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ELECTRONICS AND ELECTRICAL ENGINEERING LABORATORY

1998 PROGRAM PLAN

Electronics and Electrical Engineering Laboratory

U.S. DEPARTMENT OF COMMERCE
Technology Administration
National Institute of Standards and Technology
Electronics and Electrical Engineering Laboratory

January 1998

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EEEL SEEKS YOUR COMMENTS

The Electronics and Electrical Engineering Laboratory (EEEL) reviews its plans regularly to keep them focused on the most important measurement needs of the U.S. electronics, electrical-equipment, and electric-power industries. Comments on this plan are invited and should be sent to the following address:

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U.S. DEPARTMENT OF COMMERCE
William M. Daley, Secretary

TECHNOLOGY ADMINISTRATION
Gary R. Bachula, Acting Under Secretary for Technology

NATIONAL INSTITUTE OF STANDARDS AND TECHNOLOGY
Raymond G. Kammer, Director

Bibliographic Information

Abstract

This program plan provides a detailed description of the important work that the Electronics and Electrical Engineering Laboratory at the National Institute of Standards and Technology is undertaking to provide measurement capability for U.S. industry. This measurement capability underlies the development, manufacturing, marketing, and after-sales support of new products in industry. The services provided by this program further U.S. economic growth and strengthen U.S. competitiveness in international markets.

The Electronics and Electrical Engineering Laboratory focuses on measurement capability needed especially by the electronics industry, the electrical-equipment industry, and the electric-power industry. This measurement capability also serves government, educational institutions, and the public broadly, either as users of that capability or as customers for the products and services of the supported industries.

Keywords

commercialization of technology; economic growth: electrical-equipment industry; electric-power industry; electronics industry; international competitiveness; measurement capability; metrology

PREFACE

This document is an integral part of a set of planning documents developed by the Electronics and Electrical Engineering Laboratory (EEEL). These documents cover five principal subjects, listed here in the order in which they are employed in EEEL's planning process: (1) an assessment of industry's measurement needs, (2) the strategic plan for responding; (3) the program plan for realizing the goals of the strategic plan through specific technical efforts (this document); (4) the technical accomplishments resulting from completed work; and (5) the economic impact of those accomplishments.

This program plan is composed of an overview followed by descriptions of the twelve programs that EEEL addresses. The overview describes the mission, customers, deliverables, resources, structure, and other basic dimensions of the overall EEEL effort in support of U.S. industry. Additional details on these subjects are included in the strategic plan referenced above. Each of the twelve programs described in the program plan, such as "semiconductors" or "lightwaves" (including optoelectronics), is responsive to the measurement needs of a selected field of technology. Most of these fields of technology are associated with specific product categories in industry. The other fields of technology, such as "electromagnetic compatibility" and "national electrical standards", are cross-cutting in nature because they support many product categories. The programs are broken down into projects. The projects may run for a few years or for many years, depending on their complexity. Each project is described in detail. Project descriptions include objectives, background information, resources, the specific tasks addressed, and the milestones required to complete these tasks. These descriptions look both forward and backward in time in order to set the current work in context.

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OVERVIEW

OVERVIEW

EEEL's mission is to promote U.S. economic growth by providing measurement capability of high economic impact focused primarily on the critical needs of the U.S. electronics, electrical-equipment, and electric-power industries, and their customers and suppliers. In fulfilling this mission, EEEL strives to provide leading-edge capability supportive of each of the major steps required to realize competitive products in the marketplace: research and development, manufacturing, marketplace exchange, and after-sales support. EEEL focuses especially on the role of competitiveness in economic growth. Good measurement support is essential for accelerating the commercialization of technology, a primary requirement for improved U.S. competitiveness. In particular, EEEL provides the fundamental basis for all electrical measurements conducted in the United States.

CUSTOMERS

Because of EEEL's primary focus on U.S. industry and its competitiveness, most of EEEL's customers are from industry. When EEEL last completed a comprehensive analysis of its customer base in 1991, about 72 percent of EEEL's customers were from U.S. industry. About 50 percent of the industrial customers were large businesses with over 500 employees, 38 percent were small businesses with 20 to 500 employees, and 12 percent were small businesses with fewer than 20 employees. About 20 percent of the Fortune 500 companies were included in EEEL's customers.[1]

EEEL's customers also include: other government agencies (Federal, state, and local); educational institutions; the research community, whether located in industry, government agencies, educational institutions, or non-profit organizations broadly; and, indirectly, the general public through services to the organizations already named. The measurement capability and other services that EEEL provides to Federal, state, and local agencies help them to fulfill their many responsibilities in areas such as defense, energy, transportation, communications, health, safety, environment, and law enforcement. The characteristics of EEEL's primary industry customers -- the electronics industry, the electrical-equipment industry, and the electric-power industry -- are discussed below.

Electronics Industry

Among U.S. manufacturing industries, the electronics industry is the largest employer with 1.7 million employees, as shown in Table 1. The electronics industry and the chemical industry have the largest values of shipments, each over $300 billion per year.[2]

Table 1: LARGEST U.S. MANUFACTURING INDUSTRIES (1995)

Industry	Shipments ($billions)	Employment (thousands)
Electronics[2(a)]	385	1,737
Chemical[2(b)]	333	812
Automotive[2(c)]	324	956
Petroleum Refining[2(d)]	129	72 (1994)
Aerospace[2(e)]	95	495

The electronics industry produces a broad spectrum of products. This spectrum is outlined in Table 2, using a condensed version of the structure employed by the industry itself through the Electronic Industries Association.[3] In addition, electronic products are built into the products of many other industries, including, for example, virtually all manufacturing equipment, motor vehicles, and aerospace products. Thus, the electronics industry exerts extraordinary influence on the performance of every other U.S. industry.

While the U.S. electronics industry is a strong one, it has been battling for market share in increasingly competitive international markets. There are several indicators of the intensity of this competition. However, those indicators suggest an improvement in 1995 relative to 1994, although the data for 1995 are still estimates. U.S. shipments increased from 1994 to 1995 by 17 percent in nominal terms, the largest increase in many years. Employment increased but only slightly. Trade, for which we have more recent data, showed an improvement, too. The balance of trade remained unfavorable for 1996 but less so than for 1995 and about the same as for 1994. For the seven broad categories of electronic products shown in Table 2 (exclusive of "Other..."), the balance of trade for 1996 remained negative for three and positive for four, as in 1995.[4]

Table 2: ELECTRONIC PRODUCTS

Electronic Components
- electron tubes
- solid-state components
- passive components

Consumer Electronics
- television and other video
- audio
- mobile
- home information
- media

Telecommunications Equipment
- commercial, industrial, military
- broadcast, studio, and related
- telephone and telegraph

Defense Communications
- search and detection
- navigation and guidance

Computers and Peripheral Equipment
- computers
- storage
- input/output
- terminals

Industrial Electronics
- controls
- processing
- industrial process display and control instrumentation
- test and measuring equipment

Electromedical Electronics

Other Related Products and Services

Electrical-Equipment Industry

The U.S. electrical-equipment industry is smaller than the U.S. electronics industry but is still quite large. EEEL has not estimated its size recently but expects it be the better part of $100 billion per year in 1997.[5]

The products of the electrical-equipment industry are outlined in Table 3, where they are arranged by the basic services that they provide. Included in this outline, among other products, are all of the electrical products used by the electric-power industry. Automobiles, too, rely heavily on electrical equipment, accounting for about 14 percent, by dollar value, of all electrical equipment shipped in the United States.[6]

Like the electronics industry, the electrical-equipment industry is also struggling against strong competitors in many market segments. This competition manifests itself both in small-scale products, such as tiny electric motors, and in large-scale products, such as electric-power generation and transmission equipment.

Electric-Power Industry

The U.S. electric-power industry is composed of the electric utilities, both private and public, and the independent suppliers of electricity. This industry is one of the largest industries in the United States. Electricity sales are $208 billion per year (1995)[7], and the industry employs 441 thousand people (1995).[8] If the electric-power industry were compared with the manufacturing industries in Table 1, its output would fall between the third largest (automotive) and fourth largest (petroleum refining).[9]

At present the electric-power industry is undergoing major changes as it encounters deregulation and domestic competition for the first time. These changes are giving rise to new measurement needs.[10]

An example of these changes is the emergence of transmission systems as common carriers, shared by multiple and competing suppliers.

Electricity plays an essential role in the manufacture of the vast majority of products. In fact, about 1.3 percent of the value of the products of all manufacturing industries in the United States is attributable to the cost of the electricity used in making them (1994).[11]

Table 3: ELECTRICAL PRODUCTS
Electrical Supply Equipment
generation
generators
transfer
transformers
insulation
wire
wiring devices
control
switchgear
relays and controls
storage
storage batteries
primary batteries
Electrical Conversion Equipment
motion
motors
light
lighting devices
heat
electrodes and spark elements
electrolytic action
electrolytic elements

Competitiveness

There are many factors that bear on the competitiveness of these industries: social, economic, and technical. Among the technical factors is the need for improved measurement capability. NIST has been a major force in this area and will continue to be. NIST's assistance has been strongly demanded by industry in many areas. An example is the additional measurement capability that industry needs to meet conformity requirements, such as electromagnetic compatibility, in order to gain market access.

Simply stated, both the electronics industry and the electrical-equipment industry are outstripping the measurement capability required for international competitiveness. Affected are such important factors such as product performance, price, quality, compatibility, time to market, and implementation of new management strategies, such as concurrent engineering and just-in-time manufacturing.

Similarly the electric-power industry needs new measurement capability to stream-line its generation and delivery methods for electricity to cope with intensifying domestic competition and to realize the aims of deregulation.

DELIVERABLES

EEEL provides three major classes of deliverables. They are listed in Table 4 and are discussed below. EEEL provides measurement capability needed to support the efforts of U.S. industry to improve its competitiveness. EEEL engages in technology development and fundamental research, and EEEL makes the findings available to industry. Each of these categories of deliverables is discussed further below.

Table 4: DELIVERABLES
Measurement Capability
absolute accuracy
reproducibility
materials reference data
Technology Development
Fundamental Research

Measurement Capability

EEEL focuses the largest part of its resources on the development and delivery of measurement capability for two principal reasons:

Measurement capability has very high impact on U.S. industry because measurement capability supports manufacturers in addressing so many of the challenges that they face in realizing competitive products in the marketplace. A detailed discussion of the dependence of competitiveness on measurement capability is provided in Chapter 1 of *Measurements for Competitiveness in Electronics*.[12]

NIST bears the official imprimatur of the U.S. Government as the lead agency for measurements.

EEEL focuses on developing measurement capability that is beyond the reach of the broad range of individual companies. Thus, EEEL does not develop measurement capability that companies can provide for themselves. Companies seek NIST's help for several reasons:

The companies need NIST's special technical capability for measurement development.

They need NIST's acknowledged impartiality for diagnosing a measurement problem affecting the industry broadly or for achieving adoption of a solution across the industry.

They themselves cannot develop measurement capability needed by the industry broadly because they cannot individually capture the returns of the cost of development.

Industry's quality standards require that key measurements be traceable to the national measurement reference standards that NIST maintains. This is a requirement of growing importance in export markets.

The reasons for NIST's involvement are reviewed in detail in Chapter 2 of *Measurements for Competitiveness in Electronics*.

Within the area of measurement capability, EEEL places its highest priority on delivering absolute accuracy. This emphasis reflects NIST's unique role as *the* national reference laboratory for measurements. Support for absolute accuracy may require a documented measurement method, a special measurement device, a reference standard to assure the accuracy of the measurement method, and a means of delivery such as a measurement assurance program or a calibration service.

EEEL places its second highest priority on delivering reproducible measurement capability. Reproducible measurement capability provides consistent measurements but does not by itself assure high absolute accuracy.

EEEL also develops reference data on the measured electronic properties of materials. EEEL undertakes this work if NIST's special measurement skills are needed for development, or if NIST's evaluation and imprimatur are needed for wide acceptance. However, when these special conditions do not apply, EEEL prefers to provide industry with measurement capability that industry can use to develop its own data, maximizing EEEL's leverage.

Technology Development

EEEL regularly engages in technology development that directly supports its measurement mission. For example, as part of developing or delivering new measurement capability, EEEL may find it necessary to build a special instrument or an integrated circuit that embodies the new capability.

EEEL transfers the technology realized in that instrument or circuit to the private sector, along with the associated measurement capability. Industry may modify the technology for incorporation in commercial products. Also, EEEL sometimes develops technology used for analyzing measured data. Examples include test strategies for complex electronic systems and expert-systems analyses for semiconductor process lines.

EEEL engages in only limited technology development that extends beyond its measurement mission. EEEL limits the fraction of its resources so applied to about 10 percent of the total. For a technology-development project to be undertaken, it must offer unusually high impact. Also, there must be specials reasons for EEEL to be the performer. For example, the project may have arisen from a fortuitous discovery at NIST, or it may require facilities or capabilities available only at NIST.

There are important reasons why EEEL limits the technology development that it undertakes outside of its measurement mission:

> EEEL generally finds that measurement development has the highest impact among the deliverables that it can provide.
>
> EEEL's funding level is far short of that required to meet all of the principal measurement needs of the U.S. electronics, electrical-equipment, and electric-power industries. Therefore, any technology development undertaken outside of the measurement mission reduces the level of measurement support that EEEL can provide to U.S. industry.
>
> Other programs exist to fund technology development, and some have considerable resources. Thus, the additional resources that EEEL could provide would not, in themselves, be significant.

Electronic data exchange is an example of a major technology-development project to which EEEL and other parts of NIST are contributing. This is a national effort. The national goal is the development of methods for codifying information to support multiple industrial needs. An important application is specifying products for manufacturing. EEEL's contributes objectivity to the broader effort focused on developing improvements in the infrastructure used for marketing electronic products. Even though this project is not focused on measurement development, EEEL's role has a measurement character: EEEL will develop methods for testing proposed schemes for data exchange.

Fundamental Research

EEEL defines fundamental research by the nature of the work conducted, not by the reason for undertaking it:[13]

> Fundamental research is the pursuit of the discovery or the understanding of the fundamental phenomena of nature.

EEEL conducts considerable fundamental research as an integral part of many of its measurement-development projects. This is not surprising, since new measurement capability is generally developed at the leading edges of science and technology. Further, EEEL endeavors to maintain a fundamental-research effort in every broad program area. Such research is an important means of nucleating pathbreaking measurement capability. For example, EEEL laid the bases for the present Josephson voltage standard with two successful theoretical inquiries: one on the interactions of series arrays of Josephson junctions, and the other on chaos in Josephson junctions.

Most of the fundamental-research projects that EEEL pursues are focused on topics likely to have outcomes benefitting measurement development for U.S. industry. That is, EEEL conducts *directed fundamental research*. EEEL does not bound the amount of directed fundamental research that it conducts to support its measurement mission. The amount conducted is determined by the needs of the individual projects pursued. For a given project, that amount may be 80 percent of project resources or next to nothing.

EEEL conducts some fundamental research that is not focused on immediate measurement needs. The criteria for identifying suitable projects are similar to those for technology development: unusual opportunity for high impact, and some special reason for EEEL to be the performer. Examples include EEEL's work on determining values for the fundamental physical constants, such as the fine-structure constant and the gyromagnetic ratio of the proton.

Table 5: MEANS OF DELIVERY

Communications	**FY97**
publications	254
software requests	197
talks	291
consultations	2100
visits	503
visitors	330
meetings	
attendees	1038
contributors	60
Joint Activities	
standards organizations	
staff participating	49
memberships	153
professional societies	
memberships	70
cooperative research	206
consortia (incl. forming)	6
guest scientists	130
Paid Services	
custom measurement development	119
standard reference materials	135
calibration service customers	275
training courses	20

MEANS OF DELIVERY

EEEL provides its deliverables by three principal means, as shown in Table 5: communications, joint activities, and paid services. FY 1996 levels of activity are shown in the table. These means of delivery involve regular interactions with industry, government agencies, and educational institutions. The interactions are essential to planning as well as to delivery. Over recent years, the levels of activity associated with the various means of delivery have varied up and down but generally not with distinct trends. An exception is a decrease in the number of customers for calibrations services. The cause, in part, is a reduction in military needs as downsizing has occurred and as the military has moved to industry standards and away from the MILSPEC standards that required calibrations directly from NIST. An examination of the workload on staff members indicates that they are operating at capacity in terms of the number of technology-transfer activities that they can handle.

RESOURCES

EEEL's funding and staff resources for FY 1997, the most recently completed year, are shown in Table 6. EEEL's funding is shown in two major categories: (1) the funds expended *in EEEL*, and (2) the funds expended *outside EEEL*. This second category represents the funds that EEEL transfers to other NIST laboratories for work supportive of its programs. For the funds expended in EEEL, the "NIST Funding" is provided by the Congress directly to NIST. The "Other Agency Funding" is transferred to NIST by other Federal agencies for the development of measurement capability supporting their programs. The "Other Funding" comes from multiple sources, including calibrations services provided to EEEL's customers. The funds expended outside EEEL but inside NIST are a combination of funds provided by the Congress directly to NIST and funds provided by other Federal agencies.

At the time this document was written, EEEL's funding levels for FY 1998 had not been determined; so no funding information for that year has been provided here.

Table 6: FY 1997 RESOURCES		
Funds (in EEEL)	$millions	percent
NIST Funding	34.6	71
Other Agency Funding	9.2	19
Other Funding	4.7	10
total	48.5	100
Funds (outside EEEL)	7.6	
Staff	number	percent
paid		
full-time permanent	272	63
other	33	8
total paid	305	71
unpaid		
guest scientists	130	30
total unpaid	130	30
total	435	100*

* Total does not add due to rounding.

PLANNING

EEEL's planning process includes five principal steps. Each step is reflected in one of the five types of published documents shown in Table 7. Also included there are the typical publication intervals and time horizons.

The needs assessments identify the principal measurement capability for which industry needs NIST's assistance. The electronics industry was examined in *Measurements for Competitiveness in Electronics* in 1993. Since then EEEL has expanded upon this analysis by conducting a number of additional assessments that maintain a current picture of the key needs for the electronics industry. The electrical-power industry was examined in *Measurement Support for the U.S. Electric-Power Industry in the Era of Deregulation* in 1997.[14] Both studies were prepared by EEEL in consultation with U.S. industry and other NIST laboratories. EEEL contemplates a third study of the U.S. electrical-equipment industry to round out coverage of the three principal industries that EEEL serves.

The strategic plan describes the overall directions of EEEL's programs in response to industry's needs. The program plan focuses on implementation of the strategic directions in specific program goals and includes both plans and detailed accomplishments. The technical-accomplishments document describes selected accomplishments for the most recently completed year in a form suitable for the general reader. The impact studies translate those accomplishments into economic and other terms and provide perspective helpful in planning new work.

Table 8 provides more information about the two types of planning documents published at varying intervals: the measurement needs assessments and the impact studies. In addition, two key activities that support assessing measurement needs are broken out separately: surveys of industry's measurement needs conducted by EEEL, and reviews of the measurement needs assessments by industry. Table 8 shows the documents published in FY 1993 through FY 1997 and, also, the documents contemplated for publication in FY 1998 and FY 1999. A full list of all of the documents referenced in Table 8 is contained in the endnote.[15]

As indicated in the key at the bottom of the Table 8, the assessments are marked "a". The review is marked "r" in the table. Reviews may be conducted before or after the publication of the assessment for a given technical field. If conducted afterward, the reviews contribute to the next assessment for

Table 7: PUBLISHED PLANNING DOCUMENTS

Time **Document**	**Publication** **Interval** (years)	**Typical** **Horizon** (years)
needs assessments	varies	10 forward
strategic plan	3	5 forward
program plan	1	varies
technical accomplishments	1	1 backward
impact studies	varies	varies

the named technical field. The surveys are marked "s" in the table. They may employ a written questionnaire, telephone calls, or visits to gather information from industry's technical and managerial personnel. The impact study is marked "i" in the table. Impact studies are sponsored by EEEL or the NIST Program Office and are conducted with the assistance of economists and industry experts to determine how completed work has affected industry.

Table 8: MEASUREMENT NEEDS AND IMPACT DOCUMENTS

Fields	Fiscal Year						
	'93	'94	'95	'96	'97	'98	'99
semiconductors	a,s	.	.	a,s	.	a,i	.
magnetics	a	.	.	.	.	.	.
superconductors	a	i	.	.	.	.	.
low frequency	.	.	.	.	.	.	.
microwaves	a	.	.	.	.	i	.
lightwaves	a,r	.	.	.	.	.	i
computers	.	.	.	.	.	.	.
video	r,a	.	.	.	.	.	.
power	.	.	i	.	a	.	a
Cross-Cutting Fields							
national electrical standards	.	.	.	.	.	.	i
electromagnetic compatibility	r,a	.	r	.	s	a	.
electronic data exchange	.	.	.	.	.	.	.

a = assessment of industry's measurement needs
r = review of measurement needs assessment
s = survey of industry's measurement needs
i = impact study

EEEL employs other mechanisms to gather information important for planning. These mechanisms may or may not result in published documents. Among them are individual contacts with industry representatives by all staff members, round-robin measurement intercomparisons, informal customer surveys, and workshops. For example, in consultation with the Telecommunications Industry Association, EEEL periodically updates its understanding of the most important measurement needs affecting the optical-fiber communications industry. EEEL and other laboratories at NIST also participate in the development of industry "roadmaps" that lay out long-range plans for technical progress and improved competitiveness in specific industries. The roadmaps have implications for needed measurement support from NIST but address the specific needs to varying degrees. Examples of roadmaps important for the electronics industry are these: (1) *The National Technology Roadmap for Semiconductors*, under the auspices of the Semiconductor Industry Association, which describes specific measurement needs;[16] (2) the *Optoelectronic Technology Roadmap: Conclusions and Recommendations*, under the auspices of the Optoelectronics Industry Development Association (OIDA), which identifies the need for improved measurement capability;[17] (3) the *National Electronics Manufacturing Technology Roadmaps*, under the auspices of the National Electronics Manufacturing Initiative (NEMI), which identifies specific measurement needs;[18] and (4) the *Optical Disk Storage Roadmap*, under the auspices of the National Storage Industry Consortium (NSIC) in collaboration with OIDA, which addresses industry directions but not yet associated measurement needs.[19] In addition, OIDA, NIST, and others are developing a study tentatively titled *Metrology for Optoelectronics*, with the intent to complete it in FY 1998.

ORGANIZATION OF THIS PROGRAM PLAN

The fields of technology that EEEL presently addresses, or plans to address in future years, are shown in Table 9. They provide the basis for the organization of this program plan. Each field of technology is associated with a responsive EEEL program of the same name. This structure has the advantage that it is readily accessible to the three supported industries and thus facilitates communication with EEEL's customers.

Almost all of these fields are seeing rapid advances in technology, in either product technology or manufacturing technology, or both. They are all the subject of current or foreseeable intense competitive pressures. They are increasingly interdependent technologies; success in any one of them is generally tied to success in one or more of the others. Because of this interdependency, it is not possible to create an entirely separable set of fields to describe these technologies and the products made from them. The arrangement in Table 9, however, has been found workable. In this scheme, products are generally associated with the first applicable field on the list, as described in the following several paragraphs.

Table 9: FIELDS SERVED (CURRENT AND FUTURE)

Fields	
semiconductors	
silicon	current
compound semiconductors	current
magnetics	
magnetic information storage	current
magnetic sensing	current
power materials	future
superconductors	
low temperature	current
high temperature	current
low frequency	
radio frequency	current
audio frequency	current
direct current	current
microwaves	
microwave signal processing	current
microwave computing	current
microwave transmission	current
lightwaves	
lasers	current
optical-fiber communications	current
optical-fiber sensors	current
optical information storage	future
optical signal processing	future
optical computing	future
computers	future
video	
vision	future
signal processing	current
transmission	current
information storage	current
displays	current
power	
generation	future
transmission	current
control	current
storage	future
conversion	current
Cross-Cutting Fields	
national electrical standards	current
electromagnetic compatibility	current
electronic data exchange	current

The three *materials* fields of technology that lead the list (semiconductors, magnetics, and superconductors) represent measurement support provided for those materials, discrete components, and integrated components that are most conveniently classified by the key material from which they are made.

The three *frequency-based* fields of technology (low frequency, microwaves, and lightwaves) that follow represent measurement support for materials, discrete components, integrated components, and equipment that are most conveniently classified by the frequency region employed. Optoelectronics is considered part of the lightwave field, since the use of light is its distinguishing feature.

The computer field of technology provides a location for measurement support for equipment and systems important to computers and their peripherals and beyond the measurement support provided for materials and components under semiconductors, magnetics, and video.

The video field of technology focuses on measurement support for integrated components, equipment, and systems that are specific to video and that are beyond the broadly applicable component technologies addressed in earlier entries in the table.

The power field of technology focuses on measurement support for materials, equipment, and systems of principal interest to the electrical-equipment industry and the electric-power industry.

Finally, three cross-cutting fields are shown. The first of these -- national electrical standards -- focuses on developing and maintaining measurement reference standards for the most fundamental dc (direct-current or zero-frequency) quantities, such as dc voltage, dc current, and dc resistance. These standards enable achieving high levels of absolute accuracy in measuring these quantities. They also provide reference values used to support the measurement of related ac (alternating-current or above-zero-frequency) quantities up to very high frequencies. In this way, the national electrical standards support the products of virtually all other fields of technology in the table. These national electrical standards underpin the national measurement system for electrical quantities. These standards also support U.S. participation in the determination of international electrical standards.

The second cross-cutting field -- electromagnetic compatibility -- addresses measurement support required to achieve two related purposes: reduced unwanted emissions of electromagnetic energy from electronic and electrical products; and increased immunity of products to incoming electromagnetic energy. By so doing, this field supports the products associated with virtually every other field in the table.

The third and final cross-cutting field -- electronic data exchange -- focuses on test methods for the evaluation of data systems intended to support the development and manufacture of the products of virtually all other fields of technology in the table. For example, the automated product descriptions that are a part of electronic data exchange support the manufacturing of electronic and electrical products.

EEEL provides some measurement support for all of the fields of technology marked "current" in Table 9. EEEL sees a need to provide support for the several fields marked "future" in the table but lacks the resources to launch significant programs.

EEEL collaborates with other NIST laboratories in providing needed support so that their special skills in related technologies, such as chemistry and mechanical engineering, can be brought into the service of the electronics, electrical-equipment, and electric-power industries. As with any industry, these industries require a broader diversity of support than any one NIST laboratory can provide. As a result EEEL engages in many collaborative activities with other NIST laboratories. The number of such collaborations typically falls between 30 and 60 per year.

The pages that follow describe EEEL's program plan in detail. The program plan is arranged by the programs that correspond one-for-one to the fields of technology shown in Table 9. The same structure is used in EEEL's *1994 Strategic Plan*. Each program is composed of number of projects. The projects are the fundamental building blocks of this program plan. A full list of all of the projects is provided in Table 11 on page 14. Also, within the plan, the page introducing each program indicates any changes in the project structure of that program for 1998.

Descriptions of the projects begin on page 21. The descriptions cover objectives, background information, resources, the specific tasks addressed, the milestones required to complete these tasks, and accomplishments. These descriptions look both forward and backward in time in order to set the current work in context.

ORGANIZATION OF EEEL

EEEL's programs are implemented through the two offices and five divisions that comprise EEEL's organizational structure. A crosswalk from the programs to the organizational units principally conducting them is shown Table 10. The table indicates that a given organizational unit may support the programs associated with more than one field of technology. For example, the Electricity Division supports the programs associated with five fields of technology directly. In addition, a given program may be supported by more than one Division. That relationship is not shown in the table.

Table 10: CROSSWALK BETWEEN EEEL'S PROGRAMS AND PRINCIPAL CONDUCTING ORGANIZATIONS

PROGRAMS: FIELDS OF TECHNOLOGY	ORGANIZATIONS: OFFICES AND DIVISIONS
Semiconductors	Semiconductor Electronics Division Office of Microelectronics Programs
Magnetics	Electromagnetic Technology Division
Superconductors	Electromagnetic Technology Division
Low Frequency	Electricity Division
Microwaves	Electromagnetic Fields Division
Lightwaves	Optoelectronics Division
Video	Electricity Division
Power	Electricity Division
National Electrical Standards	Electricity Division
Electromagnetic Compatibility	Electromagnetic Fields Division
Electronic Data Exchange	Electricity Division
Law Enforcement	Office of Law Enforcement Standards

The five divisions in EEEL manage programs conducted within their own organizational units. The two offices matrix manage programs conducted across the NIST Laboratories.

The first of the two offices is the Office of Microelectronics Programs (OMP). It manages the NIST-wide National Semiconductor Metrology Program (NSMP), which is a focused, matrix-managed effort addressing the semiconductor industry's metrology needs which are identified in the National Technology Roadmap for Semiconductors. This office and the program it manages are NIST funded. NSMP projects are conducted within EEEL and four other NIST Laboratories: the Chemical Science and Technology Laboratory, the Manufacturing Engineering Laboratory, the Materials Science and Engineering Laboratory, and the Physics Laboratory.

The second of the two offices is the Office of Law Enforcement Standards. It manages a NIST-wide program in support of the criminal-justice community and also conducts some of the work of the program. This program is funded entirely by three other Federal agencies: the National Institute of Justice of the U.S. Department of Justice, the National Highway Traffic Safety Administration of the U.S. Department of Transportation, and the Office of Management and Budget of the Executive Office of the President. The program is conducted within EEEL and five other NIST laboratories: the Building and Fire Research Laboratory, the Chemical Science and Technology Laboratory, the Information Technology Laboratory, the Manufacturing Engineering Laboratory, and the Materials Science and Engineering Laboratory.

Table 12 on page 15 associates every project in this program plan with the EEEL organization conducting it, including all five divisions and the two offices.

Table 11: EEEL PROGRAMS AND THEIR PROJECTS

PROGRAMS	PROJECTS
SEMICONDUCTORS	NIST-Wide Semiconductor Programs Metrology for Nanoelectronics Optical Characterization Metrology Scanning-Probe Microscope Metrology Thin-Film Process Metrology Silicon-on-Insulator Metrology Metrology for Simulation and Computer-Aided Design Metrology for Process and Tool Control Interconnect Reliability Metrology Dielectric Reliability Metrology Micro-Electro-Mechanical Systems (MEMS) Plasma Chemistry - Plasma Processing
MAGNETICS	Magnetic Recording Technology Magnetic Instruments and Materials Characterization Nanoprobe Imaging for Magnetic Technology
SUPERCONDUCTORS	Superconductor Interfaces and Electrical Transport High Performance Sensors, Converters, and Mixers Josephson Array Development Nanoscale Cryoelectronics High-T_c Electronics Superconductor Standards and Technology
LOW FREQUENCY	AC-DC Difference Standards and Measurement Techniques Waveform Acquisition Devices and Standards Waveform Synthesis and Impedance Metrology Measurements for Complex Electronic Systems
MICROWAVES	High-Speed Microelectronics Metrology Power Standards and Measurements Impedance, Voltage, and Dimensional Standards and Measurements Network Analysis and Measurement Noise Standards and Measurements Antenna Measurement Theory and Application Metrology for Antenna, Radar Cross Section and Space Systems
LIGHTWAVES	Dielectric Materials and Devices Semiconductor Materials and Devices Fiber and Discrete Components Integrated Optics Metrology Optical Fiber Sensors Optical Fiber Metrology High Speed Source and Detector Measurements Laser Radiometry
VIDEO	Video Technology
POWER	Dielectrics Research Metrology for Electric Power Systems
NATIONAL ELECTRICAL STANDARDS	Ohm and Farad Realization and Dissemination Quantum Voltage and Current
ELECTROMAGNETIC COMPATIBILITY	Standard EM Fields and Transfer Probe Standards Emission and Immunity Metrology Electromagnetic Properties of Materials
ELECTRONIC DATA EXCHANGE	Infrastructure for Integrated Electronics Design Infrastructure for Integrated Electronics Manufacturing
OFFICE OF LAW ENFORCEMENT STANDARDS	Enabling Technologies for Criminal Justice Practitioners

Table 12: EEL ORGANIZATIONS AND THEIR PROJECTS

ORGANIZATIONS: OFFICES AND DIVISIONS	PROJECTS
SEMICONDUCTOR ELECTRONICS DIVISION	Metrology for Nanoelectronics Optical Characterization Metrology Scanning-Probe Microscope Metrology Thin-Film Process Metrology Metrology for Simulation and Computer-Aided Design Silicon-on-Insulator Metrology Metrology for Process and Tool Control Interconnect Reliability Metrology Dielectric Reliability Metrology Micro-Electro-Mechanical Systems (MEMS)
OFFICE OF MICROELECTRONICS PROGRAMS	NIST-Wide Semiconductor Programs
ELECTRICITY DIVISION	Plasma Chemistry - Plasma Processing AC-DC Difference Standards and Measurement Techniques Waveform Acquisition Devices and Standards Waveform Synthesis and Impedance Metrology Measurements for Complex Electronic Systems Video Technology Dielectrics Research Metrology for Electric Power Systems Ohm and Farad Realization and Dissemination Quantum Voltage and Current Infrastructure for Integrated Electronics Design Infrastructure for Integrated Electronics Manufacturing
ELECTROMAGNETIC FIELDS DIVISION	High Speed Microelectronics Metrology Power Standards and Measurements Impedance, Voltage, and Dimensional Standards and Measurements Network Analysis and Measurement Noise Standards and Measurements Antenna Measurement Theory and Application Metrology for Antenna, Radar Cross Section and Space Systems Standard Electromagnetic Fields and Transfer Probe Standards Emission and Immunity Metrology Electromagnetic Properties of Materials
ELECTROMAGNETIC TECHNOLOGY DIVISION	Nanoprobe Imaging for Magnetic Metrology Magnetic Instruments and Materials Characterization Magnetic Recording Metrology Superconductor Interfaces and Electrical Transport High-Performance Sensors, Converters, and Mixers Josephson Array Development Nanoscale Cryoelectronics High-T_c Electronics Superconductor Standards and Technology
OPTOELECTRONICS DIVISION	Dielectric Materials and Devices Semiconductor Materials and Devices Fiber and Discrete Components Integrated Optics Metrology Optical Fiber Sensors Optical Fiber Metrology High Speed Source and Detector Measurements Laser Radiometry
OFFICE OF LAW ENFORCEMENT STANDARDS	Enabling Technologies for Criminal Justice Practitioners

ENDNOTES

1. EEEL's most recent analysis of the composition of its customer base was conducted in 1991 and reflected the preceding five-year period.

2. All shipments figures in the table are *product data* in current dollars. They are also estimates since no firm shipment data for 1995 were available at the time of publication of the referenced documents. Employment figures are industry data. Industry data reflect all products and services sold by establishments in the named industry, whether or not the products are classified in that industry. Product data reflect all products classified in the named industry and sold by all industries. There is some overlap in the products listed in the table. Some electronic products are included in the automotive and aerospace industries. This overlap arises because there is no set of codes in the Standard Industrial Classification (SIC) System, on which all of the figures in the table are based, that is devoted exclusively to the electronics industry. The superscripts in the table refer to the notes that follow: (a) *1997 Electronic Market Data Book*, Electronic Industries Association, pp. 1-2 (1997). The data associated with (b), (c), (d), (e) come from the International Trade Administration of the U.S. Department of Commerce are are published in the *Statistical Abstract of the United States 1996* (October 1996): (b) Table No. 1403, p. 874; (c) the figures shown reflect both the motor-vehicle bodies (Table No. 1449, p. 893) and supporting parts industries (Table No. 1426, p. 885); (d) the employment data for 1994 are the most recent available and are thus used as an estimator for 1995 (Table No. 1415, p. 879); and (e) Table 1450, p. 894.

3. *1997 Electronic Market Data Book*, Electronic Industries Association, p. 1-2 (1997), and product-specific areas throughout the publication.

4. *1997 Electronic Market Data Book*, Electronic Industries Association, pp. 2-3 (1997). The balance of trade for 1996 is positive for electron tubes, telecommunications, defense communications, industrial electronics, and electromedical equipment. The balance is negative for passive components, solid-state products, consumer products, and computers and peripherals. Together electron tubes, solid-state products, and passive components comprise the category electronic components which is negative overall.

5. The last estimate of the size of this industry made by EEEL for the year 1990, $48 billion, *Measurements for Competitiveness in Electronics,* National Institute of Standards and Technology, Report No. NISTIR 4583, p. 38 (1993). The definition used for the electrical-equipment industry, in terms of SIC codes, was developed at NIST but was influenced by the products of interest to the members of the National Electrical Manufacturers Association. The definition excludes products which employ electrical components for practical applications. For example, excluded are household appliances, transportation equipment, and manufacturing equipment. Most of these excluded products are as much the products of other industries. Further, the excluded products are difficult to bound because electricity is used so widely. Also, excluded from the definition are electronic products. For the most part, they are the products that apply electricity in electrical form rather than as motion, light, heat, or electrolytic action.

6. *Measurements for Competitiveness in Electronics*, First Edition, Electronics and Electrical Engineering Laboratory, National Institute of Standards and Technology, Report No. NISTIR 4583, from the data for 1990 in Table 13 on p. 38 (April 1993).

7. *Statistical Yearbook of the Electric Utility Industry 1995*, Edison Electric Institute, p. 56 (1997).

8. *Statistical Yearbook of the Electric Utility Industry 1995*, Edison Electric Institute, p. 85 (1997).

9. All shipments figures in the table are *product data* in current dollars. Product data reflect all products classified in the named industry and sold by all industries. Most of the shipments figures in the table are estimates since firm shipment data for 1994 were not uniformly available at the time of publication of the referenced documents. Employment figures are *industry data*. Industry data reflect all products and services sold by establishments in the named industry, whether or not the products are classified in that industry. There is some overlap in the products listed in the table. Some electronic products are included in the automotive and aerospace industries. This overlap arises because there is no set of codes in the Standard Industrial Classification (SIC) System, on which all of the figures in the table are based, that is devoted exclusively to the electronics industry. The data on the electronics industry came from the *1996 Electronic Market Data Book*, Electronic Industries Association, pp. 1-2 (1995). The other data came from the *Statistical Abstract of the United States 1995*, U.S. Department of Commerce, Bureau of the Census, p. 896, pp. 908 and 916, p. 901, and p. 917 (September 1995). For the automotive industry, the figures shown reflect both the motor-vehicle bodies and supporting parts industries. For the petroleum-refining industry, the employment data for 1992 are the most recent available and are thus used as an estimator for 1994.

10. Gerald J. FitzPatrick, James K. Olthoff, and Ronald M. Powell, *Measurement Support for the U.S. Electric-Power Industry in the Era of Deregulation*, Electronics and Electrical Engineering Laboratory, National Institute of Standards and Technology, Report No. NISTIR 6007 (May 1997).

11. *Statistical Yearbook of the Electric Utility Industry 1995*, Edison Electric Institute, p. 82 (1997).

12. *Measurements for Competitiveness in Electronics*, First Edition, Electronics and Electrical Engineering Laboratory, National Institute of Standards and Technology, Report No. NISTIR 4583 (April 1993).

13. Some definitions of fundamental research exclude any research undertaken with a view to achieving practical benefits from its successful completion. That is, they add the notion of lack of specific purpose, or for the purpose of advancing knowledge only, to the definition, even if the nature of the work is unaffected by this addition.

14. Gerald J. FitzPatrick, James K. Olthoff, and Ronald M. Powell, *Measurement Support for the U.S. Electric-Power Industry in the Era of Deregulation*, Electronics and Electrical Engineering Laboratory, National Institute of Standards and Technology, Report No. NISTIR 6007 (May 1997).

15. All documents referenced in Table 8 are shown below. They cover the period 1993 to 1999.

Semiconductors

1993 a Chapter 4, "Semiconductors", *Measurements for Competitiveness in Electronics*, First Edition, Electronics and Electrical Engineering Laboratory, National Institute of Standards and Technology, Report No. NISTIR 4583 (April 1993).

1993 s "$Hg_{1-x}C_xTe$ Characterization Measurements: Current Practice and Future Needs", *Semiconductor Science and Technology*, Vol. 8, pp. 753-776 (1993).

1996 a *Semiconductor Characterization: Present Status and Future Needs*, W. Murray Bullis, David G. Seiler, and Alain C. Diebold, ed., published by the American Institute of Physics (1996). Reporting on the *International Workshop on Semiconductor Characterization: Present Status and Future Needs*, a workshop on measurement needs conducted on January 30-February 2, 1995 in Gaithersburg, MD, sponsored by the Advanced Research Projects Agency, SEMATECH, the National Institute of Standards and Technology, and other organizations.

s *Survey of Optical Characterization Methods for Materials, Processing, and Manufacturing in the Semiconductor Industry*, National Institute of Standards and Technology Special Publication 400-98 (November 1995).

1998 a *International Conference on Characterization and Metrology for ULSI Technology*, a conference on measurement needs to be held on March 23-27, 1998, in Gaithersburg, MD, sponsored by the National Institute of Standards and Technology, SEMATECH, the Semiconductor Research Cooperative, the Semiconductor Equipment and Materials Institute, and the American Vacuum Society's Manufacturing Science and Technology Division. Proceedings should be published at the end of 1998.

1998 i Economic impact study of power-device modeling, underway.

Magnetics

1993 a Chapter 5, "Magnetics", *Measurements for Competitiveness in Electronics*, First Edition.

Superconductors

1993 a Chapter 6, "Superconductors", *Measurements for Competitiveness in Electronics*, First Edition.

1994 i Robert L. Peterson, "An Analysis of the Impact on U.S. Industry of the NIST/Boulder Superconductivity Programs: An Interim Study", Electronics and Electrical Engineering Laboratory, National Institute of Standards and Technology, Report No. NISTIR 5012 (November 1993).

Microwaves

1993 a Chapter 7, "Microwaves", *Measurements for Competitiveness in Electronics*, First Edition.

1998 i Economic impact study of near-field antenna measurements, underway.

Lightwaves: Lasers

1993 a Chapter 8, "Lasers", *Measurements for Competitiveness in Electronics*, First Edition.

1993 r Industry review: Chapter 8, "Lasers", *Measurements for Competitiveness in Electronics*, First Edition.

1999 i Economic impact study of laser and fiber-optic power calibrations services, to be started in FY 1998.

Lightwaves: Optical-Fiber Communications

1993 a Chapter 9, "Optical-Fiber Communications", *Measurements for Competitiveness in Electronics*, First Edition.

1993 r Industry review: Chapter 9, "Optical-Fiber Communications", *Measurements for Competitiveness in Electronics*, First Edition.

Lightwaves: Optical-Fiber Sensors

1993 a Chapter 10, "Optical-Fiber Sensors", *Measurements for Competitiveness in Electronics*, First Edition.

1993 r Industry review: Chapter 10, "Optical-Fiber Sensors", *Measurements for Competitiveness in Electronics*, First Edition.

Video

1993 r Industry review of draft of Chapter 11, "Video", *Measurements for Competitiveness in Electronics*, First Edition.

1993 a Chapter 11, "Video", *Measurements for Competitiveness in Electronics*, First Edition.

Power

1995 i Albert N. Link, *An Evaluation of the Economic Impacts Associated with the NIST Power and Energy Calibration Services*, Electronics and Electrical Engineering Laboratory, National Institute of Standards and Technology, Report No. NISTIR 5565 (January, 1995).

1997 a Gerald J. FitzPatrick, James K. Olthoff, and Ronald M. Powell, *Measurement Support for the U.S. Electric-Power Industry in the Era of Deregulation*, Electronics and Electrical Engineering Laboratory, National Institute of Standards and Technology, Report No. NISTIR 6007 (May 1997).

1999 a Measurement needs assessment for the electrical-equipment industry contemplated.

National Electrical Standards

1999 i Economic impact study of the Josephson voltage standard, to be started in FY 1998.

Electromagnetic Compatibility

1993 r Industry review of draft of Chapter 12, "Electromagnetic Compatibility", *Measurements for Competitiveness in Electronics*, First Edition.

1993 a Chapter 12, "Electromagnetic Compatibility", *Measurements for Competitiveness in Electronics*, First Edition.

1995 r Industry review of *EMI/EMC Metrology Challenges for Industry - A Workshop on Measurements, Standards, Calibrations, and Accreditation*, Boulder, Colorado (January 25-26, 1995).

1997 s Ramon C. Baird and Motohisa Kanda, *Electromagnetic Compatibility: Results of a Limited Survey*, Electronics and Electrical Engineering Laboratory, National Institute of Standards and Technology, Report No. 5049 (July 1997).

1998 a Contemplated publication of the findings of the *EMI/EMC Metrology Challenges for Industry - A Workshop on Measurements, Standards, Calibrations, and Accreditation*, Boulder, Colorado (January 25-26, 1995).

