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Technology Administration

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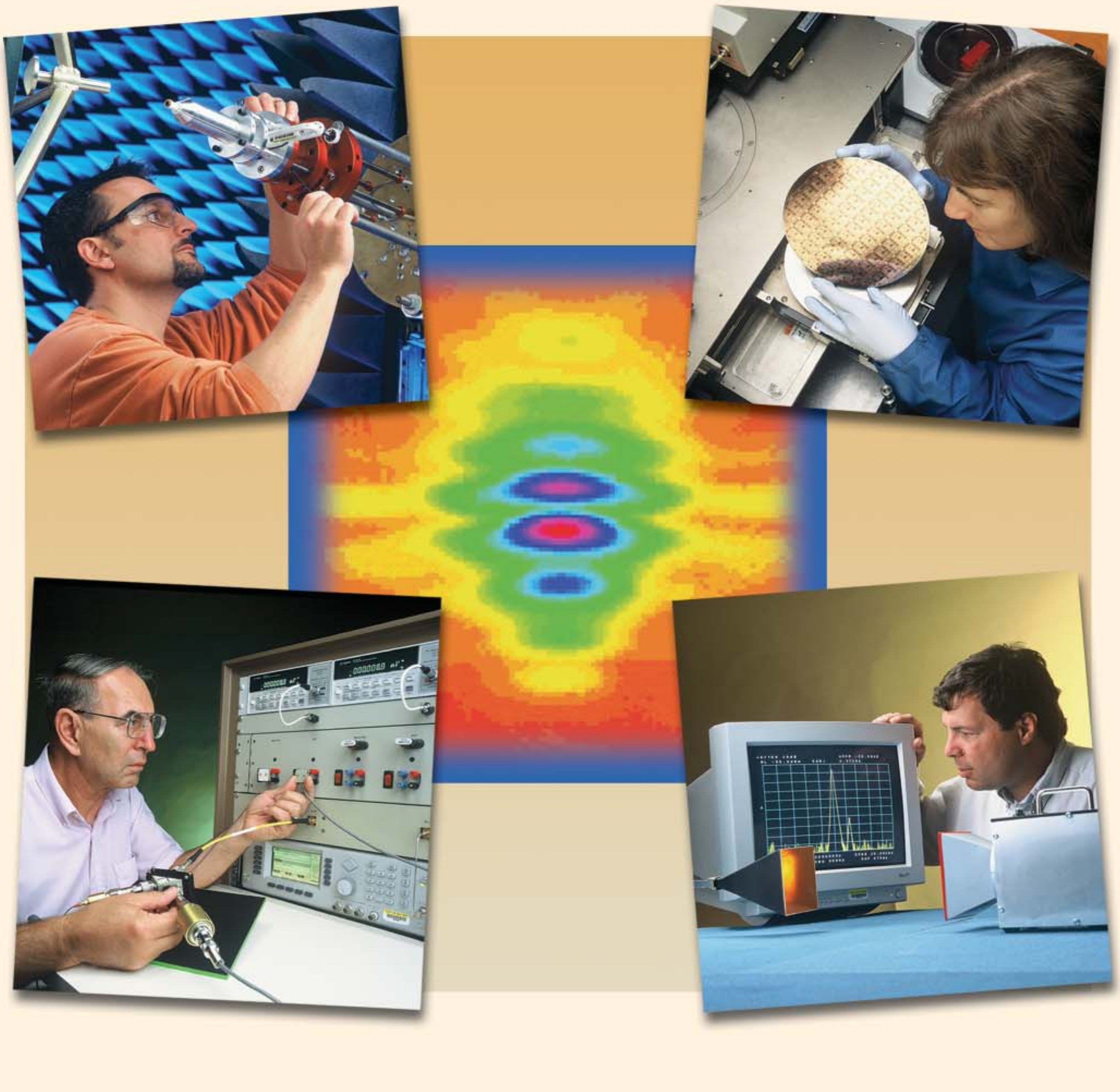
January 2003

Electronics and Electrical Engineering Laboratory

Radio-Frequency Technology Division

Programs, Activities, and Accomplishments



The Electronics and Electrical Engineering Laboratory (EEEL)

One of NIST's seven measurement and standards laboratories, EEEL conducts research, provides measurement services, and helps set standards in support of the fundamental electronic technologies of semiconductors, magnetics, and superconductors; information and communications technologies, such as fiber optics, photonics, microwaves, electronic displays, electronics manufacturing supply chain collaboration; forensics and security measurement instrumentation; fundamental and practical physical standards and measurement services for electrical quantities; maintaining the quality and integrity of electrical power systems; and the development of nanoscale and microelectromechanical devices. EEEL provides support to law enforcement, corrections, and criminal justice agencies, including homeland security.

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 Microelectronic Programs
- Office of Law Enforcement Standards

This publication 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, http://www.eeel.nist.gov. These publications are updated biennially.

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

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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 describes the research programs, activities, and recent accomplishments of the Radio-Frequency Technology Division organized by project. The Division is organized into two Groups.

The **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 for providing measurement services for power, noise, impedance, material properties, and other basic quantities.

The **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 for providing measurement services for essential parameters.

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

We hope that this collection of information will help you 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.

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About the Radio-Frequency Technology Division

Mission

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

Division 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. 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 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.

Antennas and Antenna Systems

The Antennas 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.

RADIO-FREQUENCY TECHNOLOGY DIVISION

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3131	FRIDAY, Dennis S., Chief
3132	LYONS, Ruth Marie, Secretary
3037	MARKS, Roger

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

RADIO-FREQUENCY ELECTRONICS GROUP (813.01)

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5755 RIVERA, Susie A., Secretary

Power Standards
4133 CROWLEY, Thomas (PL)
3609 FREE, George
4394 McLEAN, James
3264 ONDREJKA, Connie L.
3939 SHERWOOD, Glenn V.
5778 CLAGUE, Fred (GR)

Network Analysis
3634 GINLEY, Ronald A. (PL)
5362 JUROSHEK, John R.
5533 GROSVENOR, John H.
3210 LeGOLVAN, Denis X.
5249 MONKE, Ann F.
5231 PACKER, Marilyn

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3150 RANDA, James (PL)
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5737 BILLINGER, Robert L.
3280 TERRELL, Leon (Andy)
5490 WALKER, David K.

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

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3015 MORGAN, Juanita M.
3997 KABOS, Pavel

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5491 KAISER, Raian K.
5752 RIDDLE, Bill F.
4224 CAGE, Brant (PD)

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RADIO-FREQUENCY FIELDS GROUP (813.02)

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3321 HAAKINSON, Edit H., Secretary

Antenna Systems Metrology
5873 FRANCIS, Michael H. (PL)
3603 MUTH, Lorant A.
3326 WITTMANN, Ronald C.

Near Field Antenna Techniques
3471 MacREYNOLDS, Katherine (PL)
3302 BASSETT, David N.
3863 GUERRIERI, Jeffrey J.
3694 TAMURA, Douglas T.
3927 STUBENRAUCH, Carl F. (GR)

EM Fields and Transfer Probes
3756 MASTERSON, Keith D. (PL)
3214 CAMELL, Dennis G.
5702 CANALES, Seturnino
5958 GROSVENOR, Chriss A.
4312 HAMILTON, John (PREP)
3737 JOHNK, Robert T.
3168 NOVOTNY, David
3737 VENEMAN, Jason (PREP)
4140 ONDREJKA, Andy (GR)
5305 WEIL, Claude (GR)

EMC Measurements & Facilities
5766 KOEPKE, Galen H. (PL)
3141 FONTAINE, Jyoti (PREP)
6184 HOLLOWAY, Chris
5372 LADBURY, John
4420 LAMMERS, Todd (PREP)
3142 BHOBE, Alpesh (FGR)
3472 HILL, David A. (GR)

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

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

Fundamental Microwave Quantities

Power

Technical Contacts:
Tom Crowley
Ron Ginley

Staff-Years (FY2002):
3.0 professionals
5.0 technicians

Goals

Develop, maintain, and improve standards, systems, and methods for measuring power over the frequency range from 100 kHz to 110 GHz. Provide measurement services and support to U.S. industrial and government laboratories.

Jim McLean prepares to lower a waveguide microwave calorimeter into a waterbath. © Geoffrey Wheeler

Customer Needs

A system's output power level is frequently the critical factor in the design, and ultimately the performance, of 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 can lead to overdesign of products, and hence, increased costs. Economic gains are realized through improvements in accuracy. 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 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 110 GHz.

Technical Strategy

NIST's work in RF power metrology has three thrusts. The first is basic research into power standards based on quantum mechanical principles, the second is the addition of new capabilities at frequencies above 50 GHz, and the third is maintenance and improvement of existing standards.

Quantum Based RF Power Measurement

RF power measurements have traditionally been traceable to DC power measurements. NIST's primary and transfer standards all rely on this technique in which temperature changes due to RF and DC power are measured. The largest uncertainty in the measurements is due to differences in the location of the RF and DC power dissipation.

An alternative approach is to measure the field strength of microwaves through their effect on the quantum state of laser-cooled atoms. This is based directly on quantum mechanical principles. In this measurement, a group of atoms exists in a single quantum state. They are then exposed to microwaves at a frequency that corresponds to the energy difference between this state and a second quantum state. The atoms will oscillate between the two states at a frequency that is proportional to the field strength. The process is known as a Rabi oscillation. By measuring the number of atoms in each state, the field strength can be determined. Initial efforts in this area are being done in collaboration with the NIST Time and Frequency Division. The first experiment will use an existing small cesium fountain to measure the Rabi oscillation due to the 9.2 GHz microwave source and compare the field strength estimate with that obtained by standard techniques. This experiment is limited because the microwave cavity was not designed for this particular experiment. Our most likely second step in the process is to set up a new experiment with a similar atom trap, but a different microwave cavity that will allow a more accurate comparison with standard measurements. The new experiment would use the same lasers in the initial experiment.

Addition of High Frequency Capability and Services

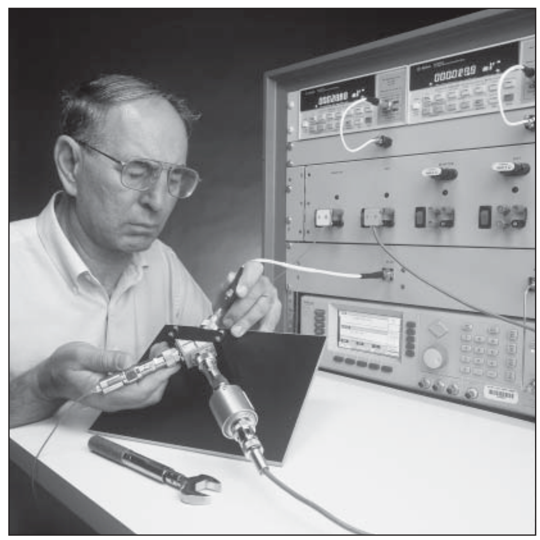
There is an increasing demand for power calibration services at frequencies above 50 GHz. This demand is being driven to a large extent by the high-bit-rate digital systems that are currently being developed for optical-fiber communications systems and the Internet. The next generation of these devices will operate at up to 40 Gbits/second. Proper characterization of these systems, that use pulsed signals instead of sinusoidal signals, requires measurements from DC to 110 GHz. Primary responsibility for characterizing these devices is in the Optoelectronics Division. In order to perform that task, they have an immediate need for RF power measurements using diode detectors with 1.85 mm coaxial connectors (up to 65 GHz). It is expected that a succeeding generation will have 1 mm connectors and require characterization to 110 GHz.

An important requirement is that measurements be performed at many frequencies. Our existing coaxial power measurements covering frequencies up to 50 GHz are well suited to this type of measurement. However, the waveguide systems that are presently used to measure power above 50 GHz require manual tuning to change frequency and are thus ill suited for this task. In addition, our WR-10 6-port system is limited by its source to coverage of only 92 to 96 GHz. In order to circumvent these difficulties, a backward-wave oscillator has been purchased that can be electronically tuned to any frequency within either the WR-15 (50-75 GHz) or WR-10 (75-110 GHz) waveguide bands. In addition, we are developing a direct comparison system for measuring microwave power in both bands. In combination with vector network analyzer measurements of scattering parameters, we will be able to perform all the functions of the present 6-port systems over a much larger frequency range.

Our experience has taught us that coaxial systems are more useful to most customers than waveguide systems. Thus, in addition to developing WR-10 and WR-15 direct comparison system, we will also develop a direct comparison system for power detectors with 1.85 mm coaxial connectors (up to 65 GHz). For the near future, this will be traceable to the WR-15 and 2.4 mm calorimeter primary standards. Although the first user of this new measurement capability will be the Optoelectronics Division at NIST, we expect other millimeter wave customers to also take advantage of the new capability.

Maintenance and Improvement of Existing Standards

Industrial demand for RF power measurements is highest for coaxial connectors. NIST presently has two primary standards for coaxial power, one with Type N connectors (50 MHz to 18 GHz) and one in 2.4 mm connectors (50 MHz to 50 GHz). The uncertainties in the 2.4 mm connector transfer standards are significantly higher than those for the Type N transfer standards, even at common frequencies. At least some of this higher uncertainty is attributable to the thermal properties of the transfer standards. During FY2002, the determination of the transfer standard efficiency has been improved by correcting for these thermal properties. Further performance improvements require modifying the thin-film resistor semiconductor chip that is the heart of the transfer standard. A second cause for concern is that we will be unable to obtain any more transfer standards from the supplier. Thus, at some point in the future when the existing standards fail, replacements will be needed. A research program to develop a new chip is planned.



John Juroshek measuring a coaxial power detector.
© Geoffrey Wheeler

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.

