamsburg, VA, pp. 3 - 8, 13 - 17 Nov. 1995.

L. A. Muth, R. C. Wittmann, R. L. Lewis, and R. J. Jost, "A review of government RCS ranges, "National Institute of Standards and Technology Report Number 813-123-95.

R. L. Lewis, L. A. Muth, and R. C. Wittmann, "Polarimetric calibration of reciprocal-antenna radars: A study of RCS polarization uncertainty due to target depolarization," National Institute of Standards and Technology, NISTIR 5033, March 1995.

R. C. Wittmann, M. H. Francis, L. A. Muth, and R. L. Lewis, "Proposed analysis of RCS measurement uncertainty," Proc. Antenna Meas. Tech. Assoc., Long Beach, CA, pp. 51 - 57, 3 - 7 Oct. 1994.

R. C. Wittmann, M. H. Francis, L. A. Muth, and R. L. Lewis, "Proposed uncertainty analysis for RCS measurements," National Institute of standards and Technology, NISTIR 5019, Jan. 1994.

Electromagnetic Compatibility

Standard Electromagnetic Fields

Technical Contact:
Dennis G. Camell

Staff-Years (FY 2001):
1.5 Professional

Funding Sources:
NIST (20%)
Other (80%)

Goals

Develop methods and techniques for establishing continuous wave electromagnetic (EM) reference fields at frequencies to 100 GHz. Maintain this measurement capability in support of U.S. industry through traceability and international compatibility of antenna standards.

Antenna under test at NIST OATS facility

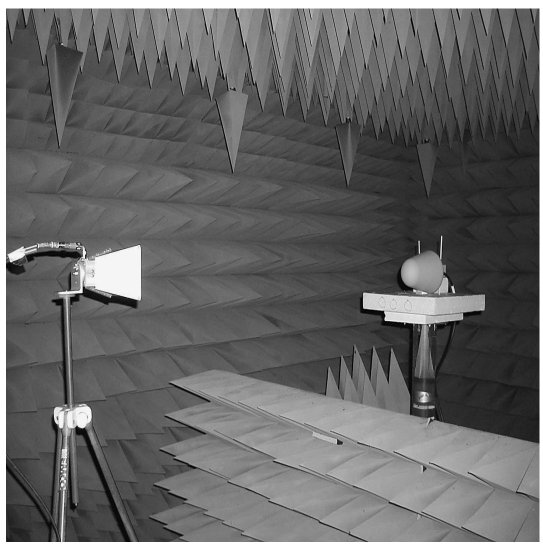
Customer Needs

Well-defined EM reference fields are necessary for antenna calibrations, antenna research and development, evaluation of EM field probes, and EM interference measurements. Standards requirements need references to establish traceability and international compatibility. Industry requires a NIST-traceable EM field measurement capability to reduce barriers to worldwide acceptance of U.S. products and practices, based on the principles of “one product, one technically valid international standard, one conformity assessment” (1998 MSL Strategic Plan).

Technical Strategy

As instrumentation and electronics in general achieve higher clock speeds, measurements are needed at higher frequencies. Techniques based on the lower frequencies can be used to create standard EM fields at these higher frequencies, given facilities and instrumentation. NIST is working to extend current facilities for these measurements. As funds become available, services for E-field sensor and antenna calibrations will be extended to frequencies above 50 GHz.

OATS (open-area test site) facilities are accepted as standard sites for EMC emissions measurements. The NIST facility’s frequency range is being extended to provide needed national-quality calibrations for antennas used in these EMC measurements. However, increased ambient signal levels are causing complications in repeatability and accuracy of measurements at some frequencies. New techniques or facilities are being sought to help industry combat these problems. Robust methods for OATS calibrations in high ambient fields are being researched.

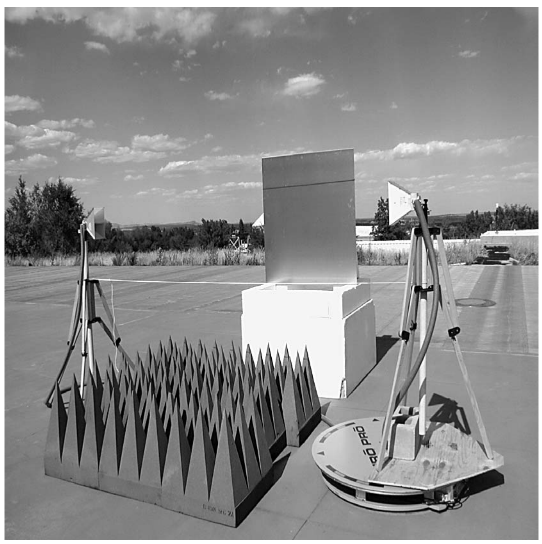


Antenna under test at NIST anechoic chamber facility

Previous comparisons of EMC emissions measurements at various industrial sites showed large variations from site to site. Development of a service to quantify the output from various reference emitters will address variations within U.S. industrial sites. Leadership and guidance from NIST is sought from industry. An RF emissions measurement service for 30 to 1000 MHz is being developed. Initial process includes involvement with independent EMC laboratory intercomparisons. An improvement in repeatability is being observed at some of these EMC labs.

Fully anechoic chamber facilities are accepted as standard sites for free-space measurements. These facilities are even being looked at for EMC product testing. Different methods, different equipment, and even different corporate philosophy cause variation in measurement results and the resulting uncertainties. NIST will focus on reducing these variations and improving congruity within the U.S. industrial community and elsewhere.