16. *The National Technology Roadmap for Semiconductors*, Semiconductor Industry Association (1994). Next edition is anticipated in late 1997.

17. *Optoelectronic Technology Roadmap: Conclusions and Recommendations*, Optoelectronics Industry Development Association, p. 6 (October 1996).

18. *National Electronics Manufacturing Technology Roadmaps*, National Electronics Manufacturing Initiative, Inc. (December 1996).

19. *Optical Disk Storage Roadmap*, National Storage Industry Consortium in collaboration with the Optoelectronics Industry Development Association (June 1997).

SEMICONDUCTORS

Office of Microelectronics Programs

Office Director:	Robert I. Scace
Staff:	4 professionals (2 physicists, 1 physical chemist, 1 secretary)
Funding level:	$10.9 million (as of end FY 1997)
Funding sources:	NIST
Objective:	Develop and execute NIST's National Semiconductor Metrology Program (NSMP); apply NIST-wide technical resources regardless of organizational location to deliver solutions to highest priority metrological problems of the semiconductor industry. Provide formal liaison to SEMATECH and the Semiconductor Research Corporation.

Background: NIST has developed metrology for the semiconductor industry for over 40 years in EEEL and its predecessors. Eleven years ago, the breadth of technology then applied in semiconductor manufacturing clearly transcended EEEL's technical scope. New appropriated funds were sought, and first obtained in 1991. The Semiconductor Industry Association (SIA) took the initiative in defining and gaining Administration support for the National Semiconductor Metrology Program, established in early 1994. The needs are identified in the National Technology Roadmap for Semiconductors, the third in a series of needs documents developed with strong industry participation led by the SIA. The technical program is confined by agreement to mainstream digital silicon complementary metal oxide-semiconductor (CMOS) technology.

Current Tasks (Listed below are NSMP-funded tasks in other NIST organizations. NSMP-funded tasks within EEEL's domain are described elsewhere in this document):

1. Dimensional Metrology at the Nanometer Level

FY 1996	Completed initial characterization of the Calibrated Atomic Force Microscope (C-AFM) performance for pitch, height, and width measurements; Completed initial measurements of silicon single atom step height specimens; Completed installation and initial optimization of both the field-emission scanning electron microscope (FESEM) and the proximal probe microscope (PPM); Provided first-order feedback to the manufacturers of both of these instruments regarding the functioning of the combined instrumentation system.
FY 1997	Installed new z-stage in C-AFM and reevaluated all motion errors in the system to further improve uncertainties; received samples for first C-AFM pitch measurements from an external customer; Completed new round of measurements on silicon single atom step samples having reduced uncertainty and improved agreement with the lattice constant value; optimized the current PPM for operation in the FESEM in collaboration with the manufacturer; Performed combined FESEM/PPM scans of the SEM sharpness standard and RM 8090; presented and published the first papers on the combined tools.

FY 1998 Complete top width measurements on several preferentially etched silicon samples for the linewidth measurement comparison; complete first report of test pitch measurements with the C-AFM for an external customer, and explore the use of such samples as pitch/height standards; disseminate silicon single atom step specimens for trials by collaborators; incorporate design improvements in the PPM to improve the performance in the combined SEM/PPM instrument; image SRM 2090 when it is delivered.

FY 1999 Certify the C-AFM as a NIST calibration facility and perform first pitch and height calibrations; complete additional top width measurements on a subsequent generation of preferentially etched silicon samples for the linewidth measurement comparison; incorporating feedback from collaborators, continue the improvement and dissemination of silicon single atom step specimens to external customers; utilize the combined SEM/PPM in the determination of the measurement uncertainty in the SEM standards; design and collaborate in the manufacture of a combined SEM/PPM which optimizes the strengths of both systems.

2. Plasma and CVD Process Measurements

FY 1995 Demonstrated utility of radio frequency (rf) measurements to monitor polymer build-up in plasma reactors; Modified Gaseous Electronics Conference (GEC) rf Reference Cell to accept inductively coupled plasma source; Measured/published spatial distribution of carbon-fluorine (CF) radicals in carbon tetrafluoride/oxygen/argon plasmas.

FY 1996 Performed critical review of available electron collision data for carbon tetrafluoride (CF_4) and trifluoromethane (CHF_3) and constructed World Wide Web-based database; Transferred rf electrical measurement techniques (hardware and software) to a specialty gas supplier and began investigation of electrical properties of nitrogen trifluoride (NF_3) discharges; Measured electron density and energy distribution functions in the inductively coupled plasma source for wide range of gases and plasma conditions; Measured first time-resolved optical emission spectra of rf biased electrode sheaths in inductively coupled plasma reactor.

FY 1997 Measured light emission from and the density of CF_2 radicals in O_2/CF_4 and C_2F_6 chamber cleaning plasmas using optical emission and planar laser induced fluorescence, respectively; Developed new non-intrusive technique for measuring ion current at wafers exposed to high-density plasmas which may be suitable for use as an ion-current sensor in industrial reactors; Measured effect of coil geometry and termination on plasma uniformity in inductively-coupled GEC Cells; Compared new diagnostic (plasma oscillation probe) for measuring plasma electron densities with Langmuir probe measurements; Measured degree of molecular dissociation in gas mixtures with argon in inductively-coupled GEC Cell; Extended electron interaction database to include dichloro-difluoromethane (CCl_2F_2) perfluoroethane (C_2F_6).

FY 1998 Perform measurement of CF_2 radical densities in inductively-coupled GEC Cell using planar laser induced fluorescence; Perform ion kinetic energy measurements and ion flux measurements in CF_4/O_2 and C_2F_6/O_2 plasmas; Develop IR laser absorption spectroscopy and tera-Hertz spectroscopy as plasma diagnostics to measure densities and temperatures of plasma species; Initiate studies of pulsed plasma characteristics; Measure ion relative ion fluxes and energies in inductively-coupled discharges; Extend electron interaction database to include C_3F_8, Cl_2, and HBr.

3. Optical CD and Overlay Metrology

FY 1996	Stewart platform strut joint patent approved, licensed to industry; UV linewidth and overlay microscope programming commenced for fully automated instrument control and data acquisition; Major components of overlay system assembled and tested; Optical system performance demonstrated on industrially supplied 8" wafer overlay targets.
FY 1997	Aligned interferometers and qualified overlay metrology system; Manufactured prototype microcone alignment artifacts and measured with the overlay system; Wrote computer code for calibrating SRM 2800 on UV Microscope.
FY 1998	Complete programming of UV microscope for pitch calibrations, align and certify, calibrate SRM 2800 pitch standards; calibrate 2-dimensional microgrid artifact; Program UV microscope for calibration of linewidth standards; develop new photomask linewidth SRM on 6x6x.25 in substrate, extending linewidths to 0.25 μm; Improve overlay metrology through modeling and new target design.
FY 1999	Complete UV microscope program for linewidth calibrations; design, manufacture and test conventional (e.g., frame in frame) overlay standard artifact; procure and calibrate 6 inch photomask linewidth SRM.

4. Fundamental Process Control Metrology for Gases

FY 1995	Developed prototype calibration system for partial pressure residual gas analyzers (RGAs); Developed primary and transfer flow standards for inert gases (10 to 1000 sccm); Published comparative evaluation of thermal mass flow controllers.
FY 1996	Developed model for residual gas analyzers that qualitatively describes commercial RGA performance in high pressure operation (0.001 to 0.1 Pa); Developed primary and transfer flow standards for inert gases (0.1 to 10 sccm); Conducted initial on-site flow proficiency tests with four mass flow controllers manufacturers (5 to 1000 sccm).
FY 1997	Developed a methodology to optimize commercial RGAs for semiconductor process control; Performed flow proficiency tests with gas handling suppliers to the semiconductor industry; Developed primary flow standards with uncertainties less than 0.05% (1 to 1000 sccm).
FY 1998	Develop and test techniques for in-situ validation of residual gas analyzers used for semiconductor process control; Develop stable portable flow standards which are compatible with corrosive and/or toxic gases used in semiconductor processes.
FY 1999	Demonstrate the use of residual gas analyzers for quantitative measurements in semiconductor process control applications; Develop in situ calibration techniques for mass flow meter which is self compensating for changes in gas properties.

5. Moisture Concentration Measurements in Process Gases

FY 1995	Demonstrated quantitative capability of optical cavity ring-down spectroscopy (CRDS) for trace contaminant measurement; Completed construction of prototype low frost-point moisture generator.
FY 1996	Began intercomparison, in cooperation with LFPG SEMI, of low moisture concentration measurement instruments and transfer standards in the 1 - 100 parts-per-million range; Demonstrated quantitative measurements of contaminants in gases below 1 ppm using CRDS.
FY 1997	In cooperation with SEMI, continued intercomparison for moisture concentration in the 1 - 100 parts-per-million range, and began evaluation of permeation-tube-based working standards in the 10 - 100 parts-per-billion range; Demonstrated capability to deliver parts-per-million down to parts-per-billion levels of humidity using the low-frost-point-moisture-generator (LFPG); Made absolute ppb-level measurements of LFPG output moisture concentration using a quantitative optical absorption technique.
FY 1998	Demonstrate quantitative measurements of LFPG output using CRDS and wavelength modulation spectroscopy, and continue intercomparisons of low moisture working standards.

6. Metrology for Contamination-Free Manufacturing

FY 1996	Completed first tests of numerical model for nucleation and transport of contaminant particles in a rotating disk CVD reactor; Completed fabrication of the reference rotating disk reactor to be used for model validation.
FY 1997	Developed particle contaminant models for prototypical perfectly-stirred and plug flow reactor configurations; Silicon hydride physical/chemical property database established on World Wide Web.
FY 1998	Begin in-situ measurements in reference rotating disk chemical vapor deposition (CVD) reactor in order to determine parameter regimes which are susceptible to particle formation during thin film growth; Initiate modifications to rotating disk reactor contaminant model necessary to accurately simulate experimental conditions.

7. Thin Film Profile Measurement Methods and Reference Materials

FY 1995	Introduced SRM 2137 as first boron implant in silicon standard; Organized profilometry round-robin for Secondary Ion Mass Spectrometry (SIMS) crater depth measurements.
FY 1996	Developed neutron activation analysis protocol for arsenic in silicon; Began developing methods for ultra-shallow profiling using SIMS.
FY 1997	Completed certification measurements of arsenic implant SRM for SIMS; Developed molecular primary ion beam source for SIMS to improve depth resolution; Demonstrated interlaboratory agreement to better than 3% by SIMS in boron implant dose calibration using NIST SRM 2137 as reference.
FY 1998	Develop prototype SIMS depth resolution reference material; Begin ultra-shallow profile measurement program using time-of-flight-SIMS; Investigate certification methods for phosphorus implant in silicon SRM.

8. Radiometric Metrology for Deep Ultraviolet Lithography

FY 1995	Developed method for calibrating discharge lamps used for ultraviolet photoresist stabilization; Continued work with commercial partner to improve accuracy of ultraviolet probes.
FY 1996	Upgraded refractometer to enable high-accuracy refractive-index measurements and began measurements for SEMATECH/Lincoln Labs near 193 nm; Began development of dielectric barrier discharge source as potential ultraviolet/deep ultraviolet standard.
FY 1997	Performed high-accuracy measurements of the refractive index of optical materials and their temperature coefficients near 193 nm for SEMATECH/Lincoln Labs; Built up new refractive-index-measurement apparatus based on interferometry, capable of improved accuracy.
FY 1998	Make refractive-index measurements of deep-ultraviolet materials at 193 nm, 157 nm, and shorter wavelengths as needed for the design of next-generation semiconductor photolithography steppers; Complete and test interferometric refractive-index-measurement apparatus.
FY 1999	Perform refractive-index-measurements interferometrically with improved accuracy in the deep ultraviolet spectral region.

9. Wafer and Chuck Flatness

FY 1996	Completed 300 mm flatness interferometer and made initial chuck distortion measurements; Initiated commercialization activities on thickness interferometer; Scaled up lap to 300 mm, demonstrated rapid silicon polishing process and potential for chem-mechanical process (CMP) applications.
FY 1997	Demonstrated principle of use of Rapidly Renewable Lap (RRL) technology for CMP of sheet oxide, copper and tungsten. Licensed RRL technology to U.S. company; Demonstrated full procedure for phase shifting 300 mm aperture flatness interferometer; Let contract to U.S. company to build 300 mm aperture IR interferometer, based on NIST developed technology, for wafer thickness, thickness variation and bow.
FY 1998	Evaluate application of RRL to photomask blank polishing and repolishing; Install IR interferometer and make comparative measurements; Demonstrate full suite of 300 mm aperture interferometers for as-chucked flatness, thickness, thickness variation, and bow.
FY 1999	Initial measurements using XCALIBIR -- the NIST X-ray Optics CALIBration InterferometeR designed for nm uncertainty measurement of flats, spherical and mildly aspheric optical surfaces.

10. Optical Scattering for Wafer Surface Metrology

FY 1996	With a commercial partner, developed reference wafers to calibrate fab line haze meters; Developed methodology for characterizing microroughness-induced optical scatter instrumentation.
FY 1997	Characterized polarization of light scattered from different scattering sources on silicon wafers; Invented tool for improving particle detection limits on rough surfaces; Developed software, to be available via the World Wide Web, to enable manufacturers and users of light-scattering wafer inspection systems to determine the response functions of their instruments.

FY 1998 Investigate scattering from particles on and defects in blanket overlayers; Extend scattering measurement capabilities into the ultraviolet.

11. High Accuracy Two Dimensional Measurements

FY 1995 Developed and tested control system for Moore Model M48 coordinate measuring machine; Began characterization of system accuracy for measurement of large (up to 750 mm x 750 mm) grid plates; Developed and tested positioning system for small grid measuring machine (M4).

FY 1996 First commercial calibrations of large grid plates made on NIST M48 coordinate measuring machine; Typical accuracy for 500 mm x 500 mm grid is 0.40 μm; Completed development of small 200 mm x 200 mm measuring machine (M4); Began characterization of geometric errors and development of error map; Developed robust edge-finding algorithms for system, and began study of methods divergence problems for grid mark edge finding.

FY 1997 Finished characterization of M4, including comparisons in one dimension measurements with the NIST Line Scale Interferometer, the most common traceability path for semiconductor length measurements; Continued development of instruments and began design of industry interlaboratory tests of length measurement capabilities; Continued study of calibration algorithms for grid calibration, including partial closure methods which calibrate the test grid and machine geometry using multiple measurements of a grid in multiple positions and orientations.

FY 1998 Begin making measurements on 200 mm grid plate to test self calibrating algorithms being developed under currently funded SBIR grant; Work with research partners to refine current algorithms and work toward commercial version of package; Participate in interlaboratory tests of measurement accuracy for grid plates; Continue study edge finding methods and develop methods to reduce these effects between industrial and measuring systems; Develop robust measurement algorithms which can be used to measure grids while providing useful control data for statistical process control (SPC).

FY 1999 Using lessons learned from current instrument begin upgrading the system to improve accuracy, particularly focusing on new problems associated with 300 mm and larger wafer sizes.

12. Improved High Temperature Thermometry

FY 1996 Completed reference function data collection for Pt/Pd thermocouples (TCs) at NIST and the Italian national standards laboratory, Instituto di metrologia "G. Colonnetti" to 1500 °C; Developed a system for calibration of thin film thermocouples on silicon wafers up to 900 °C; Selected materials system, including thermocouples, insulators, and bond coats for use on silicon wafers.

FY 1997 Completed experimental aspects of study of Pt/Pd TCs from 0 °C to 1500 °C at NIST and at the Italian national standards laboratory, Istituto di Metrologia "G. Colonnetti," and derived the reference function for the Pt/Pd TCs. Also, Pt/Pd thin-film thermocouples were deposited on 200 mm diameter silicon wafers and evaluated for stability at temperatures up to 800 °C in the NIST rapid thermal processing (RTP) tool.

FY 1998 Write paper on Pt/Pd investigation and publish the reference function for the Pt/Pd TC for the range 0 °C to 1500 °C. This TC has significantly-improved performance over type S TCs and is highly suited for use in the semiconductor industry. Conduct industrial trial of the performance of Pt/Pd TC relative to that of type S TCs in semiconductor manufacturing environments and evaluate the data obtained. Pt/Pd thin-film TCs deposited on 200 mm diameter silicon wafers will be used in the NIST RTP tool along with radiation pyrometers to evaluate temperature measurements in the device by the different techniques at temperatures up to 800 °C. The radiation pyrometers will be calibrated against Pt/Pd wire and thin-film TCs.

FY 1999 Continue industrial trials of the performance of highly-accurate TCs in semiconductor manufacturing environments and evaluate the data obtained. Calibration measurements of the wire TCs and thin-film TCs in air and nitrogen will be made and the hysteresis and drift of the TC measurements will be quantified for industrial applications at temperatures up to 1400 K. Also, characterize NIST thin-film TC instrumented wafers for durability, stability, and repeatability in industrial RTP environments at temperatures up to 1300 K. These data will be related to the mechanisms of failure, hysteresis, and drift, enabling specific design parameters to be determined for industrial applications.

13. Micromechanical Measurements

FY 1996 Tested polysilicon in sample microelectromechanical systems (MEMS) devices; Extended electron beam moiré measurements to biaxial displacements; Applied technique to measurement of thermal deformation of conductive adhesives.

FY 1997 Measured thermomechanical deformations in low-dielectric-constant, back-of-the-chip interconnect structures; Measured local stresses and strains in VLSI interconnects; Measured mechanical properties of metals for low-cost solder bumps.

FY 1998 Measure local microstructures and chemistries in stress-voided interconnects. Measure thermal conductivity in thin film lines using microscale test structures. Investigate the feasibility of using the atomic force microscope to make moiré gratings with smaller pitches than previously possible.

FY 1999 Determine effects of stress voiding on electromigration in narrow interconnects. Demonstrate measurement technique for tensile testing of submicron-width copper and aluminum interconnect traces using the atomic force microscope to apply and measure the tensile force and the resulting displacement. Measure thermomechanical deformations of back-of-chip layered interconnect structures.

14. Solderability Measurements for Microelectronics

FY 1996 Research showing errors present in the interpretation of dynamic and nonisothermal wetting balance tests published in ASME Journal of Electronic Packaging; Results incorporated in new standard tests proposed by the Institute for Interconnecting and Packaging Electronic Circuits (IPC) Solderability Committee.

FY 1997 NIST co-invented a new method to enhance manufacturability and allow improved performance and new temperature ranges for step soldering for die attach and flip chip applications.

FY 1998 Provide leadership in work with the NCMS Consortium on High-Temperature Fatigue Resistant Solders on phase diagram analyses of solder melting ranges

	and establishing other critical properties of solder alloys for high temperature die attach and harsh automotive applications.
FY 1999	Determine mechanism that causes failure in through-hole soldering of lead-free solders, working in collaboration with U.S. companies.

15. Hygrothermal Expansion of Polymer Thin Films

FY 1996	Demonstrated capacitance cell measurement method for out-of-plane coefficient of thermal expansion (CTE) of polymer thin films. Using near infrared spectroscopy, concluded that moisture absorbed from a humid environment by unfilled polyimide and epoxy molding resin is molecularly dispersed.
FY 1997	Provide data on hygroscopic out-of-plane expansion of thin polymer films used in electronic packaging; work with standards-setting bodies to consider adopting capacitance cell technique for measuring expansion of thin films.
FY 1998	Complete a capacitance cell modification which will reduce systematic and temperature-dependent errors from 100 ppm to 1 ppm, and verify uncertainties using standard materials, such as thin sapphire films, and experimental designs to establish measurement protocols. This modification will also allow CTE measurements of conductive thin films; Identify industry's high priority out-of-plane CTE data needs for high density interconnect substrate materials and provide these data to CINDAS. To enhance the industry exposure of this capacitance cell technique, instrument manufacturers, material suppliers and testing laboratories interested in adopting this technology will be identified and contacted.
FY 1999	The work on a capacitance cell will be concluded, and in years beyond 1999 work will be continued with material suppliers and testing laboratories to broaden industrial acceptance of this capacitance cell technology. New measurement technique for in-plane CTE will be developed. Correlation between out-of-plane CTE and in-plane one for polymer thin films will be examined in terms of the molecular orientation.

16. Temperature Measurement for Rapid Thermal Processing

FY 1997	Developed Test Bed for evaluation of new temperature sensor systems; Established procedures for comparison of new thin-film thermocouples (T-FTCs) and radiation thermometers (RTs) using an instrumented calibration wafer; Developed calibration procedures for new generation of optical-fiber (OF) and spot-type radiometers; Established two Cooperative Research and Development Agreements (CRADAs) with instrumentation-related objectives; Formed a 20-company advisory group to connect research to the user community.
FY 1998	Modify the Test Bed to permit characterization of the target radiation environment; Perform detailed intercomparison of T-FTCs and RTs with calibration wafer; Characterize the performance of new RTs, especially rod-types; Develop strategy and methods for measuring and generating emissivity standards.
FY 1999	Demonstrate new methodologies for improved temperature measurement in a production tool; Develop emissivity standards for use in production tools; Complete methodology and modeling tools for characterization of the radiation environment.

17. Chemical Characterization of Thin Films and Particle Contaminants

FY 1997	Collaborated with MIT Lincoln Labs to characterize advanced processing technologies being developed for silicon-on-insulator CMOS devices; Developed and tested high-resolution, high-vacuum goniometer for synchrotron grazing incidence X-ray photoelectron spectrometry; Installed and validated field emission scanning electron microscope with X-ray analyzer; Developed digital-image visibility standard for electron microscopy; Determined X-ray spectroscopy signal-to-noise requirements for automated X-ray analysis of particles.
FY 1998	Coordinate interlaboratory characterization test of a standard TiN thin film on silicon; Determine accuracy of electron microprobe analysis of thin film composition; Determine limits of detection for particle analysis by field emission scanning electron microscopy; use grazing incidence X-ray photoelectron spectroscopy to characterize oxygen on silicon.

Metrology for Nanoelectronics

Project Leader:	Joseph G. Pellegrino
Staff:	4.5 Professionals, 1.0 Technician
Funding level:	$0.8 M
Funding sources:	NIST (100%)
Objective:	Provide technological leadership to semiconductor and equipment manufacturers by developing and evaluating the methods, tools, and artifacts needed to improve the state of the art in compound-semiconductor growth and nanometrology (measurements on a scale of 10 to 100 nm). Provide measurements of growth and structural parameters in addition to fabrication properties required for the reliable manufacture of nanostructure devices. Develop research materials and methods to improve measurement standards.

Background: The yield and reliability of nanostructure devices (having feature sizes between 10 and 100 nm) critically depend on the quality of the materials and processes that are used to manufacture them. Industry needs NIST to provide the methodology, both experimental and theoretical, to evaluate and improve these materials and processes at resolutions on the order of 10 nm. Improved materials growth, evaluation techniques, and models are needed by the compound-semiconductor industry to manufacture useful and reliable devices based on advanced quantum phenomena. There is a great need for standard reference artifacts to reduce measurement ambiguities and uncertainties.

Current Tasks:

1. Develop an in-situ metrology effort for the real-time, in-situ characterization of advanced III-V epilayers

FY 1994	Designed state-of-the-art molecular beam epitaxy (MBE) facility to specifically address real-time, in-situ measurement of growth parameters critical to improved performance of lattice-matched, thickness-dependent, compositionally controlled heterostructures. Designed a unique state-of-the-art X-ray detector in order to implement, for the first time, X-ray fluorescence as an in-situ compositional probe during MBE growth.
FY 1995	Designed equipment and software for in-situ optical reflectometry; Designed multiple-wavelength reflectometer to improve thickness resolution to 5 nm level.
FY 1996	Used in-situ X-ray fluorescence capability in MBE growth chamber to measure and control composition and possibly thickness of MBE layers; Equipped MBE with in-situ ellipsometer for measuring thickness, composition, and roughness of MBE layers; Initiated plans to implement pyrometric interferometry as an in-situ optical probe to measure temperature.

FY 1997 Correlated X-ray fluorescence probe measurements with RHEED (reflection high-energy electron diffraction) measurements of the composition in InGaAs heterostructures. Implemented an in-situ ellipsometry capability for measuring composition and thickness in real time during growth.

FY 1998 Develop an in-situ method for the optical determination of sample temperature during growth. Implement a capability for performing accurate Hall measurements of mobility and doping density of III-V material in order to conduct round-robin measurements among GaAs manufacturers.

FY 1999 Develop an optical probe capable of determining sample temperature and thickness in real time.

2. Develop a measurement infrastructure pertinent to the interface characterization of advanced III-V heterostructures

FY 1993 Characterized interface roughness in low-order aluminum arsenide/gallium arsenide superlattices and determined the influence of the gallium arsenide buffer layer thickness on the subsequent superlattice interface quality; Obtained smoother interfaces in samples with buffer layers with a thickness 250 nm and greater; Using high-resolution X-ray diffraction, showed that the quality of the superlattice interfaces is markedly affected by the growth technique; Also found interfaces were sharper in a migration-enhanced epitaxy sample than in an equivalent superlattice sample grown by the interrupted-growth technique.

FY 1994 Measured anisotropic strain and tilt along orthogonal directions in indium aluminum arsenide/indium phosphide heterostructures used in optoelectronic devices; Used the X-ray standing-wave technique to learn that the buried indium arsenide strained layer in Pseudomorphic High Electron Mobility Transistors (PHEMTs) is only 76% coherent. (Collaboration with Materials Science and Engineering Laboratory)

FY 1995 Correlated roughness properties of MBE-grown aluminum arsenide/gallium arsenide superlattices with carrier mobility in the associated modulation-doped field-effect transistor (MODFET) channel layers; Demonstrated that interface roughness is a function of the growth temperature and that room temperature X-ray diffraction spectra of the roughness can be related to the measured electron mobility in the channel.

FY 1996 Studied interface and structural properties with X-ray diffraction and X-ray standing-wave techniques to optimize layer quality. (Collaboration with Materials Science and Engineering Laboratory)

FY 1997 Used the X-ray standing wave technique to examine bond length contractions in the InGaAs on the GaAs heterostructure system.

FY 1998 Measure the influence of the interface quality on the performance of InGaAs-based MODFET devices using X-ray, optical, and magneto-transport techniques.

FY 1999 Use in-situ X-ray reflectivity to study interface formation in real time for InGaAs-based hetero-interfaces.

3. Develop and address measurement issues pertaining to nanostructure characterization and fabrication

FY 1991 Generated nm-scale patterns on hydrogen-passivated Si by using scanning tunneling microscope (STM) techniques; STM-patterned oxide serves as a

	mask for selective-area GaAs heteroepitaxy on silicon, an essential step in mating GaAs and silicon device technologies. (Collaboration with Manufacturing Engineering Laboratory)
FY 1992	Grew high-quality GaAs samples for the quantum-Hall resistance standard. (Collaboration with Electricity Division)
FY 1993	Studied nm-scale oxides patterned by means of scanning tunneling microscopy and showed they are readily generated in an air ambient, easily imaged by scanning electron microscopy and other microprobe techniques, capable of surviving realistic processing environments, and useful as masks for etching and selective area growths. (Collaboration with MEL)
FY 1994	Designed a new series of superlattice structures to increase the confinement of the optically produced carriers and obtain stronger exciton peaks. (Collaboration with the University of Iowa)
FY 1995	Continued scanning tunneling microscopy effort (Collaboration with MEL); and made contributions to single electron transistor effort (Collaboration with Division 811). Fabricated "shadow masks" in MBE for use in growing vertically interdigitated optical switches. The interdigitated sample has been metallized and shows proper diode behavior. Characterized sample by photoreflectance while optically biased. Data indicate an upshift of the quantum well energy, as predicted. (Collaboration with the University of Iowa)
FY 1996	Installed focused-ion-beam (FIB) lithography system in MBE chamber for patterning III-V and possibly silicon wafers; Assisted optimization of STM system for measuring nanostructures; Grew specialized heterostructures for electronic and optoelectronic devices. (Collaboration with University of Iowa and others)
FY 1997	Used FIB to direct write on "two-dimensional" electron gas (two dimension electron gas) materials of InGaAs/GaAs heterostructures to produce confinement of the electrons at the nano-scale. The FIB-processed "laterally in-plane gated field-effect transistors (FETs)" demonstrated very good current-voltage and transfer characteristics at room temperature. Overall characteristics are similar to that of silicon depletion-mode MOSFETs.
FY 1998	Utilize FIB lithography to develop research artifacts for improved standards.
FY 1999	Integrate FIB and MBE to develop research artifacts for improved standards.

Optical Characterization Metrology

Project Leader: Paul M. Amirtharaj

Staff: 2.2 Professionals, 1.0 Post Doc

Funding level: $0.9 M

Funding sources: NIST (90%), Other Government Agencies (10%)

Objective: Develop and implement advanced and robust optical probes needed by the semiconductor industry. Apply infrared absorption and photoluminescence (PL) for impurity analyses of silicon. Advance and optimize modulation spectroscopy for the study of compound semiconductor materials and microstructures. Employ photoluminescence and Raman scattering to characterize SiGe-based quantum structures to develop Si-based optoelectronic devices. Collaborate with Nanoelectronics Project and compound-semiconductor-based industries to advance optical in-situ probes. Develop standard research materials and methods and compile data to improve standards.

Background: Manufacturers of electronic components for a wide variety of applications, extending from digital circuitry for computers to light emitters for optical communication, need reliable analytical methods and well-established standards for characterizing the behavior of elemental and compound semiconductor materials. The continual reduction in feature size set forth in the National Technology Roadmap for Semiconductors for increased packing density and the complex optoelectronic device structures that use 10 to 100 layers place stringent demands on the current analytical probes. Further device advances can be commercially realized only with the enhanced yield possible with sophisticated and dependable characterization, including real-time in-situ materials monitoring. Optical and electrical activity form the foundation of all the major electronic devices today. Optical probes are attractive and powerful for a variety of reasons. They are contactless and nondestructive, compatible with any transparent gas, capable of remote sensing and compatible with hostile environments and, hence, useful for in-situ probing during growth and processing.

Current Tasks:

1. Develop metrology to identify and quantify impurities in silicon

FY 1988 Assisted American Society for Testing and Materials (ASTM), a voluntary standards organization in the U.S., through its Subcommittee F1.06 in a pilot study on the determination of trace impurities in silicon by photoluminescence; Determined the conversion coefficient for infrared measurement of oxygen in silicon. Wrote two new standard test methods adopted by ASTM: Method F 1188, Interstitial Atomic Oxygen Content of Silicon by Infrared Absorption, and Method F 1189, Using Computer-Assisted

	Infrared Spectrophotometry to Measure the Interstitial Oxygen Content of Silicon Slices Polished on Both Sides.
FY 1989	Published archival summary and extended report of analysis of International Round-Robin-on-Oxygen conversion-factor for infrared measurements.
FY 1990	Developed fully automated analytical procedure to study oxygen in double-side-polished silicon wafers.
FY 1991	Completed installation and testing of high resolution and high-stability Fourier transform interferometers for impurity analysis in silicon.
FY 1992	Completed oxygen-in-silicon Standard Reference Material (SRM) production methodology.
FY 1993	Completed certification and related measurements for 100 sets of SRM 2551 for Interstitial Oxygen in Silicon. Analysis of data indicates an uncertainty of certification, relative to the master calibration set, of better than 0.17% (2σ). SRMs are required by integrated circuit manufacturers to determine oxygen concentrations.
FY 1994	Demonstrated the use of Fourier transform infrared (FTIR) absorption for measurement of boron and phosphorous in high-purity silicon at densities of less than 10^{12} per cubic cm.
FY 1995	Applied the above capability for Defense Production Act-Title III high-purity silicon materials qualifications. NIST was requested to provide this assay of dopants by the Department of Defense.
FY 1996	Applied spectroscopic and photoconductive probes to investigate the origin of persistent-photoconductivity and/or slow traps in integrated circuit grade silicon. Applied FTIR spectroscopy to determine the densities of technologically important impurities in silicon, especially integrated circuit grade wafers.
FY 1997	Developed improved optical probes for process-induced impurities in integrated circuit-grade wafers.
FY 1998	Develop FTIR methodology for characterizing silicon starting material for integrated-circuit fabrication. Apply technique to study impurities, including low concentration oxygen and oxygen in conducting wafers.
FY 1999	Apply technique to analyze thin SiO_2.
FY 2000	Develop infrared ellipsometry to improve accuracy of optical constants measurements.

2. Develop and apply nondestructive optical probes of the electronic behavior of technologically important semiconductor materials and device structures

FY 1990	Developed and published "A Software Program for Aiding the Analysis of Ellipsometric Measurements, Simple Spectroscopic Models" as NIST Special Publication 400-84.
FY 1991	Completed building and testing a state-of-the-art spectroscopic ellipsometer with near monolayer sensitivity; Applied instrument to study real-time oxidation of the gallium arsenide surface.
FY 1992	Provided optical characterization of silicon carbide for X-ray mask application and cadmium zinc telluride substrates for infrared materials growth.
FY 1993	Achieved a critical advance in the quantitative understanding of the optical properties of the silicon dioxide/silicon interface region by conducting accurate spectroscopic-ellipsometry measurements and by developing an analysis that, for the first time, comprehensively accounted for strain and

	microroughness. This was a necessary step in the development of thin (d < 10 nm) silicon dioxide/silicon SRMs.
FY 1994	Advanced the state of the art of photoreflectance spectroscopy for semiconductor analyses through the use of double-modulation and multiple-pump beams. Detailed analysis of complex laser structures was now possible.
FY 1995	Completed one-of-a-kind selective-excitation system operable in the 350 to 1100 nm range and initiated comprehensive defect and impurity analyses in gallium nitride.
FY 1996	Completed automation of the selective excitation system, with capability from the ultraviolet to the infrared region of the optical spectrum, for high-resolution optical spectroscopy. Used system to investigate gallium nitride and related materials; Applied spectroscopic ellipsometry for the optical analyses of ultra thin semiconductor and insulator layers.
FY 1997	Conducted selective-excitation spectroscopy and analysis of dopants, including magnesium and silicon in gallium nitride.
FY 1998	Complete photoluminescence study of SiGe quantum structure grown with H-surfactant assisted growth to optimize growth conditions for Si-based optoelectronic devices.
FY 1998-99	Collaborate with Nanoelectronics Project and compound-semiconductor based industries to advance optical in-situ probes.

3. Provide coordination and leadership to industry in optical characterization and related activity

FY 1989	Organized and hosted the International Conference on Narrow-Gap Semiconductors and Related Materials in Gaithersburg, MD, June 1989.
FY 1990	Edited and published Proceedings of the International Conference on Narrow Gap Semiconductors.
FY 1991	Developed detailed questionnaire on optical characterization techniques needed by the industry; Presented invited tutorial talk, "Optical Characterization of Electronic Materials," at two-day symposium, Microanalysis of Electronics, organized by ASM International and NIST Office of Microelectronics Programs.
FY 1992	Distributed to major semiconductor companies a questionnaire regarding the use of optical characterization techniques for materials and device analysis by the semiconductor industry.
FY 1993	Wrote chapter on "Optical Properties of Semiconductors" for the *Handbook of Optics*, second edition, for the Optical Society of America and McGraw Hill; Provided review of all important optical properties and techniques for measuring them; Second mailing of optical characterization survey sent out.
FY 1994	Presented an invited review entitled "Optical Properties and Characterization Methods for HgCdTe" at the 1993 U.S. HgCdTe Workshop that emphasized industrial applications for semiconductors. Mercury cadmium telluride (HgCdTe) is a material used to make detectors for infrared light. Carried out analysis of optical characterization survey results.
FY 1995	Organized and conducted the Workshop on Planning for Compound Semiconductor Technology, attended by 60 participants and 6 invited speakers, with a panel discussion. Participants agreed on consensus-based planning to help the North American segment remain competitive.
FY 1996	Presented invited paper entitled "Double Modulation Photoreflectance" at the Symposium on Diagnostic Techniques for Semiconductor Materials Processing, Materials Research Society Fall Meeting, November 1995;

Published Proceedings of the International Workshop on Semiconductor Characterization by the American Institute of Physics Press; Published and distributed to industry NIST Special Publication 400-98 containing results of the Optical Characterization Survey.

FY 1997 Contributed chapter on optical properties to book on properties of narrow-gap II-VI semiconductors published by Chapman-Hall, United Kingdom; Edit proceedings of the 1996 U.S. Workshop on the Physics and Chemistry of II-VI Materials and publish as a special issue in the *Journal of Electronic Materials*.

FY 1998 Edit proceedings of the 1997 U.S. Workshop on the Physics and Chemistry of II-VI Materials and publish as a special issue in the *Journal of Electronic Materials*.

4. Compile near-edge fundamental parameters for III-V binary semiconductors

FY 1996 Initiated the Standard Reference Data (SRD) Project entitled, "Near Band-Edge Fundamental Parameters for III-V Binary Semiconductors" and review of relevant published literature.

FY 1997 Completed review of published literature.

FY 1998 Compile parameter values and initiate publication.

Scanning-Probe Microscope Metrology

Project Leader: Joseph J. Kopanski

Staff: 4.4 Professionals

Funding level: $0.8 M

Funding sources: NIST and OMP (100%)

Objective: Provide technological leadership to semiconductor and equipment manufacturers and other government agencies by developing and evaluating the methods, tools, and artifacts needed to apply scanning-probe microscopes and other electrical characterization to semiconductor materials and processes; provide silicon and compound-semiconductor manufacturers with advanced scanning-probe electrical metrology techniques and models to improve device performance and reliability.

Background: The reduction in feature sizes to near 100 nm predicted by the goals of the semiconductor industry for the early 21st century requires new and improved measurement methods to characterize materials and processes to the required 10 nm resolution scale. Industry needs NIST to provide the methodology, both experimental and theoretical, to evaluate and improve materials and processes by implementing scanning-probe microscope-based and traditional electrical techniques. Measurements of the dopant density, lifetime, and mobility of charge carriers in wafers and thin layers are essential for materials and process qualification. The National Technology Roadmap for Semiconductors has challenged NIST with responsibility for developing the technology needed to determine the dopant distribution across a processed silicon wafer to a resolution of 20 nm. Scanning capacitance microscopy is being developed as a new tool to achieve this goal.

Current Tasks:

1. Develop scanning-probe microscopy and models for dopant profiling

FY 1989 Demonstrated two-dimensional mapping of silicon resistivity striations with resolution of 40 μm by high-density four-probe structures.

FY 1990 Demonstrated and verified high-spatial-resolution resistivity mapping with ion-implanted test structures and theoretical modeling; Showed that lateral resistivity variations over dimensions as small as 45 μm can be mapped, which has important application to gallium arsenide and mercury cadmium telluride materials.

FY 1991 Applied fine-scale resistivity mapping technique to specimens of mercury cadmium telluride; Showed that nonuniformity patterns are correlated with the type of crystal growth, LPE (liquid-phase epitaxy) or SSR (solid-state recrystallization).

FY 1992 Prepared detailed specifications for a scanning tunneling/atomic force microscope for scanning capacitance microscopy (SCM); the microscope is

	one of the first to be made with a large sample stage, compatible with semiconductor wafers with diameters to 250 mm. Began development of the capacitance-sensitive circuit and theoretical modeling of the SCM measurement.
FY 1993	Designed, constructed, and tested an SCM for nanoscale (10 to 100 nm) profiling of semiconductor junctions; the design is the first to take advantage of incorporating a commercial atomic force microscope (AFM).
FY 1994	Obtained capacitance-voltage curves with the SCM as a function of probe position. Implemented tapping-mode capability on SCM to reduce damage to probe and specimen and give improved reproducibility and signal-to-noise ratio. Developed three-dimensional collocation code to solve Poisson's equation for SCM.
FY 1995	Demonstrated a new mode of scanning capacitance microscopy: imaging the high-frequency capacitance directly. This enables imaging of metal lines on an insulating substrate for overlay metrology. Produced two-dimensional (2D) images of dopant profiles from cross-sectioned silicon wafers with better than 30 nm resolution; Modeled the probe-ambient-insulator region with commercial code, which solves Laplace's equation in three dimensions (3D); Combined solutions with those from 3D collocation code for semiconductor region to obtain total solution of electric potential; Computed capacitance as a function of bias voltage for uniformly doped silicon wafer.
FY 1996	Established reliable techniques to obtain SCM data of carrier profiles; Applied SCM method to overlay metrology; Obtained solutions in 2D and 3D for the charge density in doped silicon wafers and simulate SCM data; Developed useful, simple methodology to relate SCM data to dopant profiles.
FY 1997	Interacted strongly with equipment and user community to transfer NIST technology; Validated SCM model and methodology from measurements on well-known samples provided by industry; Used developed code to produce model database; Investigated ways of including dopant gradient effect; Implemented data conversion methodology in a user-friendly and 2D format; Developed tapping-mode SCM for overlay measurements; Identified SRMs needed to support industry use of SCM measurement standards.
FY 1998	Improve spatial resolution and accuracy of SCM 2D dopant profile measurement by including the secondary effects of the dopant gradient and junction. Refine the SCM "wafer-to-profile" measurement methodology. Transfer the NIST SCM models and image conversion routines to industrial users.
FY 1999	Continue refinement of SCM model/measurement formalism to keep pace with the {semiconductor} technology computer-aided design (TCAD) 2D dopant profiling spatial resolution and accuracy goals. Extend model to true 3D to validate and improve current 2D approach. Update and support SCM image interpretation software, incorporate compound semiconductor material parameters, assist industrial users.

2. Perform bulk/thin film magnetotransport analyses of carrier densities and mobilities; develop silicon resistivity Standard Reference Materials (SRMs)

FY 1989	Completed extensive evaluation of a technique for impedance measurement using time varying signals for high-resistivity silicon (from 2 to 50 Ω-cm); Developed silicon resistivity SRMs.

FY 1990 Demonstrated validity of the impedance technique for measuring high-resistivity silicon by comparison with traditional techniques; Certified 155 sets of bulk silicon resistivity SRMs (51 mm diameter, 0.01 to 180 Ω-cm); Transferred, to SRM office, 101 sets of these and the final 40 sets of spreading resistance SRMs.

FY 1991 Certified over 400 50.8 mm (2 in.) diameter wafers having resistivities, from 0.01 Ω-cm to 200 Ω-cm, for use in multiwafer silicon resistivity SRM sets; Established facility for variable magnetic field transport measurements over the temperature range from 10 to 400 K and tested specimens of aluminum gallium arsenide/gallium arsenide, indium antimonide/indium arsenide, and mercury cadmium telluride; Developed a procedure for efficient identification of single- or multiple-carrier conduction.

FY 1992 Developed and applied a general technique for analyzing multicarrier conduction; Made extensive Hall and resistivity measurements on several structures; Continued work on silicon SRMs.

FY 1993 Developed a simple, accurate measurement method for determining the electron density and Hall mobility of semiconductor layers, based on the magnetic-field dependence of the two-terminal magnetoresistance of a rectangular layer; Applied this method to characterize accumulation layers of n-type mercury cadmium telluride infrared (IR) detectors; Provided NOAA with characterization study of mercury cadmium telluride detectors used in Geostationary Operational Environmental Satellite weather satellites; Completed certification and system control measurements for 135 units of SRM 2547 100 mm diameter silicon resistivity at the 200 Ω-cm level.

FY 1994 Established high-field magnet facility; Studied two-dimensional magnetophonon effect and universal conductance fluctuations in gallium arsenide/aluminum gallium arsenide heterostructures grown in Division's MBE system as well as in silicon/germanium heterostructures grown at the Naval Research Laboratory; Continued certification of silicon SRMs.

FY 1995 Determined carrier densities and mobilities in mercury cadmium telluride, III-V, and high-resistivity silicon samples; Completed calculations of mobility of gallium arsenide, including electron-electron and electron-phonon scattering; Continued to measure 100 mm silicon resistivity SRMs; Discovered photosensitivity of resistivity to fluorescent room light, which requires that two of the seven SRMs (1 and 10 Ω-cm) be removed from series; Showed need for further research of cause of effect before proceeding with these two SRMs.

FY 1996 Provided information from electrical methods as to the cause of photoresponse in several of the 100 mm diameter silicon resistivity SRMs; Characterized the electrical properties of samples grown in molecular beam epitaxy machine, fabricated in focused ion beam machine, or supplied by industry.

FY 1997 Delivered 100 mm resistivity SRMs for sale to industry (completed); Characterized traps responsible for photoeffect in SRM p-type silicon by deep level transient spectroscopy and photoconductivity; Developed instrumentation and theoretical understanding to implement the photo-Hall effect and magnetoresistance measurements. (Task redirected and continued as Task 5 [on next page].)