Deliverables

- Perform initial experiment that measures microwave signal strength using Rabi oscillation and traditional principles. (FY2003)
- Design experiment to be used in second stage of Rabi oscillation experiments. (FY2004)
- Complete WR-10 and WR-15 direct comparison system. (FY2003)
- Characterize high speed diodes for Optoelectronics Division up to 65 GHz. (FY2003)
- Complete a direct comparison system for power detectors with 1.85 mm coaxial connectors. (FY2003)
- Improve direct comparison system in 1.85 mm coaxial line. (FY2004)
- Complete conceptual design of the 2.4 mm coaxial power transfer standard. (FY2003)
- Develop prototype 2.4 mm power transfer standard. (FY2004)
- Deliver database system to military primary standards labs. (FY2003)
- Implement database system for use with NIST scattering parameters measurements. (FY2003)

FY2002 Accomplishments

■ The 2.4 mm coaxial power measurement service is widely used, and the integrity and accuracy of this service have been improved through better understanding of its uncertainties. These important changes and enhancements were the result of critical evaluations of preexisting designs and measurement procedures. The method for measuring the effective efficiency of 2.4 mm thin-film bolometers has been changed in two ways. First, a slow thermal response of the sensors when in the calorimeter (10-30 minutes) is now corrected by using changes in substituted power measurements performed on a shorter time scale (30 seconds). This makes the calorimeter measurements more consistent with the direct comparison measurements that are used to transfer power measurements to customers. Second, a new open and a new short whose thermal properties better match those of a bolometer have been used to re-evaluate the calorimeter correction factor. Each of the two effects can change the effective efficiency by about 0.015 at 49 GHz. However, they counteract each, other resulting in a net change of less than 0.004 for most sensors. This is the result of about 1.5 years of study that was initiated after problems surfaced in the fall of 2000. The uncertainty has been increased since then, but this is because we have uncovered issues that were not fully understood when the mounts were originally evaluated. A better understanding of their operation is also important for building the next generation of detectors since they are likely to use similar detector components.

■ A direct-comparison power measurement system was delivered to the Air Force Primary Standards Laboratory (AFPSL) in Newark, Ohio, in May, and an identical system was delivered to the Army Primary Standards Laboratory (APSL) in Huntsville, Alabama, in July. The AFPSL and the APSL personnel were trained on the use of the system at the time of each delivery. The system can measure power standards based upon either Type-N, 7 mm, 3.5 mm, or 2.4 mm coaxial connectors and lines. Devices that can be measured on the system include thermistor detectors, thermocouple detectors, diode detectors and the 2.4 mm thin-film detectors. The system will be used initially to augment the existing microwave power calibration systems at AFPSL and APSL, and in the long run, replace their older systems. This NIST-developed system gives both primary standards labs, and therefore DOD, a more efficient, more versatile and more accurate, microwave-power measurement capability.

■ The NIST direct comparison power measurement system has been upgraded with better instrumentation and software. The enhanced system hardware now allows measurement runs from 50 MHz to 50 GHz in a single measurement pass. The system software has also been upgraded significantly so that all files are now stored in a common ASCII format, system power levels are stored and can be retrieved for different system configurations, and different types of sensors can be used as the monitor power sensor (not just thermistor-type sensors). This next-generation direct comparison system now provides much more efficient calibration services to our customers.

■ The capabilities of the Direct Comparison systems and other power measurement systems were extended for use with the newer 2.92 mm coaxial geometry, via adapters. The uncertainties for 2.92 mm measurements on the direct comparison system were evaluated. Furthermore, the 2.92 mm capability was extended to include the use of calibrated 2.4 mm to 2.92 mm adapters and power sensors and meters. The 2.92 mm measurement capability was verified by comparisons to transformed 2.4 mm and WR28 measurements.

■ The documentation has been completed for the NIST microwave power measurement system used for calibration of coaxial power standards up to a frequency of 50 GHz. The documentation includes a full system description, theory, and uncertainty analysis, and has been submitted for internal review. It represents the conclusion of a multi-year effort to compile all necessary information on these systems.

■ Preliminary work has been completed to explore a fundamentally new approach to microwave power measurement. The rate at which an atom, in the presence of an RF electromagnetic wave, oscillates between two quantum states under certain experimental conditions is proportional to the field strength. This oscillation, called a Rabi oscillation, is a property that is implicit in the design of atomic clocks and all related experiments. An initial proof-of-principle experiment designed to make an absolute measurement of RF power based on this principle is being planned in collaboration with the Time and Frequency Division. It will make use of the apparatus from a cesium fountain experiment already available at NIST, with necessary modifications. The experiment will provide an alternative approach to results already reported by NRC-Canada, and will commence as soon as possible with preliminary support from EEEL. If successful, this technique could replace the present basis of RF signal-level measurements based on RF-to-DC thermal equivalence into one based on more fundamental quantum principles and greatly change the accuracy and portability of such measurements. Ultimately, this work may impact the SI definition of RF Power units.

■ We procured new Type N mounts since only one good transfer standard remained, and the continuity of these measurements was critical. We obtained 12 new 2.4 mm bolometer transfer standards from our commercial supplier, and completed evaluation of all of them in the calorimeter. Nine of the new, and one of the old, transfer standards were transferred to the military calibration labs. Three of the new ones are kept at NIST. The fabrication of six new Type-N bolometer transfer standards yielded five good mounts. Parts to make an additional four are available and they will be assembled when workloads permit.

■ We made two improvements to the high-power measurement system, which allowed us to reopen the measurement service for high-power wattmeters. First, we solved the problem of overheating by installing directional fans and vents at critical points in the shielded room. Second we developed new algorithms to set the power levels and read the data from the system. Using the new algorithm, the error between the power setting and the nominal power requested appears to be less than 5 watts in all cases. Thus the random error in the reported values has also been reduced. The new measurement algorithm has also reduced the time required for a measurement by approximately 15 %.

FY2002 Outputs

Calibrations

Calibrated 227 devices for customers that generated an income of $460,105.

Recent Publications

T.P. Crowley, F.R. Clague, *"A 2.4mm Coaxial Power Standard at NIST,"* 2001 British Electromagnetic Conference, Nov 06-08, 2001, Harrogate, United Kingdom.

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 (FY2002):
0.75 professionals
2.0 technicians

Goals

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

NIST S Parameter Measurement Comparison Program Kits.

Customer Needs

Vector network analyzers (VNAs) are the single most important instruments 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 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, verify and improve 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 calibration and 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 is developing improved and more cost-effective services in scattering parameters and power to support those needs.

New connectors are being developed for instrumentation and cables, as the electronics applications move to 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 6-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 designs of the NIST 6-port systems and will provide upgrades to the military laboratories as needed. The DoD's expanded use of commercial VNAs is also being supported.

The Department of Defense relies on 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. 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 is 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 accuracies 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 investigate the relationship between the calibration standards and the error sources involved in reflection coefficient calibrations on VNAs. With an understanding of this relationship, we will establish a method to correct less accurate reflection coefficient calibration techniques such as OSL (open-short-load) to near the accuracy of airline based calibrations. An offshoot of this work will be an evaluation of the various different models used in different calibration techniques and the relative accuracies of the different techniques. We will then begin to extend this approach to full two-port s-parameter calibration techniques such as OSLT (open-short-load-through). We expect that this work will continue into the following year. Comparisons of two-port calibration techniques will include those techniques based on various different models. Additionally, 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 measurement 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 metrology 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 and 2.4 mm within the next year.

Deliverables

- Establish 1.85 mm s-parameter calibration service. (FY2003)
- Deliver the upgraded dual 6-port system (18 to 40 GHz) to the Navy Primary Standards Laboratory. (FY2003)
- Provide software and techniques to support the DoD's use of commercial VNAs. (FY2003)
- Establish web-based check standard database. Implement for s-parameter and power measurements and deliver to the Army Primary Standards Laboratory. (FY2003)
- Establish new Type-N and 3.5 mm MCP Kits. (FY2003)
- Develop online access to MCP data. (FY2003)
- Evaluate the models used in OSL calibrations. (FY2003)
- Develop software to correct/enhance OSL calibrations.
- Compare the accuracies of different reflection coefficient calibration techniques. (FY2003)
- Perform initial investigation into OSLT and other two-port calibration techniques (FY2004)

FY2002 Accomplishments

- Delivered the upgraded System 1 Dual 6-port System (100 kHz to 1 GHz) to the Army Primary Standards Laboratory.
- Extended WR-15 and WR-10 s-parameter calibration services to full band coverage.
- Performed many special reflection coefficient measurements of digital oscilloscope modules and photodetectors to support work being done in the Optoelectronics Division.
- Evaluated the Air Force Primary Laboratory's use of VNAs and provided a plan that would allow them to accomplish their program objectives.

FY2002 Outputs

Calibrations

Calibrated 89 devices for customers that generated an income of $96,032.

Fundamental Microwave Quantities

Noise

Technical Contact:
Jim Randa

Staff-Years (FY2002):
2.5 professionals
2.0 technicians

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 will grow larger. Important trends that must be addressed include the utilization of higher frequencies, the growing importance of low-noise amplifiers and transistors, 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.

Noise power is also the quantity that is measured in passive remote sensing, such as that used to measure properties of the earth's surface from satellites or airplanes. The growing importance of such measurements for climate monitoring, weather forecasting, agriculture, and other applications has highlighted the need for better calibration techniques, smaller uncertainties, and compatibility between results from different instruments.

Technical Strategy

We are working in three general areas: traditional noise-temperature measurements, characterization of amplifier and transistor noise properties, and calibration of remote-sensing radiometers. In traditional noise-temperature measurements, we offer measurement services at 30 MHz and 60 MHz and from 1 GHz to 40 GHz for coaxial sources and from 8.2 GHz to 65 GHz for waveguide sources. Recent improvements have reduced the time required for these measurements, thereby reducing the costs to our customers.

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

A new thrust of the project is in improving methods for calibration and validation of microwave radiometers used for remote sensing from satellite or airplane. This will include compilation of standard terminology used in that field, as well as improvements in the assessment of uncertainties, and it may extend to development of a calibration capability for such radiometers.

Deliverables

- Perform measurements for international noise comparison at and below 1 GHz. (FY2003)
- Develop and test a strategy for measuring amplifier noise parameters, as well as a consistency check for such measurements. (FY2003)
- Design a variable termination unit for use in noise-parameter measurements. (FY2003)
- Complete linearity study of detectors used in remote-sensing radiometers; develop procedure for including results in uncertainty analysis. (FY2003)

- Use variable ambient-temperature source to verify uncertainties for noise-temperature measurements near ambient temperature. (FY2003)
- Build and test variable-termination unit for use in noise-parameter measurements. (FY2004)
- Develop, expand, and maintain list and web page for standard terminology for microwave remote sensing; complete relevant chapters of Committee for Earth Observing Satellites (CEOS) document. (FY2004)
- Develop general form for uncertainty analysis for microwave total-power radiometers used for remote sensing. (FY2004)
- Assist other laboratories in the planning and evaluation of calibration and validation of new remote-sensing microwave radiometers. (FY2004)

FY2002 Accomplishments

- Completed the testing of the 1 GHz to 4 GHz units of the new coaxial radiometer (NFRad) and of the 30 and 60 MHz radiometer, and reopened the noise-temperature measurement services for those frequencies. This marked the completion of a multi-year effort to restore and extend noise-temperature measurement services for coaxial and waveguide noise sources. Noise temperatures of noise sources can now be measured at virtually any frequency from 1 GHz to 65 GHz, as well as at the two low-frequency points at 30 MHz and 60 MHz.

- Wrote and tested a Monte Carlo program to evaluate the uncertainties in measurements of amplifier noise parameters. The program was used to study the dependence of the uncertainties in the output noise parameters on the uncertainties in the underlying measured quantities. Both correlated and uncorrelated underlying uncertainties were considered. The program was also used to evaluate possible alternative measurement strategies. It was documented in a conference paper presented at the 2002 International Microwave Symposium and in a journal paper in the NIST Journal of Research.

- Assisted in evaluating the calibration of NASA's Conical Scan Microwave Radiometer (CoSMIR), resulting in an improved uncertainty analysis, as well as a design improvement to reduce the uncertainties. The work was reported in two joint papers presented at the Second International Microwave Calibration Workshop.

FY2002 Outputs

Calibrations

Calibrated 9 devices for customers that generated an income of $64,234.

Recent Publications

M.H. Weatherspoon, L.P. Dunleavy, A. Boudiaf, J.P. Randa, *"Vector Corrected Noise Temperature Measurements,"* Intl. Microwave Symp., June 02-07, 2002, Seattle, Washington, pp. 2253-2256.

J.P. Randa, *"Simulations of Noise-Parameter Uncertainties,"* Intl. Microwave Symp., June 02-07, 2002, Seattle, Washington, pp. 1845-1848.

C.A. Grosvenor, R.L. Billinger, *"The 30/60 MHz Tuned Radiometer-The NIST System for Noise Temperature Measurements,"* NIST Tech. Note 1525, May 2002.

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, Vol. 49, No. 10, 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.

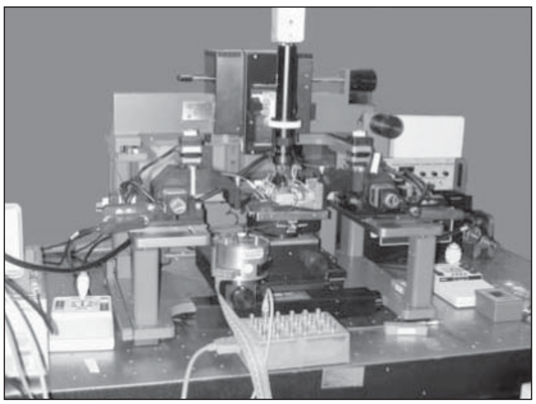
High-Speed Microelectronics

Technical Contact:
Dylan Williams

Staff-Years (FY2002):
2 professionals
1.0 technician
0.5 guest researcher

Goals

Support the microwave, telecommunications, magnetic recording, and computing industries through research and development of high-frequency on-wafer electrical metrology. The goal of the project is to develop electrical metrology for microwave signal and signal source characterization in 30 GHz to 100 GHz wireless systems, high-speed microprocessors, and high-speed nanocircuits and interconnects, and electronics for high-speed optical links, by establishing accurate on-wafer waveform and frequency-domain micron and nanoscale metrology at frequencies up to 110 GHz and higher.