Measurement results performed in anechoic chamber, OATS, TEM cells and semi-anechoic facilities often disagree. NIST will provide a hub to systematically investigate these deviations and reduce discrepancies due to the measurement environment.



Scattering object testing at NIST OATS facility

Accomplishments

■ Bi-monthly testing on the NIST OATS showed normal site attenuation (NSA) values within ±2.0 dB of predicted values. This value is the basis for new ANSI EMC standards directives.

■ Comparison between the standard-antenna method and the standard-site method by analysis of uncertainties and measurement repeatability provided test houses with support for current EMC standards.

■ Intercomparison of radiated-field method to equivalent capacitive substitution Method for monopole antennas in cooperation with U.S. manufacturers provided ANSI and CISPR with correlative data for inclusion in draft EMC standards.

■ Cooperative measurements with U.S. national laboratories provided key data for new EMC standards work above 1 GHz. Studies were done on scattering objects and the effects of test environments on antenna measurements.

FY Outputs

External Recognition

Staff engineer Dennis Camell was recognized as a Senior Member of IEEE through the EMC Society for his contributions to RF and microwave metrology.

Calibrations

Tests were performed on probes/antennas for several companies and/or government agencies covering the frequency range of 10 kHz to 45.5 GHz using TEM cell, anechoic chamber and OATS test facilities. Field levels varied from 1 V/m to 250 V/m.

Collaborations

As part of the RF emissions calibration development, collaboration was continued to re-measure a reference RF emitter through USCEL (the U.S. Council of Electromagnetic Laboratories). This round robin involved 20 EMC test laboratories and provides a reference for cohesion and improved accuracy. Some of the laboratories showed improvements over the first round-robin measurement.

Standards Committees

This year’s involvement with ANSI ASC C63 on EMC working group 1-15.6 on ‘Geometry Specific Antenna Factors’ provided technical insights that led to new versions of current standards ANSI C63.5 and CISPR 16.

This year’s contribution with ANSI ASC C63 on EMC working group 1-13.2 on “Measurement Techniques above 1 GHz” provided method improvements that are leading to collaborations with industrial representatives for corrections to current standards ANSI C63.4 and CISPR 22.

Dennis Camell was appointed chair of the newly formed IEEE Working Standards Committee ASC C63 WG 1-15.7, “Determination of Fully Absorber Lined Rooms”. This group will work closely with CISPR to incorporate international harmony into this standard.

Direct attendance and participation with ANSI ASC C63 on EMC committees and interaction with its members guide the theoretical and measurement work to future gains.

Recent Publications

M. Windler, D.G. Camell; Measuring Antennas Above 1 GHz; Zurich EMC Symp., IEEE EMC Society Workshop Record; Feb. 2001.

D.G. Camell, R. Johnk, K. Hall; Exploring Site Quality Above 1 GHz Using Double Ridged Horns; Zurich EMC Symp., IEEE EMC Society Workshop Record; Feb. 2001.

G. Kangiser, D.G. Camell; New Antenna Positioner Improves NIST's Capabilities; Industrial Robot, vol. 27, no. 1, pp.34-38; Jan. 2000.

M. Kanda, et. al.; International Comparison GT/RF 86-1 Electric Field Strengths: 27 MHz to 10 GHz; IEEE Trans. Electromag. Compat., vol. 42, no. 2, pp.190-205; May 2000.

D.G. Camell, K. Cavcey**;** NIST Assessment of Uncertainties for Standard Antenna Measurements; Electromagnetic Compatibility, 1999 IEEE International Symposium on, vol. 1, pp. 386 –391; Aug 1999.

D.G. Camell; Uncertainty Assessment for Standard Antenna Measurements on the Open Area Test Site; NIST TN 1507; Sept. 1998.

K.H. Cavcey, D.G. Camell; Scanning Height for ANSI C63.5 Calibration Methods; Electromagnetic Compatibility, 1998 IEEE International Symposium on, vol. 2, pp. 935-938; Aug. 1998.

S.F. Kwalko, M. Kanda; Numerical and Analytical Monopole Nonplanarity Correction Factors; IEEE Trans. Electromag. Compat., vol. 40, no. 2, pp. 176-179, May 1998.

Electromagnetic Compatibility

Field Transfer Probe Standards

Technical Contact:
Keith D. Masterson

Staff-Years (FY 2001):
1.5 Professional
0.5 Technician

Funding Sources:
NIST (50%)
Other (50%)

Goals

Provide electromagnetic transfer field probes with calibration traceable to NIST. These probes are used by various U.S. industries including private test laboratories and by other governmental agencies. Due to the wide range of applications, probes with different sensitivities and frequency responses are required. Projections for future spectrum usage indicate that probes with millimeter-wave and terahertz responses need to be developed.