3. Develop and apply models of scanning electron microscope signals for critical-dimension metrology (Collaboration with Manufacturing Engineering Laboratory)

FY 1993	Surveyed and used existing code for modeling scanning electron microscope (SEM) signals.
FY 1994	Wrote and documented a new Monte Carlo code, MONSEL-I, to simulate the transmitted and backscattered signals from a multilayer specimen in an SEM; Code has been used to provide a quantitative description of the signals from a gold line on a silicon substrate used in critical-dimension metrology.
FY 1995	Completed improved Monte Carlo code, MONSEL-II, for simulating transmitted, backscattered, and secondary electron signals in SEM; Model target is three parallel lines on multi-layer substrates; Completed work on MONSEL-III, a code for simulating short lines and vias as well as tilted substrates; Compared results of simulations with those from measured scans to obtain line edge locations to less than 10 nm.
FY 1996	Developed methodology to optimize Monte Carlo simulations of SEM signals and enhance codes as required.
FY 1997	Advised industrial users of MONSEL-II and MONSEL-III regarding their proper use, and extended codes based on feedback from user community; Provided modeling for development of SRMs for critical-dimension metrology. (Task completed) (Related work continues in the Manufacturing Engineering Laboratory)

4. Develop scanning-probe microscopes (SPM) and models for semiconductor and device electrical characterization. (New task)

FY 1998	Investigate measurement of stimulated capacitance transients with SPMs for development of a microscope sensitive to semiconductor lifetime. Investigate the ac impedance measurement techniques and models necessary to implement an ac version of nano-spreading resistance. Apply SPM electrical characterization to compound semiconductors.
FY 1999	Investigate further applications of optically pumped SPMs and impedance measurements with SPMs. Develop models to make lifetime measurements quantitative by extending codes developed for SCM. Refine lifetime and nano-spreading resistance microscopies as practical metrologies. Apply SPM characterization to carrier lifetime measurement, dielectric layer characterization, and lithographic overlay applications.

5. Perform bulk/thin film magnetotransport analyses of carrier densities and mobilities; utilize conventional electrical characterization techniques in support of scanning probe microscopes. (New task)

FY 1998	Continue development and applications of photo Hall effect measurement; Apply existing electrical characterization techniques to advanced materials fabricated by the Division and others. Maintain proficiency in SEM model codes.
FY 1999	Apply Hall effect, photo-Hall effect and magnetoresistance measurements and models to materials provided by industrial and internal collaborators. Address magnetotransport measurement interpretation needs as defined by industrial

users and instrument makers. Apply existing expertise in electrical characterization to advanced materials with collaborators at NIST.

Thin-Film Process Metrology

Project Leader: James R. Ehrstein

Staff: 3.2 Professionals, 2.0 Technicians

Funding level: $0.8 M

Funding sources: NIST (100%)

Objective: Develop new and improved measurements, models, data and reference materials, and mechanisms for traceability to NIST to enable better and more accurate measurements of select critical silicon-technology thin-film process parameters.

Background: Fabrication of thin films of various types is a fundamental building block in semiconductor device fabrication. The rapid, continuing requirements for ever thinner films place increasingly stringent requirements on the composition and structure of those films. This, in turn, places increasingly stringent requirements on the metrology tools and procedures used for process development and process monitoring. The drive in the industry is toward establishing in-situ process-monitoring capabilities for all major process steps. Yet as layers and structures are refined and shrunk, improved in-line, at-line, and off-line capabilities will also be necessary to verify the relations between material parameters resulting from the process steps and the parameters being monitored in situ. Among the thin-film process metrology challenges, two are targeted initially: dielectric layers, particularly gate dielectrics, and ion-implant dosimetry. The National Technology Roadmap for Semiconductors identifies robust gate dielectrics with 2 nm thickness as a specific near-term on-chip materials issue and gate dielectrics with sub 1 nm oxide-equivalent thickness as an issue that will impact the ability to achieve the 15-year goals of the Roadmap. NIST work will provide the metrology support required for the controlled processing of these films in the semiconductor manufacturing environment.

Current Tasks:

I. Establish and transfer basis for accuracy of measurement of silicon-related dielectric layers, in both at-line and in-situ modes.

1. Establish traceability to NIST for measurements of critical dielectric layers of silicon

FY 1988	Certified and released the first Standard Reference Materials (SRMs) for thickness of silicon dioxide, at thicknesses from 50 nm to 200 nm.
FY 1989	Developed computer code and released documentation for ellipsometric analysis of thickness of dielectric layers and interface region.
FY 1992	Developed and certified 14 nm and 25 nm silicon dioxide thickness SRMs.
FY 1994	Developed and certified 10 nm silicon dioxide thickness SRMs; Completed intercomparison with nine select laboratories for measurements of 10 nm oxides; demonstrated interlaboratory repeatability consistent with industrial

requirements. National Technology Roadmap for Semiconductors reaffirms critical nature of ultrathin gate oxide fabrication control.

FY 1995 Developed cooperative program with commercial source of reference materials to establish traceability to NIST for thin oxide materials.

FY 1996 Initiated Cooperative Research and Development Agreement (CRADA) experiments to establish traceability of ellipsometer-based Reference Materials.

FY 1997 Completed CRADA experiments and analysis to demonstrate traceability to NIST within 0.1 nm for single-wavelength ellipsometry measurements of oxide films between 4.5 nm and 100 nm. Conducted workshop for industry experts in the optical characterization of thin dielectrics to focus on issues of standards and traceability for future generations of very thin films.

FY 1998 Implement workshop recommendations for improving traceability to NIST. Reduce uncertainty of NIST ellipsometry measurements in order to keep pace with NTRS requirements.

FY 1999 Prototype and evaluate NTRM measurement exchange with one or two laboratories for next-generation silicon dioxide films.

2. Develop understanding of relation between silicon/dielectric layer physical and interface properties, and measurements by optical and electrical characterization techniques for dielectric layer thickness.

FY 1994 Used spectral ellipsometry measurements to validate interface model used for single-wavelength oxide Reference Material certification. The National Technology Roadmap for Semiconductors affirms the need to understand and control surface on which gate oxide is grown.

FY 1995 Established capability for "Weak Localization" measurement technique to extract quantitative measure of electronic roughness at layer-interface.

FY 1996 Extended this technique to the quantitative measurement of interface roughness in typical silicon metal oxide-semiconductor field-effect transistor (MOSFET) test structures.

FY 1997 Compared experimentally optical measurements of dielectric and interface properties with electrical, and/or "beam-probe" determinations of those properties.

FY 1998 Begin to evaluate, implement, and improve models for the interpretation of thickness from electrical measurements in conjunction with the establishment of electrical measurement capabilities for determining the electrical thicknesses of nanometer-thickness films.

FY 1999 Apply electrical analysis methods to determining thicknesses of very thin dielectric films; correlate results with ellipsometric determinations of thickness.

3. Develop high-accuracy database for optical constants of silicon and its dielectric layers at elevated temperatures used for integrated circuit processing

FY 1995 Contracted for design and fabrication of customized vacuum chamber with in-situ ellipsometry and high-temperature film growth capability; The National Technology Roadmap for Semiconductors asserts need for in-situ metrology of film thickness and gate dielectric composition.

FY 1996 Installed test chamber at NIST; Began test and evaluation of chamber.

FY 1997	Completed test of chamber and instrumentation, developed control and analysis software.
FY 1998	Begin program of determining optical constants of silicon and critical thin films of silicon at elevated temperatures.
FY 1999	Implement a film etching process to evaluate the possibility of real-time in-situ elevated temperature application of spectroscopic ellipsometry in conjunction with the high-temperature optical constants already obtained for silicon and silicon dioxide.

II. Develop reference materials for ion implant dosimetry

FY 1992	Established need and potential guidelines at SEMATECH-sponsored workshop for transfer standards between implant dose and sheet resistance.
FY 1995	Initiated program to develop reference materials for ion implant dosimetry; Provided leadership and planning input to Third International Workshop on the Measurement and Characterization of Ultra-Shallow Doping Profiles in Semiconductors; Edited Workshop Proceedings.
FY 1996	Modeled the sensitivity of the implant dose/sheet resistance relation (for boron) to starting material and implant condition parameters.
FY 1997	(Task terminated to permit resources to be applied to higher-priority work.)

Silicon-on-Insulator Metrology

Project Leader: Peter Roitman

Staff: 1.0 Professional, 1.0 Technician, 1.0 Student

Funding level: $0.4 M

Funding sources: NIST (50%), Other Government Agencies (50%)

Objective: Develop advanced measurement methods for defect detection in silicon-on-insulator material; develop silicon-on-insulator material for insertion in silicon integrated circuit manufacturing; provide expertise to other government agencies regarding silicon-on-insulator programs.

Background: Silicon-on-Insulator (SOI) wafers have advantages over bulk silicon for isolation and process simplicity, for short channel device performance, and for applications involving low power, high temperature, high speed, integrated power, and radiation hardness (including soft errors). The National Technology Roadmap for Semiconductors 1997 Edition states that SOI technology needs to be investigated for critical dimension of 0.13 and smaller. However, several different types of defects have been identified which are unique to these materials and the conditions of their fabrication. Identification of defect types and development of characterization techniques suitable to SOI are prerequisites to both the minimization of the number of defects, through process control, and to the commercial acceptance of the material. The primary focus of this project has been on the development of characterization techniques and methods, to facilitate material improvement to the point of commercial viability. Also, several government agencies have been involved in programs to develop SOI materials, due to particular requirements of their mission, and the project has interacted with them.

Current Tasks:

1. Develop characterization techniques for SOI material

FY 1988 Evaluated the many existing SOI technologies. SIMOX (formation of a buried oxide by high dose ion implantation) was chosen as the most promising and, hence, the focus of the project. Completed construction of high-temperature furnace essential for SOI (SIMOX) fabrication; Completed secondary ion mass spectrometry and Rutherford backscattering round robin to calibrate impurities of importance in SOI material; Developed the use of electron channeling patterns to nondestructively measure oxide precipitates and silicon dislocations.

FY 1989 Began work on transmission electron microscopy (TEM) and materials analysis. (Collaboration with Arizona State University) TEM cross-sections used to show effect of annealing temperature and ambient on oxide precipitates and dislocations in the silicon film; Established limits of detectability for electron channeling pattern technique for defect detection: Developed etch pit with scanning-electron-microscope counting technique for

	low-density defects in the silicon film; Developed a complementary metal oxide-semiconductor (CMOS) on SIMOX process at NIST. Designed two CMOS on SIMOX test chips.
FY 1990	Established 1300 °C as minimum temperature for dissolution of oxide precipitate complex. Industry adopted 1310 °C or 1325 °C as standard for SOI (SIMOX) processing. Established 600 °C as the minimum implant temperature required for low-defect-density silicon films; Developed and experimentally verified a theoretical model for the analysis of the capacitance-voltage curve of a complete SOI stack; Demonstrated the improvement in spectral fit which occurs as the ellipsometric model is made increasingly physical; Completed NIST3A4 mask set for CMOS on SIMOX test chip. Processed initial lots at NIST.
FY 1991	Proved that high-leakage currents in buried oxides were due to "pipes" of silicon caused by particles on the surface of the wafer during the SIMOX oxygen implant; Transferred potassium hydroxide etch technique and results to industry. Particle problem largely eliminated by industry. Developed modified Secco/HF etch for reliable delineation of silicon defects; Transferred technique to industry (has become industry standard); Proved existence of large numbers of silicon dangling bond defects uniformly distributed through buried oxide by spin resonance capacitance voltage, etc.
FY 1992	Showed reduction in silicon defect density by annealing sequence; Identified high-field conduction mechanisms for buried oxides. CMOS on SIMOX processing at NIST ended.
FY 1993	Demonstrated the effect of nitridation of the buried oxide, using nitrogen, ammonia, and nitrous oxide ambients; Explained the full mechanism for formation of silicon defects in high dose SIMOX. Demonstrated the defect types present in bonded silicon wafers (BESOI) using the techniques developed for SIMOX. Showed the experimental physics of the formation of silicon precipitates in the buried oxide at low and medium dose.
FY 1994	Demonstrated the effect of high-temperature annealing in the range of 1300 °C to 1350 °C on silicon defect structure and interface roughness. Explained the mechanism for formation of silicon defects in low and medium dose SIMOX.
FY 1995	Showed leakage current in low dose SIMOX due to effects of silicon precipitates.
FY 1996	Developed etch technique for silicon precipitates in SIMOX buried oxides and applied technique to experimental low and medium dose material; Determined effect of dose on precipitate density; Started development of novel process for low defect, low dose SIMOX.
FY 1997	Developed and characterized processes for low dose SIMOX material; Characterized bonded and thick silicon SIMOX material.
FY 1998	Develop experimental techniques and data-reduction algorithms for characterization of SOI material using simple electrical test structures. Process test structures on SOI material. Optimize process parameters for fabrication of thin film SOI material by the room temperature implant process. Establish relation between measurements of material properties and circuit performance for SOI.
FY 1999	Continue development of wafer level transistor measurements. Develop gate oxide integrity test capability. Optimize low dose SIMOX process. Evaluate defects in commercial bonded material.

2. Provide technical support and assist in oversight of SOI projects for other agencies of the U.S. government

FY 1988-94	The primary driver for SOI development in the U.S. was the need for radiation-tolerant electronics for satellite applications. The Defense Nuclear Agency and the Strategic Defense Initiative Office were the agencies primarily concerned. The project participated in contract reviews and planning activities with these agencies.
FY 1995-97	The application driver for SOI development changed to low power, battery-operated, portable electronics. The Defense Advanced Research Projects Agency initiated a program in Low Power Electronics. The project is heavily involved with the planning and management of this program
FY 1998	The Low Power Electronics program is ending. The justification and strategy for a new program, which includes SOI technology development, will be developed with DARPA. The program must be approved by DARPA management, advertised, and bids analyzed. If approced, technical would start in FY 1999.

Metrology for Simulation and Computer-Aided Design

Project Leader: Allen R. Hefner

Staff: 3.8 Professionals

Funding level: $1.1 M

Funding sources: NIST and OMP (86%), Other Government Agencies (14%)

Objective: Facilitate the efficient and reliable application of semiconductor computer-aided design (CAD) tools by: developing metrology necessary for providing model data, developing methods for simulator model validation, and providing simulation capability benchmarks; develop additional models and techniques necessary for advanced device, process, package, and system simulation; and support and participate in national and international standards and industry organizations.

Background: The project addresses needs at the boundary between model and simulator development and the application of computer-aided-design tools. The National Technology Roadmap for Semiconductor identifies modeling and simulation as cross-cutting technologies, and the availability of calibrated and easy-to-use technology computer-aided-design tools for device, process, and circuit simulation as areas requiring development and support to achieve the 15-year goals of the Roadmap. The Roadmap also states that using accurate computer models shortens time scales, lowers costs, and increases quality of each technology area. Advanced device electrical and thermal characterization procedures and validation of models used in computer-aided-design tools have not kept pace with the application of the new device types and processes. This project's goals are to develop methods and procedures and to support an industry infrastructure for establishing model accuracies.

Current Tasks:

1. Develop metrology for MEMS and package thermal simulations

FY 1997 Developed validation procedure for compact package models for use in computational fluid dynamics simulations in natural convection environment; Provided demonstration for multiple-package, highly confined, highly interacting system.

FY 1998 Develop metrology for MEMS system simulation and implement prototype MEMS flow rate sensor model in MAST.

2. Develop metrology for integrated system simulation capability

FY 1997 Developed required electrical measurement techniques to support integrated system simulation capability for U.S. Navy's Power Electronic Building Block Program's modules and chips and also the Partnership for a New

Generation Vehicle electric vehicle propulsion systems; Developed module thermal model for inclusion in system simulation programs.

FY 1998 Develop metrology for integrated package and circuit board electrical interconnect simulation and validation; Develop metrology for state-of-the-art power device reliability.

FY 1999 Develop methodology for virtual prototyping of advanced power device structures, materials, and packages.

3. Develop models and validation metrology for circuit simulation

FY 1997 Began draft of IEEE-recommended practice standard for Insulated Gate Bipolar Transistor (IGBT) model validation and completed the draft of IEEE-recommended practice standard for microelectronic MOSFET model validation procedures; Applied model validation procedures to IGBT component libraries provided in commercial simulator software, and recommended improvements for commercial version of NIST IGBT model.

FY 1998 Investigate tools for improving analog-hardware-description language model development productivity. Complete IEEE standards for microelectronic MOSFET and IGBT circuit simulator model validation. Transfer NIST vertical double-diffused MOSFET (VDMOSFET) model to system simulator software vendors. Develop test method for validating power device models for soft switching applications.

FY 1999 Develop models, extract parameters, and simulate advanced silicon double injection devices.

4. Develop physics, validation metrology, and benchmarks for device simulation

FY 1996 Determined suitability of aluminum gallium arsenide mobility models in commercial device simulators.

FY 1997 Investigated with industry partners methods for measuring mobilities in aluminum gallium arsenide and other compound semiconductor devices; Investigated influence of the mobility models on device simulation; Investigated with industry partners methods of implementing aluminum gallium arsenide mobility models into device simulation programs.

FY 1998 Investigate the development of benchmarks for determining suitability of effective intrinsic carrier concentration in device simulators for compound semiconductor devices; Use simulator that accounts for quantum mechanical tunneling to calibrate and benchmark simulators for ultra-thin layered structures.

FY 1999 Investigate SiC carrier transport physics, develop a physics-based electro-thermal model for SiC gate turn-off thyristors (GTOs), and extract parameters for various devices SiC produced commercially.

5. Develop metrology for calibration and benchmarking of process simulation parameters

FY 1987-95 Developed ion transport simulation code and used to investigate secondary ion mass spectrometry and sputtering; Developed dopant diffusion simulation capability including implant damage; Formed Ion Implant Users Group.

FY 1996 Initiated and organized first national ion implant users group meeting; Reported on simulation of boron-10 implants for SRM design and sensitivity analysis.

FY 1997	Configured computer-aided design systems to run SUPREM4 process simulation program.
FY 1998	Calibrate implant models in SUPREM4 process simulator using Monte-Carlo ion implant simulator; Investigate methods to benchmark SUPREM4 for boron diflouride implant including anneal; Investigate methods of simulating low-energy boron including backscattering and sputtering using SUPREM4 and calibrate using TRansport of Ions in Matter (TRIM).
FY 1999	Investigate methods of simulating arsenic implants using process simulation programs process simulation programs UTMARLO and SUPREM4.

Metrology for Process and Tool Control

Project Leader: Michael W. Cresswell

Staff: 2.5 Professionals, 0.2 Guest Scientist, 1.4 Technician

Funding level: $0.9 M

Funding sources: NIST and OMP (84%), Other Government Agencies (16%)

Objective: Develop test-structure-based electrical metrology methods and related reference materials with primary emphasis on overlay and linewidth metrology and calibration; contribute to standards groups supporting the development of a litho-metrology infrastructure for the semiconductor industry.

Background: Successive generations of integrated circuits are characterized by the widths of the narrowest lines that are replicated during the wafer-fabrication process. Control of gate length is a key factor driving device performance and yield. Overlay control is necessary for yield maintenance and economically viable manufacturing. Metrology for monitoring these parameters has been identified in the National Technology Roadmap for Semiconductors as a central requirement for maintaining fabrication-process control. The requirements of linewidth and overlay metrology are increasing as the complexity and density of integrated circuits increase from one generation to the next. Critical dimension (CD) and overlay tool manufacturers, and users, are expressing concern that current instrument technology may not have the capability to perform at the sub-quarter-micrometer level. However, electrical test structures have a measurement reproducibility that conforms with future projected error budgets and may be suitable as a low-cost means of reference-material certification to support the extension of current instrument technology to meet the requirements of the roadmap out-years.

Current Tasks:

1. Develop metrology for electrically-measured feature linewidth

FY 1988	Documented and extended statistical model and error analysis for characterizing the performance of a submicrometer lithography based on electrical test structure measurements.
FY 1989	Demonstrated lithography-process diagnosis using rule-based analysis of spatial linewidth variations extracted from multiple design-rule structures replicated in polysilicon on 100 mm wafers.
FY 1990	Developed and demonstrated guidelines for characterizing electron-beam pattern-generator linewidth control by extracting electrical linewidth measurements from electrical test structures.
FY 1991	Compared measurements extracted from scanning electron microscope measurements and measurements using electrical cross-bridge structures having design linewidths to 0.3 µm.

FY 1992	Applied principles of empirical tap-width correction to linewidth extraction from cross-bridge test structures having bridge lengths shorter than 10 µm.
FY 1993	Demonstrated static measurement precision of 1 nm for lines with 350 nm design linewidths.
FY 1994	Compared measurements of lines having drawn widths from 0.35 µm to 1.5 µm by a range of metrological techniques including optical, electrical, and scanning electron microscopy.
FY 1995	Showed agreement to within 10 nm for several materials for electrical linewidth and the NIST Molecular Measurement Machine (M^3) when operating in scanning-tunneling-microscope mode. Optical and electrical linewidth measurement differences are on the order of 100 nm. (collaboration with MEL)
FY 1996	Developed first electrical linewidth test structures with atomically-planar sidewall vertical features having known sidewall slopes in monocrystalline material; Tested to identify origins of critical dimension metrology methods divergence.
FY 1997	Developed electrical test structures having features with atomically-planar vertical sidewalls, which will enable co-calibration by transmission-optical, electrical, scanning-probe, and scanning electron-microscope metrology.
FY 1998	Fabricate and evaluate CD artifacts having features with known sidewall slopes patterned in silicon-on-insulator material. Compare properties of BESOI- and SIMOX-based prototype CD reference-materials. Develop application of electrical test structures to CD measurements (known as ECD) techniques to on-reticle metrology.
FY 1999	Investigate utility of multi-temperature electrical testing to reduce uncertainties of physical CD certification. Fabricate ECD artifacts in highly degenerate single-crystal silicon to reduce uncertainty of physical CD estimates.

2. Develop metrology for electrical overlay and registration

FY 1991	Demonstrated novel electrical test-structure based on the linear voltage-dividing potentiometer for the determination of accuracy and precision of feature placement by primary-pattern-generator systems; Demonstrated sub-15 nm electrical metrology with commercially-available test equipment.
FY 1992	Introduced voltage taps extending across the current-carrying bridge for feature-placement metrology, thereby substantially eliminating process-induced shifts resulting from asymmetrical inside-corner rounding.
FY 1993	Demonstrated the dynamic precision of electrical overlay test structures to be 1.5 nm, and their uncertainty less than 10 nm, by comparing electrical measurements with those made by the NIST Line-Scale Interferometer. (collaboration with MEL)
FY 1994	Developed and obtained patents for improved optical overlay-instrument calibration substrates and for electrical certification of graduated scales.
FY 1995	Designed, fabricated, and electrically tested substrates at multiple sites co-inspected by the NIST Line-Scale Interferometer. (collaboration with MEL)
FY 1996	Presented paper at SEMATECH to invited industry audience on new hybrid optical-electrical test structure to facilitate pixel-calibration of optical overlay systems; Initiated a consortium with industry to evaluate new overlay-metrology methods; Developed plan to implement mix-and-match overlay metrology for 193 nm lithography system.

FY 1997	Incorporated electrical edge-detectors into the design of hybrid optical-electrical test structures to enable fabrication of artifacts for estimation of process-specific wafer-induced shift. Developed a wafer-fabrication process for fabrication of structures for tool-induced shift estimation.
FY 1998	Fabricate prototype structures for estimation of tool-induced and process-specific wafer-induced shift. Evaluate suitability of large-area wafer-grade micro-machined silicon to provide reference grids for precision-metrology tool control. Evaluate scanning-capacitance for process-induced shift estimation.
FY 1999	Fabricate and evaluate prototype overlay reference artifacts in SOI films using MEMS (micro-electro-mechanical systems) processes. Investigate electron channeling effects for certification of overlay artifacts.

3. Contribute to development of X-ray lithography mask and metrology infrastructure

FY 1992	Led development of consensus among eight DoD industry contractors for mask-support ring dimensional standards for DARPA X-ray lithography based on finite-element analysis of residual distortion for beam-line applications.
FY 1993	Extended capability of mask-support ring dimensional standard for point-source systems.
FY 1994	Drafted initial international voluntary standard for X-ray mask configurations and chaired video-conference between U.S.-industry representatives and a Japanese task force on convergence between North American and Japanese standards.
FY 1995	Prepared revisions to draft of U.S. standard and obtained concurrence with the Japanese on almost all major points previously under contention.
FY 1996	Developed further agreement between U.S. industry and Japan on final draft of new international voluntary X-ray mask standard.
FY 1997	Submitted revised draft of the X-ray mask standard agreed to, in principle, by both Japanese and American companies to SEMI balloting process.
FY 1998	Provide consultation to international X-ray community on standard non-circular masks.
FY 1999	Investigate applications of ECD metrology to extraction of linewidths of absorber features on X-ray masks.

4. Back-End-of-Process Characterization

FY 1994	Identified potential process control issues; Obtained design rules.
FY 1995	Designed contact resistor test strip and a back end of process test chip (NIST 23); Delivered designs to contractor.
FY 1996	Tested and evaluated test strip and provided results to collaborator.
FY 1997	Task inactive.
FY 1998	Design a large-area test-structure architecture for the characterization of electrical integrity of, and defect-classification and extraction from interconnect systems.
FY 1999	Develop ECD metrology for extracting electrical linewidths of test features on active areas of pelliclized reticles.

Interconnect Reliability Metrology

Project Leader: Harry A. Schafft

Staff: 2.2 Professionals, 0.2 Technicians

Funding level: $0.5 M

Funding sources: NIST and OMP (89%), Other Government Agencies (11%)

Objective: Provide domestic manufacturers with test structures, test methods, and diagnostic procedures for improving the reliability of metal interconnects used in integrated circuits and promote the use of a building-in reliability approach within the semiconductor industry.

Background: Interconnect reliability in integrated circuits continues to be a topic of intense interest, as evidenced by an increasing number of publications on the subject each year. This intense interest is the result of the planned aggressive scaling of integrated circuits and the need for ever greater product reliability, as expressed in the National Technology Roadmap for Semiconductors. The key underpinning of efforts in this area is the development of the measurement tools and standards to facilitate the goals of the industry.

Current Tasks:

1. Develop electromigration standards and metrology methods

FY 1988 Submitted drafts of three electromigration-related documents for balloting as standards to the American Society for Testing and Materials (ASTM), a U.S. voluntary standards organization, through its Subcommittee F1.11 on Quality and Hardness Assurance; Developed a wafer-level test station for making steady state and pulsed electromigration stress tests at temperatures as high as 300 °C; Initiated pulsed stress electromigration testing; Completed collaborative effort with a large semiconductor company and the NIST Statistical Engineering Division on the statistics of electromigration testing.

FY 1989 Discovered a new measurement interference for highly accelerated electromigration stress tests; Developed a new, state-of-the-art wafer test station to perform dc and pulsed electromigration stress tests at room temperature to over 300 °C; Designed a test chip (NIST-2) for use in optimizing the procedure for measuring the thermal conductivity of thin, dielectric films and for conducting pulsed and dc electromigration stress tests.

FY 1990 Demonstrated that the pulsed enhancement of electromigration is dependent on current density; Guided the adoption of three ASTM standards for electromigration that represent first standards for the characterization of interconnect metallizations.

FY 1991 Completed study of power lognormal distribution for modeling electromigration failure times which predicted much lower early reliability values for metallizations; Designed a test chip (NIST 13) to evaluate validity of power lognormal distribution for describing electromigration-related failures.

FY 1992	Showed that the classical electromigration stress test can be used at ultra-high stress levels; Discovered an unusually large enhancement of conductor lifetime under pulsed dc stress that depends on current density and oxide thickness.
FY 1993	Characterized the power lognormal distribution for modeling electromigration failure-time data which include a quantification of the length dependence and of a worst-case estimate of the early reliability of conductor lines.
FY 1994	Initiated work on a new package-level electromigration test station; Began interlaboratory electromigration comparison.
FY 1995	Completed initial draft of a Joint Electron Device Engineering Council (JEDEC) standard for calculating the acceleration factors for electromigration for JEDEC Committee 14.2; Completed extensive revisions to ASTM F 1261, Standard Method for Determining the Average Electrical Width of a Straight, Thin-Film Line, including a bias and precision statement (from the results of an interlaboratory experiment) for subcommittee F1.11.
FY 1996	Completed revision of ASTM Standard Guide F 1259 for designing electromigration test structures and of ASTM Standard F 1260 for characterizing electromigration; Explored use of Matthiessen's rule to measure electrical thickness and area of copper interconnects.
FY 1997	Completed JEDEC standard for calculating the model parameters for electromigration; Completed JEDEC guide for standard probe pad sizes and layouts for wafer-level electrical testing; Designed test chip for conducting second electromigration interlaboratory experiment to determine the precision of the ASTM standard method for characterizing electromigration and of two JEDEC test-procedure standards, SWEAT and isothermal tests; Began task for measuring abrupt changes in resistance for the characterization of electromigration and of stress voiding in interconnects.
FY 1998	Conduct JEDEC inter-laboratory experiment to determine precision of JEDEC test method standards JEP119 (SWEAT test) and JESD61 (isothermal test). Evaluate feasibility of conducting inter-laboratory experiments to evaluate industry best practice test-structure designs and accelerated stress test methods for copper interconnects. Use new system for detecting small, abrupt changes of resistance in lines subjected to electromigration and stress-voiding stresses in variety of test parts.
FY 1999	Evaluate results of JEDEC inter-laboratory experiment and plan next actions. Plan inter-laboratory experiments for evaluating best-practice test structures and test methods for copper interconnects. Evaluate the measurement of small, abrupt changes in resistance for characterizing electromigration and stress-voiding processes.

2. Develop thin-film characterization methods

FY 1988	Initiated work on developing techniques for measuring the thermal conductivity of thin-film dielectrics used in very large scale integrated circuits.
FY 1989	Reported results of thermal conductivity measurements of thin-film silicon dioxide.
FY 1990	Began a study to evaluate the use of Matthiessen's Rule for electrically determining the thickness of aluminum-based metallizations.
FY 1991	Explored use of sophisticated mechanical probe to evaluate electrical method for measuring metal film thickness.

FY 1992	Began exploration of a scanning electron microscope as means to evaluate electrical method for measuring metal film thickness.
FY 1993	Developed method for making cross sections of metal-film specimens for SEM examinations using a scanning electron microscope.
FY 1994	Refined use of Matthiessen's rule to measure thickness of metal films by an electrical method; Demonstrated agreement with calibrated measurements. (Collaboration with Rensselaer Polytechnic Institute) Measured thermal conductivity of different types of oxide films.
FY 1995	Documented the use of Matthiessen's rule for determining aluminum film thickness and line cross-sectional area from electrical resistance measurements.
FY 1996	Completed first phase of interlaboratory experiment to assess reproducibility of thickness measurements; initial results show good agreement.
FY 1997	Continued plans for selective thermal conductivity measurements of silicon dioxide thin films and modeling experiments to improve characterization; Continued an inter-laboratory experiment to verify the reproducibility of thickness measurements of thin metal film using Matthiessen's rule.
FY 1998	Conduct electromigration testing to establish degree of correlation between t_{50} values and crystallographic measures determined by NIST's Materials Reliability Division-Boulder.
FY 1999	Evaluate the use of grain-size and grain-orientation distributions as measures for interconnect reliability. Complete draft of a JEDEC test method procedure for measuring the electrical thickness of metal films and the area of interconnect lines.

3. Develop improved temperature coefficient of resistance (TCR) metrology
[Task began in FY 1990; completed in FY 1996; information included for completeness.]

FY 1995	Documented the results of the JEDEC inter-laboratory experiment for TCR, joule heating, linewidth, and hot-chuck measurements; Authored revised bias and precision section for JEDEC standard JESD33 (Standard Method for Measuring and Using the TCR to Determine the Temperature of a Metallization Line) for JEDEC.
FY 1996	Revised standard JESD33 distributed by JEDEC; News release announcing revised standard prepared by NIST. Task completed.

4. Promote Building-in Reliability (BIR) infrastructure development

FY 1989	Developed plans for highlighting the critical changes needed for industry to meet future reliability and market-entry demands.
FY 1990	Developed technical program for the International Reliability Physics Symposium (IRPS) 1990 that introduced new focus for the Symposium: Building-In Reliability.
FY 1991	Promoted building-in reliability approach for industry by delivering invited keynote talks at IRPS, European Symposium, Reliability of Electron Devices, Failure Physics, and Analysis (ESREF) Workshop sponsored by the Semiconductor Research Council.
FY 1992	Took lead role at industry request, in developing technical advisory group from the industry for continuing an important workshop for wafer level reliability.

FY 1993	Developed a management structure for the Wafer Level Reliability Workshop to enable it to be a self-sustaining entity.
FY 1994	Began plans for the preparation of an invited presentation on BIR at a reliability conference in Budapest and of an invited paper on the same subject for a special issue of the Microelectronics and Reliability Journal.
FY 1995	Prepared three papers to promote a more rapid transition from a testing-in-reliability to a building-in-reliability approach in the semiconductor industry.
FY 1996	Worked with members in the semiconductor industry to develop plans and to organize a seminar on building-in reliability (BIR) for customers of semiconductor vendors.
FY 1997	Provided leadership to U.S. industry in the area of BIR; Served as editor of e-mail newsletter for BIR newly formed Special Interest Team; Published invited paper on BIR in *Microelectronics and Reliability* with industrial co-authors; Made plans for other seminars and papers with industrial colleagues.
FY 1998	Continue to serve as editor of newsletter; Spearhead efforts to develop industry consensus definition of BIR; Collaborate with industry representatives in development of papers addressing significant BIR issues.

Dielectric Reliability Metrology

Project Leader: John S. Suehle

Staff: 1.0 Professionals, 1.0 Graduate Research Fellow

Funding level: $0.5 M

Funding sources: NIST and OMP (62%), Other Government Agencies (38%)

Objective: Provide domestic semiconductor manufacturers with improved test structures, test methods, models, and novel sensor-based metrology for improving device reliability and monitoring tool performance and manufacturing processes.

Background: The domestic semiconductor industry is aggressively scaling gate oxides in microelectronic devices to achieve higher chip performance and packing density. Reduced time-to-market and new oxide processes require fast and effective reliability characterization techniques. Physically correct models and tests to predict reliability of thin oxides under dc and ac operating conditions are needed. As the semiconductor industry rapidly builds capacity to meet worldwide demand for their products, national standards are required to characterize dielectric integrity for plant-plant and vendor-customer evaluation. Finally, it has been recognized by the National Technology Roadmap for Semiconductors that reliability and novel in-situ process sensors are required to manufacture competitive, cost-effective semiconductor products and improve manufacturing process and tool control.

Current Tasks:

1. Develop dielectric reliability standards and metrology methods

FY 1991 Organized, designed, and conducted an international Joint Electron Device Engineering Council (JEDEC) interlaboratory experiment (with nine labs) to evaluate two JEDEC-proposed dielectric breakdown test methods involving current- and voltage-ramp stresses; Analyzed the measurement results and found good agreement; Modified a commercial hot chuck and controller to enhance capabilities for making measurements of test-line temperatures repeatable at the wafer level.

FY 1992 Developed a document for Wafer-Level Testing of Thin Dielectrics which was accepted as Electronic Industries Association (EIA)/JEDEC Standard JESD35.

FY 1993 Presented first Time Dependent Dielectric Breakdown (TDDB) data at temperatures up to 400 °C. Before this time it was not known if silicon dioxide could be used for high temperature electronics.

FY 1994 Improved understanding of TDDB in thin silicon dioxide films by verifying the electrical field dependence of the mechanism at low stress electrical fields (4×10^6 V/cm) by using novel high-temperature wafer-level probe station.

FY 1995 Revised and had approved by committee ballot two new JEDEC standards: "General Guidelines for Designing Test Structures for the Wafer-Level

Testing of Thin Dielectrics" and "Addendum on Test Criteria for the Wafer-Level Testing of Thin Dielectrics." The first standard has been approved by JEDEC Council. Awaiting Council approval on second standard. Demonstrated differences of electric field and temperature dependence of TDDB for bimodal failure distributions; Performed TDDB characterization of 9 to 22 nm thick oxides with unipolar and bipolar pulsed bias stress over wide range of temperature and electric field.

FY 1996 Coordinated joint JEDEC-ASTM (American Society for Testing and Materials) working group to develop standard voltage ramp gate oxide integrity tests; Studied charge-trapping characteristics of thin oxides when subjected to dc or pulsed voltage stress.

FY 1997 Continued nine-laboratory round robins to evaluate new ASTM-JEDEC V-ramp Test for ultra-thin oxides; Developed new model to extract long-term TDDB acceleration parameters from highly accelerated Q_{bd} tests; Technique reduces test time by over 1 order of magnitude and can be used in a production environment; Showed that electrically active defects are not produced and responsible for breakdown during long-term low-electric field aging; Utilized Fowler-Novdheim tunneling technique to monitor latent, electrically inactive defects that are produced in gates oxides during low-electric field stress.

FY 1998 Develop improved lifetime model for gate oxides less than 5 nm thick and operating in the direct tunneling regime under either time invariant or varying voltages operating under dc and ac conditions; Work with ASTM and JEDEC to modify and produce new standard gate oxide integrity test procedures that will be effective in characterizing ultra-thin gate oxides having thicknesses down to 2 nm.

FY 1999 Conduct study using electron spin resonance (ESR) to investigate the role of oxygen vacancy defects in the aging and breakdown in ultra-thin SiO_2 films.

2. Develop micro-hotplate gas sensor

FY 1992 Filed three patents on the micro-hotplate and tin oxide gas sensor. (Collaboration with the NIST Chemical Science and Technology Laboratory [CSTL]).

FY 1993 Developed the first monolithic tin oxide gas sensor realized with commercial processing by silicon micromachining. (Collaboration with CSTL)

FY 1994 Conducted a study on the reliability of micromachined polysilicon heaters when subjected to constant current stress. High-gain Optical Beam Induced Current (OBIC) imaging was used for the first time to examine the structural effects of stress on the devices. The results indicate that the resistance drift exhibited by the resistors during stress is due to electromigration of the dopant atoms.

FY 1995 Designed a new micro-hotplate chip, NIST21, and had fabricated by the Microelectronics Research Laboratory (NSA). The devices have tungsten metallization for improved heater stability and reliability.

FY 1996 Demonstrated four-element gas sensor array for compositional gas analysis with CSTL.

FY 1997 Demonstrated chemical sensor prototype in industrial application to monitor manufacturing process of titanium matrix composites.

FY 1998 Complete development of multi-element chemical sensor array that incorporates several different metal-oxide sensing films. Collaborate with

MIT Lincoln Laboratories to produce micro-chemical sensor arrays in Lincoln's advanced CMOS process. These devices will incorporate planarized top contacts via damasine plugs.

Micro-Electro-Mechanical Systems (MEMS)

Project Leader: Michael Gaitan

Staff: 1.6 Professionals, 1.7 Guest Scientists, 0.5 Graduate Research Fellow, 0.2 Technicians, 0.2 Faculty Hire

Funding level: $0.5 M

Funding sources: NIST (44%), Other Government Agencies (56%)

Objective: Provide domestic industry with MEMS-based test structures and test methods for characterizing the thermo-electro-mechanical properties of thin films used in ICs and MEMS manufacturing, work with IC and MEMS foundries to develop infrastructure for improved accessibility of MEMS manufacturing, and research and develop novel metrology applications of MEMS technology.

Background: The emerging technology of Micro-Electro-Mechanical Systems (MEMS) utilizes mechanical structures, fabricated in an integrated-circuit-based process, to miniaturize mechanical elements and integrate them within the ICs. Applications for this technology include pressure sensors, inertial sensors, gas and fluid regulation and control, process control, optical switching, and mass data storage. Market studies forecast a worldwide market of nearly $14 billion by the year 2000, enabling almost $100 billion in new or improved systems. Domestic industrial needs for MEMS manufacturing include the development of standardized characterization techniques for thin-film electromechanical properties. Such MEMS-based test structures also have applications for critical needs identified in the National Technology Roadmap for Semiconductors. These needs include the characterization of thin-film thermo-mechanical properties in ICs, measurement of electrical properties of thin films in the 2 GHz to 10 GHz frequency bands, and sensors for in-situ semiconductor fabrication process monitoring and control. Meeting these objectives will enable industry to manufacture competitive, cost-effective products, and improve manufacturing processes, device performance, and device reliability.

Current Tasks:

1. Develop electromechanical test structures/promote MEMS infrastructure

FY 1992 Designed test structures to determine design rules needed for design and fabrication of complementary metal-oxide semiconductor (CMOS)-compatible MEMS devices.

FY 1993 Submitted a design library to University of Southern California/Information Sciences Metal Oxide Semiconductor Informational Services (MOSIS) of CMOS-compatible MEMS devices and test structures. MOSIS announced its official support of CMOS compatible MEMS as a result of this effort.

FY 1994 Designed a set of test chips in collaboration with the Massachusetts Institute of Technology, Case Western Reserve University, and the University of California at Berkeley, and fabricated through the Microelectronics

Center/North Carolina MUMPs service that contained electromechanical test structures. A test chip was also designed in collaboration with others at NIST.

FY 1995 Procured and installed an optical profilometer interferometric microscope system for measurement of deflections of the electromechanical test structures; Began deflection measurements of the MEMS test structures.

FY 1996 Worked with the NIST MEMS Strategic Planning Committee to hold a Strategic Planning Workshop in November 1995 in an effort to determine whether there is a need for a NIST-wide MEMS program; Completed characterizations of cantilever and fixed beam MEMS test structures; Competence proposal submitted and review held.

FY 1997 Continued work on MEMS-based test structure development. Developed a model that describes the fixed-fixed (attached at both ends) beam deflection data. Worked with MOSIS and the MEMS technical community to correct run-to-run uniformity problems with the open design rule and to attempt a CMOS foundry-compatible process through alternative technologies. Organized and held the first MEMS Test Structure Workshop at Transducers 97. Organized a second MEMS Test Structure Workshop at Society for Optical Instrumentation Engineers (SPIE) MEMS Conference. Developed a white paper on MEMS-based test structures for CMOS and submitted a proposal to NIST Office of Microelectronic Programs for this work.

FY 1998 Demonstrate the concept of using MEMS-based test structures in CMOS technology to characterize the thermo-electro-mechanical properties of thin films in ICs. Continue work on the development of standardized MEMS test structures for the MEMS community and continue work with MOSIS and industry to correct run-to-run uniformity problems with the open design rule and to attempt CMOS foundry-compatible process through alternative technologies.

2. Develop thermal flat-panel display

FY 1991 Initiated a program to develop a CMOS-based thermal flat-panel display; Demonstrated the concept of fabricating micro-heating elements through a commercial CMOS process; Designed, fabricated through MOSIS, performed silicon micromachining on CMOS chips, and tested the elements for applications as infrared emitters or pixels in a thermal flat-panel display.

FY 1992 Demonstrated the concept of using micro-heating elements as pixels in a small size thermal (infrared) flat-panel display; Designed, fabricated, and tested a 4 x 4 infrared pixel array for application as a thermal flat-panel display.

FY 1993 Designed, fabricated, and tested a 16 x 16 infrared pixel array; Interfaced the array to a computer and a video interface; Collected thermal images of the output of the display; Designed 64 x 64 and 128 x 128 infrared (IR) pixel array thermal flat-panel displays.

FY 1994 Completed the demonstration of concept of using micro-heating elements, fabricated in a commercial foundry process, to fabricate thermal flat-panel displays; Fabricated 64 x 64 and 128 x 128 infrared pixel array thermal flat-panel displays; Completed testing of 64 x 64 and 128 x 128 infrared pixel arrays.

FY 1995 Initiated a 3-year program to build prototype thermal flat-panel displays. (Collaboration with industrial partner)

FY 1996	Worked with industrial partner to design, fabricate, and test 64 x 64 pixel array prototype thermal display to be inserted in optical projection system for the first phase field demonstration; Initiated work to design and fabricate 128 x 128 pixel array prototype thermal display for the second phase of the task.
FY 1997	Completed second-generation design for a 64 x 64 pixel array thermal display, submitted the design for fabrication, and tested the fabricated array for operation; Completed designs of 128 x 128 pixel array prototype thermal display IC to be inserted in the optical projection system.
FY 1998	Complete a working demonstration 128 x 128 pixel array thermal display unit with projection optics in collaboration with industrial partner.