Prototype universal test-bed for nanoscale electrical probing.

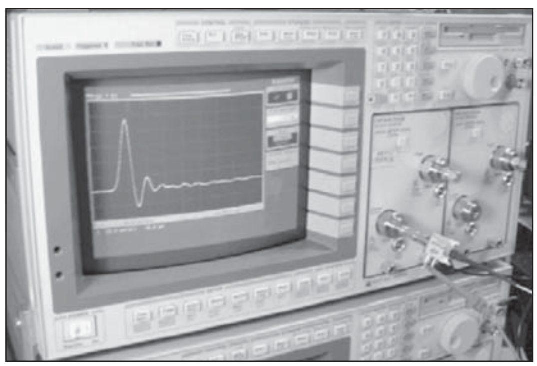
Customer Needs

The rapid advance in the speed of modern telecommunications and computing systems drives this project. Characterizing signal integrity in microprocessors and magnetic recording applications requires at least 10 GHz of calibrated measurement bandwidth on nanoscale-size structures. Limited available bandwidth is pushing wireless systems into the millimeter-wave region of 30 GHz to 100 GHz, where accurate microwave signal and signal source characterization is difficult. Optical links require electrical metrology to 110 GHz and beyond. These extraordinary advances in technology require new high-speed frequency-domain and on-wafer measurements of microwave signals and waveforms at both conventional IC and nanoscale dimensions.

Technical Strategy

Coaxial connectors pose insurmountable economic hurdles for high-speed telecommunications and computing. This project focuses on the only feasible alternative: high-speed on-wafer metrology. The project's initial focus on developing metrology for on-wafer network analysis for MMICs has been expanded to include metrology for silicon ICs and differential interconnects. More recently, the project has expanded the focus to noninvasive probing of nanoscale structures and to ultra-high-speed modulated microwave signal and signal-source characterization.

We are working with the Magnetic Technology Division to apply on-wafer measurement methods to nanoscale devices and interconnects. We are developing techniques for performing noninvasive on-wafer waveform measurements for signal-integrity characterization in digital silicon ICs and in magnetic recording media, and calibration procedures for nanoscale electrical and magnetic probing systems like those shown on the left.



Traceable mismatch-corrected microwave oscilloscope calibration with an EOS-characterized photodetector.

Extending fundamental microwave and on-wafer metrology to higher frequencies and modulated signals is a second important focus of the project. Working together with EEEL's Optoelectronics Division, we have developed a fully calibrated electro-optic sampling system for characterizing photodetectors and calibrating oscilloscopes for microwave signal characterization. This has formed the foundation for a number of new developments in microwave metrology, including: modulated microwave signal and signal-source characterization to 110 GHz, verifying the 3-mixer calibration method, and performing electro-optical on-wafer scattering and waveform measurements beyond 110 GHz. This fundamental metrology tool will be crucial to bringing calibrated oscilloscopes, MTAs, and related instruments to the microwave engineer's workbench.

Deliverables

- Develop complete electrical characterization for commercial high-impedance probes, including transfer function, invasiveness, and noise immunity. (FY2003)
- Construct universal test bed for nanoscale electrical probing. (FY2003)
- Compare frequency-domain, nose-to-nose oscilloscope calibration to electro-optic sampling system up to 50 GHz; calibrate oscilloscope. (FY2003)
- Establish high-speed optical receiver special test to 110 GHz. (FY2003)
- Measure broadband microwave signal with electro-optic sampling system (FY2004)
- Develop alternative to the 3-mixer method. (FY2005)
- Develop 200 GHz on-wafer sources and measurement method. (FY2005)

FY2002 Accomplishments

- Built an on-wafer electro-optic sampling system calibrateable to 110 GHz.
- Constructed a prototype of a universal test bed for characterizing electrical probes for nanoscale device and interconnect characterization.
- Compared waveform measurements performed on our electro-optic sampling system to oscilloscope measurements, and compared to the nose-to-nose calibration for frequencies to 40 GHz.
- Developed a frequency-domain method of characterizing high-impedance probes suitable for performing noninvasive on-wafer waveform and signal-integrity measurements. Developed instrumentation and methods for accurately and completely characterizing small printed coupled lines.
- 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 accurate multiline TRL on-wafer calibrations, on-wafer calibration verification methods, and compact calibration alternatives with verified accuracy.
- In collaboration with the Electromagnetic Properties of Materials Project, we characterized low-k dielectrics fabricated at International SEMATECH using transmission-line methods developed at NIST.

FY2002 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 line 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

P. Kabos, H.C. Reader, U. Arz, and D.F. Williams, *"Calibrated Waveform Measurement with High-Impedance Probes,"* accepted for publication in IEEE Trans. Microwave Theory and Tech.

M.D. Janezic, D.F. Williams, V. Blaschke, A. Karamcheti, and C.S. Chang, *"Permittivity Characterization of Low-k Thin Films from Transmission-line Measurements,"* IEEE Trans. Microwave Theory and Tech. January 2003.

T.S. Clement, P.D. Hale, D.F. Williams, and J.M. Morgan, *"Calibrating Photoreceiver Response to 110 GHz,"* 15th Annual Meeting of the IEEE Lasers and Electro-Optics Society Conference Digest, paper THAA4, Nov. 10-14, 2002, Glasglow, Scotland.

U. Arz, D. Williams, H. Grabinski, *"Characteristic Impedance Measurement of Planar Transmission Lines,"* URSI-GA 2002, Aug 17-24, 2002, Maastricht, Netherlands.

U. Arz, D. Williams, *"Applications of Calibration Comparison in On-wafer Measurement,"* URSI-GA 2002, Aug 17-24, 2002, Maastricht, Netherlands.

U. Arz, H.C. Reader, P. Kabos, D.F. Williams, *"Wideband Frequency-Domain Characterization of High-Impedance Probes,"* 58th ARFTG Conference Digest, pp. 117-124, Nov. 29-30, 2001.

D. Williams, C.L. Holloway, *"Transmission-line Parameter Approximation for Digital Simulation,"* IEEE Trans. Electromagn. Compat., Special Issue Printed Circ, Vol. 43, No. 4, pp. 466-470, November 2001.

U. Arz, D. Williams, H. Grabinski, *"Experimental Study of the Ground Plane in Asymmetric Coupled Silicon Lines,"* 2001 Elect. Perform. Of Electronic Pkg., Oct 23-25, 2001, Boston, Massachusetts, pp. 317-320.

P.D. Hale, T.S. Clement, D.F. Williams, E. Balta, and N.D. Taneja, *"Measuring the Frequency Response of Gigabit Chip Photodiodes,"* J. Lightwave Technol., vol. 19, no. 9, pp. 1333-1339, September 2001.

D. F. Williams and K.A. Remley, *"Analytic Sampling-circuit Model,"* IEEE Transactions on Microwave Theory and Techniques, vol. 49, no. 6, pp. 1013-1019, June 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 and Wireless Components Letters, vol. 11, no. 5, pp. 196-198, May 2001.

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 2000.

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 Mode,"* Dig., IEEE Microwave Theory Tech. Intl. Symp., 11-16 June 2000, Boston, Ma, pp. 1797-1799; June 2000.

Wireless Systems

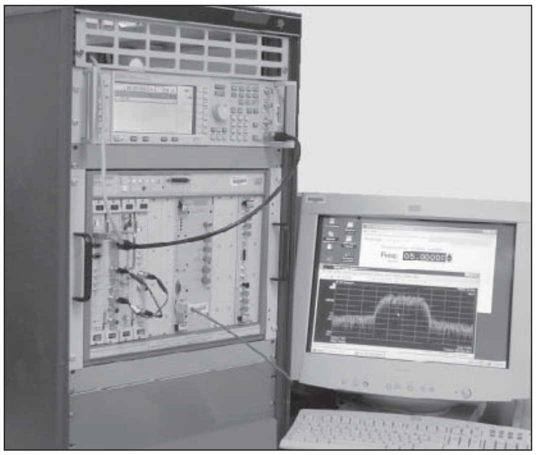
Nonlinear Device Characterization

Technical Contact:
Don DeGroot

Staff-Years (FY2002):
3.0 professionals
0.4 guest Researcher

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.



Test instrumentation that will aid in the refinement and development of metrology for wireless systems.

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 % to 70 % of base station costs and 20 % to 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 when their circuits include a nonlinear element, engineers lose the ability to predict circuit performance across operating environments or states. 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 interchangeability 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.

In 2002, the NDC Project launched an expanded effort to characterize and improve measurements for wireless systems that incorporate nonlinear devices. Through collaborations with NIST's broadband standards development effort, members of the NDC Project have assembled a measurement system to characterize the performance of communication links. Combined with NDC Project work in measurement-based modeling and NNMS metrology, this measurement system will enable us to develop new and refined metrology for wireless systems.

In cooperation with the Optoelectronics Division, 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.

The measurement system is also 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 embarked on an examination of the link between nonlinear circuit descriptions and system performance. Utilizing newly acquired vector signal-generation and analysis instrumentation, performance of wireless systems can now be assessed through both measurement and simulation. This work will lead to refinement of standard methods for characterizing wireless systems, as well as development of new methods that account for the nonlinearities inherent in wireless systems.

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.

Deliverables

- Provide a first estimate of measurement uncertainty in NNMS data. (FY2003)
- Complete the first round of the interlaboratory comparison of nonlinear network analyzers. (FY2003)
- Fabricate and test a diode frequency doubler circuit based on ANN models and nonlinear large-signal scattering parameters. (FY2003)
- Develop a methodology for characterization of vector signal generation and analysis instrumentation and compare to NNMS measurements. Apply to system characterization. (FY2003)
- Verify ANN-base S-parameters through comparison to physical model of superconducting nonlinear DUT. (FY2003)
- Apply superconducting nonlinear phase standard to NNMS calibrations. (FY2003)
- Identify individual sources of measurement uncertainty in NNMS instrument. (FY2004)
- Add new NIST calibration to NNMS. (FY2004)
- Complete feasibility study of alternative phase-dispersion standard. (FY2004)
- Assess effects of vector signal instrumentation on measurements of wireless systems. (FY2004)

FY2002 Accomplishments

- Completed an advanced numerical study of the sensitivity of the phase error in the nose-to-nose calibration to sampling-circuit component variation. Parametric perturbation of component values was carried out on a model representing the sampling circuitry in the type of oscilloscope used in nose-to-nose calibrations. Uncertainty in the phase error due to parametric variation was calculated based on these results. The nose-to-nose calibration currently represents the most practical method for estimating the phase response of digital sampling oscilloscopes that have a two-diode sampling circuit configuration. U.S. manufacturers of high-speed test equipment rely on the nose-to-nose calibration for phase calibration. As yet, there is no uncertainty bound on measurements made with nose-to-nose calibrated equipment. This study represents the first estimate of uncertainty due to sampling-circuit error mechanisms, one of several sources of error.

- Assembled test equipment for characterizing communication links, including those with nonlinearities, up to 40 GHz and modulation bandwidths up to 40 MHz. Ascertained requirements for system, assessed availability of equipment, and ordered and assembled the system. Established the link between the software used to generate and analyze waveforms and the hardware. This test system may ultimately provide measurement assurance to the U.S. wireless industry, especially in the characterization of communication links that include nonlinear devices such as power amplifiers. The system can be configured in a variety of ways to characterize components, subsystems, and systems to aid in the development of better metrology for the wireless industry.

- Collaborated with the NIST Statistical Engineering Division to select suitable methods for comparing the common data collected in nonlinear network analysis. The RF characterizations of nonlinear circuits include wave-variable data for multiple frequency components and, alternatively, the time-domain representations of the wave variables or the associated currents and voltages. The identified comparison metrics report on the differences between two or more nonlinear circuit characterizations, either from simulations or from measurements. Development of accurate models and measurements for nonlinear RF circuits is critical to increasing the efficiency of the wireless system design process as well as the physical performance efficiency of the resulting circuits. The metrics are important in assessing the value of new models and in comparing new measurement strategies.

■ A more general, nonlinear, definition of scattering parameters was developed, in collaboration with Prof. K.C. Gupta of the University of Colorado that uses a matrix formulation and reduces to the classical definition for linear networks. Transformations were also developed for converting these large-signal scattering parameters into nonlinear large-signal impedance and admittance parameters. Conducted a sensitivity analysis for computing the nonlinear large-signal scattering parameters using artificial neural network models, and compared the definitions of nonlinear large-signal scattering parameters to a form of nonlinear mapping known as nonlinear scattering functions, previously published by Jan Verspecht of Agilent Technologies. These derivations provide a theoretical foundation for defining scattering parameters that can be used in the design and characterization of nonlinear circuits. They provide a strict definition of engineering figures of merit for a specific application and network configuration. The comparison to an existing method provides sound evidence that our nonlinear large-signal scattering parameters are more general than the narrow definition traditionally used. Designers now have detailed information on the definition and procedures, and on know-how to generate such representations themselves.

■ As a demonstration of a practical application of the new large-signal scattering parameters, we used these to design a diode frequency-doubler circuit with a commercial harmonic-balance simulator. This example illustrates the power of generalized large-signal scattering parameters in all stages of design, including determining optimum bias conditions, verifying proper performances of filtering networks, and determining matching input and output networks.

■ We developed the only sound method of describing the phase relationship of two signals that are at two different, but harmonically related, frequencies. This methodology is essential for generating time-invariant nonlinear large-signal scattering matrices, and has potentially wider applications to other nonlinear physical processes.