Customer Needs

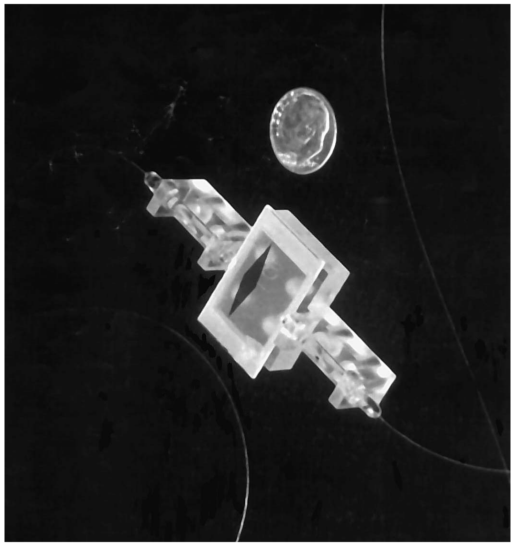
Many U.S. industries, including the electronics, communications, law enforcement, aircraft, and automotive industries, require accurate quantitative knowledge of the intensity of electromagnetic fields in test chambers, on open-area test sites (OATS), or produced by various sources. These fields may be generated as standards that are used to calibrate antennas and test hardware for susceptibility to electromagnetic interference, generated by security detectors or by electromagnetic emissions from various electronic devices. Although most present applications cover frequencies from about 1 MHz to 10 GHz, systems that operate up to nearly 100 GHz, such as automotive collision avoidance radars, are being developed. Future applications with frequencies up to 1 THz are envisioned.

Technical Strategy

NIST maintains parallel efforts both to generate standard reference fields and to develop the probes required for their accurate measurement. The two efforts complement each other and allow cross checking in order to reduce the uncertainties inherent in each effort. NIST also cooperates with the national test laboratories of our international trading partners to perform round-robin testing and intercomparison of various standard antennas and probes. This assures international agreement in their performance and reduces the uncertainties in the areas of metrology that affect international trade. The probes we develop for this purpose also serve as the transfer standards needed by industry and other governmental agencies. Standard probes are designed both so that response can be calculated from first principles, if possible, and to minimize errors that occur from pickup of unwanted signals. For instance, at frequencies below about 5 GHz, the voltage generated across a tuned half-wave dipole can be calculated accurately and monitored as a DC signal across resistive lines. However, this approach is subject to errors introduced by the pickup of ambient electromagnetic fields by the dipole elements. Probes that maintain phase and amplitude information are needed for pulsed-signal applications. If electrically coupled to readout instruments, such probes are subject to errors caused by pickup of common-mode signals in the lead wires. In addition to pioneering several probe designs currently in use, such as electrically coupled RF dipoles and resistively tapered dipoles, NIST has applied photonic technologies to electromagnetic field probes. Building on this expertise, we are pursuing programs discussed below.

With commercial applications at millimeter-wave frequencies already under development, the need for standard millimeter-wave probes increases. Our current probes are limited to the low-frequency end of this regime. As frequency increases, the losses and uncertainties associated with electrically connected probes become significant. Photonic technologies that transmit the signals along an optical fiber hold a clear advantage. We will explore ways to utilize these advantages to fabricate and test probes with frequency responses above 100 GHz. Techniques that offer possibilities to extend the response to still higher frequencies will be favored. Thermo-optic probes already explored by NIST will be reviewed in this context.

Testing of electromagnetic compatibility of large structures, such as aircraft, often requires intense fields that are available only close to high-power, pulsed sources. In these near-field regions, neither the electric nor the magnetic components alone give an accurate measure of the total intensity. NIST has demonstrated a loop antenna with double gaps that simultaneously measures both the electric and magnetic components of the field. When coupled to appropriate instrumentation through optical fibers, it is ideally suited for accurately measuring such fields. NIST is building a field-usable system that will further demonstrate the utility of such measurements and that will serve as a prototype transfer standard for simultaneous measurement of electric and magnetic fields.



Integrated resistively-tapered dipole and electromagnetic modulator

Standard RF Dipole

NIST provides calibration services for antennas used in EMC testing. The frequencies of interest are often in the range from 1 to 400 MHz, where the electromagnetic wavelength is too long for the tests to be done in existing enclosed test chambers. For these calibrations, we use an open-area test site (OATS) that consists of a smooth conducting ground plane about 50 m wide that is situated in an area with a relatively low ambient EM-field background. Unfortunately, the rise in wireless telecommunications, ranging from commercial radio to cellular phones, has led to an increase in the ambient field levels and a resulting increase in measurement uncertainty when using such outdoor sites. OATS are also used by commercially operated test laboratories and by numerous companies for testing their own products. Thus, they are located in many parts of the country and in many different ambient environments. The strength of the test fields are determined by measurements using standard electrically coupled dipole antennas. NIST is pursuing the development of standard RF dipole measurement systems that reduce errors due to the presence of ambient signals and common-mode pickup.

Accomplishments

■ Developed an RF dipole probe with electrically conducting leads that has been adopted as a standard by national test laboratories in the UK and Austria.

■ Developed tuned, half-wave antennas that cover a frequency range from 30 MHz to 1 GHz and have carefully calculated their response.

■ Developed resistively tapered dipole probes with frequency responses up to 40 GHz. Probes based on this design are now being produced commercially by private industry.

■ Developed a thermo-optic probe with millimeter-wave frequency response.

■ Fabricated and tested probes with resistively-tapered dipoles and electro-optic coupling for measuring pulsed electromagnetic fields with bandwidths up to 5 GHz and amplitudes up to 40 kV/m.

■ Fabricated a standard RF dipole with electro-optic coupling that covers a range from 10 MHz to 1.5 GHz.