3. Develop microwave power sensor

FY 1991	Began development of a CMOS equivalent to the multijunction thermal converter fabricated in the Semiconductor Process Laboratory (collaboration with the Electricity and Electromagnetic Fields Divisions); Initial designs sent to the MOSIS service for fabrication.
FY 1992	Fabricated improved designs of thermal converter elements and tested ac/dc conversion accuracy to 1 MHz with conversion error under 200 parts per million.
FY 1993	Initiated a program to develop a high-precision low-cost RF and microwave power sensor to 10 GHz. Fabricated transmission lines and power sensors. Began the Cooperative Research and Development Agreement (CRADA) with industrial partner.
FY 1994	Demonstrated the concept of fabricating silicon micromachined microwave transmission lines in CMOS technology; Tested the transmission line elements to 20 GHz and demonstrated the benefits of silicon micromachining to reduce the attenuation of the lines.
FY 1995	Demonstrated the concept of fabricating silicon micromachined power sensors and coupling these devices to the CMOS transmission lines; Tested the CMOS silicon micromachined microwave power sensors to 20 GHz.
FY 1996	Developed a working prototype microwave power meter in collaboration with industrial partner; Incorporated the transmission line elements and the microwave power sensors with circuits on an IC chip and test and characterize the elements and circuit performance.
FY 1997	Began work on characterization of polysilicon load element and investigation of techniques to control its stability for accurate power measurement in May; Assembled computers and controller boards for the characterization experiment. Software to run the test is currently being developed.
FY 1998	Continue work on characterization of polysilicon load element and investigation of techniques to control its stability for accurate power measurement; Develop and characterize antenna structures and passive resonant filters in collaboration with industrial partner.
FY 1999	Complete work on characterization of polysilicon load element and investigation of techniques to control its stability for accurate power measurement; Complete a working demonstration hand-held microwave power sensor unit based on the CMOS foundry-compatible microwave power sensor technology, in collaboration with the industrial partner.

Plasma Chemistry - Plasma Processing

Project Leader: James K. Olthoff

Staff: 1.5 professionals, 1.0 guest scientist

Funding level: $0.4 M

Funding sources: NIST and OMP (100%)

Objective: To aid the semiconductor industry in the characterization of discharges used in plasma processing. Specifically by investigating 1) the effects of surface charging, 2) the chemical composition of capacitively- and inductively-coupled rf plasmas, 3) the performance of ion energy analyzers for use as plasma diagnostics, 4) the effect of ion-molecule collisions on the ions striking surfaces exposed to the plasma, and 5) fundamental collision data required for analysis of plasma processing data.

Background: The Electricity Division's work in plasma processing began in 1989 as an outgrowth of NIST's work in gaseous dielectrics. Initial work involved the evaluation of a mass spectrometer with an ion energy analyzer as a plasma diagnostic for SEMATECH. Subsequent research has been supported primarily by the EEEL Office of Microelectronics Programs under the National Semiconductor Metrology Program, and has emphasized the characterization of diagnostic devices and validation of theoretical models. In the past 5 years NIST has become a leader in the development of "reference" discharges for use in these studies, including GEC rf Reference Cells with capacitively- and inductively-coupled sources, and a Townsend discharge cell. A "GEC rf Reference Cell" is a test chamber, "cell", in which the plasma is sustained by applying a high frequency electric field, "rf". The GEC refers to the Gaseous Electronics Conference where the need for such a standard test system was first discussed. Application of a wide range of diagnostic measurements, (electrical, mass spectrometric, ion energy analysis, optical emission and laser-induced fluorescence) to these well-characterized discharges, allows the accumulation of baseline plasma data necessary to confirm the performance of both the measurement techniques and the predictive models used to describe the discharge.

Current Tasks:

1. Application of mass spectrometric, ion energy diagnostics to discharges

FY 1989	Interacted with SEMATECH concerning need for characterization and calibration of a mass spectrometer/ion energy analyzer and a Langmuir probe.
FY 1990	Fabricated and brought to full operation GEC rf reference cell with optical, mass spectrometric, and electrical diagnostics.
FY 1991	Characterized mass spectrometer/energy analyzer for use as a real time diagnostic in rf production reactors; Sent results to SEMATECH for publication as a SEMATECH report.

FY 1992	Installed improved mass spectrometer/ion energy analyzer system to GEC Cell; Measured ion energy distributions in argon, argon/oxygen, and argon/helium mixtures and correlated with electrical and optical measurements.
FY 1993	Measured effects of trace impurities, such as oxygen or water, on electrical characteristics of argon discharges.
FY 1994	Performed comprehensive studies (including mass spectrometric, ion energies, optical emission, and electrical) of rf discharges in hydrogen and argon/hydrogen; Performed preliminary ion energy measurements in dc Townsend discharges.
FY 1995	Edited special journal issue dedicated to research performed on GEC rf Reference Cells; Constructed new inductively coupled GEC rf cell.
FY 1996	Completed investigation of rf discharges in SF_6; Completed investigation of ion energy diagnostic measurements for dc Townsend discharges in argon, helium, oxygen, nitrogen, CHF_3, and SF_6.
FY 1997	Measured gas decomposition in inductively coupled argon plasmas containing O_2, N_2, SF_6, and Cl_2.
FY 1998	Extend ion energy diagnostics to rf plasmas.
FY 1999	Extend mass spectrometric diagnostics to rf plasmas in the presence of silicon wafers and transfer technique to industry.

2. Investigations of surface-charging in plasma processing

FY 1994	Observed effects of surface charging on ion energies in rf plasmas; Initiated compilation of surface-charge related bibliography.
FY 1995	Demonstrated measurement of electric fields using optical techniques; Completed surface charging bibliography.
FY 1996	Discontinued project based upon review of industrial needs and upon conclusions of strategic plan for support of electric power utilities. Resources redirected to tasks of higher priority.

3. Compilation and analysis of fundamental data for the semiconductor industry

FY 1995	Initiate investigation of known electron impact cross sections for CF_4 and CHF_3.
FY 1996	Completed electron-impact investigation for CF_4 and CHF_3; Published comprehensive paper and made summary data publicly available on World-Wide Web; Measured electron attachment to CCl_2F_2 molecules.
FY 1997	Investigated electron impact cross sections for CCl_2F_2, C_2F_6, and C_3F_8; Papers were prepared for CCl_2F_2 and C_2F_6 and the summary data were made available on the World Wide Web.
FY 1998	Complete electron-impact cross section review for C_3F_8 and extend investigation to CL_2 and HBr; Develop capability to measure electron attachment cross sections using crossed beam method.
FY 1999	Measure electron attachment cross sections for radicals and excited species using crossed beam method.

MAGNETICS

Magnetic Recording Metrology

Project Leader: David P. Pappas

Staff: 4.0 Professionals, 1.0 Guest Researcher, 0.25 Undergraduate Student

Funding level: $0.84 M

Funding sources: NIST (STRS-44%, Competence-18%), ATP (11%), Other Agency (27%)

Objective: Develops measurement methods and standards required by the magnetic data storage industry to further the development of ultra-high density magnetic recording, the performance of advanced heads, and nanoscale magnetic recording techniques.

Background: Magnetic data storage is one of the key industries driving the revolution in information technologies. Information systems, for both commercial and military applications, requiring terabytes of data storage and gigabyte transfer rates, are envisioned in the next 10 to 20 years. To achieve these storage densities and transfer rates, the size of magnetic bits and sensors needs to be reduced to submicrometer dimensions and the sensors and write elements need to work at very high frequencies. To enable these technological developments, new measurement methods and standards are needed. These include methods to measure domain structure of submicrometer magnetic devices, methods to accurately simulate read head and magnetoresistive random access memory components, and standards for magnetic imaging and high frequency thin-film permeability. Techniques based on scanned-probe microscopies need to be developed to address specific issues in magnetic recoording.

Current Tasks:

1. Develop methods to characterize submicrometer magnetoresistive devices for use in recording heads

FY 1994	Developed Micromagnetic Probe station to look at local magnetoresistance and domain structure in magnetoresistive sensors.
FY 1995	Characterized magnetoresistive device performance as a function of device size in collaboration with industry and the National Storage Industry Consortium; Performed and developed Barkhausen and low frequency noise, high current density, and magnetostriction measurements; Developed techniques to measure wafer level response to magnetic fields at frequencies up to 100 MHz.
FY 1996	Investigated size effects and high current density in magnetoresistive sensors and random access memory cells; Assisted industry in characterizing read head, sensors.
FY 1998	Work moved to Magnetic Instruments and Materials Characterization Project.

2. Develop computer models of magnetic devices

FY 1994	Developed micromagnetic model of dual-layer magnetic media; Developed model of magnetic force microscopy (in collaboration with Nanoprobe Imaging Project).
FY 1995	Developed micromagnetic and analytical models of giant magnetoresistive devices.
FY 1996	Performed detailed comparison of modeling results of spin-valve devices and magnetoresistive memory cells with experimental data; Packaged evaluation software for distribution to U.S. magnetics companies; Began developing standards for micromagnetic codes and round robin comparisons of standard sample.
FY 1997	Produced final software for transfer to industry.
FY 1998 - 2000	Distribute software by Web; Include more sophisticated micromagnetic models; Maintain distributed software; Develop Web-based software as common interface for micromagnetic models from various institutions.

3. Develop magnetic imaging reference standards (MIRS)

FY 1995	Fabricated magnetic imaging standards.
FY 1996	Began round robin tests of magnetic imaging using imaging standards; Samples distributed for magnetic force microscopy, SEMPA (scanning election microscopy with polarization analysis), and Lorentz characterization.
FY 1997	Began magnetic media survivability studies using magnetic imaging standards; Prepared imaging standards for general distribution.
FY 1998 - 2000	Incorporate SPM (scanned-probe microscopy) metrology and develop low-temperature SPM tasks from Nanoprobe Imaging for Magnetic Technology Project; Develop ability to record bit patterns at NIST; Collaborate with Physics Laboratory (especially PL's SEMPA team) to make MIRS quantitative.

4. Develop nanoscale magnetic recording system

FY 1995	Built prototype nanoscale recording system; Recorded and imaged bits using advanced commercial heads.
FY 1996	Equipment and parts ordered and delivered; Project temporarily on hold due to staff departures.
FY 1997	Purchased advanced commercial spin stand and developed knowledge of its use.
FY 1998 - 2000	Develop capability of recording bit patterns for MIRS; Develop understanding of limits and improve characterization of commercial spin stands; Develop and promulgate techniques for improved recording and reading with commercial spin stands.

5. Develop advanced techniques for the use of scanned probe microscopy in the magnetic data storage industry.

FY 1998 - 2000	Develop chemical-mechanical methods to measure the efficacy of novel magnetic disk lubricants; Develop variable temperature instrument for magnetic force microscopy (MFM); Correlate grain structure measured by atomic force microscopy with magnetic noise measured by MFM; Investigate

incorporating an MFM head into the new spin stand for fast *in situ* imaging of the recording processes.

Magnetic Instruments and Materials Characterization

Project Leader: Ron B. Goldfarb

Staff: 4.0 Professionals, 2.0 NRC Postdocs, 0.5 Graduate Student, 0.25 Undergraduate Student

Funding level: \$0.92 M

Funding sources: NIST (STRS-44%, Competence-16%), ATP (12%), Other Agency (28%)

Objective: Develop instruments, measurement protocols, and theoretical models to characterize the magnetic properties of films, particles, and bulk solids as functions of magnetic field strength, field history, temperature, and time. Develops, promotes, and transfers to industry magnetic metrology for applications in magneto-optics, magnetic data storage, magneto-chemistry, power conversion, and high frequency electromagnetics.

Background: Researchers, developers, producers, and users of magnetic materials need tools for the accurate determination of magnetic properties and the analytical interpretation of data. Industries supported include: manufacturers of inductive recording heads, magnetoresistive read-back heads, thin-film and particulate recording media, and magnetoresistive magnetic memories; producers of microwave materials; companies researching magnetoresistive sensors; superconductor wire manufacturers, and magnetic-particle researchers in medicine. The Project provides measurement services, often in the form of collaborations, to laboratories that do not have magnetic measurement and analysis capability.

Current Tasks:

1. Develop new magnetic measurement instruments and techniques

FY 1987 - 1996 See report for FY 1997.

FY 1997 Developed background subtraction and sample-change techniques in reciprocating-sample method of magnetization measurements; Improved sensitivity and reduced noise in vibrating-sample magnetometer; Developed pulsed-field apparatus for magneto-optics.

FY 1998 Improve magnetometer techniques used in magnetic recording industry: alternating gradient magnetometer (AGM), magnetization-field (M-H) looper, vibrating-sample magnetometer (VSM).

2. Develop methods to measure magnetic relaxation in record bits approaching the superparamagnetic limit of magnetic recording

FY 1997 Developed capability to deposit quality hard disk media; Developed VSM technique to simulate thermal decay of bit transitions and extract fundamental energy barrier to thermal erasure; Developed magnetometer techniques to measure thermal decay and switching volumes of hard magnetic media at various temperatures.

FY 1998 Continue studies of time and temperature dependence of magnetic viscosity using different magnetometers; Use Kerr microscopy to measure viscosity at nanosecond time scales; Develop capability to measure viscosity continuously from nanoseconds to seconds; Develop capability and standard protocol for measuring thermal decay using spin stand and correlate with magnetometer measurements of thermal decay.

FY 1999 Develop ability to make patterned media and measure thermal stability as a function of lithographically defined bit size; Determine possibilities for magnetoresistive measurement of thermal decay in longitudinal media.

3. Develop time-resolved magneto-optic Kerr-effect metrology for dynamical magnetic domain imaging of nanoscopic magneto-electronic devices

FY 1994 - 1996 See report for FY 1997.

FY 1997 Demonstrated sub-picosecond time-resolved magnetic characterization using second-harmonic magneto-optic phenomena in the far-field; Characterized dynamical response of thin-film magnetic recording head materials at frequencies above 100 MHz; Collaborated with National Storage Industry Consortium (NSIC) on fundamental limits of magnetic recording; Began to correlate SH-MOKE results with neutron and X-ray measurements of surface/interface magnetic properties in Permalloy; Investigated diagnostic uses for SH-MOKE in electromigration, surface oxidation, and interface diffusion; Developed inductive method to measure magnetic relaxation times in magnetic films; Compared surface dynamics measured with time-resolved SH-MOKE and bulk dynamics measured inductively; Performed dynamical measurements on FeTaN films; Designed and fabricated reference coplanar waveguides for comparing switching speeds of different materials.

FY 1998 Continue development of time-resolved SH-MOKE and compare with inductive method; Determine role of spin-wave generation in precessional damping; Benchmark switching speeds in alternative head materials; Study uniformity of switching in thin-film head materials with Kerr microscopy; Study role of inhomogeneity in anisotropy on damping of precession; Continue collaboration with NSIC on limits of magnetic recording; Image narrow NiFe stripe domain patterns after switching by high-speed pulses. Extend dynamical measurements to different film thicknesses and shapes; Demonstrate performance of SH-MOKE at small spot sizes (2-4 μm).

FY 1999 Continue optical and inductive studies of high speed magnetic response; Continue benchmarking of switching speeds; Extend techniques to higher coercivity materials; Continue short-time thermal decay studies; Extend resolution of SH-MOKE technique to micrometer scales or smaller; Continue studies of fundamental origins of precessional damping and fundamental processes in thermal decay of magnetization. Continue collaboration with NSIC.

4. Measure interfacial magnetostriction in multilayer magnetic films (New task)

FY 1998 Construct apparatus to measure surface and interface magnetostriction; Develop microwave structures for fast pulse delivery and dynamical magnetoresistance read-out; Perform surface magnetostriction measurement using SH-MOKE and bulk magnetostriction using MOKE; Test microstructural origins of magnetostriction; Correlate dynamical and magnetostriction measurements to determine role of magnetostriction in magnetodynamics.

FY 1999 Extend surface magnetostriction measurements to study effect of local stress variations on magnetic properties; Perform time-resolved magnetostriction measurement using time-resolved magnetoresistance.

5. Develop methods to characterize sub-micrometer magnetoresistive devices for use in recording heads, magnetoresistive random access memory (MRAM), and sensors.

FY 1994 - 1996 See report for FY 1997.

FY 1997 Compared effects of high pulsed currents and elevated temperatures on magnetoresistive response of films; Measured and characterized low frequency noise in spin-valves in collaboration with magnetic recording companies; Measured size and magnetostatic effects in spin-valves designed for use in recording heads and Block line Random Access Memories (MRAM); Performed detailed comparisons of spin-valve performance with magnetic models.

FY 1998 Design circuits to measure high-speed response of sub-micrometer giant magnetoresistive material (GMR) devices and tunnel junction devices to be used in recording heads and MRAM; Perform initial measurements of highspeed response of devices used in DARPA MRAM program; Fabricate magnetic tunnel junction arrays and optimize for sensor applications; Develop low-noise test apparatus to quantify ultimate performance of giant magnetoresistive material GMR sensors; Fabricate magnetic nanostructures for characterization of advanced media and read head concepts.

FY 1999 Complete high-speed measurements for DARPA MRAM program; Apply high-speed metrology to submicrometer GMR devices for use in recording applications; Complete low noise measurement system and measure GMR sensor response down to 10 $pT/\sqrt{Hz}$; Characterize magnetic properties of sub-100 nm structures including isolated switching properties and cluster interactions.

6. Conduct fundamental studies of practical magnetic materials and new materials of current interest

FY 1990 - 1996 See report for FY 1997.

FY 1997 Measured magnetic properties of nanoparticles and molecules of iron, iron oxides, and ferritin.

FY 1998 Measure ac losses of Nb_3Sn multifilamentary superconductors for fusion and high energy physics applications; Identify means to reduce losses while maintaining high critical current density and transfer information to U.S. wire manufacturers; Measure magnetic particles of ferritin, iron carbides, iron oxides in collaboration with other laboratories.

7. Develop instruments, standard procedures, and calibration standards for ac loss determination in superconductors. TASK COMPLETED. Project resources redirected to magnetic data storage. Loss measurements continue as a measurement service on a cost-reimbursable basis

FY 1987 - 1996 See report for FY 1997.

FY 1997 Provided consultation and measurements on ac loss behavior of superconductors for fusion energy and high energy physics projects, including contributions to benchmark interlaboratory comparisons.

Nanoprobe Imaging for Magnetic Technology

Project Leader: John Moreland

Staff: 1.0 Professionals, 1.0 NRC Postdoc, 1.0 Guest Researcher

Funding level: $0.27 M

Funding sources: NIST (STRS-44%; Competence-56%)

Objective: Develop scanned probe microscopy (SPM) in support of the magnetic storage industry and work with industry to understand and relate SPM images to magnetic and electronic properties of media and devices that affect the performance and manufacture of current technologies as well as the direction of future developments in the recording industry.

Background: The intense competition for a magnetic data storage market exceeding $50 billion/year has led manufacturers to push the limits of drive technologies. Heads and media are affected by nm-scale morphological and electronic properties which directly or indirectly influence the performance of current drive designs with regard to speed and storage capacity. Nm-scale measurements of roughness, critical dimensions, field patterns, and local electronic processes provide information about the fundamental operation and ultimate performance limitations, which is useful in the development process. In addition, nondestructive, quality-assurance measurements can be performed during the manufacturing process on components prior to assembly of a complete drive. Scanned probe microscopies such as atomic force microscopy (AFM), magnetic force microscopy (MFM), and scanning potentiometry are examples of imaging techniques that are uniquely qualified for these applications because of the nm-scale dimensions of the various probes. NIST has recognized that there is a need to develop and test SPM techniques, demonstrate their usefulness, and generally facilitate the transfer of the latest innovations in SPM technology to the storage industry. [See also Magnetic Recording Metrology project.]

Current Tasks:

1. SPM imaging of magnetic materials and devices

FY 1989	Invented tunneling stabilized magnetic force microscopy (TSMFM) using scanning tunneling microscopy for MFM.
FY 1990	Observed superconducting vortices with TSMFM - the first observation of vortex cores using force microscopy.
FY 1991	Began investigating the utility of TSMFM for imaging disk drive components; imaged bit tracks on hard disks.
FY 1992	Imaged domain walls in garnet films provided by Jet Propulsion Laboratory for studies of vertical Bloch line random access memories (MRAMs).
FY 1993	Performed AFM and MFM on Permalloy thin-film MRAMs.
FY 1994	Began collaboration with U.S. disk manufacturer, and observed nanoparticles causing high error rates on hard disks, with AFM. Several labs world wide by that time had adopted TSMFM.

FY 1995 Awarded patent for reading and recording with TSMFM; Demonstrated utility of AFM for measuring pole tip recession on thin film heads; Obtained first scanning potentiometry images of magnetoresitive test structures fabricated at NIST.

FY 1996 Provided facility open to industry collaboration; Optimized SPM techniques for the development and production of disk drives; Imaged roughness and morphology of heads and media being developed for current and future storage technologies; Focused on wear studies of the head media interface; Imaged magnetic fields near heads and media with better than 50 nm resolution; Correlated images to spin-stand data from U.S. company; Investigated "dip stick" force microscopy for studying lubrication layers.

FY 1997 Developed high-resolution scanning potentiometry based on SPM; Provided images of devices being developed by U.S. company for MR heads; Installed and tested e-beam system for depositing ultra-pure magnetic films for MFM tip coatings.

FY 1998 Develop high-bandwidth (500 MHz) scanning potentiometry for imaging magnetic thin film devices; Develop theoretical understanding of phase imaging for applications to friction/adhesion studies; Develop data acquisition and analyses for "dip stick" adhesion force microscopy.

FY 1999 Improve voltage sensitivity and spatial resolution of scanning potentiometry instruments; Build and test puck level scanning potentiometry instrument; Perform measurements of electromagnetic fields as a function of frequency a few nm above the air bearing surface of thin film recording heads; Develop controlled chemistry of tip coatings for quantitative measurement of adhesion and stiction between disk drive components.

FY 2000 Develop SPM instrumentation for molecular scale tribology molecular scale surface potential imaging of disk drive components; Transfer resulting technology to industry.

2. SPM Metrology

FY 1995 Demonstrated superparamagnetic cantilever coatings for MFM in collaboration with the University of Nebraska; hailed by SPM manufacturers as the first step towards quantitative MFM; NIST employee sent to U.S. company, as part of NIST Industry Fellows Program, to develop SPM for industrial applications.

FY 1996 Developed standards and standard measurement practices for MFM; Designed Magnetic Imaging Reference Sample (MIRS) as a qualitative reference for MFM; Started three-way collaboration among ourselves, a U.S. company, and the Electron Physics Group of the Physics Laboratory at NIST; Improved MFM resolution and image interpretation by investigating new cantilever coatings.

FY 1997 Began significant distribution of MIRS.

FY 1998 Task transferred to Magnetic Recording Metrology Project.

3. Magnetic resonance force microscopy (MRFM)

FY 1996 Began development of MRFM for three-dimensional imaging of magnetic phenomena.

FY 1997 Constructed optical fiber interferometer for cantilever motion detection, constructed rf circuit for sample excitation, observed resonance for first time,

	and developed imaging algorithm to generate real space magnetic resonance image output.
FY 1998	Install and test diffusion furnaces for fabrication of ultra sensitive cantilevers; Demonstrate MRFM imaging with better than 1-μm resolution in three dimensions; Develop high-bandwidth MRFM techniques for imaging electromagnetic fields at frequencies as high as 1 GHz; Construct 3-axis magnet cryostat for MRFM below 1 K; Develop capabilities for micromachining high-performance, specialized SPM cantilevers.
FY 1999	Fabricate ultra high sensitivity cantilevers for single-spin atomic-scale MRFM; Fabricate cantilever chips with integrated detectors for single-spin atomic-scale MRFM; Demonstrate atomic resolution MRFM; Integrate fiber optic motion detector, cantilever, rf resonator, and magnetic films, onto a microchip for ultra-sensitive magnetic resonance spectroscopy.
FY 2000	Optimize MEMS (micro-electro-mechanical) processing for totally integrated microchip MRFM instruments and magnetic resonance spectrometers; Study atomic scale magnetic phenomena relevant to the development of heads and media; Study organic structures and processes with the MRFM;
FY 2001	Establish world class facility for atomic resolution magnetic resonance imaging.

4. Develop low-temperature SPM

FY 1989	Bathysphere cryostat (developed at NIST for superconductor transport studies) adapted for scanning tunneling microscopy (STM).
FY 1996	Began construction on cryogenic multimode AFM to extend SPM capabilities to low temperatures for fundamental studies of magnetic phenomena.
FY 1997	Completed construction of low temperature AFM cryostat and tested at room temperature.
FY 1998	Task transferred to Magnetic Recording Metrology Project.

SUPERCONDUCTORS

Superconductor Interfaces and Electrical Transport

Project Leader: Jack W. Ekin

Staff: 2.0 Professionals, 1.0 Guest Researcher, 1.0 Technician, 1.0 Graduate Student

Funding level: $0.77 M

Funding sources: NIST (STRS, 37%), Other Agency (63%)

Objective: Develop measurement methods and obtain data for industry and for other projects within the Division in support of low-temperature and high-temperature superconductor applications in magnetics, power transmission, electronics, and microwaves. Characterize superconductor interfaces to aid in the commercial application of superconducting high current density wire and integrated circuits. Use unique measurement capabilities to develop transport and electromechanical measurement methods of the highest sensitivity and accuracy to assist industry in improving the performance of commercial thin films and wires.

Background: The high-temperature-superconductor (HTS) industry has asked for NIST's help to measure and develop high quality contacts and interfaces for both thin-film and bulk superconductor devices. The basic interface conduction and noise mechanisms are not yet understood. In magnet technology, both HTS and low-temperature superconductor (LTS) magnets are being developed in the direction of higher fields (for nuclear magnetic resonance and high-energy physics) and larger magnets (especially with the increased interest by U.S. industry in superconductor power conditioning magnets since the announced deregulation of power utilities). Both directions lead to higher magnetic loading of the superconductor, which necessitates the need for measurements of the effect of stress on their electrical performance. The new HTS materials also have significant magnetic field anisotropy which has created a new set of measurement problems and modeling equations for conductor performance.

Current Tasks:

1. Develop metrology for characterization of electromechanical performance of superconductors and perform measurements needed by industry to create a database for commercial design of large superconductor magnet systems and transmission lines

FY 1994 Published chapter on electromechanical testing and modeling for book entitled *Composite Superconductors*; the critical J_c-B-strain surface, first discovered and modeled in our project group, was featured as the cover photo; Obtained first electromechanical data on a small *coil* of HTS bismuth conductor; these data and our accompanying interpretation were the basis for a U.S. company finding a superior epoxy system for their magnet fabrication; Measured and published the first data showing that the critical point in HTS bismuth-tape superconductor magnets will be at the ends of the magnet rather than at the high-field position in the middle as for low temperature superconducting magnets. Patents were filed by a U.S. company on new schemes for compensating for this effect.

FY 1995 Performed first very-high-field (23.5T) measurements of the effect of axial strain on critical current of experimental niobium-tin superconductor for use in the design of nuclear magnetic resonance superconductor applications; Measured effect of using dispersion hardened silver-magnesium-nickel sheath material on the irreversible strain limit of bismuth superconductors; Measured effect of reaction mandrel holder on prestrain and critical current of a niobium-tin candidate conductor for the International Thermonuclear Experimental Reactor design.

FY 1996 Developed technique for accurately measuring the Young's modulus of niobium-tin superconductors at cryogenic temperatures to resolve a long standing 300% discrepancy in values reported in the literature; Designed state-of-the-art apparatus for measurement of the anisotropy of J_c with respect to magnetic field angle, for characterization of HTS at high currents in magnetic fields approaching 30 T.

FY 1997 Measured the effect of fatigue degradation of high-purity aluminum in large aluminum-stabilized conductors and showed potential for 40% reduction in materials design requirements; Modified transverse-stress apparatus for stress-free and axial-strain measurements of a Nb_3Sn tape for testing a three-dimensional strain-effect model; Installed and tested new 18 T magnet system for electromechanical testing of high-field superconductors.

FY 1998 Modify the high-field axial-strain apparatus to allow accurate testing of high-strength wire and tape conductors; Develop test method for measuring the transverse-stress effect in multifilamentary BSCCO (bismuth-strontium calcium copper oxide) conductors; Develop metrology for tensile measurements of short (1 cm gage length) rolling-assisted biaxially aligned textured substrate (RABiT) substrates at cryogenic temperatures; Collaborate with Colorado University on finite element modeling of yttrium-barium-copper oxide (YBCO) coated conductors; Complete draft of first part of text book on cryogenic metrology.

FY 1999 Measure transverse-stress irreversible strain limits as a function of filament size; Measure tensile properties of RABiT substrates as a function of specimen width and thickness; Measure the mechanical properties of RABiT substrates as a function of buffer layer additions; Measure transverse-stress effects in ion-beam-assisted deposition (IBAD) superconductors; Complete draft of 2nd part of book on cryogenic metrology.

FY 2000 Develop metrology for measuring axial strain effects at variable temperatures and strain effects on Tc; Measure the axial strain effect in IBAD superconductors and the transverse-stress effect in RABiTs superconductors; Complete test of extending the one-dimensional strain-scaling law to three dimensions using the diviatoric strain concept; Complete book on cryogenic metrology and submit to publisher.

2. Develop metrology for evaluating superconductor interfaces and obtain database needed by industry for the development of high-quality electronic contacts

FY 1991 First high-temperature superconductor contact patents issued to NIST: "Method for Making Low Resistivity Contacts To High-T_c Superconductors," and "High-T_c Superconductor Contact Unit Having Low Interface Resistivity, and Method of Making."

FY 1992 Third HTS contact patent awarded to NIST: "High-T_c Superconducting Unit Having Low Contact Surface Resistivity."

FY 1993 Performed a time exposure experiment for measuring the degradation rate of the yttrium-barium-copper oxide (YBCO) surfaces; results showed little effect of air exposure up to 100 minutes, much longer than expected; interface conductivity data showed little difference from *in situ* processed contacts, indicating that considerable improvement may be possible with *in situ* contacts. Fourth HTS contact patent awarded to NIST: "High-T_c Superconductor Contact Unit Having Low Interface Resistivity."

FY 1994 Measured the conductivity at the interface between a YBCO thin film and a silver contact, measurements covering five orders of magnitude of contact resistivity. Surprisingly, the transport characteristics of the interface indicated evidence for magnetic scattering over the entire conductivity range, indicating this may be a significant feature of HTS interfaces.

FY 1995 Performed an annealing study on a series of in-house-fabricated YBCO-silver contact interfaces to determine the effect of oxygen annealing on contact resistivity; Transferred the information to industry for optimizing the annealing conditions of *ex situ* contacts; Developed a new platinum-gold buffer layer for the integration of HTS and silicon-based contact systems.

FY 1996 Measured the 4 K, high-field (up to 12 T) tunneling characteristics of thallium interfaces fabricated at NIST using films from two manufacturers; Obtained the first high-magnetic-field tunneling conductance measurements of neodymium-cerium-copper-oxide films in collaboration with the University of Maryland; Discovered possible correlation between magnetic-field-dependent zero-bias conductance peak and evidence for d-wave pairing symmetry; Developed a method for improving the measurement sensitivity of our tunneling conductance measurements and obtained the first high-sensitivity transport properties of vertical a,b-axis superconductor/normal-metal junctions; Order-of-magnitude improvement over c-axis normal-metal interfaces achieved; Record specific resistivity of 2 x 10^{-9} ohm-cm^2 obtained for planar YBCO interfaces.

FY 1997 Measured conductance characteristics of YBCO/gold contact system as a function of oxygen annealing temperature; Determined an optimal annealing temperature range of 550 °C to 600 °C for that contact system; Established that Au diffusion along grain-boundary is the cause for reduction in contact resistance; Extended the zero-bias conductance measurement of YBCO/Au junctions to fields of 18 T and temperatures below the lambda-point in order to discriminate between the Anderson-Appelbaum model and mid-gap states model for zero-bias conductance anomalies; Acquired necessary equipment for setting up low-frequency noise measurement.

FY 1998 Develop electromechanical test capability for wire-bond pull strength and interfacial shear strength experiments; Test for a correlation between interface mechanical properties and the specific interface resistivity; Develop low-frequency noise measurement for HTS/Au junctions and characterize noise behavior in terms of junction area, temperature, and bias voltage; Fabricate Au contacts to YBCO in the ab-plane direction using ramp-edge junction geometry; Explore new approaches to low-resistance contact without oxygen annealing.

FY 1999 Develop model for characterizing noise in HTS superconductor interfaces for use in the engineering design of HTS bolometers and junctions; Develop submicrometer HTS interface test capability.

High Performance Sensors, Converters, and Mixers

Project Leader: Erich N. Grossman

Staff: 2.5 Professionals

Funding level: \$0.49 M

Funding sources: NIST (STRS-47%), Other Agency (53%)

Objective: Develop electromagnetic field sensors and frequency converters for measurements and standards in support of other NIST divisions. Apply advanced superconducting integrated circuit fabrication, cryoelectronic, infrared, mm-wave, and other techniques to solve measurement problems at the limits of technology. Projects cover applications of Superconducting Quantum Interference Devices (SQUIDS), and in the infrared (IR), precise radiometry, frequency synthesis, spectroscopy, and imaging.

Background: The project represents the consolidation of previously separate efforts in mid- and far-infrared measurements and standards development on the one hand, and low-noise SQUID development on the other. The project now focusses more closely on infrared measurement technology. Mid- and far-infrared technology (wavelength >10 μm) is now a large industry. Originally aerospace and defense-related, it is now moving to many purely commercial applications in security, night vision, materials testing, quality assurance, and more. As such applications proliferate, supporting needs for measurements and standards technology are also increasing. Accurate measurement of total power and power spectral density (i.e., radiometry and low- resolution spectroscopy) is a recognized calibration problem for manufacturers of focal plane arrays and blackbody sources. This project, in collaboration with other NIST organizations (Divisions 844, 838, 815, 811), develops precision electrical substitution radiometers based on superconducting thermometers. They can be used for radiometric measurement of absolute temperature (refining ITS-90 in the 50-200 K range), calibration of blackbodies and focal plane arrays at low power levels (⟨100 nw), absolute laser power measurements, and audio-frequency electrical power measurements. This project also investigates the properties of IR microantennas, which is a key issue for developers of engineered emissivity surfaces. Their incorporation with uncooled IR sensor materials, such as VO_2 is a key to developing new wireless telecommunications applications at far-IR frequencies. Finally, SQUID preamps enable the integration of high sensitivity far-IR sensors into large format staring arrays, using the SQUIDS as elements of a high speed multiplexer. The development of large format arrays is expected to enable new applications of far-IR imaging, particularly for satellite-borne remote sensing.

Current Tasks:

1. Develop absolute radiometer for the low background infrared (IR) facility (NIST Radiometric Physics Division), for the measurement of light with a wavelength in the range of 10 µm

FY 1986	Concept of Kinetic Inductance Thermometer (KIT) developed.
FY 1990	Demonstrated closed-loop resolution of 1 picowatt using KIT without absorber.
FY 1993	KIT integrated with absorber which degraded resolution by more than a factor of 1000.
FY 1995	Dropped KIT in favor of transition-edge thermometer to improve manufacturing; Stabilized absorber to improve resolution; Demonstrated ability to fabricate transition-edge thermometers.
FY 1996	Delivered radiometer to Radiometric Physics Division, NIST. Completed.
FY 1997	Designed and built second-generation radiometer (RAD II) with integrated blackbody source, demonstrating absolute accuracy of 0.1%.
FY 1998	Continue design and construction of RAD II.

2. Develop infrared antennas and diodes for solar power generation

FY 1995	Project begun with funding from Air Force; Collaboration with Time and Frequency Division, NIST, to develop accurate measurements of efficiency of infrared antennas and lithographic diodes.
FY 1996	Fabricated near-IR antenna using electron-beam lithography; Fabricated lithographic metal-insulator-metal diodes.
FY 1997	Continued development and IR testing of antennas and metal-insulator-metal diodes; Measured efficiency of each.
FY 1998	Compile and publish results. Task completed.

3. Develop infrared antennas and bolometers for focal plane arrays (room-temperature antenna-couples bolometers for imaging)

FY 1996	Cooperative Research and Development Agreement (CRADA) established with U.S. company; Proposal for multimode antenna-coupled array developed.
FY 1997	Designed, fabricated, and optically tested room-temperature dipole antenna/bolometers for 10-µm detection and imaging.
FY 1998	Compile and publish results; Establish second CRADA with company on measurement of "engineered emissivity" surfaces; Measure and analyze angle-dependent reflectance and transmittance at room temperature and 77 K of samples supplied by company.

4. Develop AC/DC thermal converter

FY 1994	Initiated project to apply kinetic inductance thermometers to improve the accuracy at which alternating and direct voltage signals could be compared; Discussions held with collaborators in Electricity Division.
FY 1995	Performance analysis made of alternating and direct voltage converter using transition-edge thermometers.

FY 1996	Delivered chips and cryogenic mounts to Electricity Division; Performed preliminary alternating and direct voltage conversion measurements (with Electricity Division).
FY 1997	Provided improved chips and mounting assemblies to Electricity Division; 2 ppm precision demonstrated in AC/DC measurement using transition edge thermometers.
FY 1998	Develop proposals for funding further work on AC/DC substitution.

5. Wireless telecommunications at terahertz frequencies

FY 1996	Initiated program to develop antenna-coupled vanadium-oxide room-temperature bolometer.
FY 1997	Developed phase pattern metrology of lithographic antennas at frequencies of atmospheric absorption lines.

6. Develop multiplexed arrays of 100 mK superconducting bolometers (with Nanoscale Cryoelectronics Project)

FY 1996	Wrote proposal to NASA, in collaboration with Goddard Space Flight Center.
FY 1997	Demonstrated SQUID multiplexing capability and measure noise equivalent power (NEP) of bolometers with optical absorbers; Demonstrated operation at 20 kHz using individual SQUID chips; Designed 1 x 8 array.
FY 1998	Fabricate and test 1 x 8 multiplexer; Integrate multiplexer with superconducting transition-edge sensors and 100 mK cryostat.

Josephson Array Development

Project Leader: Clark A. Hamilton

Staff: 3.9 Professionals

Funding level: $0.92 M

Funding sources: NIST (STRS-41%, ATP-16%), Other Agency (43%)

Objective: Advance the sensitivity, accuracy, and speed of electronic measurement by developing Josephson array circuits and systems for such uses as programmable dc voltage standards, waveform synthesizers, and frequency sources. Support EEEL requirements for maintaining the national volt.

Background: Manufacturers of modern precision electronic components and instrumentation need intrinsic electrical standards at a level of accuracy above that achievable by traditional electrical metrology and artifact standards. The characterization and calibration of modern digital voltmeters, reference standards, and converters between analog and digital signals require the development of new and improved intrinsic standards for the generation and measurement of dc and ac voltage. Josephson array technology provides the means to meet these requirements. This project and its predecessors have revolutionized precision voltage measurement through the development of the world's first practical Josephson-junction array standards. Target customers are electronic instrument makers, DoD contractors, and national and military standards labs (Sandia, Army, Navy, Air Force). Superior electrical metrology has and will continue to enhance the competitive position of the U.S. electronics industry.

Current Tasks:

1. Develop second-generation dc Josephson standards operating at one volt and at ten volts

FY 1995	Development of compact Josephson voltage standard for Sandia/NASA begun.
FY 1996	Prototype of compact Josephson voltage standard delivered.
FY 1997	Developed compact Josephson voltage standard for DoE; Helped organize and run 1997 National Conference of Standards Laboratories Josephson voltage standard interlaboratory comparison.
FY 1998	Add 4 K cryocooler to compact Josephson voltage standard to eliminate need for liquid helium; Deliver compact Josephson Voltage Standard to DoE; Develop and teach 3-day course on JVS for NASA.

2. Develop programmable Josephson voltage standards

FY 1993	Concept of programmable Josephson standard developed.
FY 1994	Publication of concept and first experimental results.
FY 1995	First useful measurements made with programmable standard; High speed bias system developed; Superconductor-normal-superconductor junctions developed to improve programmable voltage standard.

FY 1996 High-accuracy sine wave synthesis with programmable Josephson voltage standard demonstrated; First direct check on thermal voltage converter; Patent on programmable JVS issued.

FY 1997 Demonstrated programmable JVS at output voltage greater than one volt.

FY 1998 Deliver 1 V programmable standard to Electricity Division.

3. Develop pulse-programmable Josephson voltage standards (JVS)

FY 1995 Pulse-programmable JVS concept invented.

FY 1996 Pulse-programmable JVS demonstrated experimentally.

FY 1997 Used pulse-programmable JVS to synthesize sine waves at frequencies from one kHz to one MHz.

FY 1998 Integrate 12 GHz digital pattern generator and Josephson pulse array chip into a synthesized Josephson ac voltage standard.

4. Develop a Josephson voltage synthesis system based on single flux quantum (SFQ) voltage multipliers (New task)

FY 1998 Supervise the development of the SFQ voltage multiplier under a Phase I SBIR with U.S. company; Develop test hardware for SFQ voltage multiplier chips.

Nanoscale Cryoelectronics

Project Leader: Richard L. Kautz

Staff: 7.0 Professionals, 1.0 Technician, 1 NRC Postdoc, 1.0 PREP Postdoc, 1.2 Guest Researchers

Funding level: $1.76 M

Funding sources: NIST (STRS-33%), Other Agency (67%)

Objective: Develop ultra-small electronic devices operated at cryogenic temperatures for applications in fundamental metrology and industrial instrumentation.

Background: Electronic devices operated at the reduced noise levels afforded by cryogenic temperatures offer the ultimate in measurement accuracy and sensitivity. The goal of Nanoscale Cryoelectronics is to exploit this benefit of low temperatures and use microcircuit technology to develop new devices for fundamental metrology and industrial instrumentation. This project presently focuses on two such devices: an electron pump capable of counting electrons one-by-one and an x-ray detector that senses the temperature rise of electrons in a metallic x-ray absorber. The electron pump, based on ultra-small tunnel junctions, can accurately transfer a specified number of electrons to a capacitor. The pump will provide the basis for a new fundamental standard of capacitance and may lead to an improved measurement of the fine structure constant. The hot-electron x-ray detector achieves better energy resolution than conventional detectors without sacrificing either detection area or response time, and promises rapid commercial introduction in X-ray materials-analysis systems.

Current Tasks:

1. Develop single-electron pump for metrological applications

FY 1991	NIST Competence funding received for the first of five years to support the development of an accurate electron pump.
FY 1992	Error rate of electron pump analyzed theoretically and shown to require at least five tunnel junctions for metrological accuracy. Single-electron transistors required for testing pump performance fabricated, tested, and shown to be of adequate noise performance.
FY 1993	Five-junction electron pump fabricated and tested. Effect of environmental noise on pump accuracy investigated theoretically.
FY 1994	Experimental results on the five-junction pump were published, demonstrating an accuracy of 0.5 part per million.
FY 1995	Seven-junction pump designed, fabricated, and underwent preliminary testing.
FY 1996	Demonstrated a seven-junction pump with an accuracy of 15 parts per billion and an average time of 10 minutes between leakage events in the hold mode.
FY 1997	Determined by direct measurement that the electron temperature in an operating pump is too low to explain the observed error rate, indicating that

errors are proably due to photon-induced cotunneling; Made preliminary measurements of the effect of microwave radiation on error rates.

FY 1998 Use an electron pump to charge an external capacitor as a first step toward building a capacitance standard; Continue investigation of error mechanisms in the electron pump.

FY 1999 Develop electron pumps for use in a capacitance standard to be built by the Electricity Division.

2. Develop microcalorimeters as X-ray detectors

FY 1994 Microcalorimeter based on sensing temperature of electrons in a metallic absorber near 100 mK was conceived, fabricated, and tested, to demonstrate an energy resolution of 22 electronvolts (eV) at 6 keV, an order of magnitude improvement over conventional detectors; Achieved a sensitivity of 3 x 10-13 $W/Hz^{1/2}$, the best ever recorded for a bolometric device.

FY 1995 Detectors with large area (0.25 mm^2) and fast response time (10 microseconds) demonstrated, using a normal-insulator-superconductor tunnel junction thermometer and a superconducting transition-edge thermometer operated with electrothermal feedback; Achieved an energy resolution of 0.2 eV for a small-area detector responding to a heat pulse, the best resolution ever obtained in any calorimetric technology.

FY 1996 Demonstrated an x-ray microcalorimeter with an energy resolution of 8 eV at 6 eV and a count rate of 100 counts per second; Obtained NASA funding to work toward an energy resolution of 2 eV for x-ray astronomy over three years.

FY 1997 Demonstrated transition-edge X-ray microcalorimeters with energy resolutions as low as 7.2 eV at 6 keV and (in a separate experiment) count rates as high as 800 cps; Developed photolithographic method for fabrication of transition-edge microcalorimeters; Identified the mechanism for hysteresis in superconducting transition-edge thermometers, which presently limits the performance of microcalorimeters, as the sudden nucleation of phase slip lines.

FY 1998 Demonstrate a microcalorimeter with a count rate of 1000 cps at an energy resolution of 5 eV; Experiment with methods for reducing hysteresis due to nucleation of phase-slip lines; Investigate the possibility of discriminating X-ray position by using two transition-edge thermometers to sense the temperature at opposite ends of a single absorber.