■ Collaborated with Dominique Schreurs, Katholieke Universitet Leuven, Belgium, to construct a behavioral model for a high-electron-mobility transistor from time-domain large-signal measurements making use of artificial neural networks for the multivariate fitting functions instead of polynomials. The application of artificial neural networks significantly improved upon the next-best model based on multivariate polynomials, providing a more accurate description of the nonlinear device to RF circuit designers. This model will also be used in the planned, NIST-piloted comparison nonlinear network analyzers.

■ The first important step toward a NIST-led measurement comparison for nonlinear circuit characterization was completed. We designed and fabricated verification wafers for probe-station measurements of nonlinear circuits. Developed and tested nonlinear circuit models that will be required in the nonlinear analysis. Formulated measurement protocol and data reporting methods (joint with the Statistical Engineering Division). Applied and analyzed comparison metrics for different network analyzer configurations. This interlaboratory comparison will give the users of this new class of instruments the ability to anonymously compare their results to their peers. It is the first study of its kind and introduces new methods required in nonlinear analysis. The users will have the opportunity to correct gross errors and to gain confidence in their measurements, where no other means of measurement assurance yet exists.

■ The measurement and characterization of a candidate superconducting device, developed jointly with the Electromagnetic Technology Division as a “standard” nonlinearity, was completed. High-temperature superconducting materials exhibit a surface reactance that is dependent on the circulating surface currents. Jim Booth has shown that the nonlinear response is predictable, based on independent knowledge of the penetration-depth length scale. Measurements of the amplitude response show that the device follows the predicted nonlinear behavior extremely well. When perfected, the device will be useful as a phase dispersion standard whose properties can be derived from physical principles. These standards will be used at NIST, and possibly elsewhere, to both calibrate and directly verify the phase-dispersion calibrations of nonlinear network analyzers.

FY2002 Outputs

Software

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

Recent Publications

J.A. Jargon, K. Gupta, D. Schreurs, D.C. DeGroot, *"Developing Frequency-Domain Models for Nonlinear Circuits Based on Large-Signal Measurements,"* 2002 URSI General Assembly, Aug 17-24, 2002, Maastricht, Netherlands.

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J.A. Jargon, K. Gupta, *"Artificial Neural Network Modeling for Improved On-Wafer Line-Reflect-Match Calibrations,"* European Microwave Conference, Sep 24-28, 2001, London, England, pp. 229-232.

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

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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 Lline-Reflect-Match Calibrations,"* Internat. J. RF Microwave Computer-Aided Eng., vol. 11, no. 1, pp. 33-37, Jan., 2001.

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J. A. Jargon, *"Measurement Comparison of a Low-Intermodulation Termination for the U.S. Wireless Industry,"* NIST Tech. 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.

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Wireless Systems

Standards for Broadband Wireless Access

Technical Contact:
Roger Marks

Staff-Years (FY2002):
1.0 professional

Goals

Support the development of the broadband wireless communications industry by leading the open development of accredited voluntary consensus technical standards, including interoperability test methods, and encouraging their acceptance worldwide.

Customer Needs

Broadband wireless access systems have the potential to provide competitive alternative Internet and multimedia connectivity for residential and business sites worldwide. Innovation has brought new radio communication 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. Private industry supports standardization, and NIST leadership in efforts toward voluntary consensus standardization makes the critical difference in timely success.

Technical Strategy

The project effort has been directed toward establishing and leading a global industry effort in broadband wireless access standardization. This project gives NIST a proactive role in the development of high-quality technical standards for wireless communications.

History and Progress of Standardization Effort

Project leader Roger Marks instigated standardization in this field in 1998 with a newsletter and initial meeting. Project work soon followed in the IEEE 802 LAN/MAN [Local/Metropolitan Area Networks] Standards Committee of the Institute of Electrical and Electronics Engineers, Inc. (IEEE), a nonprofit technical professional society with a consensus standards program that is ANSI-accredited, global, open, and voluntary. The IEEE 802.16 Working Group on Broadband Wireless Access was created to conduct the work, and Marks has remained Chair. The group membership peaked at 175 Voting Members, and over 800 people from 20 countries have attended one of the group's 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's core project was published in April 2002 as IEEE Standard 802.16 ("Air Interface for Fixed Broad-band Wireless Access Systems"). Marks served as Technical Editor for both of these documents and chaired the subgroup that developed IEEE 802.16. Work to standardize interoperability test specifications (beginning with P802.16c and P1802.16.1) is proceeding, with the support of an industry association. In FY2002, the project hosted two foreign Guest Researchers working toward the development of such specifications.

While the IEEE 802.16 air interface is specific to 10–66 GHz systems, the group is developing, in P802.16a, enhancements to expand the applicability to 2 GHz to 11 GHz in both licensed and unlicensed bands. Complementary coexistence work is taking place in P802.16.2a. Extension of the air interface to accommodate mobile terminals is under active consideration.

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. He has focused on encouraging the acceptance of IEEE 802.16 standards in Europe and China.

Deliverables

- IEEE Standard 802.16a: Amendment to IEEE Standard for Local and Metropolitan Area Networks Part 16 — Air Interface for Fixed Broadband Wireless Access Systems — Medium Access Control Modifications and Additional Physical Layer Specifications for 2-11 GHz. (FY2003)

- IEEE Standard 802.16c: Amendment to IEEE Standard for Local and Metropolitan Area Networks — Part 16: Air Interface for Fixed Broadband Wireless Access Systems — Detailed System Profiles for 10-66 GHz. (FY2003)

- IEEE Standard 802.16.2a: Amendment to IEEE Recommended Practice for Local and Metropolitan Area Networks Coexistence of Fixed Broadband Wireless Access Systems. (FY2003)

- IEEE Standard 1802.16.1: Standard for Conformance to IEEE Standard 802.16 — Part 1: Protocol Implementation Conformance Statement (PICS) Proforma for 10–66 GHz Wireless-MAN-SC Air Interface. (FY2003)

FY2002 Outputs

Standards and Draft Standards

IEEE Standard 802.16-2001: IEEE Standard for Local and Metropolitan Area Networks — Part 16: Air Interface for Fixed Broadband Wireless Access Systems, April 8, 2002, 351 pages.

IEEE Draft P802.16a/D5: Draft Amendment to IEEE Standard for Local and Metropolitan Area Networks Part 16 — Air Interface for Fixed Broadband Wireless Access Systems — Medium Access Control Modifications and Additional Physical Layer Specifications for 2-11 GHz, July 30, 2002, 329 pages.

IEEE Draft P802.16c/D4: Draft Amendment to IEEE Standard for Local and Metropolitan Area Networks — Part 16: Air Interface for Fixed Broadband Wireless Access Systems — Detailed System Profiles for 10-66 GHz, October 1, 2002, 90 pages.

IEEE Draft P802.16.2a/D1: Draft Amendment to IEEE Recommended Practice for Local and Metropolitan Area Networks Coexistence of Fixed Broadband Wireless Access Systems, August 19, 2002, 114 pages.

Recent Publications

Marks, R. B. *"Advances in Wireless Networking Standards,"* Pacific Telecommunication Review (invited submission to November 2002 issue).

Eklund, C., Marks, R.B., Stanwood, K.L., and Wang, S. IEEE Standard 802.16: *"A Technical Overview of the WirelessMAN Air Interface for Broadband Wireless Access,"* IEEE Communications Magazine, pp. 98-107, June 2002.

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, 3-5 October 2001.

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.

Electromagnetic Properties of Materials

Technical Contact:
Jim Baker-Jarvis

Staff-Years (FY2002):
5.0 professionals

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.

High Frequency Network Analyzer and Probe Station.

Customer Needs

The trends in high-frequency materials include applications at higher frequencies, variable temperatures, nanoscale materials, and artificial and biological materials. Substrate-based components employing thin films form the basis for microelectronic circuitry. Electronic substrate 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. Data on temperature-dependent dielectric and loss properties of ceramics, substrates, and crystals at microwave and millimeter frequencies is crucial in the wireless and time-standards arena. For example, computer-based design methods require very accurate data on the dielectric and magnetic properties of these materials over wide ranges of frequency and temperature. An understanding of loss mechanisms in low-loss crystals is important when interpreting measurement results.

Various applications require composite dielectrics that emulate the human body's electrical properties for testing metal detectors and analyzing electromagnetic interference (EMI) to implanted medical devices. Measurements of liquid permittivity are needed to support biotechnology research. To support the evolving microelectronics industry, methods for characterizing nanoscale and metamaterial properties will be necessary for the development of novel new technologies. On-chip, microscale-to-nanoscale measurements of permittivity are important for the microelectronic industry. Both solid and liquid dielectric reference materials are needed to provide measurement traceability to NIST. Measurement intercomparisons provide assessments of the quality of material characterization.

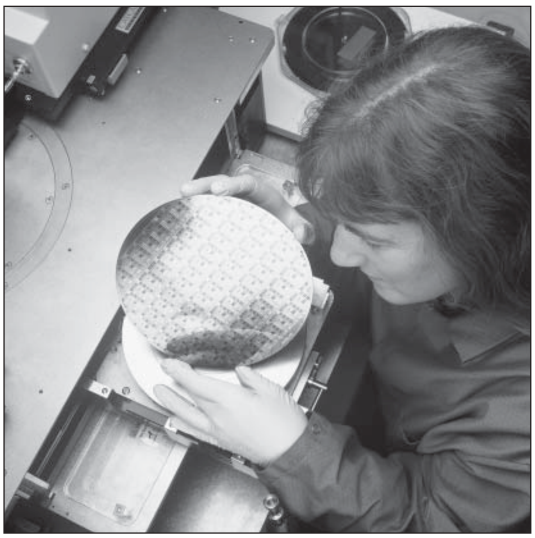
Technical Strategy

The project's main thrusts in 2003 next year are to develop measurement methods to support the health care industries, measure materials at higher frequencies, broaden our measurement temperature range, and measure advanced materials over smaller dimensions. The current specific areas of research are thin films and printed wiring boards, applications to biotechnology, low-loss dielectric and magnetic crystals, probing methods for micro-nanoscale permittivity, dielectric metrology of advanced materials such as metamaterials, and theoretical modeling of dielectric relaxation.

In response to needs in the microelectronics industry, we are developing accurate methods for measuring the dielectric properties of thin films using both transmission-line and resonator methods. Using a previously developed on-wafer transmission-line model, we will extend measurements of thin films to frequencies above 40 GHz at nanometer scales, and we will also develop a new resonator method. We will also aid the PWB and LTCC industries in measuring the permittivity of substrates at high frequencies. To this end, we will further enhance our wideband, variable-temperature metrology. We will extend the capability of our Fabry-Perot measurement system to include variable temperatures, and will complete the model for the split-post resonator. We will measure a wide spectrum of ceramic materials commonly used in the electronics industry, as a function of temperature. We will continue to work with and support IPC Tasks Groups and the LTCC Working Group through measurement assistance.

To satisfy documented needs in the health care, biotechnology, and metal detector industries, we will characterize materials that emulate the electrical properties of the human body. Through funding from the Justice Department, we will continue to develop measurement metrology for composite phantom materials. We will also develop a coaxial probe for in vitro measurements in support of research on detection of breast cancer. In addition, to support the biotechnology industry, we will improve our liquid measurement metrology and will compare our measurements with NPL's using the liquid measurement methods we have developed.

To enhance the understanding of the physics of high-frequency losses in dielectrics we will test crystals over wide temperature and frequency ranges using an in-house developed whispering-gallery-mode model for determination of permittivity. We will also compare the measured losses as functions of temperature and frequency to expressions in the solid-state literature.



Raian Kaiser prepares to measure the dielectric properties of Low-k thin films. © Geoffrey Wheeler

To support the microelectronics industry in on-chip dielectric measurement metrology, we will develop methods for evanescent microwave probing and atomic-force microscopy. In collaboration with Division 816 we will construct a nanoscale permittivity probe.

To support basic research on advanced composite materials technologies, we will develop measurement metrology on metamaterials, and develop an on-wafer material that has negative permittivity and permeability from 60 GHz to 70 GHz.

We will support the development of standards by attending and contributing to standards committee meetings.

FY2002 Accomplishments

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

- The full-mode split-cylinder software has been generalized to allow determination of permittivity at higher frequencies using higher-order modes. The 10 GHz split-cylinder cavity can now be used to measure at frequencies up to 20 GHz and the 30 GHz split-cylinder cavity can measure up to 40 GHz.

- In response to a documented need from industry for measurements at higher frequencies, a newly designed 33 GHz split-post resonator has been constructed in collaboration with visiting scientist Jerzy Krupka. The fixture can measure printed wiring board, thin films, and substrates less than 0.4 mm in thickness at 33 GHz.

- The Electromagnetic Properties of Materials Project has performed theoretical and experimental research into the emerging area of metamaterials. These materials allow for novel electromagnetic behavior by using the effective negative permittivity and permeability. In collaboration with Steve Russek of Div 816 we have developed and fabricated thin metamaterials that we will measure. In collaborations lead by Chris Holloway from NIST and Ed Kuester of the University of Colorado, we have developed a new theoretical model for a material that can simultaneously exhibit negative permeability and permittivity. A paper has been submitted for publication to IEEE Transactions on Antennas and Propagation.

- The Electromagnetic Properties of Materials Project has assisted the IPC-NEMI-ITRI task group by measuring at high frequency the permittivity and loss of a selection of printed-wiring-board materials. This work has benefited our project by testing our measurement methods for materials with medium loss.

- We measured a suite of ferroelectric thin films with a thickness of 160 nanometers at 10 GHz. The goal of the research was to correlate dielectric properties to material properties and compositions of film. The results have been summarized in a paper published in Applied Physics Letters.

- A Technical Note was completed summarizing the metal losses in LTCC substrate high-frequency measurement technology. We also collaborated and performed measurements for the Ceramics Division of MSEL in the LTCC Working Group.

- We worked closely with Ferro Corporation, Heraerus, and Dupont to measure commonly used LTCC materials and to solve a 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 was funded by the Justice Department for use in modeling the performance of metal detectors. The results have been summarized in a Technical Note.