Recent Publications

S.F. Kwalko and M. Kanda, “The Effective Length and Input Impedance of the NIST Standard Dipole,” IEEE Trans. Electromagn. Compat., EMC-39(4), pp. 404-408, 1997

Keith D. Masterson, David R. Novotny, and Kenneth H. Cavcey, “Standard Antennas Designed with Electro-Optic Modulators and Optical-Fiber Linkage,” in H.E.Brandt (ed.) Intense Microwave Pulses IV, SPIE Proceedings, Vol. 2843, pp.188-196, Bellingham, Washington, 1996

Electromagnetic Compatibility

Time-Domain Free-Field Electromagnetic Metrology

Technical Contact:
Robert T. Johnk

Staff-Years (FY 2001):
2.0 Professional
0.5 Technician

Funding Sources:
NIST (60%)
Other (40%)

Goals

Develop basic metrology and measurement techniques for a wide variety of applications such as antenna and sensor calibrations, evaluation of EMC measurement facilities, shielding performance of commercial aircraft, non-destructive testing of electrical material properties, and precise generation of standard fields.

Customer Needs

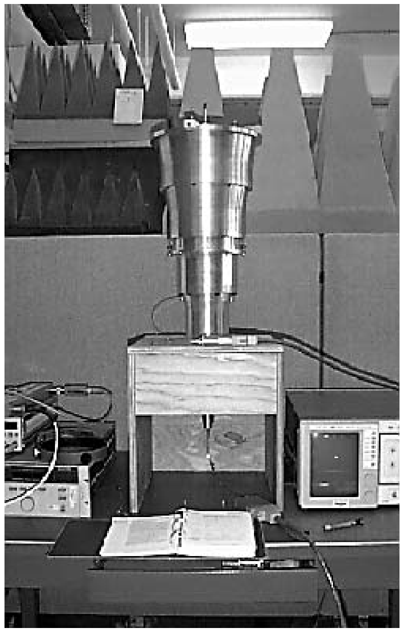
The burgeoning consumer electronics and wireless revolutions are placing a huge burden on the EMC regulatory communities. With the vast proliferation of electronics systems of all types and sizes, the emissions and immunity performance of these systems is of paramount importance, affecting issues such as health, safety, international trade, and U.S. competitiveness. Newer, more accurate, and more efficient metrological innovations need to be developed to keep pace with the increasing performance, speed, and frequency. The time-domain free-field project is well placed to provide cutting-edge innovation and support for this revolution.

Technical Strategy

The primary focus of the Time-domain Free-Field Electromagnetic Metrology Project is to perform ultrawideband electromagnetic measurements using swept frequency or direct pulse systems. Both time-domain and frequency-domain electromagnetic quantities can be extracted from our measurements. These systems exhibit high spatial resolution that can be exploited to perform a wide variety of measurements and extract useful information quickly and accurately. We have developed ultrawideband systems to determine the materials properties of dielectric panels (low-loss and high-loss), to evaluate RF absorbers at both normal and oblique incidence angles, to characterize electromagnetic (EM) facilities (anechoic and semi-anechoic chambers, shielded rooms, reverberation chambers, and OATS facilities), to perform ultrawideband RCS measurements, and to evaluate shielding performance of materials and electromagnetic penetration into commercial aircraft. We have calibrated antenna and sensors up to 14 GHz on our Cone and Ground plane facility. We are currently designing the Co-Conical Field Generation System, a closed-system test cell capable of testing small antennas, sensors, and probes from 10 MHz to 45 GHz. Also, by 2004, we will develop a rapid OATS evaluation measurement system that covers the frequency range from 30 MHz to 6 GHz. EM modeling and analysis is an integral part of our programs. In addition to standard EM theory, many numerical techniques, such as finite-difference time-domain (FDTD), finite-element modeling (FEM), and variational methods, are used to predict system performance and to improve, as well as validate, our measurements. In addition, we are continually engaged in advancing the characterization of and reducing the measurement uncertainties of our systems.

Evaluation of a commercial OATS facility using a portable NIST time-domain measurement system.

Information technology equipment (ITE) is operating at ever-faster speeds. Fundamental bus data rates are currently faster than 1 GHz. In order to perform meaningful measurements of these devices, a frequency range from 30 MHz to 6 GHz must be covered. Current ANSI and IEC standards provide coverage only up to 1 GHz. There are currently no standards for test procedures and setups above 1 GHz! As operational frequencies increase further, the ability to characterize the measurement facilities becomes more critical. The use of NIST-developed free-field time-domain measurement techniques will play a key role in the development of new techniques for facility evaluation and contribute significantly to the development of new international standards above 1 GHz. By 2002, we will develop a low-cost, ultra-wideband measurement system for evaluating the performance of EMC measurement facilities.



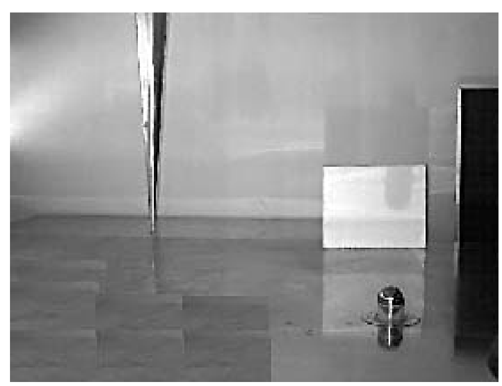
Prototype Co-Conical Field Generation System

Faster information technology equipment and wireless advances have vastly increased the frequency range over which emissions and immunity measurements must be performed. This, in turn, has increased the demand for quality measurement facilities. The quality of the facility and achievable measurement uncertainties are of paramount importance if good measurement fidelity is to be realized, particularly at higher frequencies. In order to assess these effects, NIST engineers are developing an ultra-wideband time-domain measurement system for the evaluation of EMC absorber-lined chambers. The goal of this effort is to provide coverage and site analysis capability in the frequency band from 30 MHz to 6 GHz. This system will use time-domain transmission measurements to compute the performance of absorber-lined chambers (both full and semi-anechoic). Not only will this system provide fast and accurate chamber performance data, it will completely eliminate the need for a separate antenna calibration, thereby cutting costs and improving efficiency.