FY 1999 Design, build, and test a small-scale X-ray imaging device, based either on microcalorimeter array or a multiple-thermometer pixel, as a demonstration of their potential for astronomical applications; Fabricate a microcalorimeter with 2 eV resolution.

3. Develop practical X-ray system for microanalysis applications

FY 1995 Designed, fabricated, and tested cryostat with an adiabatic demagnetization refrigerator (ADR) to achieve an operating temperature of 80 mK directly from a helium bath which nominally operates at a temperature of 4 K (or 4000 mK).

FY 1996 Fabricated and tested a complete x-ray system, including adiabatic demagnetization refrigerator, SQUID preamplifier, and superconducting

	transition-edge microcalorimeter; Interfaced system to an electron microscope and demonstrated resolution of 8 eV resolution in X-ray fluorescence spectra.
FY 1997	Fabricated and tested an improved adiabatic demagnetization refrigerator and cryostat with reduced liquid helium consumption; Increased the effective detection area of the microcalorimeter from 0.06 mm^2 to 6 mm^2 using a capillary X-ray lens; Demonstrated artifact-free fluorescence spectra at an energy resolution of 10 eV or less for a wide range of samples.
FY 1998	Deliver complete X-ray system, including cryostat, adiabatic demagnetization refrigerator, and transition-edge microcalorimeter to the NIST Surface and Microanalysis Science Division; Demonstrate an increase in count rate, by a factor of 2 to 3, using beam blanking to reduce pileup in electron-beam-induced X-ray fluorescence; Demonstrate identification of particles with dimensions of 0.3 µm or less on semiconductor substrates.
FY 1999	Transfer X-ray microcalorimeter technology to a commercial manufacturer of microanalysis systems; Demonstrate a microcalorimeter system with a 10^-4 mass-fraction level of detection; Demonstrate identification of surface particles of 0.1 µm dimension on silicon substrates.
FY 2000	Demonstrate chemical-shift analysis using a microcalorimeter with an energy resolution of better than 5 eV; Although not practical with present microanalysis systems, chemical-shift analysis would allow for example metallic aluminum to be distinguished from aluminum oxide and thus provide important new information; Survey relative weights of characteristic X-ray fluorescence lines to establish simplicity of calibration for the microcalorimeter.

4. Develop transition-edge microcalorimeters for optical and ultraviolet applications

FY 1997	Designed masks for fabrication of transition-edge microcalorimeter for detection of optical and ultraviolet photons.
FY 1998	Fabricate and test transition-edge microcalorimeter to achieve an energy resolution of 0.2 eV.
FY 1999	Demonstrate a microcalorimeter for efficient photon counting at optical and ultraviolet wavelengths with an energy resolution of 0.2 eV at account rate of 10^4 cps.

5. Develop transition-edge bolometers for infrared applications

FY 1997	Demonstrated an infrared transition-edge bolometer with a noise equivalent power of 3 x 10^-18 W/Hz$^{\wedge 1/2}$; Successfully tested a discrete-component version of the SQUID multiplexing circuit to be used with bolometer arrays.
FY 1998	Assemble a cryostat with an adiabatic demagnetization refrigerator for testing infrared bolometers; Design and fabricate an integrated circuit version of the multiplexing SQUID preamplifier for infrared bolometer arrays; Integrate a single transition-edge bolometer on a silicon pop-up thermal-isolation structure provided by NASA.
FY 1999	In collaboration with NASA, demonstrate a 32-pixel linear array of infrared bolometers.

High-T_c Electronics

Project Leader: David A. Rudman

Staff: 4.6 Professionals, 1.0 Guest Researcher, 1.0 NRC Postdoc, 1.0 Technician

Funding level: $1.57 M

Funding sources: NIST (STRS-66%, ATP-6%), Other Agency (28%)

Objective: Use the unique properties of high-temperature superconductors to develop new devices and electronics for measurements and standards for the electronics industry. Develop new measurement techniques, devices, and circuits in support of the emerging superconducting electronics industry.

Background: High-temperature superconductivity (HTS) has opened the possibility for operating superconducting electronic instrumentation at temperatures accessible with present-day cryocoolers. Low-temperature superconductors have already been used to produce unique standards, such as the Josephson volt, and measurement apparatus, such as Superconducting Quantum Interference Devices. Equivalent HTS devices would expand the applicability of these devices far beyond standards and research laboratories. Thus the primary "customer" for the devices being developed by this project are the other NIST divisions responsible for standards and measurement techniques in areas such as the volt, and infrared, terahertz, and microwave radiation. The project will also provide support for the emerging HTS superconducting electronics industry, both through measurements and through the development of HTS devices and circuits.

Current Tasks:

1. Develop microwave testing for unpatterned HTS films (Collaboration with EEEL Electromagnetic Fields Division)

FY 1992	Collaborated with University of Colorado on measurement of microwave surface resistance (R_s) of HTS films using parallel plate resonator.
FY 1993	Implemented dielectric cavity resonator technique for R_s measurements; Obtained significant improvement in measurement reproducibility; Developed novel technique to measure microwave properties of tunable thin film capacitors at cryogenic temperatures (with University of Colorado).
FY 1994	Refined dielectric resonator technique; Compared results at different frequencies; Measured microwave properties of tunable capacitors made from strontium titanate at cryogenic temperatures (76 K and 4 K).
FY 1995	Extended dielectric resonator technique to measure power dependence of R_s using pulsed microwave approach to avoid sample heating; Began industrial collaboration to improve and use measurement technique.

FY 1996	Improved R_s and power handling measurements; With industrial collaborators, compared cavity resonator measurements to other techniques; Transferred cavity technique to interested parties.
FY 1997	Developed variable temperature measurement capability with dielectric-loaded cavity resonator, including *in-situ* variable coupling; Improvements increased Q of resonator by factor of 10 (equivalent to increasing measurement sensitivity by factor of 10).
FY 1998	Implement variable temperature high power R_s measurements using dielectric-loaded cavity resonator; Construct cavities to handle full 75 mm wafers.

2. Characterize microwave performance of HTS films

FY 1995	Measured dependence of low-power R_s on film thickness.
FY 1996	Began study of R_s as a function of film processing parameters, using films made at NIST and from industrial collaborators.
FY 1997	Compared microwave properties of films deposited under different conditions; Provided measurements on films produced by different manufacturers.
FY 1998	Evaluate microwave performance of full wafers from a variety of manufacturers; Perform measurement intercomparisons with different laboratories.
FY 1999	Complete study of wafer performance; Complete intercomparisons.

3. Develop cryogenic microwave device measurement capabilities (with EEEL Electromagnetic Fields Division)

FY 1993	Fabricated and measured the first thin-film tunable resonator, operating at a frequency of 5 GHz, made from HTS films and an electrically adjustable thin film capacitor, in collaboration with University of Colorado.
FY 1994	Developed cryogenic microwave test fixture and probe for testing HTS devices; Modified NIST calibration software (DEEMBED) for use with superconducting calibration standards to perform calibrated on-chip measurements; Performed calibrated measurements on tunable thin-film superconductor-ferroelectric microwave transmission lines and resonators.
FY 1995	Compared performance of HTS microwave devices patterned by different techniques (in collaboration with other laboratories); Completed procurement for cryogenic microwave probe station.
FY 1996	Developed techniques for calibrated cryogenic microwave probing of superconducting devices; Used probe station to improve measurements of HTS devices patterned by different techniques.
FY 1997	Successfully modeled coplanar waveguide device performance based on measurements of unpatterned films; Implemented measurements of third-harmonic generation (TOI) as a function of microwave power; Found only weak dependence of TOI on patterned techniques; Measured harmonic generation as a function of line width and length
FY 1998	Implement fully calibrated high power measurement capability; Investigate effect of film properties on device performance.

4. Develop HTS Josephson junction technology for measurements and standards applications

FY 1991	Developed superconductor-normal metal-superconductor (SNS) Josephson junctions using HTS films.

FY 1992	Improved SNS junction fabrication process; Confirmed that devices behave as predicted by standard models.
FY 1993	Developed technique to increase resistance of the fabricated junctions; Coupled junctions to far infrared laser using lithographed antenna and measured response of the junctions up to the highest frequency that such junctions had ever been operated (8 terahertz); Fabricated world's first HTS SNS junctions and Superconducting Quantum Interference Devices (SQUIDs) over HTS ground plane; Demonstrated phase locking between two HTS junctions at frequencies up to 1.06 terahertz and temperatures up to 35 K.
FY 1994	Measured heterodyne mixing products from HTS junctions at frequencies as high as 30 terahertz, with difference frequencies up to 27 GHz (in collaboration with other Groups); Demonstrated that HTS junctions produce sufficiently large steps at a temperature of 38 K and a frequency of 62 GHz for use in programmable voltage circuits.
FY 1995	Determined that microwave-induced Shapiro steps in these junctions flat to approximately 5 parts per million at a temperature of 4 K and 100 parts per million at 76 K (both numbers measurement limited), indicating junctions may be appropriate for voltage standard applications; Demonstrated resonant phase-locking scheme for HTS arrays for use as mm-wave sources; Developed first SNS junctions on silicon substrates (in collaboration with a U.S. company).
FY 1996	Tested alternative junction technology (bicrystals) for application to voltage standards and other measurements; Fabricated first bicrystal junctions on sapphire substrates; Developed novel multilayer process for HTS circuits.
FY 1997	Completed study of junctions on sapphire bicrystals; Completed demonstration of multilayer circuit fabrication.
FY 1998	Complete evaluation of stacked-junction circuit performance; Transfer technology to industry; End task.

5. Develop HTS bolometers as improved radiometers

FY 1994	Fabricated first HTS antenna-coupled microbolometers using thermally-isolated yttria-stabilized zirconia membranes on silicon substrates; Devices were the lowest noise, fastest liquid-nitrogen-cooled detectors ever.
FY 1995	Developed process to fabricate large-area HTS films on silicon membranes; Device geometry suitable for electrical-substitution radiometer.
FY 1996	Measured electrical noise in HTS films at transition temperature on different substrates, including silicon; Noise approached the Johnson limit, verifying that films are appropriate for thermometer applications (with U.S. companies).
FY 1997	Fabricated HTS films on large-area silicon membranes; Devices currently under test for use in electrical substitution radiometers (same collaborations).
FY 1998	Fabricate prototype electrical-substitution radiometer using HTS transition-edge thermometer (same collaborations).

6. Develop micromachined ion traps (with Physics Laboratory's Time and Frequency Division)

FY 1996	Developed initial design to test micromachining concepts for ion trap fabrication; Selected laser cutting as most appropriate initial approach for substrate machining.
FY 1997	Fabricated and assembled first micromachined ion traps; Traps currently under test by Time and Frequency Division.

FY 1998 Based on results from tests of first devices, fabricate improved traps.

Superconductor Standards and Technology

Project Leader: Loren F. Goodrich

Staff: 1.0 Professional, 1.0 Technician

Funding level: $0.4 M

Funding sources: NIST (63%), Other Agency (37%)

Objective: Provide standards, measurement techniques, quality assurance, reference data, and issue clarification for both high- and low-temperature superconducting wire technology in support of applications involving U.S. industry such as magnetic resonance imaging, and development of laboratory magnets, fault current limiters, magnetic energy storage devices, motors, generators, and transmission lines.

Background: The project is internationally recognized as the leader in the development of standards for critical-current measurements and is leading the international effort for all superconductor standards. This effort is vital to U.S. industry, which now concentrates on conventional low-temperature superconductor (LTS) materials. This effort will become more vital to U.S. industry as additional new applications that use high-temperature superconductors (HTS) are commercialized. One of the most important performance parameters for large-scale applications is the critical current, I_c, of a superconductor, which is the current level that under given conditions, marks the transition between the superconducting state and the normal state. The critical current is difficult to measure correctly and accurately, and these measurements are often subject to scrutiny and debate. This is especially true for measurements on HTS.

Current Tasks:

1. Develop international standards for superconductors

FY 1989	International Electrotechnical Commission (IEC) Council established Technical Committee, TC 90, to create international standards for superconductivity.
FY 1990	First Technical Committee meeting held in Japan; two Working Groups formed. First Working Group meeting held; Goodrich became U.S. Technical Advisor to TC 90.
FY 1991	Working Group meeting in Boulder; Goodrich became the Convener of Working Group 2 and drafted the first IEC standard test method.
FY 1992	Working Groups 1 and 2 draft documents were reviewed; a third Working Group was formed.
FY 1993	Five New Working Item Proposals were considered and accepted; Meetings were held in France.
FY 1994	Japanese National Committee (JNC) created the first draft of three of the five proposals; Goodrich became Chairman of TC 90.

FY 1995 — Working Group meeting held to advance draft documents; Meetings were held to discuss the status and existing Committee Drafts.

FY 1996 — Worked on draft documents from Working Groups 1, 2, 4, 6, and 7; Approved Committee draft for voting from Working Group 2.

FY 1997 — Meetings held in China; Worked on documents from Working Groups 1, 2, 3, 4, 5, 6, and 7.

FY 1998 — Voting on Committee drafts from Working Groups 2 and 7; Meetings to be held in Germany; Work on documents from Working Groups 1, 3, 4, 5, 6, and 7.

2. Develop metrology for I_c measurements on HTS

FY 1993 — Technical Working Area (TWA) "Characterization and Evaluation of High-Temperature Oxide Superconductors" proposed at meeting of Versailles Project on Advanced Materials and Standards (VAMAS).

FY 1994 — Started separate interlaboratory comparisons of I_c measurements on HTS samples in U.S., Europe, and Japan. Two samples from U.S. industry used.

FY 1995 — Reported preliminary results of U.S. comparison, the first successful comparison of I_c on HTS; measurements in U.S. comparison completed.

FY 1996 — Completed final report on U.S. comparison; Completed comparison in Europe; Planned comparison in Japan; Planned second stage international comparison.

FY 1997 — China reported results of their comparison which confirmed the results from the U.S. comparison; Japan completed their domestic comparison.

FY 1998 — Conduct second stage interlaboratory comparison; Analyze results from second stage and draft set of guidelines for measurement of I_c in HTS materials; Complete construction and testing of high-current, variable-temperature I_c measurement system for HTS samples.

FY 1999 — Conduct a U.S. interlaboratory comparison of variable-temperature I_c measurements using HTS samples.

3. Develop metrology for I_c measurements on LTS

FY 1986 — VAMAS established technical working area on superconducting materials.

FY 1987-88 — First international interlaboratory comparison of I_c measurements started; Three samples were used, one each from Europe, Japan, and USA; NIST discovered significant source of variation in measurements.

FY 1989 — NIST asked to draft a test procedure for second comparison.

FY 1990,91,92 — Second comparison started and continued, using NIST procedure; a NIST Standard Reference Material and a wire sample were used.

FY 1993 — Final report on VAMAS comparison started.

FY 1994 — NIST helped establish standard I_c measurement technique for superconducting wire for International Thermonuclear Experimental Reactor (ITER); Participated in and reported on the first ITER interlaboratory comparison of niobium tin compound (Nb_3Sn) I_c measurements.

FY 1995 — U.S. procedure used in a second ITER interlaboratory comparison. Conducted comparisons with members of the ITER U.S. Home Team to determine the accuracy of I_c measurements on superconducting wires and assist them in reducing their uncertainties; Produced a 1-hour training video.

FY 1996 Created an accurate database of magnetic field and temperature dependence of I_c up to temperatures of 5.0 K in liquid helium; Confirmed capability to measure I_c at 12 T with current pulses

FY 1997 Developed I_c measurement capability up to 200 A in helium gas over the temperature range of 4.2 K to 18 K to determine the temperature stability margin for ITER and magnets that operate near 10 K; Created database for the temperature stability margin of Nb_3Sn wires; Studied effect of sample coil diameter on the measured I_c.

FY 1998 Measure I_c as a function of magnetic field and temperature of niobium titanium alloy wires, to be used as control samples for interlaboratory comparisons of HTS samples.

4. Develop metrology for sensitive low-temperature measurements

FY 1989 Developed first passive I_c simulator; new design is sample-substitution box which can be used to compare dc and pulse techniques for measuring I_c.

FY 1990 Direct comparison made of steady state and pulse techniques on HTS samples and an I_c simulator.

FY 1991 Developed new active simulator with I_c selectable from 0.001A to 10,000 A; first 50-A I_c simulator built and used in an interlaboratory comparison.

FY 1992 Developed hybrid simulator which is easier to calibrate; Conducted a simulator comparison with two other U.S. labs; Developed high-current (100-300 A) pressure contacts to HTS tapes; Began design and construction of a high-current variable temperature cryostat.

FY 1993 Participated in VAMAS interlaboratory comparison of critical magnetic fields, using SRM-1457 to check magnetic field calibrations among 11 laboratories; Designed custom simulator of high mutual inductance to simulate coils; Started preliminary testing of high-current variable temperature cryostat.

FY 1994 Made transport residual resistivity ratio measurements on high purity aluminum bars to compare with eddy current decay method. Conducted a simulator interlaboratory comparison with 12 U.S. laboratories.

FY 1995 Developed a custom simulator for a U.S. company; Made transport magnetoresistivity measurements on high purity aluminum and copper bars to compare with eddy current decay method.

FY 1996 Finished fabrication and testing of custom simulator; Loaned I_c simulators to two U.S. laboratories; Developed and verified capability to acquire voltage-current characteristics using variable-duration current pulses.

FY 1997 Developed capability of delivering 5000 current pulses to sample in a 12 T magnetic field to study fatigue due to Lorentz force cycling.

FY 1998 Implement and verify differential thermometry to control temperature gradients in samples during variable-temperature I_c measurements.

LOW FREQUENCY

AC-DC Difference Standards and Measurement Techniques

Project Leader: Joseph R. Kinard

Staff: 2.0 Professionals, 1.0 Technician

Funding level: $0.6 M

Funding sources: NIST (50%), Other Government Agencies (17%), Other (33%)

Objective: Provide U.S. industry with the link between the direct voltage and current standards and alternating quantities by maintaining and improving the U.S. national standards of ac-dc difference, and the working standards, measurement systems, and techniques needed to provide viable calibrations and measurement services for thermal converters and shunts.

Background: Nearly all measurements of electric power, energy, alternating voltage and alternating current are traceable to the volt and ohm (dc quantities) through thermal transfer standards. Modern electronics makes possible digital instruments which can produce and measure alternating voltage and current parameters with precision and stability rivalling those of the best direct voltage and current standards. Improved NIST thermal transfer standards are needed to support the development, testing, production, and maintenance of such instruments. Thermal transfer standards are used to measure a quantity called "ac-dc difference," where ac, literally "alternating current," refers to the time varying signals and dc literally "direct current," refers to time invariant signals. NIST has developed new standards, nearly as good as existing national standards, based on semiconductor and thin-film processing technologies that are about to be commercialized and hence widely available. Present NIST standards are inadequate to calibrate these devices over their full range of capability. Moreover, manufacturers are introducing high-output current amplifiers and improved high-voltage resistors. An extension of the parameter space and improved accuracies of NIST calibration services are required to support these developments.

Work is underway to develop new primary, thermal transfer standards operating at cryogenic temperatures and with sensitivity approaching the quantum limit. This effort builds on the experience gained in the development of film multijunction thermal converters and on the design and application of extremely sensitive cryogenic thermometers. The new standards are expected to reduce uncertainties from the present lowest value of 0.8 mV/V to 5 mV/V to <0.1 mV/V to 1 mV/V. A new investigation of bootstrapping techniques to support high-voltage and current measurements is also being performed. This will be based on earlier, pioneering NIST work in this field and is expected to result, not only in improved NIST services, but in better, more efficient techniques for industrial standards maintenance as well. The U.S. has the largest manufacturing industry for thermal transfer instrumentation. NIST continues to provide support for this U.S. industry through an expanded ac-dc difference calibration service, Cooperative Research and Development Agreements (CRADAs), and international comparisons and cooperations.

Current Tasks:

1. Maintain the primary, reference, and working sets of thermal transfer standards for ac-dc difference; provide and improve the ac-dc difference calibration service for voltage from 0.1 V to 1000 V at 2 Hz to 1 MHz; and for current from 1 mA to 100 A at 2 Hz to 100 kHz

FY 1986	Studied multijunction thermal converters and established them as the NIST primary standards of ac–dc difference for alternating voltage and current.
FY 1988	Recharacterized thermal voltage converters and reduced uncertainties in the frequency range 0.1 MHz - 100 MHz.
FY 1994	Studied the voltage dependence of thermal converters in the 200 V - 1000 V range and recharacterized the NIST high-voltage standards.
FY 1995	Studied and recharacterized thermal converter standards at 10 Hz to permit reduction in calibration uncertainties; Provided new ac-dc difference reference values from 10 kHz up to 30 MHz to maintain consistency between this activity and NIST's higher frequency ac-dc difference calibration service.
FY 1996	Fabricated and tested new high-current, multi-converter module to replace damaged traditional converters; Published results; Fabricated and tested high-voltage, binary divider to confirm scaling of 200 V to 1000 V ranges (recent international comparisons revealed significant variations between national laboratories at these voltages); Prepared documentation for extending transfer shunt calibrations up to 100 kHz.
FY 1997	Completed total reassessment of ac-dc difference calibration service uncertainties with significant reductions; Documentation prepared for extension of transfer shunt calibration down to 10 Hz.
FY 1998	Publish reports on uncertainties and transfer shunt calibration; Upgrade automated comparator systems to provide unassisted data analysis and interface with Electricity Division Calibration Service Database; Remodel and improve ac-dc calibration laboratory physical plant; Carry out international comparisons at ≥500 V and at ≥100 kHz.
FY 1999	Establish thin-film multijunction thermal converters as working standards.

2. Develop new thin-film converter technology and assist with the transfer of this technology to industry

FY 1989	Designed structure and photomasks for prototype thin-film multijunction thermal converters.
FY 1990	Perfected stress-balanced, multilayer membrane required for thin-film converter fabrication.
FY 1991	Mounted and tested completed chips.
FY 1992	Developed improved bonding pads for thin-film converters to greatly reduce errors as current converters; Patent granted February 1995; Cooperative program with industrial partner directed to the development and production of thin-film multijunction thermal converters.
FY 1993	Designed and produced integrated micropotentiometers which combined high performance multijunction converter and thin-film output resistors on the same chip; Patent granted February 1994.
FY 1995	Solved a remaining problem with wafer cleaning and metal to metal contacts, and continued successful production of converter chips; Fabricated additional converter chips, mounted, and characterized as working standards; Provided chips to DoD and Sandia laboratories as per agreements.

FY 1996	Characterized thin-film converters at various voltages, currents, and frequencies at room and cryogenic temperatures and began study to incorporate these devices as reference and working standards; Constructed and tested new thin-film thermal converter chips for currents above 0.5 A; Presented invited summary paper at CPEM 96 on thin-film converters.
FY 1997	Began development of broadband mounting substrate to permit extension of integrated micropotentiometer and thin-film converter frequency range.
FY 1998	Develop and test vacuum mountings and new longer time-constant versions of film multijunction converters; Design and fabricate improved high-current converters; Explore front-surface etching technique in collaboration with Division 812.

3. Develop new low-temperature thermal converter standards and study fundamental limitations on the thermal transfer process

FY 1993	Developed preliminary design for low-temperature primary standard converters based on superconducting kinetic inductance thermometer sensor.
FY 1994	Began equipment procurement; Performed preliminary, low-temperature ac-dc difference measurements on thin-film multijunction thermal converters.
FY 1995	Began study of low-temperature converter design using alternative superconducting transition edge device as sensor; Transition edge device appears more conducive to fabrication and incorporation into converter than kinetic inductor as originally planned.
FY 1996	Assembled cryogenic system, made prototype converter chips using transition edge thermometers; Began initial testing of new low-temperature devices.
FY 1997	Developed suitable designs and geometries for low temperature standards and investigated fundamental limitations on the thermal transfer process; Achieved first ac-dc difference measurements at cryogenic temperatures; Presented results in paper at the IMTC/97 in Ottawa.
FY 1998-99	Confirm accuracy of new low-temperature converters and establish them as NIST primary standards, if appropriate; Characterize existing thin-film converter designs at cryogenic temperatures.

4. Support the measurement of ac quantities through interaction with industry and other national laboratories

FY 1993	Cooperative program with industrial partner directed to the improvement of single junction thermoelements; Second cooperative program directed to characterization of a new automated thermal transfer standard.
FY 1994	New cooperative program with industry directed to the improvement of voltage coefficients and frequency compensation for their high voltage range resistors; Cooperative program with University of Maryland, Department of Materials and Nuclear Engineering, directed to utilization of thin-film multijunction thermal converters to measure properties of sputtered metals during deposition.
FY 1995	Trained professional staff member and provided equipment and extensive calibrations to the Mexican national measurement laboratory, CENAM; Participated in an international comparison of a multijunction thermal converter travelling standard at the highest uncertainty level.
FY 1996-97	Participated in international comparisons of high-frequency thermal converters with the laboratory responsible for their maintenance in Spain (INTA);

Assisted various companies to develop improved thermal converter instrumentation.

FY 1998-99 Assist laboratories of developing nations in the Americas to bring their capability up to international standards; Participate in international intercomparisons, including intercomparisons for high-voltage; Collaborate with University of Maryland in study of in-situ properties of sputtered materials.

Waveform Acquisition Devices and Standards

Project Leaders: T. Michael Souders, Nicholas G. Paulter, Jr.

Staff: 4.0 Professionals, 0.9 Technician

Funding level: $0.9 M

Funding sources: NIST (44%), Other Government Agencies (50%), Other (6%)

Objective: Develop standards, test methods, and analysis techniques for waveform acquisition devices. Expand and improve the present time domain waveform measurement services to support high performance samplers and digitizers, as well as fast pulse and impulse sources, operating over frequencies to 50 GHz.

Background: Manufacturers and users of time domain instrumentation need state-of-the-art methods and standards for characterizing the performance of increasingly sophisticated products. Waveform sampling has become a critical, pervasive technology in instrumentation and continual advances are being made. The digital oscilloscope market alone was estimated to be $60 M in 1995. This industry needs advances in standards, test methods and error analyses to facilitate continued growth. In turn, the computer, telecommunications and integrated circuit industries (each critically dependent on sampling technology) will all benefit. Improved optoelectronic technology will be needed for advancement and development of state-of-the-art electronic devices, semiconductor structures, and printed circuit board materials. NIST has pioneered many of the techniques and standards used today for testing and calibrating precision time domain instruments and systems. In response to new advances in devices and products, NIST will expand and improve the present time domain waveform measurement services to support high performance samplers and digitizers, as well as fast pulse and impulse sources, operating over frequencies up to 50 GHz. Specific goals include: (1) developing and applying accurate sampling comparator systems to measure the settling parameters of fast pulse generators, amplifiers, and digital-to-analog converters (as well as making accurate voltage measurements); (2) providing error analyses on the effects of non-idealities in sampling systems; (3) researching and developing optoelectronic devices and techniques for ultra-fast sampling and pulse generation applications and electric-field probing; and (4) supporting and contributing to consensus standards for specifying and testing waveform acquisition devices, and standards for pulse terminology and characterization.

Current Tasks:

1. Data converter/waveform recorder testing

FY 1990	Studied effects of timing jitter in sampling systems; Award-winning paper published.
FY 1991	Characterized filters for analog-to-digital (A/D) converter test bed; Subcommittee on A/D converters formed under IEEE.
FY 1993	Developed reference pulse generator for use in pulse measurement intercomparison program (round-robin); Analyzed performance of least-

	squares sine wave curve fitting algorithms used in digital oscilloscope and A/D converter testing.
FY 1994	Began pulse measurement round-robin; Studied phase-plane compensation method to reduce dynamic nonlinearity errors in sampling channels; Presented paper on results; Institute of Electrical and Electronic Engineers (IEEE) 1057-1994 *Standard for Digitizing Waveform Recorders* approved, developed under NIST leadership; Many NIST-developed test methods are included.
FY 1995	Developed analysis of bounds on frequency response estimates derived from uncertain step response data and presented paper; Completed testbed hardware for characterizing high performance A/D converter (up to 14 bits, 1 GHz sample rate).
FY 1996	Began development of a wideband oscilloscope calibration system in response to needs articulated by the Air Force.
FY 1997	Completed development of oscilloscope calibration system and delivered to sponsor; Concluded first pulse measurement round-robin and prepared documentation to publish results; Revisited phase-plane characterization of sampling channels for waveform generation.
FY 1998	Continue phase plane analysis on waveform generation.
FY 1999	Renew development of the high performance A/D converter testbed.
FY 2000	Complete development of the high performance A/D converter testbed; Incorporate test methods into IEEE Standard 1241.

2. Sampling comparator systems

FY 1992	Completed design and fabrication of integrated circuit sampling comparators and incorporated into sampling comparator system (SCS); Design goals met: 2.5 GHz bandwidth, elimination of "thermal tails" (settling to 0.1% in 2 ns).
FY 1993	Developed ultra-flat response, ± 20 V attenuator for SCS.
FY 1994	Began development of wideband (10 Hz - 200 MHz) sampling voltmeter.
FY 1995	Developed quasiequivalent-time time-base, probe control, and memory management circuits; Produced a working prototype voltmeter.
FY 1996	Completed signal-conditioning front end, second generation time-base, and time-base autocal circuits for sampling voltmeter, and presented paper on design, architecture, and error sources.
FY 1997	Completed prototype of wideband sampling voltmeter; Upgraded SCS using new time-base and control circuitry developed for voltmeter; Began development of a triggerable-oscillator time-base; Carried out feasibility study for a 5 GHz bandwidth comparator for use in SCS.
FY 1998	Deliver stand-alone wideband sampling voltmeter to sponsor; Complete the design for the new comparator; Complete new time-base and install in SCS.
FY 1999	Fabricate and test new comparator; Incorporate into the SCS.
FY 2000	Offer 5 GHz bandwidth fast settling parameter calibration services.

3. Pulse measurement services

FY 1993	Began special measurement services for settling performance using SCS; Implemented "nose-to-nose" method for measuring the impulse response of high speed scopes; Developed improved gallium arsenide photoconductors for high-speed pulse generation.

FY 1994	Provided assessment of pulse energy measurements for inkjet print head industry (using SCS); Brought new, computer-based pulse measurement system on-line.
FY 1995	Trained new operator to perform the 65000 series of NIST Special Tests; Completed error analyses for Impulse Spectrum Amplitude, Baseband Pulse Parameters, and Pulse Delay Time tests.
FY 1996	Evaluated deconvolution algorithms and selected new algorithm for use in pulse parameter estimation software; Coded deconvolution and pulse parameter estimation algorithms in LabView™ software; Developed control and automation software to upgrade pulse parameter measurements; Performed pulse settling calibrations for 8 precision step generators and 3 high speed digital-to-analog converters, and pulse energy calibrations for 11 pulse generators.
FY 1997	Evaluated time-base linearity test methods, began coding the selected method in LabView™; Refined control and automation software to upgrade pulse parameter measurements; Uncertainty envelope determined for entire measured waveform on point-by-point basis for two commercial pulse calibrators.
FY 1998	Develop an algorithm to correct for timing errors in sampled waveforms; Provide improved uncertainty envelope calculations for entire measured waveform on point-by-point basis; Begin characterization of 50 GHz sampler.
FY 1999	Complete characterization of 50 GHz sampler and incorporate into broadband pulse measurement system; Offer 50 GHz bandwidth fast pulse calibration services.
FY 2000	Upgrade time delay and impulse spectrum amplitude measurement services.

4. Optoelectronic technology

FY 1994	Improved performance of packaged photoconductors and reduced aberrations.
FY 1995	Investigated potential replacement systems for YAG laser; Ordered diode-laser system; Extended time-domain printed wiring board measurement technique to provide dielectric loss information.
FY 1996	Introduced optical delay/splitter to reduce laser jitter effects from 7 to 0.5 ps.
FY 1997	Tested diode-laser based system operation; Made improvements in operating frequency and optical pulse duration.
FY 1998	Demonstrate optical pulsewidth measurement capability with autocorrelator; Test photoconductor performance using diode-laser system.
FY 1999	Determine impulse response of NIST's pulse calibration systems using diode-laser based system.

5. Pulse Measurement Applications

FY 1996	Developed time-domain method to measure the dielectric constant of printed wiring board materials; The method uses inexpensive equipment and provides accuracy comparable to frequency domain techniques.
FY 1997	Investigated short and long term repeatability of the dielectric measurement technique; Reported results in paper submitted to IEEE Trans. on Components, Hybrids, and Manufacturing Technology; Studied various transmission line structures for extracting permittivity of dielectrics with low d_K values.

FY 1998 Develop high-bandwidth (≈15 GHz), high cycle (>100,000), low-cost probe for measuring printed-wiring-board (PWB) transmission line impedance; Investigate PWB sample holder design intended to reduce variation in the extracted dielectric constant values of PWB materials; Report results; Complete analysis of procedure to extract complex permittivity values for thin-film dielectrics used in integrated circuits.

Waveform Synthesis and Impedance Metrology

Project Leader: Nile M. Oldham

Staff: 4.0 Professionals, 2.0 Technicians

Funding level: $0.9 M

Funding sources: NIST (50%), Other Government Agencies (30%), Other (20%)

Objective: Provide calibrations and special tests and develop new measurement capability to support the basic quantities of voltage, current, phase angle, power/energy, ratio, and impedance using waveform synthesis and sampling techniques as well as classical electrical measurement methods spanning a frequency range of dc to 100 MHz.

Background: Industrial, university, and government laboratories have calibration requirements for basic instrumentation standards to support calibrators, digital multimeters (DMMs), impedance (LCR) meters, and phase meters. With multifunction/multirange capability, wide frequency ranges, and sophisticated self-calibration features, the ability to provide a comprehensive coverage of the calibration quantities for these instruments, at desired accuracies and ratios, is increasingly challenging. The market for these instruments is over $550 million annually. Similarly, the power industry legally requires NIST traceability to equitably distribute over $208 billion of electric energy generated annually. High-accuracy power measurements are required to determine the efficiency of electric equipment during development and manufacture, and for quality control. Power and energy measurements have been complicated by an increasing proportion of nonlinear loads and alternate energy generators, which produce nonsinusoidal waveforms with frequency components in excess of 100 kHz. In response to the above needs, new waveform generation and measurement capability at NIST will be developed to support the basic quantities of voltage, current, phase angle, ratio, and impedance, using techniques for generating and measuring voltage and current waveforms over the frequency range up to 100 MHz. Specific goals include: (1) developing techniques to measure generalized impedances at signal frequencies up to 1 MHz; (2) developing automated measurement systems capable of providing near state-of-the-art traceability for voltage, current, resistance, and phase angle in the frequency range from dc to 30 MHz; and (3) developing new 60 Hz power/energy standards and extending the frequency range of power measurements up to 400 kHz.

Current Tasks:

1. Voltage and current

FY 1989 — Completed a digitally synthesized source (DSS) to generate signals at frequencies up to 50 kHz with calculable voltage output and a transconductance amplifier with an output current of 20 A and maximum operating frequency of 100 kHz.

FY 1990 — Developed a technique to measure low voltages (2 mV - 200 mV) at frequencies up to 1 MHz with a factor of 10 improvement in uncertainty;

Patents issued on the DSS and the transconductance amplifier and licensed both to a commercial instrument manufacturer.

FY 1991 Completed initial development of the multifunction calibration system (MCS) and offered Special Tests for DMMs (all functions); Demonstrated the DSS as a calculable current source.

FY 1992 Completed two measurement assurance programs for ac voltage using the DSS.

FY 1993 Completed a new version of the DSS controlled using a standard computer interface and delivered 15 copies to sponsor (Sandia National Laboratories - SNL).

FY 1994 Announced a 25-point multifunction Special Test for DMMs with one-week turn-around time.

FY 1995 Completed development of a new transconductance amplifier with an output current of 100 A; Offered new 230-point test for DMMs used to provide state-of-the-art traceability for multifunction calibrators.

FY 1996 Extended the range and characterized the MCS for the calibration of currents up to 10 A; Developed a model to describe the low frequency performance of thermal voltage converters; Developed a scheme to reduce low voltage measurement uncertainties due to complex loading errors; Began organizing an international comparison of electrical units (with North, South, and Central America) using DMMs as transportable standards.

FY 1997 Trained participants and began the interamerican international comparison using DMMs; Completed software for using the DSS to make low frequency (<10 Hz) ac-dc measurements.

FY 1998 Complete documentation for the MCS and offer extended calibration services.

FY 1999 Develop a Special Test service for DMMs used by NIST's voluntary laboratory accreditation program to audit basic electrical units (voltage, current, and resistance).

2. Impedance

FY 1990 Designed a new dual-channel, digitally synthesized source as a first step in modernizing low-frequency ratio and impedance bridges in the Division.

FY 1991 Demonstrated a digital impedance bridge (DIB) using a dual-channel, digitally synthesized source; Developed a programmable 30-bit binary inductive voltage divider (BIVD); Completed an inductance comparison with the Canadian national laboratory.

FY 1992 Incorporated the BIVD into an automatic bridge to measure the linearity of precision commercial inductive voltage dividers.

FY 1993 Constructed and tested a sampling probe for the DIB to measure standard inductors; Established a procedure to use a commercial impedance meter to replace the manual Type 12 capacitance bridge; Used the BIVD bridge to evaluate a temperature bridge for use in a NASA Space Shuttle experiment.

FY 1994 Completed and documented the sampling probe for the DIB; Completed an international comparison of inductance (10 mH); Described a new error decomposition method for characterizing inductive voltage dividers based on modeling techniques; Developed software to improve inductance measurements by using predicted values based on a regression of previous test results.

FY 1995 Completed an analysis of uncertainties of capacitance calibrations; Developed a VXIbus-based impedance synthesizer and used it to test bioelectrical impedance analyzers for sponsor (National Institutes of Health); Began using a commercial capacitance meter for the calibration of capacitors; Evaluated a new commercial fused silica capacitor.

FY 1996 Completed the impedance calibrator; Demonstrated a multirange 3-voltmeter probe to measure inductors; Demonstrated a modeling-based system for characterizing 4-terminal pair capacitors.

FY 1997 Completed a prototype system for characterizing 4-terminal pair capacitors at frequencies up to 1 MHz; Completed the 3-voltmeter probe and begin using it to calibrate inductors; Documented the capacitance calibration services.

FY 1998 Begin using the 3-voltmeter probe-based DIB to provide special tests for inductors up to 100 kHz; Offer special tests for four-terminal capacitors (capacitance and dissipation factor) up to 1 MHz.

FY 1999 Begin using the automatic binary inductive divider system to perform special tests; Replace the Type 2 capacitance bridge.

FY 2000 Develop a general-purpose impedance bridge that employs a waveform generator and equivalent-time sampling probes; Document the new impedance calibration services; Offer special tests for LCR meters.

3. Phase

FY 1990 Developed a dynamic test method for high frequency phase meters to support laser interferometry.

FY 1991 Completed development of a phase standard for signals between 1 and 20 MHz and identified the phase meters in commercial interferometers as major source of error; Developed a state-of-the-art sampling phase meter and offered a Special Test for phase generators which produce signals at frequencies up to 100 kHz.

FY 1992 Developed new signal processing algorithms for the NIST sampling phase meter; Developed a self-calibration technique to characterize phase meters and generators out to 20 MHz.

FY 1993 Developed a VXIbus-based system for calibrating phase meters and generators ("VXIbus" refers to Institute of Electrical and Electronis Engineers Standard 1155-1992, a specification for the backplane interconnection and communications protocol of standard-sized modules).

FY 1994 Simulated a phase measuring system for measuring very-high-frequency omni-directional ranging (VOR) phase meters for aircraft navigation system now expected to be in use beyond 2000.

FY 1995 Developed a VXIbus-based test set for VOR phase meters.

FY 1996 Tested and delivered a VXIbus-based system for testing the phase meters in VOR receivers to the sponsor.

FY 1997 Developed an improved VXIbus-based test set for VOR phase meters.

FY 1998 Offer a Special Test service for VOR phase meters.

FY 1999 Upgrade and document the NIST phase angle calibration facility and offer extended calibration services.

4. Power and energy

FY 1989 Participated in an international comparison of audio-frequency power (NIST only participating national lab with capability to measure power at signal frequencies above 5 kHz); Began development of a prototype power-frequency sampling wattmeter.

FY 1990	Completed the NIST audio-frequency power bridge.
FY 1992	Completed the prototype power-frequency sampling wattmeter.
FY 1993	Investigated the possibility of using a miniature current-comparator-based power bridge as an ultra-stable transport standard for international comparisons.
FY 1994	Demonstrated a power measurement at a signal frequency of 200 kHz to support wideband commercial wattmeters and power system analyzers.
FY 1995	Began the planning stage of a NIST-sponsored international comparison of 50/60 Hz power.
FY 1996	Completed the first stage of the international comparison (with the national measurement laboratories of Canada and Germany); Demonstrated a 3-voltmeter technique for measuring wideband power at frequencies up to 500 kHz; Assumed chair of ANSI Committee on Electricity Metering (C-12).
FY 1997	Began development of a new 50 Hz - 400 Hz power measurement system; Complete half of the 50/60 Hz international comparison.
FY 1998	Complete 50 Hz - 400 Hz power measurement system; Report on the international comparison of 50/60 Hz power.
FY 1999	Document power measurement capabilities at frequencies up to 500 kHz and offer extended calibration services.

Measurements for Complex Electronic Systems

Project Leader: Gerard N. Stenbakken

Staff: 2.0 Professionals, 0.2 Guest Scientist, 0.1 Technician

Funding level: $0.5 M

Funding sources: NIST (51%), Other Government Agencies (49%)

Objective: Develop improved methods and techniques for optimum testing scenarios by: (1) developing improved mathematical models and test procedures; (2) estimating the confidence and test coverage in a given calibration or test procedure; (3) developing a Testing Strategies Software Toolbox; and (4) researching modeling approaches and techniques that accommodate the effects of embedded software.

Background: For both manufacturers and users, the testing and calibration costs of complex electronic devices and instrumentation have become a dominant factor in total life-cycle costs. For example, typical test costs for mixed-signal integrated circuits range from 20% to 50% of the sale price. Similarly, in the acceptance and field maintenance of electronic equipment, the costs of testing can equal or exceed the initial purchase price. Confidence levels, test coverage, and test and calibration procedures are often inadequate to assure the extremely low defect levels and tight performance tolerances that are now required. This is a generic problem throughout the spectrum of electronic products. It has been shown that the testing strategies developed at NIST can have a substantial impact on the production costs. These cases have been made for both analog and mixed-signal products, such as data converters and multirange measurement instruments. However, the existing strategies are often inadequate for systems that rely on embedded software. New approaches are needed to accommodate software-driven systems that are adaptive, reconfigurable, or highly nonlinear. The prominence of quantization in these systems in part determines the approaches that can be used; new approaches are needed for both coarsely quantized systems, such as digital communications devices, and high resolution quantized systems, such as instrumentation systems.

Current Tasks:

1. Testing strategies

FY 1989 — Evaluated limitations of linear models, and developed a capability for modeling second order time-domain sensitivities; Published papers on "Time-Domain Testing Strategies and Fault Diagnosis for Analog Systems" and "Ambiguity Groups and Testability".

FY 1990 — Successfully applied NIST-developed testing strategies to a population of 128 commercial 13-bit analog to digital converters; Achieved 0.03 least-significant-bit (rms) uncertainty in linearity estimates at all 8192 codes using 64 measurements; Presented paper on method and results.

FY 1991	Conducted the first NIST testing strategies workshop; Two integrated circuits manufacturers began using NIST method in production testing; A testing company announced software product based on NIST work; Published tutorial paper in IEEE's *Spectrum* and paper on analog to digital converter application in a conference proceedings.
FY 1992	Developed an accurate error model for multifunction instrument and demonstrated effective test results with 80% reduction in test cost; Began analysis of theoretical performance limits of empirical models.
FY 1993	Prepared two papers on modeling and test point selection for a commercial thermal transfer standard; Conducted second testing strategies workshop.
FY 1994	Established theoretical basis for, and proof of, maximum likelihood properties of empirically derived error models; Developed expressions for statistical confidence intervals for results obtained from linear models; Began development of Testing Strategies Toolbox; Conducted third testing strategies workshop.
FY 1995	Completed work on procedures to estimate the effects of nonmodel errors and to compute prediction intervals that account for them; Demonstrated application of nonmodel error analysis to two instruments and began applying the approach to a NIST calibration service (with estimated savings to customers of $26k per test); Completed subroutines and user interface for NIST Testing Strategies Toolbox; Demonstrated prototype; Developed and demonstrated an empirical model and efficient test plan for a multifunction calibrator.
FY 1996	Completed 2/3 of NIST Testing Strategies Toolbox tutorial guide (mathematical background) and 1/2 of user's manual (in browsable hypertext), and released version 1.0; Completed analysis and issued first test report based on NIST Empirical Linear Prediction approach and presented paper on results.
FY 1997	Prepared and conducted fourth workshop and training program (for DoD sponsors); Completed Toolbox tutorial guide and user's manual, and completed and released version 2.0 of toolbox; Demonstrated NIST approach on commercial multirange ac voltage standard; Developed a plan for an adaptive modeling approach in which calibration history is used to iteratively reduce subsequent calibration costs.
FY 1998	Document NIST testing strategies methods for analog and mixed-signal devices. Present fifth workshop and training to promote use of the NIST HELP Toolbox by national calibration laboratories. Demonstrate adaptive modeling approach on typical instrument.
FY 1999	Complete development of adaptive modeling appraoch. Develop auxiliary toolbox to perform adaptive modeling.