- 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 permittivity for a number of commonly used plastics was performed, and the results are in press in IEEE Transactions MTT.

- Completed the documentation and measurements for the cross-linked polystyrene dielectric standard reference material (SRM) at 10 GHz.

Deliverables

- Extend thin-film measurements to include dielectric resonator and evanescent microscope methods and measure substrate materials on wafer. (FY2003)

- Develop high-frequency, variable-temperature metrology and perform measurements on ultra low-loss dielectric, PWB's and substrates. (FY2003)

- Develop a new coaxial probe, model, and software for support of in vitro measurements in support of breast cancer therapy. (FY2003)

- Characterize a set of high-loss liquids from 50 MHz to 10 GHz to help industry calibrate dielectric measurements on biological materials. (FY2003)

- Characterize and measure a metamaterial and compare the results to our developed theory. (FY2003)

- Complete the fabrication and implementation of an open-ended coaxial resonator, cantilever and/or atomic force microscope (AFM) applied to measurements of local permittivity. (FY2004)

- Complete measurement theory, software, and uncertainty analysis for an in vitro coaxial biological probe for cancer detection, and perform measurements. (FY2004)

- Develop relaxation models for dielectric and magnetic response in advanced materials such as metamaterials, magnoelectric, and photonic band-gap materials. (FY2004)

Recent Publications

J.R. Baker-Jarvis, R.K. Kaiser, M.D. Janezic, N.G. Paulter, K.L. Stricklett, *"Metal Detector Studies: Research Materials,"* NIST Tech. Note 1514, 2002.

R.G. Geyer, P. Kabos, J.R. Baker-Jarvis, *"Dielectric Sleeve Resonator Techniques for Variable-Temperature Microwave Characterization of Ferroelectric Materials,"* 2002 IEEE MTT-S International Microwave Symposium, Jun 02-07, 2002, Seattle, Washington, pp. 1657-1660.

J.R. Baker-Jarvis, R.K. Kaiser, M.D. Janezic, *"Phantom Materials for Metal Detector Research,"* 2002 URSI General Assembly, Aug 17-24, 2002, Maastricht, Netherlands.

M.D. Janezic, E.F. Kuester, J.R. Baker-Jarvis, *"Nondestructive Permittivity and Loss Tangent Measurements Using a Split-Cylinder Resonator,"* 2002 URSI General Assembly, Aug 17-24, 2002, Maastricht, Netherlands.

R.G. Geyer, M.W. Cole, P.C. Joshi, E. Ngo, C. Hubbard, W. Nothwang, M. Bratcher, M. Ervin, M. Wood, *"Correlation of Microwave Dielectric Properties and Microstructure of Unpatterned Ferroelectric Thin Films,"* Materials Research Society Symposium, Apr 01-05, 2002, San Francisco, California, pp. 123-128.

M.W. Cole, P.C. Joshi, E. Ngo, C. Hubbard, M. Ervin, M. Wood, R.G. Geyer, *"Structure-Property Relationships in Pure and Acceptor-Doped $Ba_{(1-x)}Sr_{(x)}Ti_{(3)}$ Thin Films for Tunable Microwave Applications,"* J.Appl. Phys., Vol. 92, No. 1, pp. 475-483, 2002.

J. Krupka, K. Derzakowski, B.F. Riddle, J.R. Baker-Jarvis, R.N. Clarke, A. Abramowicz, O.C. Rochard, *"Bounds on Permittivity Calculations using a TE01 d Dielectric Resonator,"* 14th International Conference on Microwaves, Radar and Wireless Communications - MIKON-2002, May 20-22, 2002, Gdansk, Poland, pp. 394-396.

J. Krupka, K. Derzakowski, A. Abramowics, J.R. Baker-Jarvis, R.H. Ono, R.G. Geyer, *"Surface Impedance of Thin High Temperature Superconducting Films with a Sapphire Dielectric Resonator,"* 14th International Conference on Microwaves, Radar & Wireless Communications, MIKON-2002, May 20-22, 2002, Gdansk, Poland, pp. 391-393.

J.R. Baker-Jarvis, P. Kabos, *"Dynamic Constitutive Relations for Polarization and Magnetization,"* Physical Review E, Vol. 64, No. 056127, pp. 1-14 October 2001.

M.D. Janezic, J. Krupka, J.R. Baker-Jarvis, *"Nondestructive Permittivity Measurements of Dielectric Substrates Using Split-Cylinder and Split-Post Resonators,"* Intl. Conf. Advances in Processing, Testing and Applications of Dielectric Materials, Sep 17-19, 2001, Wroclaw, Poland, pp. 116-118.

R.G. Geyer, P. Kabos, J.R. Baker-Jarvis, *"Dielectric Sleeve Resonator Techniques for Microwave Complex Permittivity Evaluation,"* IEEE Trans. Instrumen. Meas., Vol. 51, No. 2, pp. 383-392 October 2001.

J.R. Baker-Jarvis, *"RF Materials Characterization Metrology at NBS/NIST: Past and Recent Work, Future Directions and Challenges,"* Conf. Electrical Insulation Dielectric Meas., Oct 14-17, 2001, Kitchner, California, pp. 265-267.

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 Tech. Note 1520, July 2001.

R.G. Geyer, W.E. McKinzie, *"VHF Tunability Measurements of Ferroelectric Materials Using Doubly Reentrant Cavities,"* Ceram. Trans. Dielectric Materials and Devices, pp. 187-203 June 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.

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.

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.

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.

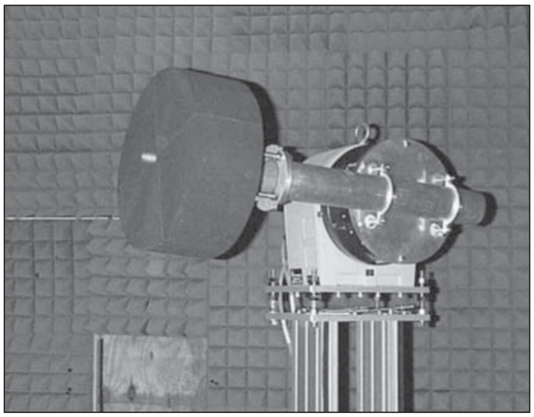
Jones, C. A.; Grosvenor, J. H.; Weil, C. M.; *"Rf Material Characterization Using a Large-Diameter (76.8 Mm) Coaxial Air Line,"* NIST Tech. Note 1517; February 2000.

Antennas and Antenna Systems

Antenna Measurement Theory

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.

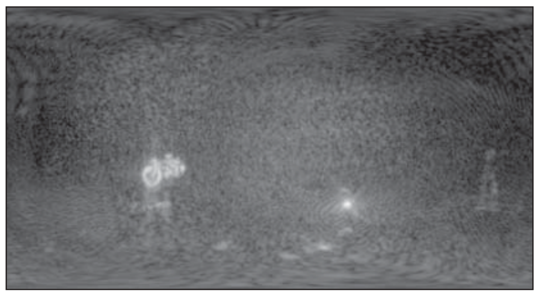


Image of measurement laboratory at 16 GHz, focused on bicycle (left) and also showing illuminating source horn (center), ladder (right), and undesired room sources (lower center).

Technical Strategy

NIST is expanding its frequency coverage for antenna calibrations to meet the demands of government and industry. We are upgrading special test services to include the frequencies from 75 GHz to 110 GHz.

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 possible, however. We are extending the extrapolation software to take full advantage of phase information and to analyze the conditioning of the algorithm.

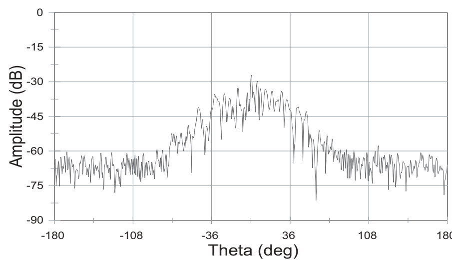
An uncertainty analysis was developed in the past for planar near-field measurements. A similar analysis is needed for spherical and cylindrical near-field measurements.

Technical Contact:
Mike Francis

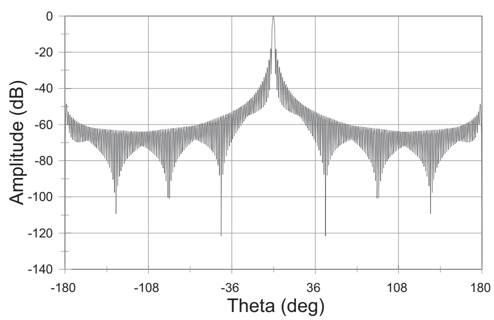
Staff-Years (FY2002):
2.0 professionals

Deliverables

- Extend the extrapolation software to take full advantage of phase information and to analyze the conditioning of the algorithm. (FY2003)
- Develop an uncertainty analysis for spherical near-field measurements. (FY2003)
- Develop an uncertainty analysis for cylindrical near-field measurements. (FY2004)



The far-field pattern computed for a maximum directivity antenna (N=128), ignoring probe position errors.

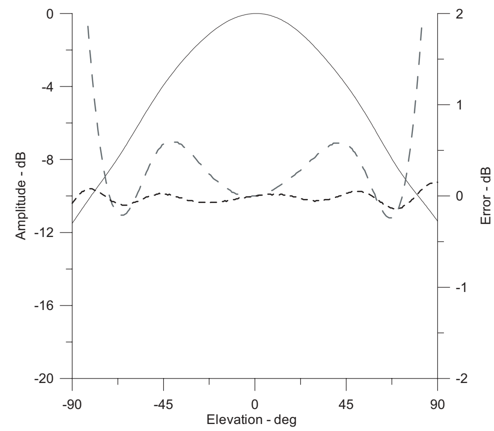


The far-field pattern of a maximum directivity antenna (N=128) with position correction.

FY2002 Accomplishments

- A 3D probe position-error correction scheme has been developed for spherical near-field scanning applications. This complements the 3-D probe-position software completed earlier for planar near-field scanning. Software is available to the public. A 3D probe position-error correction scheme has been developed and published for planar near-field scanning applications. Software is available to the public.

- A computer program has been completed to ameliorate the effects of partial sphere data that can occur due to blockage or incomplete measurement data in the back hemisphere. This partial sphere data can result in a sudden drop in the measured amplitude of the near field. When transformed to the far field, ringing results in portions of the far field. The computer program does a constrained least squares fit by using forward hemisphere data and gain information to ensure a smooth transition to the back hemisphere. The smooth transition effectively eliminates the ringing in the far field.



Cylindrical waveguide probe: Deviations from the full-sphere pattern (errors) are shown for the truncated (long dash) and constrained least squares (short dash) techniques. The full-sphere pattern is the solid line.

FY2002 Outputs

External Recognition

Mike Francis chairs the Antenna Standards Committee of the IEEE Antennas and Propagation Society.

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 near-field scanning applications. Probe position-correction software is available for the planar and spherical methods. The constrained least squares for partial sphere data is also available. Quiet-zone evaluation and imaging programs should be available soon.

Recent Publications

Wittmann, R. C.; Alpert, B. K.; Francis, M. H.; *"Spherical Near-Field Antenna Measurements Using Nonideal Measurement Locations,"* Proc. Antenna Meas. Tech. Assoc., Nov. 2002.

Wittmann, R. C.; Stubenrauch, C. F.; Francis, M. H.; "Spherical Scanning Measurements Using Truncated Data Sets," Proc. Antenna Meas. Tech. Assoc., Oct. 2002.

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

Antennas and Antenna Systems

Antenna Measurement Applications

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.

Jeff Guerrieri aligns a probe (right) for measuring a WR-15 parabolic dish antenna (left). © Geoffrey Wheeler

Customer Needs

NIST continues to upgrade its antenna metrology capability to meet evolving customer needs. Current demands include:

Probe characterization: Accurate probe characterization is time-consuming and costly for the customer. It requires facilities they may not have available. Probe correction coefficients are provided for use in planar, spherical and cylindrical near-field facilities.

Antenna standard characterization: Industry and government require their own antenna standards for use in-house antenna measurements.

Planar and spherical near-field measurements: These are required to accurately characterize large aperture, high frequency antennas such as phased array and dish antennas used in satellite communications.

Measurement traceability: Many program specifications require NIST traceability.

Requests for measurements and calibration services at higher frequencies: Our current capability is 75 GHz. An upgrade to 110 GHz is near completion.

Comparison measurements: Government and industry request measurements to verify that their measurement and analysis procedures produce the predicted and correct results.

Technical support: Assistance on measurement techniques and analysis algorithms are requested by antenna facilities that are implementing near-field measurement methods.

Technical Strategy

NIST currently maintains antenna measurement standards and capabilities for frequencies from 1.5 GHz to 75 GHz. Some automobile radars will operate at frequencies from 76 GHz to 77 GHz and aircraft radars will operate at frequencies from 94 GHz to 96 GHz. NIST will complete upgrades to provide special measurement services in the WR-10 band (75 GHz to 110 GHz).

Measurements will be completed to support the extension and improvement of the "Three-Antenna Extrapolation Technique." This should provide improved on-axis gain evaluation.

Measurements will also be completed to provide a comparison of planar, spherical and cylindrical near-field techniques in our laboratory.

Deliverables

- Complete upgrade of planar near-field scanning capability to 110 GHz. (FY2003)
- Complete measurements to provide a comparison of planar, spherical and cylindrical near-field techniques in our laboratory. (FY2003)
- Develop a method for mitigating the truncation effects in planar scanning. (FY2004)

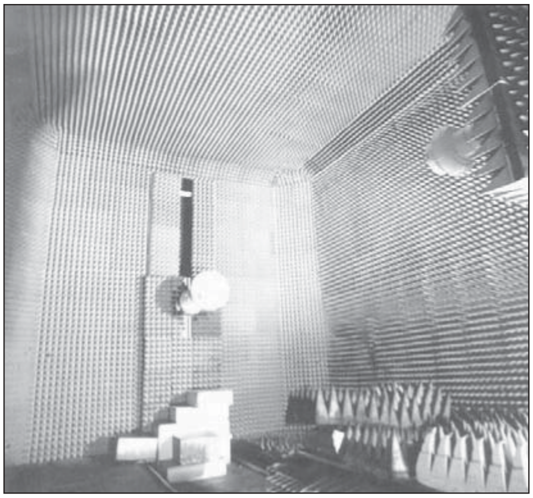
FY2002 Accomplishments

- Completed mechanical and software upgrades for the millimeter-wave planar near-field scanner to provide measurement capability up to 110 GHz.