Accurate and reliable primary standards will play a key role in the development of next-generation measurement techniques. The central component of this program is a large cone and ground-plane system that is currently being constructed at NIST-Boulder.

Absorber-lined chamber testing using NIST-developed time-domain fast-pulse measurement techniques.

By 2003, we will complete this facility, which will be capable of generating standard fields from 30 MHz to 18 GHz and accommodate a wide variety of practical measurements covering calibrations of antennas and sensors, precision scattering measurements, and evaluations of EMC shielding performance. This system will incorporate a moveable cone system that will permit the simulation of some features of OATS environments for the development and verification of next-generation measurement techniques. This facility will also be a valuable tool for NIST participation in domestic and international EMC standards committees such as ANSI and IEC.



D-Dot Sensor calibration using a cone and ground plane standard-field generation system.

Accomplishments

The NIST free-field time-domain project has made significant advances during the past decade. Some of the more significant advances are:

- Active participation in domestic and international standards committees: ANSI, CISPR, IEC.

- Performed feasibility study of using time-domain methods to measure the shielding performance of commercial aircraft. Boeing Company sponsored this effort. An evaluation of a Boeing 737-800 jet was conducted at the Boeing commercial aircraft manufacturing plant located in Renton, Washington in October 2001.

- The NIST time-domain team evaluated an OATS shelter for TUV product services

- Characterization of ultrawideband devices for interference study conducted by ITS. This work was vital in understanding potential interference effects of ultrawideband radio and other devices on existing radio services such as GPS and airport navigation systems. This work was sponsored by OSM and NTIA.

- Robert Johnk convened the ANTCAL working group meeting at the June 2001 Bristol, England meeting of CISPR. ANTCAL will develop site-qualification measurement techniques for antenna and compliance test sites. This work will be incorporated into future revisions of CISPR-16.

- Provided numerical modeling support for ANSI working group 1-15.6, which will revise the ANSI C63.5 standard on antenna calibrations.

- Development of measurement methods for product emissions testing above 1 GHz. This work is being done for ANSI working group 1-13.2 on site qualification above 1 GHz.

- Development of ultrawideband chamber qualification tools based on time-domain site attenuation. This method will eliminate cumbersome quasi-free-space references required for fully-anechoic chamber testing defined in draft CENELEC and IEC standards.

- Applied new time-domain site attenuation technique to EMC compliance chamber at the Hach Company's Chamber in Loveland, Colorado. The new NIST system was successfully used to assess improvements in performance after a chamber retrofitting process.

- Used NIST-developed time-domain measurement technology to evaluate the effects of electromagnetic radiation on commercial aircraft. This effort was sponsored by the FAA.

- Completed a feasibility study of the co-conical field generation system. A full turnkey facility development effort will be initiated in the near future. This system will be used as a standard-field generation system for probe calibrations in the frequency range from 10 MHz to 45 GHz. This effort is currently sponsored by the U.S. Air Force.

- Performed precisions calibration of D-Dot sensors used in commercial aviation safety studies. NASA sponsored this effort.

- Measured small samples of hybrid absorber used in commercial EMC testing chambers using a free-space time-domain reflectometer. This work has had a number of industrial sponsors: Lehman Chambers Inc., Hewlett-Packard, Lindgren RF Enclosures Inc, Advanced Electromagnetics Inc., Schaffner EMC, and IBEX/ Panashield

- Performed in situ measurements of the installed absorber system in a large commercial EMC emissions chamber. This work was sponsored by Lindgren RF Enclosures Inc. "…to offer our support to conduct in situ measurements inside anechoic chambers with time-domain that will later yield digitized data. Lehman Chambers has developed a 3-D Finite-Difference Time-Domain (FDTD) computer modeling program for the design and analysis of anechoic chambers for EMC applications. The work that NIST is intending to do will further validate our techniques and is of extreme interest to us."…Charles Devor, Vice-President, Lehman Chambers, Paul E. Lehman, Inc.

- Assessed the effects of equipment shelters on OATS facilities using time-domain measurement systems. This effort was jointly supported by Storage Technology Inc. and NIST.

- IDEMA Task Force — In collaboration with the International Disk Drive Equipment and Materials Association (IDEMA), we participated in a task force to (a) write a standard method for measuring magnetic properties and (b) design a new interlaboratory comparison to test the written standard. The study will include industry and instrument manufacturers and is targeted at understanding the needs of the industry and how NIST and instrument manufacturers can accommodate them.

Recent Publications

R.T. Johnk & D.R. Novotny, “Characterization of ultrawideband emissions using a time-domain measurement system,” Presented at the 2001 AMTA Symposium, held in Denver, CO, 21-26 October 2001

D. R. Novotny, R. T. Johnk, C. M. Weil, & N. Canales, “Time- and frequency-domain analysis of EMC test facilities,” Presented at the 2001 AMTA Symposium, held in Denver, CO, 21-26 October 2001

C.M. Weil, N.R. Novotny, R.T. Johnk & A. Ondrejka, “A New Broadband RF Field Standard using a Coaxial Transmission Line of Conical Geometry: Progress Report,” Presented at the 23rd Annual Meeting of AMTA, Denver, CO, 21-26 October 2001.