2. Device/system analysis

FY 1992	Began feasibility study of new, hardware-efficient, on-line error detection approach for analog systems.
FY 1993	Completed study of on-line error detection scheme and documented results.
FY 1994	Assisted Office of Law Enforcement Standards in development of integrated services digital network (ISDN) telecommunications equipment.
FY 1995	Developed approach for analyzing self-calibrating systems and applied to a self-calibrating instrument; Began development of ISDN standard for state and local law enforcement agencies.
FY 1996	Continued development of the ISDN standard.

FY 1997	Continued development of the ISDN standard.
FY 1998	Complete and disseminate the ISDN standard.

3. Testing embedded systems

FY 1997	Submitted proposal and received Director's approval for a NIST 5-year Competence Project on Strategies for Testing Software-embedded Systems; Submitted proposal to ATP for Read Channel electronics.
FY 1998	Determine problems and impact of testing systems with embedded software. Select at least one test case that is representative of coarsely quantized systems and at least one test case that is representative of high resolution quantized systems. Propose approaches to the development of testing strategies for selected systems. Select analytic tools.
FY 1999	Become familiar with analytic tools useful in analyzing testability of embedded software systems. Apply analytic tools to selected test cases. Gather test data on selected test cases. Develop model of at least one selected test case. Develop improved test plan for selected test cases. Compare improved test plans with traditional test methods.
FY 2000	Publish paper on new analytic techniques. Determine generic approach to analyzing systems with embedded software. Develop software for generic analysis of the testability of embedded software systems. Participate in workshop on testing embedded software.
FY 2001	Select additional test cases. Apply software to new cases. Publish paper on new generic approach.
FY 2002	Develop additional analytic tools to analyze systems with embedded software. Refine software to make use of additional analytic tools.

MICROWAVES

High-Speed Microelectronics Metrology

Project Leaders: Roger B. Marks and Dylan F. Williams

Staff: 6.0 Professionals, 1.0 Technician, 1.0 Student

Funding level: $1.3 M

Funding sources: NIST and OMP (85%), Other Government Agencies (5%), Other (10%)

Objective: Support the electromagnetic characterization of microelectronic structures

Background: This project was formed in 1989 to address industry demands for metrology appropriate to monolithic microwave integrated circuits (MMICs), which have become increasingly prevalent in low-cost, low-power wireless communications systems. This demand led to the creation, with industry funding, of the NIST Industrial MMIC Consortium, which was extended beyond its initial five-year lifetime. The project has been expanded to include high-speed microelectronics packaging and nonlinear device characterization.

Current Tasks:

1. Develop metrology and software for on-wafer characterization

FY 1990	Developed multiline Thru-Reflect-Line (TRL) calibration method and software, now accepted as the most accurate on-wafer calibration method available.
FY 1991	Developed first procedures to accurately measure characteristic impedance and capacitance of planar transmission lines on lossless dielectric.
FY 1992	Published General Waveguide Circuit Theory, accounting for conductor loss.
FY 1993	Developed calibration method based on lumped elements.
FY 1994	Reduced size of calibration set using compact on- and off-wafer standards.
FY 1995	Released MultiCal® software for improved calibration; Developed equivalent circuit theory for coupled lines.
FY 1996	Introduced multiline TRL for low-cost network analyzers; Developed off-wafer coplanar-waveguide calibration accounting for changes in contact geometry; Demonstrated algorithm for calibration in multiconductor lines.
FY 1997	Explored membrane probe calibration; Studied an improved Open-Short-Load-Thru (OSLT) calibration; Began converting MultiCal software to standalone code with C++ links.
FY 1998	Finalize and release standalone MultiCal software; Release an improved Open-Short-Load-Thru (OSLT) calibration; Develop calibration for membrane probes and compare it to standard industry calibrations; Develop 4-port measurement capability and integrate it into multiconductor transmission line methods.

2. Standardize on-wafer measurements, develop verification tools, and introduce traceability paths

FY 1989	Formed NIST/Industrial MMIC Consortium.
FY 1990	Completed on-wafer round robin.
FY 1991	Developed calibration comparison method.
FY 1992	Applied calibration comparison method to assess error in industry measurements; Found errors as large as seventy percent.
FY 1993	Designed calibration verification procedures and completed on-site tests.
FY 1994	Demonstrated effectiveness of accuracy assessment methods in tests at Consortium sites.
FY 1995	Tested method to verify probe station according to ANSI Standard Z540.
FY 1996	Determined requirements for certifying on-wafer artifacts as SRMs; Initiated IEEE Working Group to develop Standard on Microwave Network Parameters.
FY 1997	Developed software for comparing internal vector network analyzer calibrations; Finalized Reference Material qualification procedures for on-wafer standards.
FY 1998	Introduce on-wafer standards as Standard Reference Materials; Complete error analysis required to release on-wafer standards as Standard Reference Materials; Release standalone software for comparing internal vector network analyzer calibrations; Write draft IEEE Standard on Microwave Network Parameters.
FY 1999	Release on-wafer standards as Standard Reference Materials.

3. Design and fabricate calibration artifacts and test structures

FY 1990	Designed coplanar waveguide (CPW) standards and built prototypes.
FY 1991	Fabricated CPW standards and distributed them to consortium.
FY 1992	Developed improved photoresist process.
FY 1993	Designed and fabricated on-wafer noise test structures.
FY 1995	Fabricated and tested microstrip artifacts.
FY 1996	Fabricated prototype Standard Reference Materials (SRMs).
FY 1997	Fabricated and began qualification of a limited number of SRMs.
FY 1998	Complete qualification of SRM supply.

4. Develop procedures for time domain network analysis (TDNA)

FY 1992	Identified industrial need for TDNA, particularly for packaging.
FY 1993	With industry cooperation, demonstrated feasibility of applying multiline Thru-Reflect-Line calibration for time domain network analysis.
FY 1994	Established cooperative research program with instrument manufacturer.
FY 1995	Introduced MultiCal® calibration for time domain network analyzer.
FY 1996	Developed TDNA software in BASIC; Optimized TDNA parameters.
FY 1997	Released TDNA software for standalone use or as front end to MultiCal®.
FY 1998	Develop and characterize enhanced TDNA error model; Implement multiport TDNA software interface.

5. Develop procedures for characterization electronic packaging

FY 1992	Developed new method to measure characteristic impedance of transmission lines built on lossy dielectrics such as silicon.

FY 1993	Developed method to measure impedance parameters of devices built on lossy dielectrics; Established Cooperative Research and Development Agreement (CRADA) with industrial partner.
FY 1994	Began industrial cooperation to characterize flip-chip MMICs.
FY 1995	Characterized flip-chip MMIC components.
FY 1996	Designed test structures for flip-chip MMIC packages and three-ports.
FY 1997	Collaborated with industry on characterization of interconnects on silicon.
FY 1998	Continue industry collaborations to investigate characterization of single-mode transmission lines on silicon; Use multiport network analysis to characterize multiconductor cables and coupled lines on silicon; Collaborate with industry on characterization of active digital devices.
FY 1999	Apply methods to differential lines and more complex interconnect structures.

6. Develop methods to characterize cryogenic on-wafer devices

FY 1993	Designed, fabricated, and tested cryogenic test structures.
FY 1994	Completed cryogenic experiments with Electromagnetic Technology Division (Div. 814) and University of Hawaii.
FY 1995	Cooperated with Division 814 on tunable cryogenic resonators.
FY 1996	Began effort on cryogenic interconnection characterization with Division 814 and Georgia Institute of Technology; Installed cryogenic probe station.
FY 1997	Finalized measurement methods.
FY 1998	Characterize fast superconducting interconnects fabricated commercially.

7. Material characterization

FY 1994	Developed on-wafer measurement concepts for extracting material parameters.
FY 1995	Cooperated with Division 814 to study superconducting thin films.
FY 1996	Cooperated with Electromagnetic Properties of Materials Project to apply frequency domain network analysis to material characterization, improved transmission/reflection software to account for nonideal lines, and investigated thin-film characterization methods with industry.
FY 1997	Introduced methods to characterize dielectric thin films deposited on planar transmission lines; Applied methods to commercial samples.
FY 1998	Apply thin-film characterization methods to a wider variety of industry characterization problems; Develop methods to characterize magnetic thin films; Investigate membrane probes to characterize thin films.

8. Characterization of nonlinear components for digital wireless communications

FY 1996	Successfully proposed topic for Competence Project.
FY 1997	Consulted with industry and university experts; Consulted with company unveiling a commercial nonlinear network analyzer and discussed ordering a key component of that system; Developed concept of nonlinear network analyzer based on time domain network analysis.
FY 1998	Study alternative network analyzer designs, based on time domain network analysis, with regard to their applicability to nonlinear network analysis; Purchase key components; Begin assembling system for evaluation.
FY 1999	Build prototype nonlinear network analyzer; Develop calibration software.
FY 2000	Evaluate characterization schemes.
FY 2001	Identify optimal characterization methods.

9. Exchange technology through workshops

FY 1991	Organized on-wafer measurement workshop at International Microwave Symposium (IMS).
FY 1994	Organized on-wafer measurement workshop at IMS and at Automatic RF Techniques Group Conference (ARFTG).
FY 1995	Organized measurement workshops at Electrical Performance of Electronic Packaging and Wireless Communications meetings.
FY 1996	Founded and chaired Wireless Communications Conference; Organized on-wafer measurement workshop and short course on package measurements; Organized technical agenda for short course on wireless measurements.
FY 1997	Participated in organizing 1997 International Microwave Symposium: organized workshop program, on-wafer measurement workshop, special session on multiconductor transmission lines, and Plenary Session; Organized and chaired 49th ARFTG Conference and 1997 Wireless Communications Conference.
FY 1998	Organize packaging workshop, special session on digital interconnects, and special session on broadband telecommunications for the 1998 International Microwave Symposium; Organize and chair the 1998 IEEE Radio and Wireless Conference.

Power Standards and Measurements

Project Leaders: Fred Clague and John Juroshek

Staff: 2.5 Professionals, 3.8 Technicians

Funding level: $0.9 M

Funding sources: NIST (30%), Other Government Agencies (38%), Other (32%)

Objective: Develop coaxial and waveguide transfer standards, microcalorimeters, measurement techniques, and automated instrumentation which supports and provides the calibration services for customer transfer standards.

Background: Microwave power is the high-frequency equivalent to 60 Hz power. Information can only be passed from one place to another by means of energy transfer, and is therefore a commodity as are gas and electricity. The measurement of microwave power is one of the most fundamental test requirements, necessary for the determination of output levels of signal generators, radio and television transmitters, all types of radars, and wireless communication sources. Systems and products that are overdesigned because of poor power standards are expensive and non-competitive. All commercial applications of microwave energy, including communications, navigation, surveillance, manufacturing, aerospace, medicine, defense, entertainment, and advanced computing require accurate measurement of microwave power. International marketing of U.S. microwave instrumentation and devices requires power standards that are recognized and accepted by our trading partners. The ability to accurately measure microwave power over the frequency ranges from 10 MHz to 100 GHz in coaxial transmission line, and from 18 GHz to 110 GHz in waveguide is needed to support a wide range of applications.

Current Tasks:

1. Develop coaxial power standards using a specific commercial connector (Type N) for use over the frequency range from 50 MHz to 18 GHz

FY 1987	Initiated program to rebuild the coaxial microcalorimeter and transfer standards.
FY 1988	Refurbished and tested the calorimeter; Designed new transfer standard.
FY 1989	Completed prototype transfer standard; Assembled instrumentation to automate calorimeters.
FY 1990	Completed uncertainty analysis of calorimeter; Negotiated arrangement with private company to provide the thermistor bead assembly for the transfer standard; Finished automated calorimeter software.
FY 1991	Completed total uncertainty analysis of calorimeter.
FY 1992	Began special test service providing direct calorimeter calibration of both in-house and external customer's transfer standards.

FY 1993	Solved transfer standard internal resonance problem; Published report describing standard; Published report describing calorimeter. Delivered 12 standards to sponsor and company customers.
FY 1994	Published calorimeter evaluation method in a technical journal.
FY 1995	Calibration service for standard received final NIST approval; Resolved calibration uncertainty issue.
FY 1996	Established quality control charts for service based on three NIST standards.
FY 1997	Assembled, tested and calibrated one standard; Calibrated customer and NIST standards. Updated NIST quality control charts.
FY 1998	Design new Type N coaxial calorimeter.
FY 1999	Complete and evaluate new Type N coaxial calorimeter.

2. Develop power standards for systems having 2.4 mm conductors and coaxial connectors for use over a frequency range from 1 MHz to 50 GHz

FY 1991	Initiated NIST program to develop calibration service; Found that a transfer standard is not commercially available.
FY 1992	Determined that a particular commercial power sensor is a suitable basis for new thin-film bolometric transfer standard.
FY 1994	A private company agreed to develop a prototype transfer standard.
FY 1995	Received and tested the transfer standard; Designed and began fabrication of a microcalorimeter.
FY 1996	Tested and approved prototype transfer standard with improved design; Finished microcalorimeter assembly and began uncertainty evaluation.
FY 1997	Completed uncertainty evaluation; Developed transfer technique and specified instrumentation for a calibration service.
FY 1998	Document uncertainty evaluation; Develop new Type IV power meter; Assemble and test transfer instrument.
FY 1999	Initiate calibration service; Provide standards and transfer instruments to Other Agency customers.

3. Develop new waveguide power standards for use over the frequency range from 18 to 110 GHz

FY 1987	Initiated program to restore or build new microcalorimeters starting with WR-22 (33-50 GHz).
FY 1988	Began parallel effort to develop a WR-22 cryogenic power standard.
FY 1989	Completed design of the WR-22 calorimeter.
FY 1990	Finished drawings for the WR-22 calorimeter.
FY 1991	Assembled WR-22 calorimeter; Completed design of the WR-42 (18-26 GHz) and WR-15 (50-75 GHz) calorimeters; Assembled three WR-15 transfer standards.
FY 1992	Assembled the WR-42 calorimeter; Completed design of WR-15 calorimeter; Finished construction of the WR-42, WR-22 and WR-15 transfer standards.
FY 1993	Completed assembly of WR-42 and WR-10 (75-110 GHz) calorimeters; Finished WR-10 transfer standards.
FY 1994	Assembled the WR-15 calorimeter and transfer standards.
FY 1995	Completed operational tests of the isothermal mode on the WR-22 calorimeter; Developed thermal model using finite element analysis to improve the calorimeter evaluation.

FY 1996	Completed uncertainty evaluation of WR-15 calorimeter; Began WR-10 evaluation.
FY 1997	Continued uncertainty evaluation measurements of WR-10 calorimeter; Started WR-22 evaluation measurements.
FY 1998	Complete uncertainty evaluation of WR-22 calorimeter; Contingent on source availability, complete uncertainty evaluation of WR-10 calorimeter.
FY 1999	Start uncertainty evaluation measurements of WR-42 calorimeter; Re-evaluate WR-15 calorimeter.

4. Provide calibration and measurement services for microwave power

FY 1990	Initiated a power calibration service for (0.01-33 GHz) in systems using conductors having a 3.5 mm connectors.
FY 1994	Developed a direct comparison system for power calibration services in Type N connectors, revised all uncertainty statements for power to conform to NIST policy and international guidelines.
FY 1995	Developed techniques for the Army for providing power calibration in systems using Type N connectors at frequencies above 18 GHz.
FY 1996	Added power calibration services for GPC-7 connectors to the direct comparison system; Reduced measurement time of low frequency power measurements done in six-port laboratory and low frequency impedance laboratory.
FY 1997	Conducted experiments with thermo-electric, diode, and the 2.4 mm thin-film power sensors in the process of developing calibration transfer systems.
FY 1998	Complete development of the 2.4 mm coaxial direct comparison power calibration system (to 50 GHz); Complete development of a calibration service for thermo-electric and diode power sensors; Improve power calibration services in the WR-22, WR-15 and WR-10 waveguide bands.
FY 1999	Develop a power calibration service for 2.92 mm coaxial sensors; Improve the power calibration service for 3.5 mm coaxial sensors.
Ongoing	Provide coaxial and waveguide calibration, measurement and consultation services to 110 GHz.
Ongoing	Provide calibration, measurement services and consultation in high power from 1-30 MHz at 1-1000 W and from 30-400 MHz at 1-500 W.

5. Develop high power microwave system, (10W-1000W, 10 MHz-1000 MHz) for the Air Force

FY 1995	Determined optimum technique for transfer standards calibration; Investigated availability of high power components and instrumentation.
FY 1996	Developed system architecture; Purchased most system components and instrumentation; Assembled prototype system; Began writing operational software; Began uncertainty analysis.
FY 1997	Assembled final hardware configuration; Integrated high power amplifier in system; Completed uncertainty analysis of calibration technique.
FY 1998	Complete documentation of system; Calibrate transfer standards at specified frequencies and power levels; Deliver transfer standards to sponsor; Initiate NIST high power calibration service.

6. International comparisons

FY 1998	As pilot laboratory, submit proposal to BIPM for WR-22 comparison and solicit participation from foreign national standards labs; Prepare new WR-22 transfer standards for use in comparison.
FY 1999	Measure and circulate WR-22 transfer standards; Participate in WR-10 comparison.
FY 2000	Continue to measure and circulate WR-22 transfer standards.
FY 2001	Compile and publish results of WR-22 of comparison.

Impedance, Voltage, and Dimensional Standards and Measurements

Project Leader: George Free

Staff: 1.0 Professional, 1.5 Technicians

Funding level: $0.4 M

Funding sources: NIST (46%), Other Government Agencies (28%), Other (26%)

Objective: Provide measurement services in voltage and impedance over a frequency range from 10 KHz to 1000 MHz. Enhance services through system development, improved transfer standards and new measurement techniques.

Background: Manufacturers of electrical/electronic equipment and components, research and development laboratories, DoD and industrial standards laboratories continually demand better uncertainties, broader frequency coverage, and improved standards and measurement techniques. Voltage, power and impedance are important electromagnetic quantities that support the production and performance verification of signal generators, receivers, voltmeters, spectrum analyzers, field strength meters, resistance-capacitance-inductance (RLC) meters and impedance analyzers. Traceable measurements are required to support the quality and reliability of these instruments. These instruments are used in the production and testing of civilian and military aircraft, radar, space exploration, nuclear research, and other applications. Improvements in new electronic products require better support and NIST is responding through enhanced measurement technology.

Current Tasks:

1. Provide calibration and measurement services and consultation in impedance measurements from 10 KHz to 300 MHz

FY 1991	Implemented low frequency calibration services (< 200 MHz) using a commercial impedance bridge.
FY 1995	Calibrated and documented high frequency Twin-Tee bridge for the coaxial termination calibration service.
FY 1996	Completed international comparison in Quality Factor of inductance standards, sent final draft to BIPM, document not to be published as decided at CPEM; introduced state-of-the-art instrumentation, did initial test on equipment from 100 kHz to 30 MHz.
FY 1997	Completed documentation on enhancement of capacitance measurement service, determined uncertainty, announced expanded frequency range in the calibration of two-terminal capacitance standards; Designed and tested prototype low frequency (10 Hz-10 kHz) four-terminal bridge for measuring dielectric properties of liquids.
FY 1998	Test three-terminal capacitance standards using enhanced measurement system from 100 kHz to 30 MHz.
FY 1999	Document three-terminal capacitance measurements and announce expanded frequency range from 100 kHz to 30 MHz.

FY 1999	Develop adaptors and standards to calibrate RLC meters in the frequency range 10 kHz to 1 GHz.
FY 2000	Develop computer programs and do tests necessary to automate one and two port inductance and resistance standards.
FY 2001	Document the automated resistance and inductance measurements.

2. Determine resistivity of NIST airline standards.

FY 1995	Designed and constructed measurement system to measure resistivity of airline components; Completed initial testing.
FY 1996	Completed test on NIST 14 mm airline standards.
FY 1997	Improved dc resistivity measurement system and tested various methods to measure resistivity up to 200 MHZ.
FY 1998	Complete dc measurements of resistivity on NIST airlines.

3. Provide calibration and measurement services and consultation in voltage at frequencies from 10 KHz to 1000 MHz, and voltages from 1 μV to 600 V.

FY 1996	Completed rf voltage comparison measurements with Spanish standards laboratory (INTA); Revised calibration reports according to new NIST policy on TVCs, Micropots, Peak-to-Peak Detectors, Thermistor Mounts, Milliwatt Power Meters; Transferred rf voltage calibration data electronically for calibration reports; Completed recalibration of NIST voltage working standards against NIST-Gaithersburg calibrated standards from 0.5 V to 3 V from 30 kHz to 100 MHz to improve uncertainties; Completed round-robin calibration of 4 TVC transfer standards (0.5V-3.0)V at (1,10,30,50,70,100) MHZ.
FY 1997	Completed report on round-robin measurements; Completed International comparison GTRF-92-6 measurements and wrote report; Initial modifications to micropotentiometer measurement system completed and tested; Computer programs written for data acquisition and measurement prompts.
FY 1998	Complete modifications to micropotentiometer system; Write data analysis programs for calibration of system and customers standards; Calibrate NIST standards from 10 kHz to 1 GHz; Complete documentation of the new system; Complete modification of low-frequency, i.e., to 100 MHz, TVC system; Re-calibrate NIST low-frequency TVC standards; Reevaluate measurement uncertainties; Document system and measurement service.
FY 1999	Design and construct system to automate the calibration of High-Frequency TVCs (100 MHz-1 GHz); Do initial testing of the system.
FY 2000	Complete testing of automated High-Frequency TVC system and re-calibrate NIST standards.
FY 2001	Complete documentation on High-Frequency TVC calibration system.
FY 2002	Document peak-to-peak detector calibration service.

4. Provide consultation and dimensional measurement of coaxial airlines, waveguide sections and materials.

FY 1996	Up-graded coordinate measuring machine and expanded versatility, compiled user's manual on operation; Measured: 2.4 mm, 2.92 mm, 3.5 mm, 7 mm, 14 mm airlines, WR-10 & WR-15 devices, ferrite samples; Assisted Division 813 personnel in construction of calorimeter, radiometer, waveguide

	standards, other miscellaneous fixtures and adapters; Assisted Division 815 personnel in thickness measurements; Assisted personnel in Time and Frequency Division with atomic clock setups.
FY 1997	Provided dimensional measurements of airlines and verification of characteristic impedance from dimensional measurements.
FY 1998	Complete documentation for the dimensional measurement of airlines; Develop plans and investigate equipment available to measure coaxial airlines smaller than 2.4 mm.
FY 1999	Purchase new equipment or augment present measurement systems to measure coaxial airlines down to 1 mm; Do initial testing of the systems.
FY 2000	Document system for measuring small airlines.

Network Analysis and Measurement

Project Leader: John Juroshek

Staff: 2.5 Professionals, 2.3 Technicians

Funding level: $0.6 M

Funding sources: NIST (45%), Other Government Agencies (31%), Other (24%)

Objective: To provide traceability for microwave measurements in scattering parameters, impedance, and attenuation. Support the microwave industry by developing standards and new measurement techniques. To develop methods for assessing and verifying the accuracy of automatic network analyzers.

Background: Vector network analyzers are the single most important instrument in the microwave industry. These instruments are commonly found on production lines, in calibration laboratories, and in research laboratories. Vector network analyzers are typically calibrated daily and the accuracy of their measurements can vary significantly after a calibration depending on the operator skills, the quality of the calibration standards, and the condition of the test ports. The microwave industry needs cost effective techniques to monitor and control the accuracy of their microwave measurements. It also needs help in developing the techniques, procedures, and documents to ensure conformity with international standards. NIST directly supports the microwave industry by providing measurement traceability through calibration services in scattering parameters and power. NIST also provides consultation to industry on measurement techniques and accuracy issues.

Current Tasks:

1. Provide and upgrade coaxial and waveguide calibration services for scattering parameters to 110 GHz

FY 1993	Initiated a calibration service for scattering parameters when using 2.92 mm diameter conductors (0.1-40 GHz) with coaxial connectors; Initiated WR-90 (8-12 GHz) and WR-62 (12-18 GHz) waveguide calibration services on the dual six-ports.
FY 1994	Initiated a calibration service for scattering parameters in systems using 2.4 mm diameter conductors (0.1-50 GHz) and coaxial connectors.
FY 1995	Began offering a reduced cost calibration service for systems using 2.92 mm and 2.4 mm diameter conductors on the commercial network analyzer.
FY 1996	Purchased components for traveling verification kits; Assembled kits; Conducted initial measurements on kits; Added calibration services for time delay to existing scattering parameter services.
FY 1997	Completed analysis software and report generating software for NIST S-parameter MAP, kits are now available for 3.5 mm, 2.92 mm, and 2.4 mm coaxial connectors; Conducted experiments on thermo-electric and diode

	power meters necessary to establish a calibration service; Investigated systems for transfering 2.4 mm power calibrations to industry; Began construction of a direct comparison system for 2.4 mm power calibrations; Developed a new method for measuring effective source mismatch of 3-port couplers and power dividers; Published results in Microwave Journal.
FY 1998	Expand and improve the calibration service for NIST traveling verification kits; add a Type N traveling verification kit; Begin offering a calibration service to industry using the traveling verification kits.
FY 1999	Offer a calibration service for effective source mismatch for 3-port couplers and power dividers.
FY 1999	Add calibration services for systems in currently unsupported connector types (i.e., 75 Ω, SMA, SMP, 1.85 mm).

2. Develop quality assurance procedures for network analyzers

FY 1993	Evaluated stability of a solid state impedance generator for use as a transfer standard in conjunction with a cooperative research and development agreement with the manufacturer.
FY 1994	Revised all uncertainty statements for scattering parameters to conform to NIST policy and international guidelines; Completed a cooperative agreement with a manufacturer of network analyzers to develop verification techniques.
FY 1995	Prepared a report on verification techniques for commercial network analyzers; Completed an Army sponsored project to investigate and recommend verification procedures for vector network analyzers.
FY 1996	Developed a software package that verifies and analyzes the performance of a commercial network analyzer by analyzing the difference in calibration constants; Began circulating software to industry.
FY 1997	Submitted a journal article on the statistical analysis of network analyzer data for publication in CAL LAB; As pilot laboratory, developed robust statistical procedures for analyzing measurement data from the Automatic Radio Frequency Techniques Group (ARFTG) measurement comparison program.
FY 1998	Expand and improve calibration service for NIST traveling verification kits.

3. Develop dual six-port network analyzers

FY 1990	Developed waveguide six-ports for WR-42 (16-26 GHz), WR-28 (24-35 GHz), WR-15 (50-75 GHz), and WR-10 (75-110 GHz).
FY 1991	Developed line-reflect-line (LRL) software for calibrating the dual six-ports.
FY 1992	Developed 18-40 GHz coaxial six-ports using diode detector technology; Developed software and techniques for correcting the diodes for deviation from square law; Developed WR-42 (18-26 GHz) and WR-28 (24-35 GHz) dual six-ports for the Navy Primary Standards Laboratory.
FY 1994	Designed and built new test ports and standards for WR-22 (30-50 GHz) waveguide calibration services; Completed construction of 100 kHz to 1.0 GHz for the Air Force and procured and/or manufactured system components and devices to supplement calibration kits; Initiated documentation.
FY 1995	Developed line-reflect-match (LRM) calibration technique for the dual six-port which uses one port terminations instead of air lines; Completed equipment up-grade, testing and documentation of a dual six-port which operates over the frequency range from 0.25 GHz to 18 GHz; Delivered dual six-port system operating over the frequency range between 0.1 MHz and

	1000 MHz to the Air Force and provided on-site training to Air Force personnel.
FY 1996	Modified current six-port software so that it runs on PC-compatible computers; Increased speed of six-ports with new software; Delivered dual six-port system operating over the frequency range between 0.25 GHz and 18 GHz to Army and provided on-site training to Army personnel; Ordered calibration and verification kits for devices with 3.5 mm, 2.92 mm, WR-42 and WR-28 connectors.
FY 1997	Completed construction of the 18-40 GHz dual six-port; currently in the process of evaluating, documenting and delivering the system to the Air Force.
FY 1998	Complete construction of the 2-18 GHz dual six-port for the Navy; Evaluate, document, and deliver the system to the Navy.
FY 1999	Upgrade and modify mm wave six-ports for increased performance; Reduce costs of mm wave calibration services.

4. Develop, analyze, and improve NIST impedance standards

FY 1991	Developed techniques for modeling the dimensional variability in coaxial and waveguide airline standards.
FY 1991	Developed WR-90 waveguide standards; Developed new Type N, GPC-7 impedance standards.
FY 1996	Ordered and received improved air line impedance standards for 2.4 mm coaxial transmission lines; Developed computer program for analyzing surface roughness in airline standards; Began documentation of NIST coaxial impedance standards.
FY 1997	Upgraded 2.92 mm coaxial impedance standards; Began documentation of the uncertainty of NIST coaxial impedance standards.
FY 1998	Complete documentation of the uncertainty of the NIST coaxial impedance standards; Begin documenting the uncertainty of the NIST waveguide impedance standards.
FY 1999	Develop impedance standards for new calibration services (i.e., 75 Ω, SMA, SMP, 1.85 mm).

5. Develop automated data analysis techniques

FY 1990	Installed hardware for a local area network for calibration related activities.
FY 1992	Completed software development for on-line data management with the local area network.
FY 1993	Check standard data base ready for online access by calibration staff.
FY 1996	Upgraded and automated quality control procedures; Transferred and converted all calibration, measurement, and quality control software to run under Microsoft® Windows® on PC-compatible platforms.
FY 1997	Began testing NIST developed ORACLE data base for microwave calibration activities.
FY 1998	Develop techniques and software for analyzing Type A uncertainties of scattering parameter measurements; Reevaluate Type A uncertainties for scattering parameter measurements; Document Type A uncertainties for scattering parameter measurements.
FY 1999	Upgrade software for analyzing check standard and customer data.

Noise Standards and Measurements

Project Leader: James Randa

Staff: 2.0 Professionals, 3.0 Technicians

Funding level: $0.8 M

Funding sources: NIST (60%), Other Government Agencies (20%), Other (20%)

Objective: 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.

Background: 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 not just communications systems, such as cellular phones or home entertainment systems, but also systems with internal signal detection and processing, such as guidance and tracking systems or electronic test equipment. The global market for microwave and mm-wave devices in these areas is already huge and is undergoing explosive growth. Important current trends which must be addressed include the utilization of higher frequencies, the growing importance of low-noise amplifiers, the demand for and lack of repeatable and traceable on-wafer noise measurement techniques, and the perpetual quest for faster, less expensive measurements. The two most important noise-related technical parameters for industry are the noise temperature of a one-port source and the noise figure of an amplifier.

This project focuses on three areas. In traditional (connectorized) noise temperature measurements and calibrations, the aim is to cover the frequency range 1 GHz to 75 GHz, including 1 GHz to 25 GHz in systems using coaxial connectors. Concurrently, staff is also attempting to reduce the time required for such calibrations, thereby reducing the costs. The second general thrust of the project is in amplifier noise figure measurements, where the goal is to develop cost-effective measurement services for amplifiers with coaxial connectors over the frequency range 1 GHz to 18 GHz. The third major effort is in developing on-wafer noise measurement methods, first for noise temperature and subsequently for amplifier noise figure. Central to all three of these efforts is the new noise-figure radiometer system which is currently under development. It has been designed to measure either one-port noise temperature or amplifier noise figure, and it has the potential to be an order of magnitude faster than our existing radiometers.

Current Tasks:

1. Provide, upgrade and expand waveguide and coaxial noise temperature calibration services and capabilities

   FY 1992 Extended upper frequency limit of WR-42 (18-26.5 GHz) to 26 GHz (previously was 22 GHz).

FY 1993	Began new noise temperature special test services in WR-15 (50-75 GHz), WR-62 (12.4-18 GHz), and systems using 3.5-mm coaxial conductor (12-26 GHz).
FY 1994	Organized and presented a one day noise measurements seminar at the IEEE International Microwave Symposium in San Diego; revised measurement uncertainties per NIST guidelines.
FY 1995	Completed construction of WR-28 (26.5-40 GHz) noise-temperature calibration system; Began testing; Developed and documented improved technique for assessing adapter effects in noise temperature measurements.
FY 1996	Completed testing of WR-28 system; Revised and documented uncertainty analysis for waveguide noise-temperature calibrations; Developed plans for documentation of each Noise Project measurement service.
FY 1997	Documented and offered WR-28 measurement service; Fabricated improved coaxial primary standard; Revised, automated, and documented uncertainty analysis for noise temperature calibrations in coaxial systems; Compiled histories for check standards.
FY 1998	Develop and offer 2.4-mm coaxial measurement service; Test improved coaxial primary standard; Begin development of WR-22 (33 to 50 GHz) measurement service.
FY 1999	Complete development of and offer WR-22 measurement service; Develop new WR-15 measurement service; Compare different NIST primary noise standards; Develop and offer off-site noise-temperature comparison service.
Ongoing	Provide noise temperature calibration, measurement and consultation services.

2. Serve as pilot laboratory for international noise temperature measurement comparison

FY 1992	Noise comparison proposed by NIST and approved (GTRF 92-2) with NIST as pilot lab.
FY 1993	International noise community canvassed for possible participants; preliminary plans made.
FY 1995	Noise sources were purchased for circulation among participants.
FY 1996	Developed protocol and schedule; Performed first round of NIST measurements; Measurements also completed at LCIE and NPL.
FY 1997	Completed measurements at other laboratories (PTB); Performed second round of measurements at NIST; Collected and analyzed results.
FY 1998	Write report and present results.

3. Develop noise-figure measurement capability

FY 1992	Completed development of noise-figure measurement theory and established possible experimental measurement procedure; Performed measurements to test the viability of this procedure.
FY 1993	Completed basic design of amplifier noise radiometer.
FY 1994	Completed and tested prototype of amplifier noise radiometer. Found to be stable to within 0.002 dB/day, 150 times better than present NIST systems. This promises to significantly reduce the need for repetition of measurements, thereby reducing the time for calibrations.
FY 1995	Refined noise-figure measurement techniques for low-noise amplifiers with adapters; Performed preliminary measurements on two low-noise amplifiers with adapters.
FY 1996	Completed measurements of two low-noise amplifiers with adapters.

FY 1997	Completed hardware and noise-temperature software for total-power radiometer for 8-12 GHz, to replace the existing system for noise temperature measurements and for use in the noise-figure measurement system.
FY 1998	Characterize and test new radiometer for 8-12 GHz; Analyze uncertainties for noise-temperature measurements with new system; Formalize noise-figure measurement techniques and write associated software.
FY 1999	Construct and test new radiometer for 1-2 GHz; Offer a measurement or comparison service for amplifier noise figure for 8-12 GHz and 1-2 GHz; Construct and test new radiometer for 2-4 GHz.

4. Develop methods for on-wafer measurement of noise

FY 1992	Conducted preliminary experiment to measure the noise figure of a MMIC amplifier on wafer (in collaboration with MMIC project).
FY 1994	Measured one-port noise of a diode on-wafer at a frequency of 8 GHz using the prototype Noise-Figure Radiometer.
FY 1995	Designed, performed, and analyzed experiments to measure known and unknown noise temperatures on wafer at frequencies between 7.8 GHz to 8.2 GHz.
FY 1996	Refined, extended, and repeated experiment demonstrating capability of measuring noise temperature on wafer.
FY 1997	Documented on-wafer noise-temperature measurement methods and theory; Designed on-wafer noise-temperature transfer standard.
FY 1998	Fabricate and test on-wafer noise-temperature transfer standard(s); Begin round-robin comparison of noise temperature measurements with industrial labs.
FY 1999	Develop on-wafer noise-figure measurement capability.

Antenna Measurement Theory and Application

Project Leader: Carl F. Stubenrauch

Staff: 5.0 Professionals, 2.0 Technicians

Funding level: $1.1 M

Funding sources: NIST (60%), Other Government Agencies (12%), Other (28%)

Objective: The near-field antenna characterization methods invented and developed by NIST, offer improved accuracy and reduced costs that are unmatched by other methods. However, new extensions of this technique are needed for advanced antenna designs. In response, NIST will develop near-field theory, standards, and methodology to support characterization of gain, pattern, and polarization of advanced multi-element antennas at frequencies up to 500 GHz. Specifically, NIST will extend cylindrical and spherical scanning capabilities to the frequency range, 26.6 to 100 GHz and planar methods for the frequency range, 40 to 500 GHz. Goals include (1) achieving uncertainties less than ±0.2 decibels in the gain, (2) implementing probe-position error correction for mm wave measurements, (3) determining field uniformity using spherical near-field techniques for antenna measurement range characterization, and (4) developing and testing adaptive phased array diagnostic methods.

Background: Manufacturers of antennas and microwave systems incorporating antennas need practical, rapid and efficient methods for characterizing antenna performance. Operation at higher frequencies, the use of advanced phased arrays for steering beams, the use of conformal structures in aircraft, and the use of active arrays challenge existing methods. These systems also support national goals for information highways and personal communications, and new radars for air traffic control to make more efficient use of airspace without jeopardizing safety. Advanced civilian systems include new generations of communications systems at higher frequencies and with greater spatial discrimination to alleviate overcrowding of current and synchronous-orbit satellites. The personal communications market is estimated to be billions of dollars by the year 2000.

Current Tasks:

1. Develop planar near-field metrology for measuring microwave antennas operating at frequencies up to 500 GHz

   FY 1995 — Completed first phase of the certification process for the new NIST 2.5 M by 2.5 M planar scanner; Documented certification plan for this range and distributed it to industry for use for their ranges; Incorporated fifth-order Taylor-series method for z probe-position error-correction into the planar near-field library.

FY 1996	Implemented two fully 3-dimensional iterative methods, the steepest descent method and the conjugate gradient method, to improve computational efficiency and convergence for probe-position error-correction.
FY 1997	Completed the certification process for the new 2.5 M by 2.5 M planar scanner and receiver; Conducted simulations on the effects of probe-position errors.
FY 1998	Evaluate on-site planar near-field methods for determining phased-array aperture distributions. Many antennas require periodic performance verification. Near-field techniques may be the only viable techniques to test next generation high performance antennas; Develop planar near-field review process; Investigate conditioning for near-field extrapolation algorithm; Publish results.
FY 1999	Develop methods for mm-wave measurements at frequencies from 75 to 110 GHz.
FY 2000	Develop new methods for measurements at frequencies from 110 to 325 GHz.

2. Develop new metrology methods for rapid microwave antenna measurements and diagnostics

FY 1995	Evaluated the mirror/self-calibration method for determining antenna gain using three probes. Developed thermal imaging theory for rapid measurements used for determining antenna performance; Simulated measurements for thermal imaging method.
FY 1996	Completed analysis of mirror/self-calibration data and documented results; Conducted measurements on thermal imaging method in cooperation with the University of Colorado, Colorado Springs. Completed measurements on holographic (phaseless) antenna measurements for applications at mm and sub-mm frequencies.
FY 1997	Analyzed data obtained at Rome Laboratory to determine limitations and improvements to experimental techniques for near-field determination using thermal imaging; Published results.
FY 1998	Evaluate and report on thermal imaging technique for rapid measurement or other applications; Compare to planar near-field results.
FY 1999	Collaborate with Fields and Interference Group to construct a one-dimensional photonic probe array for rapid scanning; Evaluate array in planar near-field/cylindrical near-field measurement systems.

3. Develop non-planar near-field measurements for antenna and probe measurements

FY 1995	Completed evaluation of the new spherical/extrapolation range. This range is capable of fast and accurate measurements of antennas up to 3.5 M in diameter in the frequency range from 1 to 75 GHz.
FY 1996	Published the calibration results on the standard gain horns for the International Gain Comparison measurements; Aligned vertical probe transport on multipurpose range for cylindrical near-field measurements; Provided technical support and near-field probe measurements to JPL for cylindrical near-field measurements on satellite antenna.
FY 1997	Completed development of cylindrical capability and calibrated probes for intercomparison measurements to be made on suitable antennas using all available NIST ranges (two planar, cylindrical, and spherical); Documented rail alignment results for cylindrical scanning.

FY 1998 Experimentally determine field uniformity (quiet zone) of an antenna measurement range using spherical near-field technique (range to be determined); Document results for certification of 2.5 by 2.5 m planar near-field scanner; Complete measurements on intercomparison begun last year.

FY 1999 Develop three-dimensional probe-position correction for spherical and cylindrical near-field scanning; Develop upper bound error expressions; Develop technique to improve extrapolation range error analysis based on measurement condition number.

FY 2000 Refine the spherical near-field scanning technique for outdoor in-situ testing of antennas; Develop methods for range evaluations using spherical measurements.

4. Develop metrology for complex antennas for emerging technologies

FY 1994 Completed spectral merge analysis to determine antenna-array excitation using planar near-field measurements from several beam positions.

FY 1995 Completed software and analysis for spectral merge project; Completed analysis of a 60 GHz phased-array antenna using measurements taken on the new 2.5 M by 2.5 M planar scanner.

FY 1996 Documented the results of the spectral merge method for the alignment of phased arrays; Designed and constructed a 32 by 32 X-band (8.2 to 12.4 GHz) computer-controlled phased array to validate new antenna metrology and diagnostic methods.

FY 1997 Completed report documenting array evaluation using merged spectrum; Evaluated mutual coupling methods for rapid testing of phased arrays.

FY 1998 Obtain antenna suitable for experimental work on array characterization and alignment; Implement and evaluate iterative array alignment techniques, if a suitable array is obtained.

FY 1999 Develop merged spectrum method for non-rectangular phased array lattices.

5. Provide technology transfer through courses

FY 1995 Participated as major lecturers in short course, "Microwave Antenna Measurements" at California State University, Northridge.

FY 1996 Updated and presented NIST biannual short course, "Antenna Parameter Measurement by Near-Field Techniques," in Boulder; Presented NIST short course at Antenna Measurement Techniques Association Symposium; Updated short course with the Georgia Institute of Technology on "Near-Field Antenna Measurements and Microwave Holography."

FY 1997 Update lectures for short course in collaboration with California State University, Northridge and Georgia Institute of Technology.

FY 1998 Present NIST short course in Boulder; Present short course with Georgia Tech.

FY 1999 Present short course with Georgia Tech; Participate in major lectures at Cal. State Northridge short course.

Metrology for Antenna, Radar Cross Section and Space Systems

Project Leader: Michael H. Francis

Staff: 2.0 Professionals, 1.0 Technician

Funding level: $0.5 M

Funding sources: NIST (22%), Other Government Agencies (75%), Other (3%)

Objective: NIST will develop the standards, measurement techniques, and instrumentation required for measuring critical performance parameters of earth terminals and satellites, and for the absolute calibration of the Air Force Satellite Control Network (AFSCN) metrology earth terminals. Critical parameters include noise temperature (T), antenna gain (G), earth terminal figure of merit (G/T), and satellite effective isotropic radiated power (EIRP). In addition, NIST will provide technical support to the Government Range Radar Cross Section (RCS) Measurement Working Group to improve the quality and reliability of range measurements. This will be accomplished by evaluating the measurement processes determining uncertainties, evaluating the design and analysis of required artifact standards, and providing the consultation and support necessary to establish a range certification process.

Background: Satellite communication is a finely tuned technology requiring accurate measurements of antenna gain, noise temperature, G/T (system gain divided by system temperature), and EIRP (effective isotropic radiated power) to assure optimum performance. Ground metrology stations needed to monitor performance of commercial and government satellites require traceability to the NIST standards. Some stations measure performance to determine incentive-clause payments to satellite contractors or charges billed to users or lessees. Industry and government own and operate a number of antenna- and radar cross section-test ranges of various types such as outdoor static, indoor (compact ranges), and other specialized ranges. Results obtained on one range do not always correlate with measurements taken on another range, even if this range is of the same type. In addition, some of these ranges are used for contractual verification of vendor performance. It is necessary that the results produced at these test ranges be of the highest accuracy possible and be repeatable from one facility to another to support communications system measurements such as multiple low-earth-orbit satellite systems for worldwide coverage and radar cross section measurements for new automobile radar systems.