Technical Contact:
Katherine MacReynolds

Staff-Years (FY2002):
2.0 professionals

- Procured a dual-port linearly polarized probe to be used in the intercomparison measurements. It has been calibrated for on-axis characteristics and probe correction coefficients at 16 GHz.



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.

FY2002 Outputs

Calibrations

Completed measurements on fifteen horn antennas covering six waveguide bands from 0.5 GHz to 18 GHz for on–axis gain at three fixed frequencies per band and stepped frequencies over the band limits. These horns are used to calibrate antennas on military aircraft.

Completed measurements on a standard gain horn in the WR-42 band at three frequencies and a standard gain horn in the WR-28 band at three frequencies for on-axis gain.

Completed measurements on a WR-42 standard gain horn for on-axis gain at one frequency.

Software

Planar Near-Field Library
Cylindrical Near-Field Library
Spherical Near-Field Library

The software libraries are available via email and provide the correct algorithms for users to integrate into their software platforms.

Short Courses

- NIST and the Georgia Institute of Technology annually offer an introductory course on antenna measurements. This course is given in the fall of each year.

- Every other year NIST presents an in-depth technical course restricted to near-field methods that were pioneered at NIST. The next course will be in the spring of 2004.

Recent Publications

Newell, A., Guerrieri, J. and MacReynolds, K., *"Methods to Estimate and Reduce Leakage Bias Errors in Near-field Measurements,"* Proceedings of the Antenna Measurement Techniques Association, Oct. 2002.

Antennas and Antenna Systems

Metrology for Radar Cross Section Systems

Technical Contact:
Lorant A. Muth

Staff-Years (FY2002):
1.5 professionals

Goals

To assist the DoD and industrial radar cross section (RCS) measurement ranges in 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 from 2 GHz to 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 in order 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 essential at every RCS measurement range, if the U.S. RCS industry is to maintain its world leadership. 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 a 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 would be beneficial:

- The set of calibration artifacts used by industry should be enhanced in order to assess and improve calibration accuracy.
- Defendable range specific uncertainty analyses are needed throughout the RCS industry.
- An RCS interlaboratory comparison program and the corresponding technology need to be developed to enhance confidence in our uncertainty analysis, as well as in the calibration of RCS artifacts and in the measurements on unknown targets.

Recent project activities include the following: we concluded the RCS Range Book reviews for the DoD Demonstration Project in support of the National DoD RCS Range Certification Program, provided in-depth comments to improve on the procedures used at the RCS measurement ranges, and worked closely with a government RCS range to determine the range-specific calibration and measurement uncertainties. In FY2003 we will continue the RCS Range Book reviews for industry to make appropriate recommendations for improvements in RCS calibration and measurement procedures. We will continue to work closely with selected RCS ranges to develop and standardize procedures to determine RCS calibration and measurement uncertainty. We will develop and publish an uncertainty analysis, both for monostatic and bistatic RCS measurements, at the selected facilities. We will develop and manufacture an expanded set of RCS calibration artifacts to be able to calibrate the system at various signal levels of interest, and we will design and conduct an interlaboratory comparison to assess the results. Our goal is to fully assess the technical merit and deficiencies of existing calibration and measurement procedures, data analysis techniques and uncertainty analysis. We plan to publish recommendations for improvements in measurement procedures, and further explore known problems in areas such as dynamic sphere calibration and polarimetric calibration. The annual RCS Certification Meeting will again be held at NIST, Boulder to provide a forum for the RCS community to discuss procedural and technical issues.

Deliverables

- Complete and publish our range-specific uncertainty analysis for an outdoor, DoD RCS measurement facility in the 2 GHz to 18 GHz range. (FY2003)
- Manufacture and deliver new RCS standards artifacts to be used for calibration at low frequencies in the 50 MHz to 2 GHz range. (FY2003)
- Complete and publish a range-specific uncertainty analysis for an outdoor DoD RCS measurement facility in the 150 MHz to 2 GHz range. (FY2004)

FY 2002 Accomplishments

- 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 ongoing.

- The RCS ranges reported less than satisfactory results with existing polarimetric calibration procedures. We continue to develop a more robust calibration procedure wherein full polarimetric data are 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.

- 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.

Recent Publications

L.A. Muth, and T. Conn *"Phase-Dependent RCS Measurements"* Proc. Antenna Meas. Tech. Assoc., Cleveland, pp. 216-220, OH, Oct. 2002.

L.A. Muth, *"Phase Dependence in Radar Cross Section Measurements,"* NIST Tech. Note 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.

Electromagnetic Compatibility

Standard Electromagnetic Fields

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.

Dennis Camell tests an across-the-road radar unit using a NIST developed simulator/calibrator.
© Geoffrey Wheeler

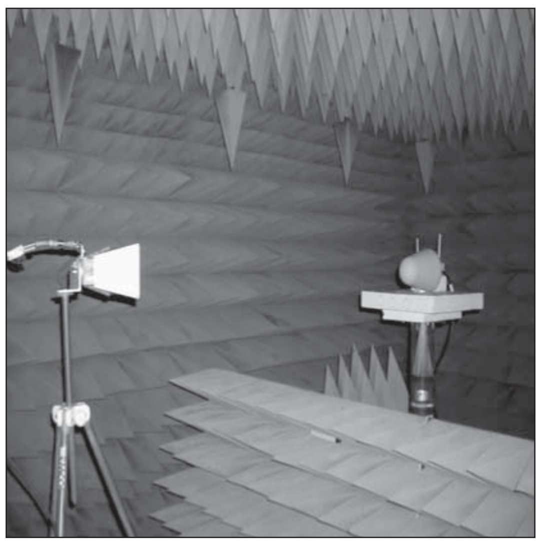
Customer Needs

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 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 levels of ambient signal are complicating 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 MHz 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.

Technical Contact:
Dennis G. Camell

Staff-Years (FY2002):
1.5 professionals

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 chambers, 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.

Antenna under test at NIST OATS facility.

Deliverables

- Develop improved methods for RF emissions measurements above 1 GHz. (FY2003)
- Improve techniques for antenna far-field characterization at OATS and in fully anechoic chambers for frequencies up to 18 GHz. (FY2003)
- Provide standards organizations with technical guidance to correlate between EMC test facilities. (FY2004)

FY 2002 Accomplishments

- A comparison between the standard-antenna method and the standard-site method provided test houses with support in implementing current EMC standards.

- Test have been undertaken to assess methods to qualify OATS and anechoic chambers for frequencies above 1 GHz. These tests are in conjunction with ANSI C63 and are ongoing.

FY2002 Outputs

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 remeasure a reference RF emitter through USCEL (the U.S. Council of Electromagnetic Laboratories).

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.

Recent Publications

M. Candidi, C. Holloway, P. Wilson, D. Camell; *"Comparison of Radiated Emission Measurements for 500 MHz to 2 GHz in Various EMC Facilities;"* Proceedings EMC Europe 2002 Symp. Sorrento, Italy, pp. 823-828, Sept. 2002.

P. Wilson, D. Camell, C. Holloway, R. Johnk, G. Koepke, J. Ladbury, K. Masterson, and A. Ondrejka*; "Electromagnetic Compatibilty Research at NIST Boulder;"* IEEE EMC Society Newsletter, Issue 194; pp. 19-28, Summer 2002.

J. Ladbury and D. Camell; *"Electrically Short Dipoles with a Nonlinear Load, a Revisited Analysis;"* IEEE Trans EMC, vol. 44, no 1, pp. 38-44, Feb. 2002.

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.

Electromagnetic Compatibility Field Transfer Probe Standards

Technical Contact:
Keith D. Masterson

Staff-Years (FY2002):
1.0 professional

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.

Keith Masterson mounts an electro-optic modulator in a circuit board carrier. This is part of a near-field probe that simultaneously measures the electric and magnetic field components. © Geoffrey Wheeler

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 to 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 so that the response can be calculated from first principles, if possible, as well as 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 information about both phase and amplitude 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 in order to reduce errors caused by scattering and pickup by conventional electrical leads. Building on this expertise, we are pursuing the 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 at and above 100 GHz. Techniques that offer possibilities to extend the response to still higher frequencies will be favored. Thermo-optic probes, already investigated 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-deployable 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.

NIST provides calibration services for antennas used in EMC testing. The frequencies of interest are often in the range from 1 MHz 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 increase 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 is determined by measurements using standard electrically coupled dipole antennas. NIST is pursuing the development of standard RF dipole measurement systems with optical fiber links that reduce errors due to the presence of ambient signals and common-mode pickup.

Deliverables

- Complete the simultaneous electric and magnetic near-field probe development. (FY2003)
- Upgrade the optical fiber linked standard RF dipole. (FY2004)

FY 2002 Accomplishments

- 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.
- Designed a loop probe system that simultaneously measures the electric and magnetic field components over the frequency range from 50 kHz to 200 MHz. The probe is intended for high amplitude, near-field applications.

Recent Publications

Masterson, K; Novotny, D; Koepke, G., *"Electromagnetic Shielding Characteristics of Optical-Fiber Feedthroughs,"*, IEEE Trans. Electrom. Compat., vol. 3, no. 2, pp 177-186, May 2001.

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.

ELECTROMAGNETIC COMPATIBILITY

TIME-DOMAIN FREE-FIELD ELECTROMAGNETIC METROLOGY

GOALS

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

Chriss Grosvenor adjusts a TEM horn on the recently completed cone and ground plane standard field generation system located in the time-domain free-field metrology laboratory. © Geoffrey Wheeler

CUSTOMER NEEDS

The burgeoning consumer electronics and wireless markets 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 efficient metrological innovations need to be developed to keep pace with the increasing performance, speed, and frequency. Recently, the FCC has permitted licensing of ultrawideband (UWB) devices for a wide variety of commercial applications. The market for UWB technology is growing rapidly. The time-domain free-field project is developing the measurement techniques needed to support this new technology.

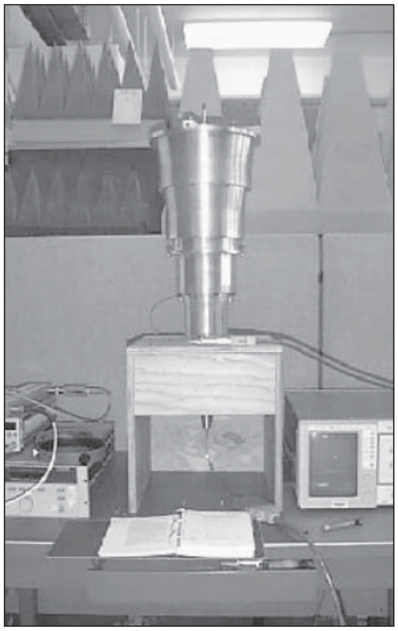
TECHNICAL STRATEGY

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, to evaluate shielding performance of materials, and to investigate 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 a co-conical field generation system, a closed-system test cell capable of testing small antennas, sensors, and probes from 10 MHz to 45 GHz. 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. 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, measurements. In addition, we are continually engaged in advancing the characterization of and reducing the measurement uncertainties of our systems.

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

Technical Contact:
Robert T. Johnk

Staff-Years (FY2002):
4.0 professionals
0.5 technicians



Prototype Co-Conical Field Generation System.

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

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. We have demonstrated and developed a portable ultrawideband measurement system for evaluating the performance of EMC measurement facilities.

Faster information technology equipment and wireless advances have 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, we 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.

This facility will be capable of generating standard fields from 30 MHz to 18 GHz and will 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.

Deliverables

- Complete upgrade of the NIST cone and ground-plane time-domain measurement facility. (FY2003)
- Develop a rapid OATS evaluation measurement system that covers the frequency range from 30 MHz to 6 GHz. (FY2003)
- Complete development of a co-conical field generation system. (FY2004)

- Develop full-bandwidth, precision time-domain measurement system for free-field ultra-wideband emissions measurements. (FY2004)
- Assessed the effects of equipment shelters on OATS facilities using time-domain measurement systems.

FY2002 Accomplishments

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

- A feasibility study on using time-domain methods to measure the shielding performance of commercial aircraft has been completed.

- An evaluation of an equipment shelter used on an OATS has been completed using a NIST-developed ultrawideband measurement system.

- Full-bandwidth measurements of selected commercial ultrawideband devices were performed. The effort was jointly carried out with ITS/NTIA. This work was a key component in understanding potential interference effects of ultrawideband radio and other devices on existing radio services such as GPS and airport navigation systems.

- Robert Johnk convened the ANTCAL working group meeting at the September 2002 meeting of CISPR held in Christchurch, New Zealand. ANTCAL will develop site-qualification measurement techniques for antenna and compliance test sites. This work will be incorporated into future revisions of CISPR-16.

- Numerical modeling support was provided to ANSI working group 1-15.6, which will revise the ANSI C63.5 standard on antenna calibrations.

- A time-domain site attenuation evaluation technique was applied to a commercial EMC compliance chamber. The system was successfully used to assess improvements in performance after retrofitting a chamber.

- The NIST-developed time-domain measurement technology was used to evaluate the penetration of electromagnetic radiation into commercial aircraft. The FAA sponsored this effort.

- Completed a feasibility study of the co-conical field generation system. A full turnkey facility development has been designed. This system will be used as a standard-field generation system for probe calibrations in the frequency range from 10 MHz to 45 GHz. The U.S. Air Force currently sponsors this effort.