C.M. Weil, N.R. Novotny, B. Riddle & R.T. Johnk: "Modal Cutoff in Conical Waveguides." Submitted as short note to Microwave and Wireless Components Letters, September 2001.

R.T. Johnk, N.R. Novotny, C.M. Weil & N. Canales, “Efficient and Accurate Testing of EMC Compliance Chamber using an Ultrawideband Measurement System,” Presented at the 2001 IEEE EMCS Symposium, Montreal, Canada, 13-17 August 2001.

.C.M. Weil, N.R. Novotny, B. Riddle & R.T. Johnk, “Modal Cut-Off in Coaxial Transmission Lines of Conical and Cylindrical Geometry,” Presented at the 2001 IEEE MTT-S International Microwave Symposium held in Phoenix, AZ, 20-25 May 2001; see IMS 2001 Digest, Vol. 2, pp 1229-1232

R.T. Johnk, D.R. Novotny, & C.M. Weil, “Evaluation of an EMC Compliance Chamber using an Ultrawideband Measurement System,” Presented at the 2000 AMTA Symposium, held in Philadelphia, PA, 16-20 October 2000; see AMTA Proceedings, pp 321-326.

R.T. Johnk, D.R. Novotny, and C.M Weil, “Assessing the effects of an OATS shelter: is ANSI C63.7 enough?” IEEE Int. Symp. Digest on Electromagnetic Compatibility, Washington D.C., Aug. 21-25, 2000, pp. 523-528.

D.R. Novotny, R.T. Johnk, and A.R. Ondrejka, “Low-cost, broadband absorber measurements,” Proc. 22nd AMTA symp., Philadelphia, PA. October 16-20, 1999, pp. 357-362.

R.T. Johnk, D.R. Novotny, and C.M. Weil, “Evaluation of an EMC compliance chamber using an ultrawideband measurement system,” Proc. 22nd AMTA symp., Philadelphia, PA. October 16-20, 2000, pp. 321-326.

R.T. Johnk, D.R. Novotny, A.R. Ondrejka, & C.L. Holloway, “Time-domain site attenuation in low-frequency ferrite-tile chambers,” Proc. 21st AMTA symp., Monterey, CA. October 3-8, 1999, pp. 413-421.

D.R. Novotny, R.T. Johnk, and A.R. Ondrejka, “Improved wideband antenna test cell: the co-conical field generation system,” Proc. 21st AMTA symp., Monterey, CA. October 3-8, 1999, pp. 144-149.

R.T. Johnk, & A.R. Ondrejka, “Low-frequency RF absorber performance with in situ and moveable sample techniques,” IEEE Int. Symp. Digest on Electromagnetic Compatibility, Denver CO, Aug. 24-28, 1998, pp. 8-13.

R.T. Johnk, A.R. Ondrejka, & C.L. Holloway, “ Time-domain free-space evaluations of urethane slabs with finite-difference time-domain computer simulations,” IEEE Int. Symp. Digest on Electromagnetic Compatibility, Denver CO, Aug. 24-28, 1998, pp. 290-295.

A.R. Ondrejka & R.T. Johnk, “Portable calibrator for across-the-road radar systems,” Natl. Inst. Stand. Technol. Technical Note 1398, May. 1998.

R.T. Johnk and A.R. Ondrejka, “Time-domain calibrations of D-dot sensors,” Natl. Inst. Stand. Technol. Technical Note 1392, Feb. 1998.

Electromagnetic Compatibility

Emissions and Immunity Metrology

Technical Contact:
Galen H. Koekpe

Staff-Years (FY 2001):
2.0 Professional
0.5 Technician

Funding Sources:
NIST (60%)
Other (40%)

Goals

Develop and evaluate reliable measurement standards, test methods, and services to support the electromagnetic compatibility (EMC) needs of U.S. industry. These needs are related to electromagnetic emissions (intentional or unintentional signals transmitted by the test device) and immunity (ability to resist external electromagnetic energy) of electronic devices, components and systems. The characterization of support hardware such as cables, connectors, enclosures, and absorbing or shielding material is an integral part of these measurements. Major challenges are to provide reliable and cost-effective test methods over a large frequency range (10 kHz to 40 GHz and, eventually, higher) and for large test volumes. The efficiencies and uncertainties of EMC measurements directly impact both the competitiveness of U.S. manufacturers and the reliability of their products. NIST research quantifies and, in some cases, reduces these measurement uncertainties. NIST expertise, focused on generating and measuring electromagnetic fields, serves as a fundamental resource for industry and government. The main objectives are to ensure harmony and international recognition of U.S. measurements for trade, to provide physically correct test methods, to provide national calibration services, and to serve as an impartial expert body for resolving measurement inconsistencies.