Current Tasks:

1. Develop metrology for wireless communications systems

FY 1994	Organized the Range Accreditation Workshop during the 1994 Antenna Measurement Techniques Association Symposium. The European Space Agency, the National Association of Testing Authorities in Australia and the National Voluntary Laboratory Accreditation Program (NIST) participated.
FY 1995	Analyzed performance of a Phased Array Sub-system (PASS) for the Air Force. This array serves as a transfer standard for their near-field range used to measure communications antennas; Completed special tests on four dual-port circular-polarized probes that will be used as standards for the Globalstar and Tempo domestic satellite programs.
FY 1996	Provided technical support and probe measurements for wireless base station antennas.
FY 1997	Began to develop data acquisition software using up-to-date personal computers for the planar and cylindrical ranges in the antenna laboratory; Completed facilities upgrade by managing installation of fire-proof absorbers and sprinkler systems for four near-field antenna ranges.
FY 1998	Complete data acquisition software development; Conduct analysis of antenna performance on a broadbeam communication wireless antenna to be supplied by industry or other agency.
FY 1999	Define anticollision radar system requirements; Evaluate existing metrology for system parameter measurements.
FY 2000	Develop new metrology and artifact standards for anticollision radar systems.

2. Develop microwave metrology applicable to Earth Stations

FY 1995	Collaborated with a U. S. company on developing near-field techniques to measure G/T, EIRP and saturating flux density for satellite and radar antennas in a controlled indoor-testing environment.
FY 1996	Analyzed G/T measurement techniques to determine if subarrays of a phased array are working properly.
FY 1997	Determined the G/T of an outdoor antenna under different operating conditions to predict system performance during a typical year; Collaborated with industry in development of software for predicting system performance.
FY 1998	Collaborate with Jet Propulsion Laboratory (JPL) in flux density measurements of extraterrestrial radio noise sources and gain calibrations of the 70 M diameter Goldstone antenna and other antennas at Owens Valley Radio Observatory; Evaluate and test software on system performance being developed under Phase II of a Small Business Innovation Research (SBIR).
FY 1999	Determine G/T of an antenna both indoors and outdoors and evaluate ability to predict outdoor performance from indoor measurements.
FY 2000	Certify standard radio sources (radio stars, satellite signals); Develop holographic methods for large antenna system diagnostics.

3. Develop metrology for radar cross section measurements

FY 1995 Completed the development and documentation of the uncertainty analysis for radar cross section measurements. The documentation has been published as a NIST report, NISTIR 5019. Completed review of the Eglin Air Force Base Radar Cross Section ranges and submitted an uncertainty analysis report to Eglin personnel; Completed the development and documentation for the polarimetric calibration of reciprocal-antenna radars (NISTIR 5033); Completed a report to sponsor entitled "A review of government radar cross section ranges." The report describes the activities, findings, and recommendations for future research by NIST. The report is a result of three years of research activities by NIST scientists, who reviewed eight government RCS ranges during that time.

FY 1996 Initiated work on the polarimetric calibration of non-reciprocal radar systems; Started work on RCS Range Characterization and completed the major part of two range-specific uncertainty analysis reports for other agencies; Conducted research on technical questions in the area of imaging, specifically image quality and interpretation.

FY 1997 Organized and held an RCS Range Certification meeting at NIST in March 1997 for government and industrial RCS professionals; Developed criteria for range characterization and certification using ISO documents; Collaborated with Wright Patterson Air Force Base to launch a Certification Demonstration Project; Continued work on polarimetric calibrations and image quality and interpretation; Studied and recommended RCS standard artifacts and began measurement intercomparisons at different RCS facilities; Developed a standard for RCS measurements in collaboration with a voluntary RCS standards committee.

FY 1998 Organize and hold an RCS Certification meeting in March, 1998 for government and industry to adopt documentation standards, evaluate results of the first industry-wide RCS measurements intercomparison study, and evaluate progress on the DoD demonstration project; Publish a Handbook for the Assurance for Radar Cross Section Measurements to be used as an industry standard; Plan and implement details of the DoD demonstration program; Develop technical criteria for certification of RCS measurement ranges; Continue basic research in polarimetric RCS calibration, and assist interested RCS ranges in developing this capability; Continue basic research for improvement of RCS uncertainty analysis, range evaluation and range characterization; Develop and refine RCS interlaboratory comparison technology.

FY 1999 Plan for an RCS Certification meeting in March, 1999 to report on progress of the DoD demonstration project and to resolve remaining certification issues; Develop procedures for the certification review by the RCS Certification Board; Develop range specific uncertainty procedures for the DoD demonstration ranges; Review and revise RCS standard Handbook as needed; Review and improve bistatic calibration techniques; Develop improved standards artifacts for intercomparisons over a wide range of RCS measurement parameters (signal levels, wideband measurements, etc.); Collaborate with DoD demonstration ranges to ensure that they will meet certification criteria.

LIGHTWAVES

Dielectric Materials and Devices

Project Leader: Norman A. Sanford

Staff: 4.3 Professionals, 1.0 Postdoc, 2.0 Students

Funding level: $1.1 M

Funding sources: NIST (96%), Other (4%)

Objective: Develop advanced measurements and critical evaluation criteria for dielectric materials used in optoelectronics systems, instrumentation, and sensors; interact with industry for the test and evaluation of advanced laser glasses and nonlinear optical materials; fabricate prototype devices from these materials.

Background: NIST's work in the characterization of dielectric materials, with emphasis on supporting new industrial developments in the field of integrated and guided-wave optics, began in 1988. The work has focused on rare-earth-doped laser glasses and ferroelectric ceramics such as lithium niobate and lithium tantalate. These materials are important since they are the backbone of new commercial directions of integrated optical technology. For example, compact solid-state glass waveguide lasers are viewed as key components for remote sensing and ranging technologies, applications requiring stable mode-locked operation for use in analog-to-digital conversion, and ultrafast sources for high-speed optical telecommunications. NIST works with industrial collaborators, supporting both device development and materials development and assessment, to help further this technology. NIST also works on the characterization of lithium niobate and lithium tantalate. These materials are used extensively in optical communication systems for modulators, switches, and acoustically-tunable optical filters. Components fabricated from these materials also find widespread use in optical guidance and control systems. Furthermore, lithium niobate waveguide devices are key elements used in compact blue/green lasers, which are in demand for data storage and reproduction graphic technologies. Project researchers fabricate devices for NIST metrology instrumentation for applications such as time and frequency standards, high speed detector measurements, and wavelength standards.

Current Tasks:

1. Rare-earth-doped solid state laser and amplifier metrology

FY 1990	First reported neodymium-doped waveguide laser for continuous operation fabricated by ion-exchange in glass.
FY 1991	Mode-locking, Q-switching and tuning reported in waveguide lasers; First reported Y-branch waveguide laser and amplifier.
FY 1992	Dispersion of optical fiber amplifiers and rare-earth-doped waveguide amplifiers measured by low-coherence interferometry; First reported linewidth-narrowed, coupled-cavity waveguide laser fabricated; First reported neodymium-diffused lithium tantalate waveguide laser fabricated.

FY 1993	High efficiency, phosphate glass waveguide laser demonstrated and characterized.
FY 1994	Waveguide grating fabrication procedures established; Waveguide lasers with distributed Bragg reflectors developed and characterized; Passively Q-switched waveguide lasers demonstrated and analyzed.
FY 1995	Phosphate glass waveguide fabrication space investigated; Numerical modeling study of continuous and pulsed erbium-doped waveguide lasers initiated.
FY 1996	Characterized near-field intensity profiles, effective indices and diffusion profiles of rare-earth-doped waveguides; Modeled continuous and Q-switched operation of waveguide lasers; Demonstrated first reported erbium-diffused and neodymium-diffused lithium niobate waveguide lasers (with titanium-diffused guides) that were stable under optical pumping at 980 nm and 800 nm, respectively.
FY 1997	Studied optimization of erbium/ytterbium co-doped silicate and phosphate laser glasses and waveguide laser fabrication in these glasses; Completed numerical analysis package for modeling amplification, cw laser operation, and Q-switched laser operation of rare-earth doped waveguide lasers; Demonstrated first reported erbium/ytterbium co-diffused lithium niobate waveguide lasers operating near 1550 nm or 1030 nm; Constructed prototype Q-switched lasers in erbium-diffused lithium niobate waveguides; Fabricated prototype distributed-Bragg reflector gratings in erbium/ytterbium co-doped silicate waveguide lasers; Began work on hybrid semiconductor saturable absorbers for mode-locking and Q-switching of waveguide lasers.
FY 1998	Demonstrate mode-locking and Q-switching of waveguide lasers operating near 1550 nm using semiconductor saturable absorbers attached to waveguide end facets; Measure absorption cross sections, emission cross sections, upconversion coefficients, and energy transfer efficiency in erbium/ytterbium phosphate and silicate laser glasses; Demonstrate distributed-Bragg reflector waveguide lasers operating near 1550 nm in erbium/ytterbium co-doped phosphate and silicate laser glasses; Explore feasibility of optically writing waveguide features in rare-earth-doped photosensitive glass.
FY 1999	Establish utility of hybrid mode-locked and Q-switched waveguide lasers for applications in areas such as high-speed optical telecommunications and eye-safe range-finding systems; Explore more advanced processing methods such as direct grafting of semiconductor saturable absorbers to waveguide surfaces; Establish designs for optimization of the combined systems of saturable-absorbers and waveguide lasers; Establish advanced metrology methods for evaluating jitter of mode-locked waveguide lasers; Establish utility of integrated multiple-wavelength distributed-Bragg reflector waveguide lasers as sources for optical telecommunication systems.

2. Metrology of nonlinear optical materials

FY 1989	Characterized photorefractive instabilities from two-wave coupling in lithium niobate waveguides formed by proton exchange.
FY 1994	Maker-fringe system constructed to map wafer uniformity for waveguide devices; Theoretical model of reflected and transmitted Maker-fringe signatures established for various sample orientations and pump and signal polarizations; Studies of domain-inverted segments in lithium niobate waveguides initiated.

FY 1995 Nonuniformities in index (and hence composition) mapped over 50-mm and 76-diameter lithium niobate wafers by Maker fringe analysis; Thickness uniformity of lithium niobate wafers also mapped; Initial correlations with X-ray topographs performed; Maker-fringe analysis used to help characterize thin lithium niobate films produced by industrial collaborators; Cross-section and shape of domain-reversed segments in lithium niobate waveguides studied

FY 1996 Mapped 100-mm diameter lithium niobate wafers by Maker fringe analysis and corroborated lithium diffusion gradient; Studied apparent stress artifacts in wafers and correlated effect with device yield data from collaborator; Obtained initial results using two non-axial pumping beams for Maker fringe analysis; Constructed apparatus for the high-voltage poling of domain-engineered lithium niobate and lithium tantalate.

FY 1997 Used Maker fringe analysis and high-resolution X-ray diffraction imaging to study electric-field-poled domain-engineering segments in z-cut lithium niobate; X-ray work confirmed presence of native domain-reversed layer on +z face of material; Established asymmetric coercive poling field in lithium niobate; Used Maker fringe analysis to measure static charge on lithium niobate plates, extract excess photoelastic strain impressed by electric-field poling, and infer secondary photoelastic tensor components for the material; Fabricated domain-engineered structures in rubidium titanyl phosphate (RTA) (in collaboration with JILA); Fabricated various domain-engineered second-harmonic generating devices for 3300 nm pump wavelength (in collaboration with Time and Frequency Division) and 1560 nm pump wavelength; Observed interfacial second-harmonic generation produced by layers of glass films.

FY 1998 Establish theoretical modeling of photoelastic strain effects present in Maker fringe patterns taken from z-cut lithium niobate plates; Establish theoretical model for intersecting-pump-beam nonlinear optical analysis of lithium niobate; Use nonlinear optical analysis and Maker fringe analysis to examine surface quality of lithium niobate wafers to be prepared by various polishing procedures; Use interfacial second-harmonic generation and sum-frequency generation to map uniformity of glass layers deposited on silicon wafers; Fabricate improved domain-engineered second-harmonic generating devices for 3300 nm and 1560 nm pumping; Fabricate domain-engineered optical parametric oscillator in lithium tantalate and compare optical damage effects with similar devices fabricated in lithium niobate; Perform transmission-electron microscopy studies of domain-engineered samples of lithium niobate; Perform atomic-force microscopy and electric-force microscopy on domain-engineered samples of lithium niobate, and image domains; Begin preparation of OH-reduced samples of lithium niobate and assess effects on the poling conditions of the material.

FY 1999 Work with crystal manufacturers of lithium niobate, and device manufacturers who use lithium niobate, in correlating the crystal quality, as revealed in nonlinear optical analysis, with device performance. This includes lithium niobate for uses in optical telecommunication systems and nonlinear optical systems which require domain-engineered lithium niobate; Refine experimental and analytical methods of interfacial second-harmonic generation for studies of glass interfaces and extend the work to include other relevant materials and interfaces; Perform detailed TEM analysis of domain-engineered lithium niobate; Establish utility of atomic-force microscopy and electric-force microscopy in characterizing domains in lithium niobate.

Semiconductor Materials and Devices

Project Leader: Robert K. Hickernell

Staff: 3.7 Professionals, 2.0 Postdocs, 0.9 Technicians, 2.0 Students

Funding level: $1.2 M

Funding sources: NIST (97%), Other Government Agencies (3%)

Objective: Develop measurement methods and provide measurements to support the efficient manufacture of semiconductor optoelectronic devices; provide custom devices to support research in NIST, other Government laboratories, and industry.

Background: This project was established in 1994 and has earlier foundations in efforts dating to 1990-91 when NIST researchers contributed to metrology for the precision manufacturing of semiconductor epitaxial multilayers. The particular impact was in assisting the development of the first commercially available vertical-cavity surface-emitting lasers, which are used in short-distance data communication links. The project has extended the *ex-situ* measurements to *in-situ* monitoring during epitaxial growth, with the goal of advancing controlled-precision optoelectronic device manufacturing and the development of standard reference materials and data. Project researchers collaborate with industry and other Division researchers to develop measurements which support the manufacture and specification requirements for lasers used in data interconnect systems. The project fabricates novel lasers and detectors used in detector metrology, high-speed measurements and sensor applications. Ultrashort pulse measurements are applied to semiconductor materials characterization and next-generation, high-speed communications research. Expertise is being developed in group III-nitride materials and devices used in displays, optical data storage, and solar blind detection, in the blue/ultraviolet region.

Current Tasks:

1. *In-situ* optical metrology and process control of epilayer manufacturing

FY 1994 — Installed atomic absorption spectroscopy (AAS) system on semiconductor growth chamber; Monitored aluminum gallium arsenide layer growth; Measured growth of Bragg reflectors by *in-situ* optical reflectance spectroscopy (ORS); Calibrated atomic absorption measurement to *in situ* measurements of epilayers; Installed shallow-angle ultraviolet reflectance (UVR) monitor; Measured growth of quantum wells in real-time.

FY 1997 — Investigated closed loop control of epilayer growth; Investigated manufacture of test structures and/or reference standards for evaluation and optimization of growth stability; Developed triggered data acquisition technique which reduced effect of substrate wobble by a factor of 10 in *in-situ* reflectance measurement; Increased operational state of crystal growth system to include source materials of indium, beryllium, silicon, and arsenic (As_2).

FY 1998	Reduce uncertainty in real-time growth rate measured to less than 1%; Develop hardware and software for *in-situ* thickness and optical constant measurement, and closed loop control of epilayer growth.
FY 1999	Achieve closed loop control of epilayer growth via *in-situ* monitoring; Use to grow test composition standards with high uniformity; Begin study of substrate temperature measurement.

2. *Ex-situ* characterization of semiconductor growth and processing

FY 1991	Characterized vertical-cavity surface-emitting laser (VCSEL) structures by X-ray, electron-beam, and optical metrologies, and by measurement simulations; Showed high degree of correlation among measurement methods for layer thicknesses, uniformity, and composition; Assisted industry in development of first commercially available VCSELs.
FY 1992	Fabricated and characterized distributed feedback VCSELs with distributed quantum wells; Verified impact of correlated characterization by demonstrating the narrowest linewidth distributed feedback VCSEL and efficient optically-pumped VCSELs.
FY 1993	Measured dielectric function of individual quantum wells from distributed reflectance spectroscopy, and confirmed theoretical model for gallium arsenide quantum wells; Developed cross-sectional micro-photoluminescence technique to distinguish features of buried semiconductor layers; Established correlation between cross-sectional and surface-normal emission measurements.
FY 1994	Quantified spatio-temporal evolution of vacancy-assisted aluminum-gallium interdiffusion in quantum well heterostructures by cross-sectional micro-photoluminescence, confirmed theoretical model, demonstrated impact on semiconductor device manufacturing; Developed test structures for evaluation and optimization of epilayer uniformity.
FY 1995	Measured and modeled period deviations in distributed Bragg reflectors by reflectance spectroscopy; Extended parameter space of interdiffusion-during-annealing studies to include matrix of arsenic overpressure and temperature.
FY 1996	Measured and modeled influence of effusion-cell temperature drift during distributed Bragg reflector manufacturing; Correlated high-resolution X-ray diffractometry measurements to reflectance spectroscopy and electron microscopy measurements of systematic and random period deviations in multilayers.
FY 1997	Correlated *in-situ* monitored structures to *ex-situ* measurements to advance controlled-precision manufacturing; Investigated influence of manufacturing variations on devices used in optical interconnect industry; Applied atomic force and scanning near-field microscopic measurements to nanoscale optoelectronic structure characterization.
FY 1998	Develop manufacturing and metrology of quantum-dot materials and devices; Grow and characterize initial samples for semiconductor composition standards tests.
FY 1999	Correlate *ex-situ* and *in-situ* measurements of composition and thickness on test standard wafers; Conduct measurement comparisons of test wafers among government and industry laboratories.

3. Semiconductor material and device metrology for advanced applications

FY 1993	Completed study of optoelectronic technology and metrology required to enhance computing; Established program to address the measurement needs of the VCSEL industry and applications of optoelectronic interconnects.
FY 1994	Assessed metrology needs of the VCSEL industry and identified complementary Division resources; Began program to assist industry with measurements and standards for VCSELs and their applications in fiber-based data interconnects.
FY 1995	Obtained VCSEL devices from industry, and established packaging for dc-biased and high-speed testing; Established measurement stations and methods for measuring large-signal return-to-zero modulation bandwidth, turn-on jitter, near and far-field beam profile, and relative intensity noise (joint with 815.01).
FY 1996	Studied VCSEL measurands as function of environmental and drive parameters; Performed data interpretation and modeling of VCSEL emission properties; Determined measurement problems and technological barriers of group III-nitride technology; Collaborated with NIST researchers on joint proposal for nitride measurements support to industry.
FY 1997	Established the ultrafast mode-locked laser and optical homodyne detection system for device and material characterization; Investigated spectral mode content of VCSEL devices for optical interconnects; Explored high-spatial resolution metrology development to support the group III-nitride industry.
FY 1998	Extend ultrashort pulse metrology to the 1.5 μm spectral region; Develop and implement technique for *in-situ* monitoring of native oxide formation.
FY 1999	Develop *in-situ* stop-growth monitor for native oxide manufacturing; Measure ultrafast properties of VCSEL cavities at the 100-fs time scale.

4. Devices for advanced metrology

FY 1994	Formulated concept of environment (e.g., temperature, electromagnetic field) sensor using microcavity devices such as VCSELs, resonant-cavity light emitting diodes, and Fabry-Perot filters; Secured NASA support.
FY 1995	Established simultaneous electrical and optical biased measurement station; Measured light-current-voltage, photocurrent spectra, and threshold conditions with mixed electro-optical addressing; Demonstrated power-by-light operation on fully-packaged and non-contacted devices; Tested industry, in-house, and university-supplied VCSELs.
FY 1996	Designed custom device which stabilized optical-pump coupling but maintained laser sensitivity to environment; Fabricated and tested prototype device; Established and characterized fiber-interfaced optical power and sensing.
FY 1997	Advanced methods of photonic/electronic band engineering into ultrafast device metrology; Developed saturable Bragg reflectors for pulsed laser in high-speed detector metrology systems in the Division; Investigated impact of optoelectronic band engineering on interconnect industries; Established capabilities and competence in the growth and fabrication of electrically injected semiconductor emitters.
FY 1998	Advance saturable Bragg reflectors into In- and P-containing compounds for metrology and sensing in the 1-1.6 μm range; Demonstrate mode-locked and q-switched rare-earth-doped waveguide lasers with the Dielectric Materials

	and Devices Project; Develop wavelength-tunable laser for use in detector calibration and communications applications.
FY 1999	Develop q-switched and mode-locked lasers for detector metrology, sensing, and communications applications; Develop laser with wavelength insensitive to temperature.

Fiber and Discrete Components

Project Leader: Sarah L. Gilbert

Staff: 2.75 Professionals, 1.4 Postdoc, 1.0 Student

Funding level: $0.59 M

Funding sources: NIST (86%), Other Government Agencies (14%)

Objective: Develop measurement methods for characterization of optical fiber components and discrete components and develop standards needed by industry for these components.

Background: This project is concerned with the characterization of optical components and development of standards needed to calibrate commercial instruments which measure component properties. Wavelength standards are needed to calibrate instruments which measure the wavelengths of sources and characterize the wavelength dependence of components in wavelength division multiplexing optical fiber communication systems. Future optical communication systems will likely incorporate recently developed components, including many promising devices such as fiber lasers, dispersion compensators, and band pass filters containing Bragg fiber gratings. There is a need for standards and characterization of these components in order to both evaluate their reliability and ensure that the system specifications can be met. Polarization dependence such as polarization-dependent loss and polarization-dependent gain in components can affect a system's performance, especially when there are many components in the system. Presently, there are commercial instruments for measuring polarization-dependent loss, but no calibration standards exist for these instruments.

Current Tasks:

1. Wavelength standards for optical communications

FY 1990 — Designed and constructed a single-longitudinal mode erbium-doped fiber laser and characterized its frequency noise.

FY 1991 — Conducted spectroscopy of acetylene using the fiber laser to assess potential use for a wavelength standard; Developed a light emitting diode and absorption cell based moderate-accuracy wavelength standard.

FY 1992 — Conducted high-resolution laser spectroscopy of rubidium to assess potential use for a high-accuracy wavelength standard in the 1500 nm region; Constructed moderate-accuracy wavelength standard for the Air Force.

FY 1993 — Stabilized the fiber laser to a narrow absorption line of laser-cooled rubidium, demonstrating the system's potential as a high-accuracy wavelength standard; Conducted a detailed study of the line shapes observed in this system.

FY 1994 — Constructed a new rubidium vapor cell trap for the high accuracy wavelength standard in the 1500 nm region; Began investigating the use of hydrogen iodide and hydrogen cyanide as wavelength references in this region for

	moderate-accuracy wavelength standards; Developed plan for meeting NIST traceability need for wavelength calibration at optical communication wavelengths via absorption cells to be distributed as standard reference material (SRM).
FY 1995	Built and tested hydrogen cyanide ($H^{13}CN$) vapor cells for moderate-accuracy wavelength references; Supplied two companies with absorption cells to evaluate whether absorption cell SRMs will meet their calibration needs.
FY 1996	Developed acetylene absorption cell standard reference material; Measured the pressure-induced shift of acetylene absorption lines; Supplied three companies with fiber-pigtailed absorption cells.
FY 1997	Provided acetylene absorption cell SRM; Developed hydrogen cyanide absorption cell SRM; Transferred absorption cell technology to a company.
FY 1998	Provide hydrogen cyanide absorption cell SRM.
FY 1999	Provide absorption cell SRM units as needed; Evaluate reproducibility of high-accuracy wavelength standard based on laser spectroscopy of rubidium.

2. Metrology for photo-induced Bragg gratings in optical fiber

FY 1992	Developed the capability to write Bragg reflection gratings in optical fiber.
FY 1993	Characterized fiber grating growth dependence on time and the intensity of the ultraviolet (UV) light, compared results with theoretical models.
FY 1994	Investigated the correlation of fiber grating growth and blue fluorescence emitted during exposure to ultraviolet light; Constructed a single-longitudinal mode fiber laser incorporating fiber gratings.
FY 1995	Evaluated the thermal stability of fiber Bragg gratings written in hydrogen-loaded and unloaded optical fiber using either pulsed or continuous-wave light; Characterized the intensity and frequency noise of fiber lasers containing fiber gratings.
FY 1997	Characterized fiber grating-stabilized diode lasers; Investigated measurement techniques to characterize bulk glass UV photosensitivity.
FY 1998	Study UV photosensitivity of bulk glass; Evaluate industry need for fiber grating Fiber Optic Test Procedures (FOTP).
FY 1999	Study UV photosensitivity of bulk glass; Assist industry in developing FOTPs for fiber gratings; construct tunable fiber-grating fiber laser for spectroscopy in the 1550 nm region.

3. Polarization-dependent loss and gain metrology

FY 1994	Developed plan for constructing a polarization-dependent loss (PDL) measurement system.
FY 1995	Assessed industry need for PDL standards; Developed two PDL measurement systems.
FY 1996	Completed characterization of PDL measurement systems; Characterized short-term stability PDL artifact reference.
FY 1997	Documented PDL measurement system; Studied PDL of fiber connectors; Developed polarization-dependent gain measurement capability and began measurements on a fiber amplifier.
FY 1998	Evaluate industry need for PDL artifact references and polarization-dependent gain (PDG) metrology; Develop plan to meet industry need; Study PDG of fiber amplifiers.
FY 1999	Develop PDL Standard Reference Material.

4. Mode-Isolation Metrology for Polarization Maintaining Fiber

FY 1991	Began work on mode-isolation (h-parameter) measurement in high birefringence optical fiber at request of the Telecommunication Industries Association (TIA).
FY 1992	NIST/TIA interlaboratory comparison of mode-isolation measurements conducted.
FY 1994	Participated in drafting a mode-isolation TIA fiber optic test procedure.
FY 1996	Worked with TIA to evaluate a new mode-isolation measurement technique.
FY 1997	Conducted and participated in a mode-isolation measurement interlaboratory comparison involving new technique.
FY 1998	Work with TIA members to evaluate mode-isolation measurement accuracy.

Integrated Optics Metrology

Project Leader: Matt Young

Staff: 1.5 Professionals, 0.7 Postdoc, 0.7 Student

Funding level: $0.4 M

Funding sources: NIST (95%), Other Government Agencies (5%)

Objective: Develop advanced measurement methods for integrated optical waveguides. Interact with standards groups to provide a metrology base for lightwave communications industry.

Background: As the optical fiber industry moves toward local area networks and toward fiber to the home, there is increasing need for inexpensive passive components such as splitters. Additionally, such components are needed because long-distance telephony is retrofitting to wavelength division multiplexing. Several companies are manufacturing 1 × N splitters or are about to market them. There are, however, no standard measurement procedures similar to those for fiber index profile and mode-field diameter, nor are there artifact standards similar to those for fiber geometry. Further, it is not obvious how to perform analogous measurements, for example, because the mode field pattern of an integrated optical waveguide is not circularly symmetric or because the fiber measurement is performed using a cutback technique or a mandrel wrap. Thus, several critical measurements need examination.

Current Tasks:

1. Develop metrology for integrated optical components

FY 1988	Developed a photo-thermal method for nondestructively measuring loss in channel waveguides.
FY 1994	Identified industry's need for measurements on passive waveguides.
FY 1995	Developed low coherence reflectometer for probing integrated optical waveguides; Started preliminary collaborations with university and industrial laboratory on integrated optical metrology.
FY 1996	Continued development of low coherence reflectometer; Characterized Y-branch waveguides and measured dispersion of an optical waveguide and performed preliminary measurements on waveguides in various substrates; Began work on confocal microscopy of waveguide end faces for mode-field diameter measurements.
FY 1997	Measured reflections in integrated optical waveguides using low coherence reflectometer; Measured mode-field diameter of waveguide with near-field methods.
FY 1998	Measure refractive index profiles of integrated-optical guides; Develop metrology to characterize wavelength division multiplexers; Measure mode-field diameter of waveguide with far-field methods.

Optical Fiber Sensors

Project Leader: Kent B. Rochford

Staff: 2.25 Professionals, 0.75 Technician, 2.0 Post Doc, 2.0 Student, 0.3 Guest Scientist

Funding level: $0.76 M

Funding sources: NIST (75%), Other Government Agencies (17%), Other (8%)

Objective: Provide metrology to support the optical fiber sensor industry and develop advanced sensing technology for other government and industry laboratories. Provide polarization measurements and develop polarization standards for industry. Provide optical disc substrate measurements.

Background: This project is responding to the growing fiber-optic sensors industry by developing standards and calibrations where few exist, characterizing sensor materials, assisting in the characterization of components and sensing methods, and educating the measurement community to the advantages of optical fiber sensors. We provide the industry and other government agencies with traceability, measurement expertise, neutral evaluation of technologies, and pre-commercial development of advanced prototypes. We recently developed a Standard Reference Material for linear retardance and perform Special Tests for retardance. We are beginning an effort to calibrate optical disc retardance measurements and perform more general measurements on optical discs.

Current Tasks:

1. Advanced sensor systems, components, and materials research

FY 1985	First demonstration of fiber annealing to remove birefringence.
FY 1986	Demonstration of optical fiber current measurements to 70 MA.
FY 1987	Extended study of precision of electro-optic and magneto-optic sensors published.
FY 1988	Research on Faraday effect in ferromagnetic iron garnets begun.
FY 1989	High speed, high sensitivity ($100 pT/\sqrt{Hz}$ noise equivalent field) sensors based on the Faraday effect in yttrium-iron-garnet (YIG) demonstrated.
FY 1990	Annealing technology transferred to industry.
FY 1991	Published description of fiber annealing technology.
FY 1993	Demonstrated very-high-sensitivity magnetic field sensor ($1.4 pT/\sqrt{Hz}$ noise equivalent field) using flux concentrators; Measured radiation effects in iron garnets; Explained polarization effects in Sagnac current sensors.
FY 1994	Completed study of impediments to commercialization of fiber sensors for Navy shipboard applications; Tested iron garnet materials resulting from Small Business Innovative Research Program grant; Designed and constructed

	a high-speed, high-sensitivity current sensor; Demonstrated improved fiber annealing technique.
FY 1995	Developed and demonstrated laser-as-detector technique in optical fiber sensor systems; Completed self-calibrating temperature sensor system; Field-tested high-speed current sensor; Work on expanded core fiber for lensless coupling begun.
FY 1996	Thermally expanded an optical fiber core; Characterized and improved high-sensitivity magnetic field sensor system.
FY 1997	Evaluated novel garnets for magnetic field sensor system; Characterized thermally expanded core fiber; Began work on low-coherence sensor systems.
FY 1998	Investigate current sensor calibration limits; Develop extended dynamic range low-coherence sensor system.
FY 1999	Deliver miniaturized magnetic field sensor to sponsor; Develop head/disk fly-height sensors.

2. Basic metrology and standards development

FY 1988	Definitive study of birefringent linear retarder (waveplate) stability.
FY 1994	Tested prototype retardance standards and demonstrated very good performance for wavelength, temperature, and incident-angle dependencies; Identified long-term drift problem due to humidity.
FY 1995	Developed and confirmed a model for the standard retarder package performance; Redesigned package to minimize water vapor transmission; completed the lifetime testing of the standard retarder.
FY 1996	Measured the Verdet constant of optical fiber with improved accuracy for Los Alamos National Laboratory; Performed special tests on retarders; Completed uncertainty analysis of standard retarder and three supporting measurement methods; Completed interlaboratory comparison of retardance measurements with eight U.S. participants; Characterized devitrification of annealed fiber sensors.
FY 1997	Established Standard Retarder as a Standard Reference Material (SRM) and provided measurement support.
FY 1998	Conduct dialogue with industry to identify priority needs for new component measurements and standards.
FY 1999	Produce standard retarder for operation at 633 nm wavelength.

3. Optical data storage

FY 1995	Investigation of optical data storage industry needs begun; Participated in NIST planning workshop.
FY 1996	Identified and prioritized measurement needs of the compact disc replication industry; Investigated limits of atomic force microscopy for disc topology measurements.
FY 1997	Developed techniques for measuring disc retardance at 780 nm.
FY 1998	Conduct interlaboratory comparison of optical disc retardance; Develop SRM for optical disc retardance; Develop vertical birefringence substrate measurement technique.

4. Optical fiber sensor commercialization

FY 1991	Transferred optical fiber annealing technology to U.S. company.

FY 1994	Transferred the improved annealing technology to U.S. company.
FY 1995	Provided garnet and annealed fiber current sensors to a U.S. company for evaluation.
FY 1996	Transferred optical fiber annealing technology to a second U.S. company.
FY 1997	Provided electric field sensor to a U.S. company for evaluation.
FY 1998	Provide annealed components to a U.S. company for evaluation; Transfer electric field sensor technology to a U.S. company; Identify U.S. companies interested in expanded fiber core technology.
FY 1999	Identify U.S. companies interested in low-coherence system technology.

Optical Fiber Metrology

Project Leader: Douglas L. Franzen

Staff: 4.5 Professionals, 0.3 Guest Researchers

Funding level: $0.9 M

Funding sources: NIST (87%), Other Government Agencies (13%)

Objective: Develop advanced measurement methods and Standard Reference Materials for optical fibers; interact with standards groups to provide a metrology base for the lightwave communication industry.

Background: During the 1980s, optical fibers were introduced into the nation's telecommunication system to carry large quantities of long distance information. As the technology matured, more fiber moved into metropolitan areas and local area networks. Local loops utilize many more connection points; therefore, dimensional tolerances are important and improvements are necessary for lower loss connectors. In addition, long distance link technology continues to improve. Bit rates are increasing and the advent of optical amplifiers allows for direct optical paths thousands of kilometers in length; this and other trends toward wavelength division multiplexing require improved measurements of fiber dispersion. Over the years, NIST's efforts have evolved along with the industry, focusing on a wide range of measurement problems as they became important, and assisting in their resolution. This has led to a close involvement with the Telecommunications Industry Association (TIA) and with international standards organizations. NIST has participated in the development of more than twenty TIA standards, often serving as a neutral party in their evaluation through interlaboratory comparisons. In recent years, the industry's need for standard reference materials (SRMs) has grown; NIST presently provides an SRM for chromatic dispersion and another for fiber cladding diameter that is used to calibrate the draw towers for most of the fiber commercially manufactured in the United States, and is preparing several other SRMs.

Current Tasks:

1. Develop dimensional metrology for optical fiber

FY 1989	TIA asked NIST to develop cladding diameter SRM.
FY 1990	Contact micrometer developed with Manufacturing Engineering Laboratory, NIST.
FY 1991	Scanning confocal microscope developed; Limitations of video microscopy studied.
FY 1992	White light interference microscope developed; International round robin completed with the International Telegraph and Telephone Consultative Committee; SRM holder evaluated in TIA round robin.
FY 1993	Definitive publication on cladding diameter published in NIST Journal of Research; Cladding diameter SRM available for sale.

FY 1994	International round robin completed to evaluate SRM housings and calibrations; Completed TIA round robin on fiber coating geometry.
FY 1995	SRM for coating geometry developed; TIA round robin to evaluate ferrule and pin gages complete; NIST Tech Note written on geometry round robins.
FY 1996	SRMs for connector ferrule outside and inside diameter (pin gages) available for sale; Investigated optical interferometric measurement methods for connector protrusion/undercut.
FY 1997	Investigated mechanical measurement methods based on a contact probe for connector protrusion/undercut; SRM for coating diameter developed and delivered to NIST Manufacturing Engineering Laboratory for final measurements; Developed reference far-field measurement system for mode field diameter.
FY 1998	Develop reference near-field measurement system for mode field diameter.

2. Develop dispersion metrology for optical fiber

FY 1993	Initiated development of frequency domain phase shift system for chromatic dispersion measurements.
FY 1994	Initiated development of measurement methods for polarization mode dispersion (PMD); Completed frequency domain phase shift system; Studied fiber configuration for chromatic dispersion SRM; Initiated PMD round robin with TIA members.
FY 1995	Completed evaluation of PMD methods; Completed PMD round robin; Initiated TIA round robin to evaluate chromatic dispersion reference fibers; Completed development of differential phase shift system to measure zero dispersion wavelength.
FY 1996	Documented performance of PMD SRM; Completed TIA chromatic dispersion round robin and documented chromatic dispersion SRM.
FY 1997	Chromatic dispersion SRM available for sale; Prototype PMD SRM manufactured by outside vendors.
FY 1998	PMD SRM available for sale; Investigate chromatic dispersion SRM for non-zero dispersion shifted (NZD) fibers; Develop system to measure multimode fiber chromatic dispersion.

3. Develop metrology for nonlinear fiber properties

FY 1994	Identified key needs of industry and initiated NIST program.
FY 1995	Measured pulse response of Fabry-Perot filters and determined effect of non-linearities; Completed capability for measuring four-wave mixing effects.
FY 1996	Determined relation between four-wave mixing efficiency and zero dispersion wavelength - published results; Presented four-wave mixing work to TIA;
FY 1997	Determine whether four-wave mixing can predict chromatic dispersion length uniformity.
FY 1998	Investigate whether it is possible to develop a practical system for measuring zero dispersion wavelength as a function of fiber length; Determine non-linear limits of high power sources for use in optical time domain reflectometry (OTDR).

4. Develop metrology for system/field measurements

FY 1992	Developed time domain methods for calibrating optical time-domain reflectometer (OTDR) group delay; Constructed moderate accuracy wavelength standard to calibrate optical spectrum analyzers; Investigated mode-locked fiber lasers as strobes for optical waveform sampling.
FY 1993	Developed interferometric low-coherence techniques for fiber length and group delay measurements.
FY 1994	Developed artifact calibration standards for group index of single and multimode optical fibers; Demonstrated efficient optical waveform sampling based on four-wave mixing effects; Initiated program to determine optimum launching conditions for multimode fibers in support of fiber computer bus interconnects (ATP funded); Developed high resolution OTDR for local area network applications.
FY 1995	Delivered group index OTDR calibration artifacts to Navy; Designed beam optics system for multimode fiber bandwidth measurements.
FY 1996	Evaluated and modified, with TIA, existing test procedures for multimode fiber bandwidth.
FY 1997	Completed multimode fiber bandwidth round robin with TIA members; Developed high resolution measurement method for differential mode delay (DMD) in multimode fibers at 850 and 1300 nm; Developed reference measurement system for multimode fiber bandwidth; Measured DMD on TIA round robin fibers.
FY 1998	Develop ultra-high sensitivity OTDR for determining the uniformity of Rayleigh backscatter along the length of fibers; Improve spatial resolution of DMD measurements for multimode fibers; Compare time and frequency domain DMD techniques; Determine zero dispersion wavelength of multimode fibers as a function of launching conditions.

5. Develop metrology for fiber amplifiers

FY 1994	Identified the key metrology issues for fiber amplifiers.
FY 1995	Collaborated with TIA and international standards groups to plan round robin for noise figure and spectral gain.
FY 1996	Initiated international round robin and obtained preliminary NIST measurements of noise.
FY 1997	Obtained results from U.S., Europe, and Japan on international round robin for spectral gain and noise figure of erbium doped fiber amplifiers (EDFA).
FY 1998	Complete international round robin on EDFAs and issue report; Complete NIST reference measurement system for determining spectral gain and noise figure of EDFAs.
FY 1999	Initiate a NIST Measurement Assurance Program (MAP) for erbium doped fiber amplifier spectral gain and noise figure of EDFAs.

High Speed Source and Detector Measurements

Project Leader: Paul D. Hale

Staff: 4.5 Professionals, 0.5 Technician, 1.0 Contractor

Funding level: $1.1 M

Funding sources: NIST (92%), Other Government Agencies (5%), Other (3%)

Objective: Provide advanced metrology, standards, and measurement services relating to temporal properties of optical sources and detectors used in association with optoelectronic systems.

Background: High bandwidth measurements are needed to support high-performance systems which take advantage of the potential bandwidth of optical fiber. Systems presently being installed operate at 5 to 10 gigabits per second using pure optical time division multiplexing (OTDM) and research is being done on the next generation of OTDM systems at 20 to 40 gigabits per second. Methods are needed to characterize the impulse and frequency response of high speed sources and detectors to at least the third harmonic of the system modulation rate. As new optoelectronic technologies have emerged, NIST has developed new laser and detector standards to support this growth. For example, the reemergence of short wavelength applications, such as optical interconnects, has shown the need for concurrent development of applicable measurement standards and techniques specific to this technology. Burst mode operation in asynchronous transfer mode (ATM) networks requires characterization at very low frequencies. Increasingly tight tolerances in both digital and analog systems require frequency response measurements with low uncertainty. Source and detector noise measurements are required to predict low bit error rates (BERs) in computer interconnects, high carrier to noise ratios (CNRs) in analog systems, and to support erbium-doped fiber amplifier (EDFA) noise figure (NF) measurements using electrical noise methods. Intensive use of laser target designators by the armed forces requires traceable low level pulse power and energy calibration standards at 1.06 and 1.55 μm.

Current Tasks:

1. Noise measurements and standards

FY 1994	Developed competence in RIN of diode lasers to determine limitations of existing measurement techniques.
FY 1995	Performed RIN measurements on edge-emitting lasers at room temperature and liquid nitrogen temperature (77 K) over the frequency range between 1 to 10 GHz.
FY 1996	Documented industry needs for optoelectronic noise measurements; Began development of techniques and apparatus for measuring RIN which are suitable for supporting optical amplifier noise measurements and low level measurements on distributed feedback (DFB) lasers; Completed cryogenic measurements of RIN of various diode laser sources.

FY 1997-98	Continued development and characterization of RIN measurement techniques supporting optical amplifier noise measurements and measurement of low RIN (-160 dB/Hz) DFB lasers.

2. Develop impulse response measurement capability

FY 1993	A titanium-doped sapphire laser which produced very short pulses (100 fs) was completed; detectors and modulators with picosecond response evaluated.
FY 1994	Received calibration requests and, consequently, modified system to accommodate customers' detectors.
FY 1995	Performed two Special Test calibrations on optical power detectors.
FY 1996	Began development of a mode-locked chromium-doped yttrium aluminum garnet (Cr^{+4}:YAG) laser for generating short (100 fs) optical pulses at wavelengths of 1.55 μm or 1.3 μm, Began development of photoconductive methods for calibrating optoelectronic frequency response above 40 GHz; Investigated industry need for on-wafer and packaged device frequency response metrology.
FY 1997	Continued development of photoconductive methods for calibrating optoelectronic response in both magnitude and phase; Performed 5 special tests.
FY 1998	Continue development of mode-locked Cr^{+4} YAG laser; Upgrade scalar optoelectronic frequency response calibration to 50 GHz by calibrating frequency response and time scale errors of high speed oscilloscopes; Compare scalar frequency response calculated using time domain method with heterodyne measurements.

3. Detector frequency response measurements

FY 1992	Received inquiries from industry for photodiode frequency response in the frequency range between 0.050 and 20 GHz; Investigated various measurement methods by literature search and talking to industry representatives; Acquired parts for heterodyne measurement system.
FY 1993	Constructed heterodyne measurement system operable over the frequency range between 0.05 and 30 GHz; Investigated candidates for transfer standards; Constructed 20 GHz transfer standard for Navy.
FY 1994	Extended heterodyne coverage up to 40 GHz and down to about 300 kHz; Participated in frequency response intercomparison with the National Physical Laboratory in Great Britain which demonstrated good agreement.
FY 1995	Developed method for transferring photoreceiver calibration; Extended range of heterodyne system to 50 GHz and down to 100 kHz; Calibrated over 20 detectors and transfer standards for industry.
FY 1996	Documented uncertainty analysis of frequency response measurements of a photoreceiver/power sensor transfer standard; Built and characterized synthesized modulation source for high-resolution measurements (between DC and 1 GHz); Continued comparison with the National Physical Laboratory in Great Britain; Calibrated 19 photodetectors and transfer standards for industry.
FY 1997	Continued documentation of photoreceiver/power sensor transfer standard towards a calibration service; Began documentation of calibration service for "bare" photoreceivers; Continued comparison with the National Physical Laboratory in Great Britain and other standards laboratories; Investigated industry and military need for 850 nm or 1550 nm wavelength ranges and

	frequency coverage up to 110 GHz; Extended measurement capability to 850 nm.
FY 1998	Continue comparisons with the National Physical Laboratory and other standards laboratories; Continue investigations of repeatability and age dependent effects in detectors; Improve frequency resolution of 850 nm system and extend measurement technology to higher frequency range up to 110 GHz for RF photonic applications; Complete documentation of photoreceiver/power sensor transfer standard as a calibration service.