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

Recent Publications

C. Grosvenor, R. Johnk, D. Novotny, N. Canales, and J. Veneman, *"A Two-phase Airframe Shielding Performance Study Using Ultrawideband Measurement Systems,"* to be published as NISTIR, Winter, 2002.

C. Grosvenor, D. Novotny, R. Johnk, N. Canales, J. Veneman, *"Shielding Effectiveness Measurements Using the Direct Illumination Technique,"* Proc. IEEE Int. Symp EMC Minneapolis, MN, pp. 389-394, Aug. 2002.

J. Veneman, D. Novotny, C. Grosvenor, R. Johnk, and N. Canales, *"Ultrawideband Antenna Characterization in a Non-ideal EM Facility,"* Proc. 2002 AMTA Symp. Cleveland, OH, Nov. 2002.

C. Grosvenor, D. Novotny, J. Veneman, and N. Canales, *"Improving Antenna Design Using Numerical Methods,"* Proc. 2002 AMTA Symp. Cleveland, OH, Nov. 2002.

C. Weil, D. Novotny, R. Johnk, and A. Ondrejka, *"Calibration of Broadband RF Field Probes Using a Coaxial Transmission Line,"* Proc. MIKON 2002, Gdansk, Poland, pp. 404-407, May 2002.

R.T. Johnk and D.R. Novotny, *"Characterization of Ultrawideband Emissions Using a Time-Domain Measurement System,"* 2001 AMTA Symposium, Denver, CO, October 21–26, 2001.

D. R. Novotny, R. T. Johnk, C. M. Weil, and N. Canales, *"Time- and Frequency-Domain Analysis of EMC Test Facilities,"* 2001 AMTA Symposium, Denver, CO, October 21–26, 2001.

C.M. Weil, N.R. Novotny, R.T. Johnk and A. Ondrejka, *"A New Broadband RF Field Standard using a Coaxial Transmission Line of Conical Geometry: Progress Report,"* 2001 AMTA Symposium, Denver, CO, 21-26 October 2001.

C.M. Weil, N.R. Novotny, B. Riddle and R.T. Johnk: *"Modal Cutoff in Conical Waveguides."* Microwave and Wireless Components Letters, September 2001.

R.T. Johnk, N.R. Novotny, C.M. Weil and N. Canales, *"Efficient and Accurate Testing of EMC Compliance Chamber using an Ultrawideband Measurement System,"* 2001 IEEE EMCS Symposium, Montreal, Canada, August 13–17, 2001.

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

R.T. Johnk, D.R. Novotny, and C.M. Weil, *"Evaluation of an EMC Compliance Chamber using an Ultrawideband Measurement System,"* Proc., 2000 AMTA Symposium, held in Philadelphia, PA, October 16–20, 2000; pp 321-326.

R.T. Johnk, D.R. Novotny, and C.M Weil, *"Assessing the Effects of an OATS Shelter: Iis ANSI C63.7 Enough?"* Digest, IEEE Int. Symp. Electromagnetic Compatibility, Washington D.C., Aug. 21–25, 2000, pp. 523-528.

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.

Electromagnetic Compatibility Emissions and Immunity Metrology

Technical Contact:
Galen H. Koekpe

Staff-Years (FY2002):
3.0 professionals
0.5 technician

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.

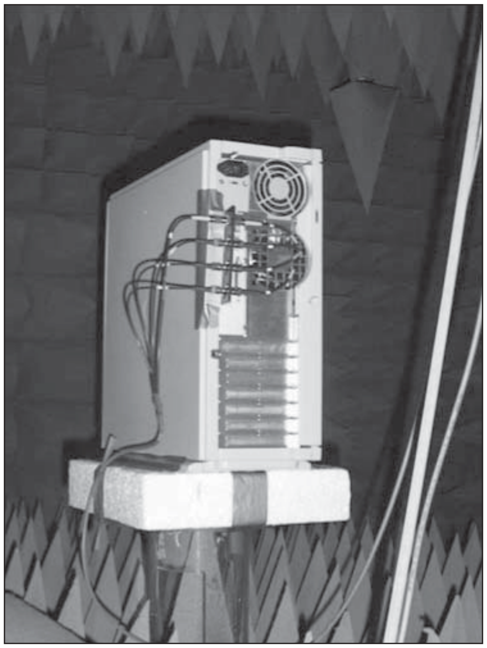
Customer Needs

U.S. industry must evaluate and control electromagnetic interference (EMI) that may impact 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.

John Ladbury tests a large number of biomaterial phantoms in a reverberation chamber. The effect of biomaterial loading on RF field uniformity is being investigated. © Geoffrey Wheeler

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 testing radiated electromagnetic field 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 EMC reverberation chamber. NIST research is on the leading edge in the development of theory and test techniques for reverberation chambers. We will develop and propose to standard committees 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 experiments in bioelectromagnetic exposure. We will evaluate the loading effect of biological (phantom) materials on performance reverberation chambers and evaluate the use of reverberation chambers for exposing phantoms to controlled RF fields.

Most EMI/EMC measurements have large uncertainties from to many sources, including insufficient sampling of the radiated fields, poor field uniformity, device-under-test directivity, 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 of 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.

Deliverables

- Complete study on the effect of loading on reverberation chamber statistics. (FY2003)
- Complete study on the use of a reverberation chamber for the calibration of multiple probes. (FY2003)
- Develop method for evaluating a reverberation chamber using a single antenna. (FY2004)

FY2002 Accomplishments

- Completed extensive measurements of electromagnetic coupling into a small (on the order of a cubic meter) metal box with a variety of different apertures. These measurements were designed to investigate the effects of aspect angle, internal changes in boundary conditions (using an internal mode tuner), and polarization on the coupling characteristics. These data are intended to simulate radio-frequency (rf) energy coupling into aircraft and other shielded structures. One application of these data will be to validate statistical processing techniques for measurements on airframe shielding.

- Completed extensive measurements of the effects of lossy dielectric loading in a reverberation chamber. The data will be used to quantify the changes in field uniformity and power requirements for various possible biological phantom test configurations.

- Completed measurements of a series of composite materials using a nested reverberation chamber. Developed a more complete theory to account for the aperture effects in the determination of the shielding effectiveness of the materials.

- Completed a series of measurements using multiple radiators in a GTEM, TEM, anechoic, and reverberation chamber. This effort was to examine emissions correlation techniques for different facilities.

- Extended a statistical theory for the directive gain of unintentional electromagnetic sources and suggested a technique for predicting maximum radiation from the average of a limited number of measurements. This approach could have an impact on the reliability and cost of emissions compliance tests, especially at higher frequencies.

Recent Publications

C.L. Holloway, R. Garzia, J. Ladbury, D. Hill, and G. Koepke, *"Nested Reverberation Chamber Measurements for the Shielding Effectiveness of Advanced Composite Materials,"* Proc. EMC Europe 2002: Internat. Symp. on Electromag. Compat., September 9-13, Sorrento, Italy, 2002, pp. 895-899.

C. L. Holloway, D. Hill, J. Ladbury, G. Koepke, R. Garzia, *"Shielding Effectiveness Measurements of Materials in Nested Reverberation Chambers,"* IEEE Trans. on Electromag. Compat., vol. 45, no. 1, 2003.

J. M. Ladbury, T. H. Lehman, and G. H. Koepke, *"Coupling to Devices in Electrically Large Cavities, or Why Classical EMC Evaluation Techniques are Becoming Obsolete".* 2002 IEEE Intl. Symp. EMC., Aug 19-23, 2002, Minneapolis, Minnesota.

J. M. Ladbury and D. G. Camell, *"Electrically-Short Dipoles with a Nonlinear Load Revisited."* Invited paper. IEEE Trans. Electromagn. Compat., Vol. 44, N0. 1, pp. 38-44, Feb. 2002.

D. A. Hill and J. M. Ladbury, *"Spatial Correlation Functions of Fields and Energy Density in a Reverberation Chamber."* Invited Paper. IEEE Trans. Electromagn. Compat., Vol. 44, N0. 1, pp. 95-101, Feb. 2002.

P. Corona, J. Ladbury, G. Latmiral, *"Reverberation-Chamber Research Then and Now: A Review of Early Work and Comparison with Current Understanding"* Invited Paper. IEEE Trans. Electromagn. Compat., Vol. 44, N0. 1, pp. 87-94, Feb. 2002.

P.F. Wilson, J.M. Ladbury, G.H. Koepke, *"A Pseudo-Isotropic Source for Anechoic Chamber Qualification."* 2002 IEEE Intl. Symp. EMC, Aug 19-23, 2002, Minneapolis, Minnesota.

P.F. Wilson, C.L. Holloway, G.H. Koepke, J.M. Ladbury, A. Ondrejka, R.T. Johnk, K.D. Masterson, D.G. Camell, *"EMC Research at NIST, Boulder,"* IEEE EMC Society Newsletter, Summer 2002.

P.F. Wilson, G. Koepke, J. Ladbury, and C.L. Holloway, *"Emissions and Immunity Standards: Replacing Field-at-a-Distance Measurements with Total-Radiated Power Measurements,"* Proc., IEEE EMC Symp., 13-17 August 2001, Montreal, Canada, pp 964-969.

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.

Appendix A: Radio-Frequency Technology Division Calibration Services

The Radio-Frequency Technology Division provides a number of for-fee calibration services for RF and microwave standards. Below is a listing of those services conducted by the Division, with the technical contacts. More information can be found in the NIST Calibration Services User's Guide SP250, available from the Calibration Program at NIST, (301)-975-2002, calibrations@nist.gov, or on the web at www.ts.nist.gov. A fee schedule is also available at the website.

Information about the availability and shipping requirements for Radio-Frequency Technology Division services may be obtained from Puanani DeLara, (303) 497-5284.

High-Frequency Standard Capacitors and Inductors
George M. Free 303-497-3609

Q-Standards
George M. Free 303-497-3609

RF-DC Thermal Voltage and Current Converters
George M. Free 303-497-3609

Thermistor Detectors
Ronald A. Ginley 303-497-3634
John R. Juroshek 303-497-5362

Scattering Parameters of Passive Multi-Port Devices
Ronald A. Ginley 303-497-3634
John R. Juroshek 303-497-5362

Thermal Noise Measurements
James Randa 303-497-3150

Dimensional Verification of Coaxial Air Line Standards
George M. Free 303-497-3609

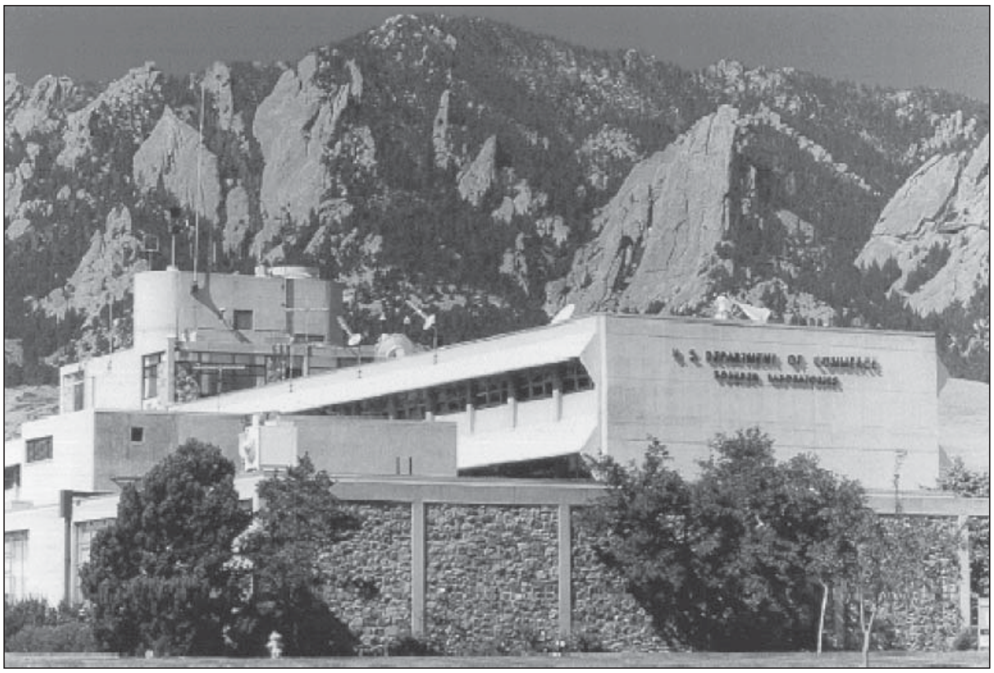
Dielectric and Magnetic Material Measurements
Jim Baker-Jarvis 303-497-5621

Microwave Antenna Parameter Measurements
Katherine MacReynolds 303-497-3471

Field Strength Parameter Measurements
Dennis Camell 303-497-3214

Appendix B:
NRC Post-Doctoral Research Opportunities

NIST offers post-doctoral research associateships in collaboration with the National Research Council (NRC). Research topics and associated advisors for the Radio-Frequency Technology Division are listed below. Complete information and applications forms for all NIST NRC post-doctoral offerings are available at www.nas.edu/rap/ (click on "RAP SEARCH"). Contact a prospective advisor to discuss details of proposed work and the application process. If you do not find a topic that exactly matches your interest, please contact an advisor in a similar discipline. U.S. citizenship is required for NRC post-doctoral appointments.



NIST's Boulder laboratories are located adjacent to the eastern foothills of the Rocky Mountains.