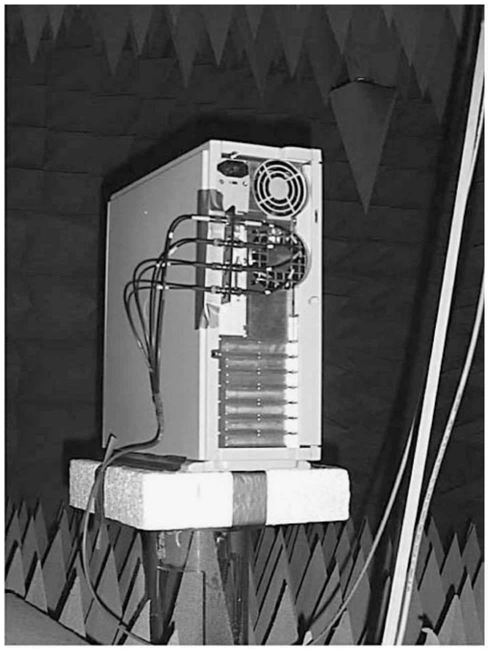
Customer Needs

U.S. industry must evaluate and control electromagnetic interference (EMI) that can impact economics and competitiveness (through trade restrictions and regulations), national security, health, and safety. EMC regulations and requirements cost U.S. industry 1 % to 10 % of the total product costs and often cause delays to market. Industrial clients for NIST research, development, and measurement procedures are manufacturers of electronic equipment (or any system that employs electronic equipment), and EMI/EMC test and product certification laboratories. Successful completion of this research should result in the development of measurement standards and techniques for EMI and EMC that are meaningful, technically practical, and cost-effective. A reduction in measurement uncertainties will lead to lower product development costs and facilitate acceptance of U.S. measurements by international regulating authorities. NIST, working with industry representatives, can help incorporate these techniques into the standards of both U.S. and international standards organizations. Coordinated international standards based on sound metrology are vital for U.S. industry to participate fully in the global markets for electronic instrumentation and goods.

Evaluation of Reverberation Chamber techniques for vehicle EMC testing

Technical Strategy

Our goal is to develop and evaluate reliable and cost-effective standards, test methods, and measurement services related to electromagnetic emission and immunity of electronic devices. This includes investigating new applications for existing test facilities as well as improving methods for evaluating the critical characteristics of support hardware, such as antennas, cables, connectors, enclosures, and absorbing material. We will continue to focus this research in areas of significant potential benefits and wide applications, including reverberation techniques, transverse electromagnetic (TEM) structures, anechoic chambers, time-domain ranges, open-area test site (OATS), and new innovative techniques. Techniques often must meet contradictory goals: they must be accurate and thorough, yet practical and cost-effective; they must have a low uncertainty, yet require minimal time and cost.



Measuring the radiation characteristics of a typical device-under-test in the NIST anechoic chamber.

Facilities for radiated electromagnetic field testing are expensive. Therefore efficient use of these facilities is essential. Hence, using them in multiple applications (emissions, immunity, shielding, etc.), and also developing new applications is necessary. A good example of a facility with a wide range of capabilities is the reverberation chamber. NIST research is on the leading edge in the development of reverberation chamber theory and test techniques. We will develop and propose to standard committee(s) a procedure for measuring the shielding and leakage properties of cables and connectors. We will also develop techniques for characterizing the efficiency and mismatch characteristics of antennas in complex environments. With this information, we can reduce the uncertainty of measurements in a reverberation chamber to the point that it is possible to calibrate some electromagnetic probes in a reverberation chamber. We will develop and evaluate techniques for rapid evaluation and/or calibration of electromagnetic field sensors (probes) in a reverberation chamber.

Another possible application for reverberation chambers is as a uniform-field environment for performing bioelectromagnetic exposure experiments. We will evaluate the loading effect of biological (phantom) material on reverberation chamber performance and evaluate the use of reverberation chambers for exposing phantoms to controlled RF fields.

Most EMI/EMC measurements have large uncertainties due to many sources including insufficient sampling of the radiated fields, poor field uniformity, device-under-test directivity and repeatability, and others. There is often a desire to simplify or shorten a test. While this reduces the cost of the test, it often results in higher uncertainties and, ironically, may require more expensive EMI testing in the product in order to pass emissions or immunity regulations. A careful evaluation of measurement uncertainties can lead to improved measurements. This will help to reduce the costs of product development and manufacturing and increase competitiveness. As the uncertainties are better understood, the credibility of the technique improves and gaining acceptance of U.S. measurements by International EMI/EMC regulating bodies becomes easier.

Due to the complexity of many electrical systems, NIST has invested significant effort into understanding the statistical characteristics of such systems. This work has been a natural extension of our work with reverberation chambers. We have several long-term goals related to this research. We will develop statistical tools for characterizing the coupling of complex fields into large cavities and develop methods to characterize the shielding effectiveness of large cavities. These tools should be applicable to aircraft, vehicles, and buildings. We will develop and validate statistical models for EMI/EMC testing procedures, and device-under-test directivity and failure distributions. These models, in turn, form a basis for the analysis of total measurement uncertainties. We will develop and validate theoretical and statistical models for the intercomparison of EMI / EMC measurement facilities and procedures.

All of our experimental and theoretical results will be available to U.S. and international standards development organizations with a goal of harmonizing EMI/EMC standards worldwide. We plan to continue our participation on the various IEC, CISPR, ANSI, SAE and IEEE standards committees.

Accomplishments

■ Refurbished the NIST Open-Area Test Site (OATS) and anechoic chamber in preparation for research in antenna and emissions measurement methods and uncertainties. These sites support several programs including antenna calibrations and field standards, probe and antenna development, and EMI/EMC metrology. We are also pursuing plans for future world-class electromagnetic research and measurement facilities.

■ Published several new NIST Technical Notes and conference papers covering recent developments in the electromagnetic theory, statistical analysis, modeling, and calibration of reverberation chambers.

■ Participated in joint research with U.S. automobile manufacturers and the U.S. Navy to evaluate reverberation techniques for vehicle EMI/EMC testing. The research team tested the research vehicles in multiple facilities including reverberation chambers and semi-anechoic chambers. NIST performed facility calibration measurements, test procedure consultation, and data analysis for this research.