Antenna Theory and Measurements

Contact: RC Wittmann 303-497-3326

A "scattering matrix description of antennas and antenna-antenna interactions" has been developed and successfully applied by researchers in this Division. Radiated fields are determined from measurements made in the near-field of the antenna under test, and the theory is suitable for describing antenna interactions at arbitrary distances (not just in the far-field region). Measurement techniques (and supporting theory) must continuously be extended to keep pace with the rapid advancement in antenna design and application. Topics that need attention include (1) better accuracy — high performance systems, especially those that are satellite based, require maintenance of tighter tolerances; (2) higher frequencies — more sophisticated near-field measurement methods are needed to handle millimeter-wave applications (up to 500+ GHz); (3) complex phased-array antennas — large, often electronically steerable, phased arrays need special diagnostic tests to ensure optimum functionality; (4) low sidelobe antennas — military and commercial communication applications increasingly specify sidelobe levels 50 dB or more below peak, a range where measurement by standard technique is difficult; (5) *in situ* (or remote) evaluation — many systems cannot be transported easily to a measurement laboratory; robust methods are needed for on-site testing; and (6) multiple reflections — methods are needed to mitigate errors caused by multiple reflections between the probe and test antenna. Research facilities include two planar near-field scanners, a multipurpose range for cylindrical and spherical antenna measurements, a precision extrapolation range, an anechoic chamber, a ground screen, and other EM experimental facilities, as well as excellent computational resources. We welcome proposals in these or in related areas that extend or improve the application of near-field antenna measurement methods.

Antenna Theory and Measurements II

Contact: RC Wittmann 303-497-3326

In spherical near-field scanning, probe pattern information and data measured at points on a spherical surface are used to determine the fields of a test antenna anywhere beyond the measurement radius (especially in the far-field zone). Although the theory is well understood, a number of areas need further work, including (1) development of more efficient measurement and computation methods; (2) analysis of, and correction for, measurement errors; (3) practical pattern correction schemes for general probes; (4) development of a simplified theory for the "quasi-far-field region" where measurements are "almost" made in the far field; and (5) extensions of near-field antenna theory to other applications such as acoustics, field synthesis, and the evaluation of far-field (compact range) measurement systems. We welcome proposals on these and other topics that extend or improve the application of spherical near-field measurement techniques.

Theory for Electromagnetic Interference Problems

Contacts: DA Hill 303-497-3472
CL Holloway 303-497-6184

Theoretical research is conducted on both forward and inverse problems in electromagnetics (EM). To characterize complex EM interference environments, a wide variety of forward problems in antennas, propagation and scattering, need to be solved. Inverse source techniques are studied to synthesize near-field antenna arrays for use in EM susceptibility testing. Inverse-scattering techniques are of interest for nondestructive evaluation of various materials. Both frequency-domain and time-domain techniques are applicable, and statistical methods are used for characterizing complex EM environments and test facilities, such as reverberation chambers. In addition to superb computational resources, excellent experimental facilities are available for verifying theoretical work. These include: a time-domain range; a reverberation chamber; an anechoic chamber; TEM cells; a ground screen; planar, cylindrical and spherical near field scanning ranges; and an extrapolation range.

Remote *In Situ* Measurements of Large Array Antennas

Contacts: RC Wittmann 303-497-3326
MH Francis 303-497-5873

Future space-borne adaptive arrays will have the capability to adapt the element excitations to compensate for failed or incorrectly working elements. However, to compensate for faulty elements or other array problems, information must be obtained on the actual performance of the array, in its operational environment. New measurement methods need to be developed in order to obtain sufficient information to effect a diagnosis. These measurements will need to be performed remotely, accurately, and without the instrumentation normally available in laboratory facilities. Research is needed to determine the optimal methods to carry out these measurements. For example, a fundamental problem is whether to add a lightweight test fixture to the satellite or whether to make the measurements from the ground. Since these large adaptive arrays are intended to be high-performance antennas, an accuracy of a few degrees in phase and a few percent in amplitude is necessary. This important problem provides a range of challenging research topics.

Electromagnetic Theory for Complex Environments

Contacts: PF Wilson 303-497-3406
DA Hill 303-497-3472

Most research and metrology focused electromagnetic field measurements seek to create a simple and well-defined environment. However, real electromagnetic environments are typically complex and poorly defined. Multiple sources and scattering objects (possibly unknown or nonstationary), complicated geometries, proximity coupling, and other real world complications make electromagnetic field measurements difficult to interpret. Statistical electromagnetic approaches are needed to quantify both real environments and complex system responses. This need already exists for large systems (e.g., avionics, interconnected electronics) and the requirement will move to the component level as frequencies of operation continue to move higher (e.g., high speed computers, digital wireless systems). Research opportunities exist for developing statistical electromagnetic models. Applications include: reverberation chamber test methods, coupling to complex systems, shielding of ill-defined geometries, radiation from statistically defined sources, propagation in non stationary environments, and characterization of complex EM environments. The goal is to develop analytical descriptions for the statistics of these environments. Numerical modeling and Monte Carlo techniques will be used to verify analytical models. Excellent experimental facilities exist to generate measured data for comparison with theoretical and simulation results.

Indoor Radio Frequency Propagation Characterization for Broadband Wireless: Modeling and Measurements

Contact: CL Holloway 303-497-6184

Research for accurate characterization of general indoor propagation environments is important for the design of future wireless communications systems. It is essential to understand the efficacy of broadband wireless communications systems in office complexes and other types of building environments. The indoor radio propagation channel is a very complicated environment with a variety of propagation issues that must be defined and understood. Our research objective is to develop competence in the area of indoor and indoor-to-outdoor radio propagation, and the effects on wireless communications systems. A particular goal is to develop propagation models that will address the needs of the telecommunications industry as related to the design of state-of-the-art wireless systems that can be utilized in indoor environments. This will generally be accomplished by developing theoretical models and then designing and carrying out experiments for the purposes of characterizing the indoor radio frequency (RF) propagation environment. This will lead to analytical tools that can be used by wireless system designers. Advanced computational tools, as well as excellent electromagnetic measurement facilities and instrumentation are available for experimentation. Topics that need attention include coupling of energy into building structures, propagation characterization of building materials, modeling of RF propagation into and within building structures, and measurements techniques for characterizing building environments.

Theoretical Development of Equivalent Generalized Impedance Boundary Conditions

Contact: CL Holloway 303-497-6184

The interaction of electromagnetic fields with rough surfaces, composite materials, thin coatings, frequency selective surfaces, and particle scattering are a few of the challenging problems of current theoretical interest. Scattering problems of this type are complicated and usually require numerical techniques. However, when the detailed surface features (roughness dimension, fiber dimensions in composites, coating thickness, scattering shapes in FSS, and particle spacing) are small compared to a wavelength, equivalent generalized impedance boundary conditions (EGIBC) can be used. These EGIBC and Maxwell's equation are all that is needed to solve these types of scattering problems. EGIBC are also very efficient in analyzing reflection problems. For example, in large electromagnetic computational codes, the use of EGIBC can eliminate the need to spatially resolve the fine detail of a particular scattering feature, which results in the abilities to solve much larger numerical problems. The proposed research direction is to use various asymptotic techniques to derive EGIBC for various electromagnetic field interactions. Specific boundary conditions will be derived so that the coefficients in the EGIBC can be interpreted in terms of electric and magnetic polarizability densities.

Fundamental Modeling for Electromagnetic Compatibility

Contact:	CL Holloway	303-497-6184
	DA Hill	303-497-3472

Analytic and numerical investigations are needed on a broad range of topics related to electromagnetic compatibility (EMC) and electromagnetic interference (EMI). The particular numerical models of interest are finite-difference time-domain, finite-elements, integral equations, and hybrid techniques. Suggested topics include printed circuit board radiation, signal integrity and coupling of high-speed digital lines and devices, lossy transmission lines, characterization and optimal design of large test facilities (e.g., reverberation, anechoic, and semi-anechoic chambers), properties of electromagnetic absorbing materials, design of advanced composite and frequency selective materials, shielding effectiveness of various materials, and other coupling problems. The broad objective is to develop accurate analytic and numerical models that will advance the fundamental understanding of critical EMC/EMI issues. Extensive measurement facilities are also available with which to assess the validity of the resulting models.

Electromagnetic Theory for Time-Domain Analysis

Contact: RT Johnk 303-497-3737

The transient behavior of both canonical and complex objects subjected to an electromagnetic (EM) impulse from a radiating source is studied. Although transient problems can be analyzed by inverse Fourier-transformation of frequency-domain data, the time-domain technique has several advantages over the frequency-domain technique. The broadband nature of time-domain analysis facilitates the understanding of nonlinearities, and the ability to model propagation delays provides improved physical insights related to the spatial geometry of the problem. Problems of both radiation and scattering from complex structures with both linear and nonlinear loadings are appropriate topics for study. The theoretical and experimental results will be applied to canonical problems to provide useful physical insights into the interaction of EM waves with devices and materials.

Electro-optical Technology for Electromagnetic Field Measurements

Contact: KD Masterson 303-497-3756

This research focuses on developing electromagnetic (EM) field probes based on electro-optical technology and optical fiber links. Such systems provide amplitude and phase information for high-frequency EM fields throughout the radio spectrum, cause minimum distortion of the field, and are immune from EM pickup and interference in the antenna leads. They increase the accuracy and information available for characterizing EM fields. Research opportunities exist in the areas of electro-optic modulators, modulated lasers, optical fiber links (including polarization effects and controllers), and related theoretical and experimental physics. Facilities include an electro-optic probe development laboratory and extensive EM-field test facilities for experimental characterization of probes, as well as opportunities for collaborative resources in electro-optics and, computational and applied mathematics.

Performance Characterization of Wireless Systems

Contact: RB Marks 303-497-3037

This topic concerns the development and application of an experimental facility for characterizing the performance of wireless systems and the dependence of such performance on components, subsystems, modulation, propagation, interference, and other factors. The interest is primarily in the characterization of fixed broadband wireless access systems from 2-40 GHz. Strong opportunities exist in correlating radio-frequency (RF) component characterizations to system performance. Other innovative research is also possible, particularly in testbed design and system simulation. A broad range of related measurement facilities, expertise and other resources will be available to the researcher, and close correlation with industry and with standards-developing bodies is encouraged.

RF Characterization of Nonlinear Devices

Contacts: DC DeGroot 303-497-7212
RB Marks 303-497-3037

Nonlinearity is an important design issue and the development of a general measurement-based theory for characterizing nonlinearities is a critical need, particularly with regard to wireless telecommunications systems. Nonlinear properties of devices are difficult to accurately model, but are also challenging to measure. Our present goal is to quantitatively characterize weakly nonlinear two-port networks (typically power amplifiers) in order to predict circuit parameters (e.g., power, gain, efficiency, intermodulation, distortion) under a variety of terminal conditions. Instrumentation for nonlinear characterization, nonlinear network theory, and calibration are essential elements of this measurement task. Excellent resources will be available to the researcher including: the first non-proprietary nonlinear network analyzer, highly accurate (linear) on-wafer and conventional measurement capabilities, microcircuit fabrication facilities, state-of-the art computational resources and on-site expertise in a diverse range of related disciplines.

Microwave Power Measurement

Contact: TP Crowley 303-497-4133

New, accurate, and absolute techniques for measuring microwave power need to be developed. NIST presently has a series of standards that operate at 10 mW and cover frequencies up to 50 GHz in coaxial line and 110 GHz in waveguide. The standards consist of bolometric transfer standards and microcalorimeters that are used to determine the bolometer efficiency. Typical standard uncertainties are less than 1%. Research is needed to extend measurements to higher frequencies in order to meet demands from communications, space, and radar applications. In addition, as systems become more integrated onto a single wafer and as transmission line losses increase at higher frequencies, it will be necessary to measure microwave power on wafer. This will require new detection principles and methods for transferring known quantities from reference standards. A wide range of microwave components, sources, and existing standards are available for experimental research. In addition, NIST has in-house capabilities for making integrated circuits for research, as well as excellent computational and collaborative resources.

Noise Measurements on Wafer

Contact: J Randa 303-497-4150

Theory, standards, methods, and systems are developed for highly accurate measurements of thermal electromagnetic noise throughout the radio spectrum. Current research focuses on developing improved methods for characterizing the noise properties of low-noise amplifiers, and on developing methods for making accurate on-wafer measurements of noise temperature. Our goal is to combine these two efforts to develop accurate methods for on-wafer measurements of noise characteristics (e.g., the noise figure) of low-noise devices. Research opportunities are supported by extensive theoretical and experimental expertise, as well as world-class noise-temperature measurement capabilities.

Electromagnetic Properties of Materials

Contact: JR Baker-Jarvis 303-497-5621

Research opportunities exist for theoretical and experimental investigations related to the precise characterization of the electromagnetic properties of bulk and thin-film materials in the frequency range of 100 MHz–100 GHz. Suggested research areas include the measurement of ultra low-loss dielectric and magnetic materials, thin films, ferroelectric materials, the uncertainty analysis of measurement techniques, the relationship of complex permittivity to material mechanical stress, linear and nonlinear response theory, maximum-entropy methods for data reduction and optimization, dielectric measurements of liquids, characterization of HTS film, and biased ferrite and ferroelectric measurements. In addition to excellent computational resources, a wide range of experimental resonators, well characterized materials, laboratory instrumentation, environmental facilities (a cryostat, a high-temperature chamber, a magnetic bias capability, etc.), and a diversity of related intellectual resources are available to facilitate research.

On-Wafer Microwave Measurements and Standards

Contacts: DF Williams 303-497-3138
P. Kabos 303-497-3997

Research opportunities exist for theoretical and experimental studies of wafer-level microwave measurement techniques in the frequency range of 50 MHz–110 GHz. Work focuses on the on-wafer measurement of S-parameters, power, and noise parameters, including the development of new measurement methodologies, modeling and analysis of single and coupled planar transmission lines, and process development. Unique opportunities exist to compare both the theoretical and experimental results.

Characterization of High-Speed Digital Interconnects and Signals

Contacts: DF Williams 303-497-3138
P. Kabos 303-497-3997

This project provides unique opportunities for theoretical and experimental studies of high-speed digital interconnects. Current research focuses on adapting microwave measurement methods to the characterization of conventional, differential, and coupled differential transmission lines fabricated on silicon substrates. This research has strong relevance to industry, and collaborators will have access to measurement equipment at frequencies beyond 40 GHz. Noncontacting measurements for digital at-speed tests are another current interest.

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