■ Developed new measurement methods and hardware to characterize ultra-weak emitters. The presence of ambient noise makes the characterization and detection of weak emitters even more difficult. However, spherical near-field scanning theory has been extended to the case where the emissions of the desired source inside the measurement sphere can be separated from the noise due to undesired sources outside the measurement sphere.

■ Characterized electrically small emitters using the intrinsic electric and magnetic dipole moments. These dipole moments are difficult to measure for weak emitters, but a sensitive TEM-cell method has been analyzed and verified experimentally.

■ Participated in joint research with the Naval Research Laboratory for EMI/EMC testing of advanced radar transmit/receive modules

■ Transferred technical information to several EMC standards committees (IEC-CISPR, IEC-TC77, RTCA DO-160, and SAE) actively drafting measurement requirements for reverberation techniques.

■ Developed statistical models describing typical imperfections and improved the statistical models of the fields encountered in reverberation chambers. After an extensive evaluation of the new reverberation chamber facility at NASA Langley Research Center, we were able to contribute significantly to better understanding of reverberation technology. Several sources of errors occur in determining the field parameters in a reverberation chamber. These sources include antenna efficiency and other antenna effects, problems with inadequate mixing due to poor paddle design and direct coupling between the antennas, and errors in the formulas used to predict the fields. After completing several billions of measurements in several different reverberation chambers, we have been able to develop new measurement and analysis techniques, significantly improving measurement accuracy and reducing uncertainties. We are now able to discern effects in chamber performance on the order of less than 1 dB.

Recent Publications

J.M. Ladbury, K. Goldsmith, "Reverberation Chamber Verification Procedures, or, How to Check if Your Chamber Ain't Broke and Suggestions on How to Fix It if It Is," Proc., IEEE EMC Symp., 21-25 August 2000, Washington, DC, pp 17-22

G. Koepke, D. Hill, J. Ladbury, "Directivity of the Test Device in EMC Measurements," Proc., IEEE EMC Symp., 21-25 August 2000, Washington, DC, pp 535-539

Ladbury, J.M., Monte Carlo Simulation of Reverberation Chambers, Proc., 18th Digital Avionics Systems Conference, 24-29 October 1999, St. Louis, MO

Ladbury, J.M.; Koepke, G.H., Reverberation Chamber Relationships: Corrections and Improvements or Three Wrongs Can (Almost) Make a Right, Proc., IEEE EMC Symp., 2-6 August 1999, Seattle WA, pp 1-6

Ladbury, J.M.; Koepke, G.H.; Camell, D.G., Evaluation of the NASA Langley Research Center Mode-Stirred Chamber Facility, NIST Technical Note 1508, January 1999, 282 p

D.A. Hill, Electromagnetic Theory of Reverberation Chambers, NIST Technical Note 1506, December 1998

Koepke, G.H.; Ladbury, J.M., New electric field expressions for EMC testing in a reverberation chamber, Proc., 17th Digital Avionics Systems Conference, 2-6 November 1998, Seattle, WA

D.A. Hill, Spherical-Wave Characterization of Interior and Exterior Sources, NIST IR 5072, December 1997

Butler, C.M.; Hill, D.A.; Novotny, D.R.; Kanda, M., EMI/EMC Metrology Challenges for Industry: A workshop on measurements, standards, calibrations and accreditation, NIST IR 5068, November 1997

Ladbury, J.M.; Koepke, G.H.; Camell, D.G., Improvements in the CW Evaluation of Mode-Stirred Chambers, Proc., IEEE EMC Symp., 18-22 August 1997, Austin TX, pp. 33-37.

Hill, D.A.; Kanda, M., Measurement Uncertainty of Radiated Emissions, NIST Technical Note 1389, March 1997.

Ladbury, J.M.; Johnk, R.T.; Ondrejka, A.R., Rapid evaluation of mode-stirred chambers using impulsive waveforms, NIST Technical Note 1381, June 1996, 40 p.

D.A. Hill, D.G. Camell, K.H. Cavcey, and G.H. Koepke, Radiated emissions and immunity of microstrip transmission lines; theory and reverberation chamber measurements, IEEE Transactions on Electromagnetic Compatibility, vol. 38, pp. 165-172, 1996

D.A. Hill, A reflection coefficient derivation for the Q of a reverberation chamber, IEEE Transactions on Electromagnetic Compatibility , vol. 38, pp. 591-592, 1996

Camell, D.G.; Koepke, G.H.; Smith, R.B.; Rakoski, B., A Standard Source Method for Reducint Antenna Factor Errors in Shielded Room Measurements, NIST Technical Note 1382, March 1996

D.A. Hill, Spatial Correlation Function for Fields in a Reverberation Chamber, IEEE Transactions on EMC, Vol. 37, No. 1, February, 1995

D.A. Hill, D.G. Camell, K.H. Cavcey, and G.H. Koepke, Radiated Emissions and Immunity of Microstrip Transmission Lines: Theory and Measurements, NIST Technical Note 1377, July 1995

Koepke,G.H.; Randa, J., Screen-room Measurements on the NIST Spherical-Dipole Standard Radiator, NIST JRES, Vol. 99, No. 6, pp. 737-749, Nov/Dec 1994

M.L. Crawford, M.T. Ma, J.M. Ladbury, and B.F. Riddle, Measurement and evaluation of a TEM/reverberating chamber, NIST Technical Note 1342, July 1990