4. Develop new pulsed laser measurement capability

FY 1992-93	Designed, constructed, and delivered two low-level radiometers for the Navy Metrology Center for measuring peak power of Q-switched pulses from laser target designator and range finder systems.
FY 1995	Delivered seven low level radiometers; Began upgrade of low-level pulse measurements system to improve accuracy by a factor of two and reduce measurement time.
FY 1996	Continued low-level system upgrade including assessment of Type B uncertainties; Transferred technology for construction of six low-level radiometers to sponsor; Calibrated two of these radiometers.
FY 1997	Calibrated remaining four low-level sponsor-constructed radiometers; Continued low-level system upgrade; Constructed low-level measurement system for 1.55 μm light.
FY 1998	Document needs of lidar and remote sensing industries for pulsed radiometric measurements; Continue low-level system upgrade and development of low-level system for 1.55 μm light.

Laser Radiometry

Project Leader: Chris Cromer

Staff: 7.0 Professionals, 3.0 Contractors, 1.5 Technicians

Funding level: $1.7 M

Funding sources: NIST (69%), Other Government Agencies (25%), Other (6%)

Objective: Develop measurement methods and standards for characterizing laser sources and detectors used primarily with continuous-wave (CW) radiation. Develop and maintain measurement services for laser power & energy, optical fiber power, and related parameters (e.g., spectral responsivity, linearity, etc.)

Background: The development of lasers in the 1960s opened the door to new technologies and industries that could make use of the peculiar properties of laser radiation (i.e., spatial coherence, temporal coherence, narrow line width, high irradiance levels, etc.). The implementation of laser sources into industrial systems as well as research laboratories has been historically limited or enhanced by the ability to accurately characterize the emitted radiation. Consequently, NIST has been developing and providing measurement services to the laser community since the late 1960s. As new wavelengths and laser types have emerged, NIST has developed the appropriate new detector standards and measurement techniques to support this growth. Optical power detectors continue to be the most common piece of test equipment for supporting optical fiber telecommunication systems and as the technology evolves, higher accuracy power measurements have become crucial. In addition to higher accuracy, calibration customers have requested that we improve our capability to measure other detector properties such as linearity and spectral responsivity. Medical uses of lasers are continuing to evolve, with photorefractive eye surgery and photodynamic drug therapy being recent examples where total beam energy and spatial beam quality are critical measurement requirements. Quantitative knowledge about the irradiance profile and propagation characteristics of laser beams is essential to understanding the properties of emerging new technologies such as vertical cavity surface emitting lasers (VCSELs). Beam profile standards are becoming increasingly important for analyzing the radiation propagating through optical systems containing many optical components (e.g., lenses, fibers, filters, etc.). Important industrial applications of beam profile standards include optical data storage, high resolution printing, and semiconductor photolithography. Applications for high power lasers such as laser welding and cutting, and laser isotope separation also require quantitative characterization of beam profile and laser power.

Current Tasks:

1. Develop spectral responsivity measurement capability for optical power detectors

FY 1993	Project initiated to develop spectral responsivity capability for optical power meters.
FY 1994	Prototype system developed and used for special test measurements at uncertainties of ±2%.
FY 1995	Improved system designed, equipment procured, and system established.
FY 1996	Began assessment and improved measurement uncertainty; Performed special test measurements for customers.
FY 1997	Completed uncertainty improvement and analysis; automated measurement system, trained technicians, and implemented fully documented measurement services.
FY 1998	Continue improvement of measurement uncertainties, and provide high quality calibration services to customers; Provide specialized tests to industrial and research communities as required; Begin development of specialized tunable laser systems for spectral response.

2. Develop and provide measurement services for optical fiber power meters

FY 1987	Received numerous requests for optical fiber power measurements.
FY 1988	Developed parallel beam measurement capability for power measurements of laser beams operating at a wavelength of 850 nm and began offering measurement services at 100 μW power level.
FY 1989	Developed parallel beam measurement capability for wavelengths of 1300 and 1550 nm and offered associated measurement services at 100 μW power level.
FY 1990	Received requests for measurements using various types of connectors as requests for parallel beam measurement declined.
FY 1991	Developed automated measurement capability for connectorized fiber delivery to power meters at 100 μW power levels.
FY 1992	Added 670 nm and 780 nm to wavelength capability.
FY 1994	Compared various methods of measuring detector linearity and selected optimum method for optical fiber power meters.
FY 1995	Developed linearity measurement system for detectors of laser radiation at wavelengths of 1300 and 1550 nm and use for Special Test measurements over wide range (60 dB) of power.
FY 1996	Developed linearity measurement capability for 850 nm; Developed tunable laser system for optical fiber power meter measurements.
FY 1997	Improved linearity and tunable laser measurement system to provide enhanced measurement support; Performed study of connector effects on measurements; Obtained formal approval for optical fiber power measurement services.
FY 1998	Continue improvement of measurement uncertainties; Develop improved transfer standards traceable to the high accuracy cryogenic radiometer; Provide high quality measurement services to industry.
FY 1999	Using in-house capabilities to build new tunable diode lasers, expand wavelength coverage of tunable laser measurement; Increase the power available for calibrations as requested by industry; Provide high quality measurement service to industry.

3. Develop and provide measurement services for laser power & energy detectors

FY 1967-93	Developed and provided power measurement services at various wavelengths at powers up to 300 W.
FY 1994	Based on requests from material processing industry, procured high power lasers and began development of high power calibration capability for lasers operating at a wavelength of 10.6 μm.
FY 1995	Provided calibrations for laser output power up to power levels of 1 kW and a wavelength of 10.6 μm; Developed fiber delivery system for high power (500 W) 1.06 μm measurements; Initiated high laser round robin.
FY 1996	Implemented high power 1.06 μm calibration measurements; Continued high power round robin.
FY 1997	Completed high power round robin; Modified high energy laser calorimeter; Investigated discrepancy with PTB.
FY 1998	Develop improved transfer standards traceable to the cryogenic radiometer for high power laser measurements; Develop linearity test methods for high power laser meters.
FY 1999	Provide high quality measurement services to industry.

4. Improve accuracy of laser and optical fiber power measurements

FY 1994	A survey of standards laboratories and customer input specified need for improved accuracy for laser and optical power measurements at NIST
FY 1995	Developed plan for obtaining improved primary standard and secondary standard; procurement of cryogenic radiometer initiated.
FY 1996	Installed and tested cryogenic radiometer; Built and tested automated measurement system.
FY 1997	Developed prototype secondary standards (diode trap and pyroelectric trap designs); Using new primary and secondary standards, began to disseminate measurements traceable to the cryogenic radiometer for optical fiber and laser power calibrations.
FY 1998	Continue development of improved transfer standards; Refine dissemination of measurements for optical fiber and laser power calibration services traceable to the cryogenic radiometer.
FY 1999	Develop improved cryogenic radiometer designs, with faster response time and improved dynamic range.

5. Develop beam profile measurement capability

FY 1993	Requested by industry to become involved in development of beam profile standards and measurements to support industry.
FY 1994	Participated with U.S. industry to help develop an international voluntary beam profile standard document; Performed beam width round robin with industry.
FY 1995	Developed state-of-the-art beam profile measurement system; Initiated second beam width and divergence round robin.
FY 1996	Improved beam profile measurement systems; Investigated sources for use in a round robin.
FY 1997	Continued development of standards for beam profile measurements; Developed beam profile measurement capabilities for excimer lasers used in

photorefractive eye surgery; Investigated methods for profile measurements of tightly focused beams used in optical data storage.

FY 1998 — Use new beam profile standards in round-robin with industry; Investigate standards appropriate for medical applications of excimer lasers; Develop beam profile measurement capability for pulsed lasers.

FY 1999 — Develop beam profile measurement techniques for very high irradiance at the focus of industrial lasers.

6. Develop deep ultraviolet (DUV) calorimeters for excimer laser measurement capability.

FY 1990 — Requested by industry to build capability for 248 nm excimer laser calibrations.

FY 1991 — With funding from SEMATECH, built and delivered to GCA two DUV calorimeters for laser energy measurements.

FY 1994 — Received calorimeters from GCA and established measurement service for excimer laser energy meter calibrations at 248 nm.

FY 1995 — Performed numerous calibrations of excimer laser power and energy meters at 248 nm.

FY 1996 — Again requested by industry to expand capabilities for excimer laser measurements to 193 nm; Began search for candidate calorimeter volume absorbing materials a 193 nm; Participated in collaboration between NIST, Massachusetts Institute of Technology/Lincoln Laboratories, and SEMATECH on DUV photolithography issues.

FY 1997 — Continued investigations of volume absorbing materials for use in extending existing DUV calorimeter design for measurements at 193 nm; Built new DUV calorimeters for 193 nm; Installed new excimer laser on loan from SEMATECH.

FY 1998 — Provide calibration services at 193 nm for excimer laser power and energy meters; Develop improved excimer laser calorimeter designs with higher accuracy and better stability.

FY 1999 — Develop improved excimer laser calorimeter designs to offer combination of higher accuracy, better long-term stability, and wider spectral coverage; Expand measurement capabilities for calibration services to include overfilled (UV dose) calibrations.

VIDEO

Video Technology

Project Leader: Edward Kelley

Staff: 5 Professionals

Funding level: $0.7 M

Funding sources: NIST (100%)

Objective: Develop the measurement support needed by U.S. industry to process, transmit, and display digital video information. Initially, develop objective measures for the characterization of the video quality of display devices, including needed measurements for quantities such as gray scale linearity, uniformity, contrast ratio, viewing angle, and brightness. Similarly, develop a collection of measurement tools for the evaluation of digital video signals, that are subjected to compression processing, which will allow the user to apply an appropriate subset of the tools to obtain an overall quality figure consistent with the task requirements.

Background: Manufacturers of flat-panel displays and manufacturers who use flat-panel displays in their products need consistent, industry-accepted measurement standards for characterizing the performance of their displays. Standards or testing procedures presently existing in industry are in their infancy or nonexistent. The lack of standards restricts the U.S. electronics industry by reducing competition between the suppliers of display products. The current world market for displays is over $11 billion per year. Also, service and manufacturing industries providing, or interested in providing, digital video services or products need test measures for evaluating the quality of their video "product." There are at present no metrologically sound measures for characterizing the quality of digital video sequences processed by lossy signal compression methods and/or transmitted over digital networks. Such characterization is fundamental to product development and marketing (price/performance targeting).

As a neutral third party, NIST is uniquely positioned to develop non-proprietary measurement tools that do not favor one technology. Further, NIST's long involvement with voluntary standards organizations, and our metrological reputation within those organizations, permit us to cooperate effectively with industrial partners and have NIST-developed technology widely accepted.

Current Tasks:

1. Develop performance measurements for the objective characterization of flat panel displays

   FY 1993 Designed measurement laboratory and ordered equipment, including colorimeters, spectroradiometers, charge-coupled-device (CCD) imaging system, signal generators, display positioning system, and spherical panel surround.

FY 1994 Assembled and tested laboratory equipment; Developed test procedures for calibrating instruments; Developed simulation and modeling programs for the Princeton Engine, a massively parallel video supercomputer, to visually simulate display performance.

FY 1995 Conducted and reported on a survey of Display Measurement Standards; Developed additional creative laboratory calibration procedures; Completed round-robin measurement using a cathode-ray-tube (CRT) display from the National Information Display Laboratory; Started evaluation of an international voluntary reflectance measurement standard.

FY 1996 Analyzed and reported on an international voluntary reflectance measurement standard; Continued development of measurement techniques for display characterization; Designed a transportable display simulator; Investigated the use of interference filters to evaluate colorimetric performance of detection systems; Developed a flat panel display characterization draft standard for the Video Electronics Standards Association (VESA).

FY 1997 Continued development of measurement procedures for display characterization, adding additional tests for viewing angle and other parameters to meet industry needs; Completed the first released version of the flat panel display characterization standard for the Video Electronics Standards Association (VESA) for direct view displays.

FY 1998 Refine measurement procedures and expand to include other display technologies and methods such as projection and head mounted display systems; Develop Display Measurement Assessment Transfer Standard (DMATS) prototype and begin preliminary round robin; Verify display reflection model, and establish measurement technique.

FY 1999 Refine measurement procedures and expand to include other display technologies and methods such as head up and stereoscopic display systems, (with a voluntary standards organization, if possible); Develop extensions to the DMATS; Develop display reflection SRMs.

2. Develop video quality metrics for quantifying video compression and viewing artifacts

FY 1993 Implemented and analyzed quality metrics for telecommunications applications; Developed a family of video test patterns for qualifying and verifying performance of metric implementations.

FY 1994 Developed an interactive method to use the Princeton Engine to measure perceptible noise threshold in video images; Held industry workshop to highlight technical issues with respect to sending video over information networks; Purchased, installed, and developed tools for additional computing capability to support video quality metric research.

FY 1995 Performed experiment to estimate flicker perception for small text fonts on interlaced displays; Collaborated with industry partner to analyze performance issues related to noise filtering and blurring of video images; Helped develop Advanced Technology Program focused program on "Digital Video in Information Networks;" Prepared assessment of industry needs for video quality metrics.

FY 1996 Reported results of font flicker metric for interlaced displays; Developed performance revealing test patterns for digital video compression systems,

	including test for motion estimation characterization; Developed analysis tools to quantify generated errors.
FY 1997	Refined performance revealing test patterns and disseminated preliminary version to industry; Extended image blocking detector to incorporate elements of human visual system and reported initial results; Measured perceptibility of compression impairments in noisy video test materials.
FY 1998	Extend quality analysis tools to improve local feature extraction; Develop transient effects detector for noise and motion impairments; Extend performance-revealing test patterns in collaboration with industry.
FY 1999	Refine analysis tools to more closely correspond to human visual system and integrate analysis tools into full performance metric with test patterns; Develop a pre-processing performance analyzer.
FY 2000	Complete transfer of measurement technology to industry through publication and dissemination of test patterns and objective metrics.

3. Participate in voluntary standards committee working groups to identify non-tariff trade barriers in new television standards. (in collaboration with Semiconductor Division)

FY 1998-99	Provide support in the form of participation in standards activities associated with digital television.

POWER

Dielectrics Research

Project Leader: James K. Olthoff

Staff: 1.5 professionals, 1 guest scientist

Funding level: $0.5 M

Funding Sources: STRS (65%), Other Government Agencies (35%)

Objective: To respond to industrial and other agency needs related to electrical insulation and its interaction with electrical breakdown.

Background: This project began in the mid 1970's with funding from Department of Energy to investigate liquid and gaseous dielectrics. Work in gaseous dielectrics emphasizes the production of corrosive and toxic by-products in SF_6 formed by exposure to electrical discharge. Present work emphasizes the production of selected toxic by-products in SF_6 insulated equipment. Recently the program has evolved to address investigations of partial discharge detection as a diagnostic of insulation conditions. Specific areas of investigation include: 1) concern by the electrical manufacturers and utilities about the formulation and detection of highly toxic compounds in gas-insulated power systems; 2) concerns over the global warming potentials of gaseous dielectrics; and 3) problems encountered by the Air Force about occurrence of corona discharges and related aging in high-voltage cables used in the space environment.

Current Tasks:

1. Perform laboratory evaluation of techniques for cable condition monitoring

FY 1993	Nuclear Regulatory Commission (NRC) requests NIST to reactivate program on cable defect detection in nuclear power plant cables.
FY 1994	Initiated evaluation of partial discharge techniques for application as cable diagnostic; Established liaison with Brookhaven National Laboratory for acquisition of aged cable specimens.
FY 1995	Completed assembly of digital recording instrument for partial discharge analysis of cables; Evaluated novel Russian-based technology; Collected literature for bibliography on application of partial discharge diagnostics to cable evaluation.
FY 1996	Completed final version of digital recording instrument, and developed required analysis software.
FY 1997	Investigated the testing of cables to determine affect of PD detection techniques on cable lifetime. NRC eliminated funding due to cost of proving safety of PD detection techniques, and systematic task shut down was begun.
FY 1998	Write final report to NRC on the application of PD detection on signal cable testing.

2. Develop digital techniques for recording and analysis of partial discharges in insulation systems

FY 1993	Built prototype of digitizer and recording system for partial discharge measurement; Developed first generation of discharge data analysis software.
FY 1994	Applied digitizer to study partial-discharge-induced aging effects of cast epoxy resin similar to that used in gas insulated substations; Presented results in invited archival paper; Digitized design presented in conference paper.
FY 1995	Updated digitizer design for application to the measurement of partial discharges under direct as well as alternating voltage; Revised analysis software for easier use as a windows application; Applied digitizer to oil and alumina insulators.
FY 1996	Completed partial discharge measurements on alumina; Adapted recorder for acoustic detection of partial discharges.
FY 1997	Completed a new digitizer design and fabrication along with documentation, and delivered unit to sponsor.
FY 1998	Measure PD inceptionin SF_6/N_2 mixtures; Use the new digitizer system to study PD on epoxy surfaces.
FY 1999	Correlate PD on insulating surfaces with accumulation of surface charge.

3. Investigate production of decomposition by-products in SF_6 exposed to electric discharge

FY 1990	Developed gas-chromatograph/mass-spectrometer technique to detect S_2F_{10} down to concentration of 2 parts in 10^8.
FY 1991	Measured production rates of S_2F_{10} production for corona discharge in SF_6; Measured dissociative electron capture cross sections for other SF_6 decomposition by-products.
FY 1992	Observed production of other possibly toxic by-products; Measured dissociative electron cross sections for selected by-products.
FY 1993	Improved procedure to detect S_2F_{10} by minimizing effects of contaminate interferences and hydrolysis of the samples; Measured decomposition of SF_6 exposed to X-rays via a Cooperative Research and Development Agreement (CRADA) with industry.
FY 1994	Completed definitive work on plasma chemical model for decomposition of SF_6; Measured production rates of by-products from corona discharge in mixtures of SF_6 and oxygen.
FY 1995	Wrote parts 1 and 2 of final report to S_2F_{10} CRADA members; Measured appearance potentials of ions from SF_6 by-products.
FY 1996	Task completed.

4. Investigate impact of SF_6 use on global warming

FY 1996	Reviewed potential impact of SF_6 on global warming, and reviewed current state of knowledge concerning use of SF_6/N_2 mixtures as a possible substitute.
FY 1997	Organized workshop and reviewed literature to determine modifications required for use of SF_6-substitute gases in power equipment, per the request of EPA; Provided EPA with report of conclusions.
FY 1998	Host Gaseous Dielectrics VIII symposium with a theme of using SF_6/N_2 mixtures as replacement gases in electrical equipment.
FY 1999	Investigate decomposition by-products in discharges in SF_6/N_2 mixtures.

Metrology for Electric Power Systems

Project Leader: Gerald J. FitzPatrick

Staff: 7.0 Professionals, 1.0 Technicians

Funding level: $1.3 M

Funding sources: STRS (33%), Other Government Agencies (38%), Other (29%)

Objective: Develop measurement technologies and provide electrical calibration services to support the operation of electrical power systems, including those used by industry, electric utilities, and related equipment manufacturers; interact with standards groups to provide a metrology base for electric power-related measurements.

Background: NIST has operated research programs in metrology areas related to the measurement of electric power for many decades. Over the years the programs have evolved to respond to the increased use of electric power in the United States, and to new technical challenges and advances in the industry. Currently energy metering of the more than 208 billion dollars worth of electrical energy used in the United States annually is traceable to NIST calibration services. In the past, additional measurement capabilities, such as impulse voltage measurements, have been developed at NIST. Tasks have also been performed in areas of concern to the electric utilities and the public in general, such as power quality, bioeffects of electric and magnetic fields, and energy efficiency in electrical equipment. The knowledge gained in these areas of research is rapidly transferred to the public through publications and the establishment of measurement standards.

Current tasks:

1. Calibration services in support of the electric power industry

FY 1993	Modernized power and energy calibration facility.
FY 1994	Performed impact analysis of power and energy calibration service on electric utilities.
FY 1995	Developed fast turn-around calibration service for selected watthour meter calibrations; Reinitiated offsite high voltage tests.
FY 1996	Initiated international power and energy intercomparison by organizing exchange of standards with Canada and Europe; Modernized high voltage facility.
FY 1997	Began design of new power and energy calibration system; Began detailed documentation of high-voltage calibration systems.
FY 1998	Complete fabrication and testing of power and energy calibration system; Complete detailed documentation of high-voltage calibration systems.
FY 1999	Design new current transformer calibration system.
FY 2000	Fabricate and test new current transformer calibration system.

2. Investigate applications and calibration methods for optical sensors applied to electrical measurements

FY 1992	Built NIST optical current transformer (OCT) to measure at power frequency current.
FY 1993	Built and documented portable Kerr Cell for optical voltage measurements.
FY 1994	Developed 0.1% calibration method for OCTs at power frequency in phase and ratio using digital techniques.
FY 1995	Initiated test of commercially produced OCTs.
FY 1996	Continued testing of commercially produced OCTs.
FY 1997	Began review of industrial OCT usage.
FY 1998	Complete review of industrial OCT usage and produce a report; Complete testing of commercial OCT.
FY 1999	Develop calibration techniques for OCTs; Initiate testing of optical voltage transformers.

3. Fast-transient measurements

FY 1992	Constructed NIST4 reference impulse divider.
FY 1993	Participated in round-robin testing of reference impulse measurement systems using NIST4 divider.
FY 1994	Completed and incorporated into IEEE standard for high voltage testing convolution technique for impulse qualification used to achieve <0.5% uncertainties.
FY 1995	Documented comparative high voltage impulse measurement techniques.
FY 1996	Investigated and documented influence of heating effects on reference divider performance.
FY 1997	Documented the rebuilt and tested NIST4 impulse reference divider.
FY 1998	Conduct measurements for international comparison of high voltage impulse measurement systems and report results to pilot laboratory.

4. Develop test procedures for energy efficient motors and transformers

FY 1993	Investigated industrial procedures for measuring efficiencies of electric motors (> 1 horsepower).
FY 1994	Investigated industrial procedures for measuring efficiencies of electric transformers.
FY 1995	Wrote test procedure for electric transformers for U.S. Department of Energy.
FY 1996	Wrote test procedures for electric motors for U.S. Department of Energy.
FY 1997	Published test procedures for energy efficient motors and transformers in the Federal Register, and documented statistical analysis of testing procedures.
FY 1998	Work to revise IEEE Standard 114 for efficiency testing of single-phase motors.

5. Metrology support for electric and magnetic field measurements

FY 1990	Published archival paper on complexities of making magnetic field measurements away from power lines.
FY 1991	Investigated experimental parameters using linear and circularly polarized magnetic fields during in-vitro exposure studies.

FY 1992	Developed spot-measurement protocol for residential magnetic field measurements in collaboration with working group developing an international standard.
FY 1993	Published primer on conducting in-vitro bioeffect studies with extremely low frequency magnetic and electric fields.
FY 1994	Determined worse-case measurement errors using 3-axis magnetic fields probe to measure dipole magnetic fields.
FY 1995	Two industrial voluntary standards, IEEE Standards 644-94 and 1308-94, written at NIST in collaboration with industry were issued by the Institute for Electrical and Electronics Engineers; Published error distribution for 3-axis magnet field probe used to measure magnetic fields.
FY 1996	Complete primer on magnetic and electric field measurements; Revised primer into draft standard; Developed for adoption internationally.
FY 1997	Prepared "Committee Draft for Voting" for proposed international standard.
FY 1998	Prepare Final Draft International Standard on measuring electric and magnetic fields.

6. Applying metrology to power quality issues

FY 1988	Published award-winning seminal paper entitled "Power Quality Site Surveys: Facts, Fiction and Fallacies."
FY 1989	Conducted investigation and published a NIST report, "Lightning and Surge Protection of Photovoltaic Installations."
FY 1990	Began now ongoing technology transfer with the Power Electronics Applications Center (PEAC).
FY 1991	Completed major revision of a voluntary recommended practice describing surge environments.
FY 1992	Began technical review of all technical publications by PEAC on power quality.
FY 1993	Wrote three technical Bulletins on power quality issues.
FY 1994	Performed measurements and published two papers on surge propagation and mitigation in the PEAC Upside-Down House.
FY 1995	Completed three fundamental international standards documents on installation and mitigation for electromagnetic compatibility; Enlisted direct support from two electric utilities.
FY 1996	Documented need to characterize surge currents rather than surge voltages as a measure of power quality.
FY 1997	Wrote report on electromagnetic immunity of Personal Protection Devices for electric vehicles, and drafted technical bulletin on surge protection requested by a major insurance company.
FY 1998	Complete documentation of PEAC Upside-Down House facility and experimental results.
FY 1999	Catalyze cooperation among electric utilities, electrical equipment manufacturers, end-users, and standard writing bodies.

NATIONAL ELECTRICAL STANDARDS

Ohm and Farad Realization and Dissemination

(Includes former projects "Resistance Standards and Measurement Methods" and "Quantum Resistance and Capacitance")

Project Leader: Randolph E. Elmquist

Staff: 7.0 Professionals, 2.6 Technicians, 2.0 Guest Scientists

Funding level: $1.5 M

Funding sources: NIST (90%), Other Government Agencies (10%)

Objective: Maintain the U.S. legal ohm and farad; support the Division's resistance and capacitance calibration services; provide industry, academia, and government with calibration services unequaled in scope and accuracy; develop new resistance and capacitance standards and improved measurement techniques; and participate in international comparisons of the ohm and farad and supporting experiments to realize the international definitions of the ohm and farad.

Background: The research work being done on this project is the key to tying the U.S. legal system of electrical units to the international system (SI) of units. Strong support in this research area allows NIST to provide the nation with the world's best basis for electrical measurements and to conduct measurements of the SI ohm and farad that have smaller uncertainties than those of any other nation. NIST's maintenance of the ohm by the quantum Hall effect -- a resistance standard dependent only on the values of fundamental constants of nature -- and the farad by the calculable capacitor -- a standard dependent only upon an SI length measurement -- provide a solid basis for measurement quality in U.S. industry. The activities of this project underlie the future development of not only the electrical measurement services provided to industry by NIST, but also the development of commercial high-precision instrumentation needed by industry to support advances in electronics. Methods developed by NIST for scaling of impedance measurements at the highest levels of accuracy will provide needed capabilities for extending the measurement range, voltage, and frequency for industry and other government laboratories.

U. S. industry requires accurate resistance and capacitance measurements for both quality and process control purposes. Not only are resistors and capacitors the most commonly used electronic components, they are important control parameters in the manufacture of semiconductor electronics and common tools for the measurement of temperature, pressure, force, light intensity, and other quantities via transducers. NIST's most visible link to these applied measurements is through the instrumentation industry. Accurate, traceable impedance measurements are vital to the development, testing, manufacturing, and maintenance of instrumentation. This is reflected in the volume of calibration work which accounts for about 50% of the Electricity Division's and over 11% of all of NIST's calibration income. The most challenging present needs are for new standards that are environmentally insensitive for supporting *in situ* maintenance of precision meters, ac resistance calibrations to support temperature measurements and calibration of impedance meters, and research to support commercialization of the cryogenic current comparator and quantum Hall effect systems for improved scaling in bench instrumentation.

NIST is uniquely qualified to interact with other national laboratories in the comparison of resistance and capacitance standards and the verification of scaling from the basic standards in support of the worldwide electronic instrumentation industry. Such comparisons ease impediments to international trade.

Current Tasks:

Resistance:

1. Determine the SI ohm

FY 1981	Initiated the development of the capability to determine the SI ohm from the newly discovered quantum Hall effect and the calculable capacitor.
FY 1987	Reported new values of the von Klitzing constant and the SI ohm.
FY 1994	Initiated performance tests of the calculable capacitor chain for an improved determination of the SI ohm.
FY 1997	Reported improved SI-unit values of the von Klitzing constant and the fine structure constant; Initiated construction of bridges for the determination of the SI ohm over an expanded frequency range.
FY 1998	Design and evaluate standard resistors and test bridges for use at multiple frequencies.
FY 1999	Make measurements of ac QHR using extended frequency bridge.
FY 2000	Determine the SI ohm using a frequency other than 1592 Hz.

2. Establish and maintain the national standards of resistance

FY 1990	Implemented the January 1, 1990 new representation of the U. S. ohm based on the quantum Hall effect (QHE) and the International Temperature Scale of 1990.
FY 1992	Developed cryogenic current comparator (CCC) measurement system for comparing quantized Hall resistances (QHR) with 100 Ω resistance standards.
FY 1993	Completed construction of a third CCC with a ratio of 129.06/1 for use in measuring the i=2 step of the QHR; Completed two comparisons of the QHR to the 1 Ω working group.
FY 1996	Built and characterized 10 MΩ and 1 GΩ resistance transfer standards and started the first leg of a high resistance international comparison commissioned by the Consultative Committee on Electricity as pilot laboratory.
FY 1997	Developed a new automated 4.2 K CCC system for scaling measurements from 1 Ω to 10 kΩ designed to reduce scaling uncertainty to less than 0.01 parts-per-million.
FY 1998	Continue international comparison and complete two measurements of the QHR.
FY 1999	Complete high resistance international comparison; prepare and disseminate results.

3. Provide resistance measurement services for our customers

FY 1994	372 standards calibrated at a cost to industry of $366,000; Completed construction of a guarded coaxial connector panel for switching resistors.
FY 1995	360 standards calibrated at a cost to industry of $338,000; Completed development of an automated 10 kΩ measurement system.
FY 1996	327 standards calibrated at a cost to industry of $329,000; Automated 10 kΩ measurement system installed for customer calibrations.
FY 1997	348 standards calibrated at a cost to industry of approximately $352,000; Automated calibration service for resistors below 1 Ω; Initiated development of an ac resistance bridge.
FY 1998	Design and construct ac/dc reference standards at 100 Ω and 1 kΩ; Initiate special test for ac resistance standards at 1 kΩ.
FY 1999	Develop ac resistance calibration service for 100 Ω and 1 kΩ resistors.

4. Develop an automated system for the measurement of high resistance standards

FY 1995	Completed modifications of electrometer for use as a programmable detector in an automated high resistance bridge with programmable voltage sources as ratio arms.
FY 1996	Completed development of high resistance active-arm bridge system and began comparisons with existing systems.
FY 1997	Evaluated performance of the automated active-arm bridge system; Began construction of new Hamon devices to reduce scaling uncertainty.
FY 1998	Initiate active-arm bridge calibration service and extend resistance calibration range to 10^{14} Ω.

5. Develop an advanced quantized Hall resistance research and measurement capability

FY 1995	Determined the potential and current distributions in a quantized Hall device for assessing the maximum electric fields for resistance values for both direct current and alternating current.
FY 1996	Acquired and installed a new quantized Hall measurement system for increased magnetic field, variable temperature, and efficient sample exchange capabilities.
FY 1997	Designed and built new dc insert probe with high leakage resistance; Tested cryogenic system.
FY 1998	Design and build probe insert for alternating current, compatible with SI ohm measurement systems.
FY 1999	Compare the resistance value of a single quantum Hall device under both dc and ac conditions.

6. Improve the quality and performance of quantized Hall devices

FY 1994	Developed advanced alloy contact techniques for low resistance contacts and new patterning techniques for fabricating heterostructure devices.
FY 1995	Prepared and tested quantized Hall devices made from new low electron density heterostructures using the developed alloy contact techniques.
FY 1996	Determined the equivalent circuit of a quantized Hall device and calculated the intrinsic inductance and capacitance for resistance studies using alternating current.

FY 1997	Published a summary of quantized Hall device preparation and characterization techniques and test results.
FY 1998	Prepare quantum Hall devices suitable for both dc and ac measurements.
FY 1999	Determine appropriate characterization process for ac QHR devices.

7. Investigate resistance scaling techniques using cryogenic current comparators (CCC)

FY 1992	Developed method for detecting leakage currents in CCC bridges.
FY 1994	Constructed a prototype high temperature superconductor (HTS) CCC achieving a 1:1 ratio balance to within a part-per-million.
FY 1995	Developed methods for measuring load coefficients of resistors using CCC scaling.
FY 1996	Constructed a prototype HTS CCC using thick-film thallium-based shields and a YBCO SQUID detector; Measured 1 kΩ/100 Ω ratios with $5x10^{-7}$ uncertainty using HTS CCC.
FY 1997	Constructed CCC operating at liquid-helium temperatures for use in resistance scaling to support calibrations from 1 Ω to 10 μΩ.
FY 1998	Complete evaluation of prototype HTS CCC system and present results and design criteria to metrology community.
FY 2000	Develop improved HTS CCC using HTS SQUID with integrated flux transformer.

Capacitance:

1. Realize the SI farad

FY 1960	Initiated construction of a calculable capacitor in order to connect the national units of impedance with the SI units.
FY 1974	Reported the determination of the SI farad from the calculable capacitor.
FY 1980	Initiated construction of a new, improved version of the calculable capacitor.
FY 1987	Determined and reported the SI farad from the calculable capacitor.
FY 1993	Improved the conical nose piece that provides the end compensation for the calculable capacitor as part of continued improvements.
FY 1996	Reported a new value for the calculable capacitor determination of the SI farad.
FY 1997	Designed and constructed calculable capacitor bridge for use with an extended frequency range.
FY 1998	Evaluate calculable capacitor system and determine the SI farad at alternate frequencies.
FY 1999	Evaluate capacitors in the 10 pF bank at alternate frequencies.
FY 2002	Design and construct new adjustable mount for upper blocking electrode of calculable capacitor.

2. Provide the national unit of capacitance

FY 1994	Designed and assembled a capacitance bridge with the potential for a wider frequency range bracketing the value presently used (1592 Hz).
FY 1996	Provided the value of the national farad capacitor bank for calibration services with an uncertainty of $2x10^{-9}$; Initiated an international comparison of capacitance for the Consultative Committee on Electricity as pilot laboratory.

FY 1997	Determined the effect of the mounting method of the capacitance elements on the temperature dependence of the reference capacitors.
FY 1998	Complete the international comparison of capacitance and provide results and interpretation to the Consultative Committee on Electricity.
FY 1999	Provide the unit of capacitance at frequencies other than 1592 Hz.

Quantum Voltage and Current

Project Leader:	Richard L. Steiner
Staff:	5.0 Professionals, 1.0 Guest Scientist
Funding level:	\$1.4 M
Funding sources:	NIST (96%), Other Government Agencies (4%)
Objective:	Maintain the U.S. legal volt; support the Division's voltage calibration services; and develop new voltage and scaling standards, measurement techniques, and means of disseminating the volt. Measure the U.S. unit of current as established from national resistance and voltage standards in terms of the internationally defined ampere; monitor the kilogram in terms of electrical units via the watt experiment; and determine the gyromagnetic ratio of the proton in terms of the U.S. electrical units. Apply the physics of these measurements and other new phenomena, such as single electron tunneling, to the development of improved measurements and standards, especially for current standards.

Background: The services provided by this project generate the basis for accuracy and compatibility for all voltage and current measurements throughout U.S. industry, technology, and science. The standards being produced by this project tie the U.S. legal system of electrical units to the international system (SI) of units permitting competitive products by U.S. industry in world markets. The research being done is the source of superior drift-free, high precision national standards for the volt and the ampere (and assists in the ohm and farad). The work also involves evaluating new measurement techniques and standards for automated and highly accurate dissemination of these units. Another very significant effect of this research focuses on the creation of an electronic replacement for the kilogram, the last remaining SI artifact standard, and exploring the application of the new single electron tunneling phenomena to the determination of the electronic charge or the fine structure constant or for application as a capacitance standard.

Current Tasks:

<u>Voltage</u>:

1. Provide the national unit of voltage

FY 1993	Developed methods for calibration of the high accuracy digital voltmeters using the 10-volt Josephson array.
FY 1996	Replaced the computers that operate the Josephson 1-volt system and developed improved software for the operations and data analysis.
FY 1997	Participated in NCSL round robin of 15 U.S., Canadian, and Mexican Josephson array 10-V systems, with an uncertainty of $3x10^{-8}$ V/V.

FY 1998	Compare accuracy and uncertainty of NISTVolt® software against new and existing array system software.
FY 1999	Develop methods to decrease the uncertainty of 10-V Zener reference transfers to $5x10^{-8}$ V/V.
FY 2000	Develop capabilities to provide direct array-to-array comparisons of the U.S. national voltage standard system to calibration laboratories within NORAMET.

2. Improve the reliability of the voltage calibration systems

FY 1994	Rewired the automatic switches that control the voltage calibration benches and the switching of customers voltage references for a three-fold increase in capacity.
FY 1995	Replaced the computers that operate the calibration benches for more efficient operation and greater capacity.
FY 1997	Provided voltage calibration services for an increase over last year of customers' voltage references, with an uncertainty of $2x10^{-7}$ V/V.
FY 1998	Begin work on maintaining a lab standard bank of Zeners at the 10-V level.
FY 1999	Purchase and install a 10-volt Josephson array system as an integral part of the voltage calibration system.
FY 2000	Provide 10-V calibration service at the $5x10^{-8}$ V/V.

<u>Current</u>:

1. Determine the value of the NIST watt

FY 1992	Incorporated a superconducting magnet into the ampere balance for improved signal-to-noise performance and increased precision.
FY 1995	Redesigned the process for the alignment of the magnetic field, the coil motion, and the earth's gravitational force for reduced uncertainties.
FY 1996	Decreased the short term uncertainty to $1x10^{-7}$ W/W; Installed the new refractometer for the determination of the index of refraction and the new gravimeter for a more precise determination of the gravitational constant.
FY 1997	Achieved long term uncertainty of $1x10^{-7}$ W/W; Evaluated all systematic uncertainties (about 35 variables) in the NIST Watt determination; Improved automated operation to about 95% reliability.
FY 1998	Determine a value for the NIST watt with a total uncertainty of $1x10^{-7}$ W/W; Begin conversion to improved system for monitoring the kilogram.
FY 1999	Integrate system automation of Watt apparatus, refractometer, gravimeter, and Josephson array.

2. Initiate redesign of the NIST watt experiment for the next generation of improvements for monitoring the kilogram

FY 1995	Initiated the redesign of the NIST watt experiment with the objective of monitoring the kilogram, including a vacuum or gas environment.
FY 1997	Initiated construction of the vacuum enclosure for the watt balance and reconstruction of the watt balance room.
FY 1998	Modify the nonmag building for installation of a vacuum/gas enclosure; make improvements to Watt apparatus; new pickup coil, volt sensing scheme.

FY 1999	Establish the ability to monitor a kilogram mass with a continued precision of $1x10^{-7}$ kg/kg in a vacuum or low pressure environment.
FY 2000	Monitor a kilogram mass with a precision of $<1x10^{-7}$ kg/kg.

3. Demonstrate a single electron tunneling electrometer

FY 1993	Initiated studies for the application of single electron tunneling devices to metrological experiments such as capacitance calibrations.
FY 1995	Demonstrated the application of a single electron tunneling electrometer as the detector in a cryogenic capacitance bridge to determine a capacitance ratio to a few parts per million.
FY 1996	Performed measurements demonstrating the extraordinarily low leakage of the single electron tunneling electrometer and cryogenic capacitor system; Began charge noise measurements.
FY 1997	Determined location and characterization of charge noise in two devices; commissioned new SET dilution refrigerator and laboratory.
FY 1998	Combine the NIST Boulder electron pump and the capacitance bridge and cryogenic capacitors to explore a capacitance calibration using single electron tunneling technology; Continue charge noise and initiate charge offset studies with Boulder.
FY 1999	Investigate operations of SET devices at higher operating temperatures; continue charge noise studies.
FY 2000	Attempt a capacitor calibration via SET pump experiment for direct comparison to the NIST calculable capacitor; Apply results to fine structure constant determination.

4. Provide magnetic field calibration services to the Navy Primary Standards Laboratory

FY 1993	Designed a low magnetic field calibration system for use at the Navy Primary Standards Laboratory.
FY 1995	Delivered the magnetic field calibration system to the Navy Primary Standards Laboratory, San Diego, California and initiated training of Navy personnel.
FY 1997	Completed training of Navy personnel and provided consultation on the implementation of the low magnetic field calibration system into the U.S. metrological system. Task completed.

ELECTROMAGNETIC COMPATIBILITY

Standard EM Fields and Transfer Probe Standards

Project Leader: Galen Koepke

Staff: 5.5 Professionals, 0.5 Technician

Funding level: $1.1 M

Funding sources: NIST (54%), Other Government Agencies (45%), Other (1%)

Objective: Develop methods and techniques for establishing continuous wave and pulsed electromagnetic (EM) reference fields to 100 GHz; develop and improve NIST's antenna calibration services; perform research and development on probes to measure EM fields and power densities.

Background: Well-defined EM reference fields are necessary for antenna calibrations, antenna research and development, evaluation of EM field probes, and EM interference measurements. Commercial antennas and probes are generally unsuitable for metrology purposes, necessitating the development by NIST of probes which can serve as transfer standards necessary for traceability. This program area was ranked second among the top priority items by the participants of the recent EMI/EMC (electromagnetic interference/electromagnetic compatibility) Metrology Challenges for Industry Workshop, Boulder, January 1995. Thus, industry has clearly identified a need for EM field measurement capabilities that are traceable to NIST.

Current Tasks:

1. Develop methods for establishing standard EM fields

FY 1990	Developed standard field capability using pyramidal horns in the frequency range between 18 to 40 GHz.
FY 1991	Developed a time-domain method for evaluation of absorbers in the frequency range between 30 to 1000 MHz.
FY 1992	Completed development of the spherical dipole standard field radiator.
FY 1993	Completed automation of the standard field facilities.
FY 1994	Analyzed anechoic chamber absorber and compared with measurements; initiated development of small-sample radio frequency absorber quality measurement system.
FY 1995	Performed a time-domain evaluation of the NIST anechoic chamber which revealed absorber and cavity characteristics.
FY 1996	Analyzed rectangular open-ended waveguides for improved standard field generation in the frequency range between 200 to 500 MHz.
FY 1997	Extended NIST's standard field generation capability into the frequency range between 40 to 50 GHz.
FY 1998	Develop a radial, guided-wave cell for broadband field generation for frequencies up to 1 GHz; Apply broadband measurement techniques to characterization of the open area test site (OATS).

FY 1999	Extend standard field generation capability to frequencies above 50 GHz.

2. Develop antenna and probe calibration service

FY 1992	Compared the standard-antenna and standard-field methods of antenna calibration and demonstrated close agreement.
FY 1993	Evaluated antenna-antenna interaction in vertical monopole calibrations and made instrumentation and mechanical improvements.
FY 1994	Developed and evaluated the standard dipoles and provided the results to voluntary standards committee.
FY 1995	Extended the vertical monopole calibration service to frequencies up to 300 MHz.
FY 1996	Prepared documentation for loop antenna calibration service; developed a calibration service for radiated fields of standard source such as the NIST-designed spherical dipole radiator which is now a commercial product.
FY 1997	Extended monopole antenna calibration service from the current upper frequency limit of 300 MHz to 3 GHz (i.e., 3000 MHz).
FY 1998	Incorporate innovations in laboratory instrumentation to reduce measurement uncertainties in antenna calibrations.
FY 1999	Design a new anechoic chamber with improved performance at lower frequencies.
FY 2000	Upgrade the NIST open area test facility and develop a new facility at a remote site (because of high ambient field in Boulder) for antenna calibrations at frequencies below 200 MHz.

3. Develop EM field probes for transfer standards

FY 1991	Improved response of double-gap loop sensor for electric and magnetic responses.
FY 1992	Developed an improved electric-field multiprobe system with increased bandwidth and reduced field line pickup.
FY 1993	Developed a special antenna array system and receiver to detect low-level signals.
FY 1994	Performed theoretical and experimental evaluation of dipole electric field probe (dipole size: 2 cm).
FY 1995	Evaluated optically pumped, vertical-cavity, surface-emitting lasers for field probe applications.
FY 1996	Disseminated NIST-developed probe calibration techniques and uncertainty methodologies to standards committees.
FY 1997	Developed probes which will provide spectral information that can be used to discriminate against electromagnetic interference.
FY 1998	Evaluate and improve concentric loop antenna system for electric and magnetic field measurements; Perform testing and characterization of field probe which will provide spectral information.
FY 1999	Develop and evaluate higher frequency probes for use up to 50 GHz.

Emission and Immunity Metrology

Project Leader: David Hill

Staff: 5.5 Professionals, 0.5 Technician

Funding level: $1.1 M

Funding sources: NIST (52%), Other Government Agencies (47%), Other (1%)

Objective: Develop and evaluate reliable test and measurement methods for electromagnetic emission and immunity of electronic devices, components, and systems.

Background: U.S. industry needs to evaluate and control electromagnetic interference (EMI) that can impact economics and competitiveness, national security, health, and safety. The uncertainties of electromagnetic emissions and immunity measurements need to be rigorously quantified and, in some cases, reduced to make EMI measurement results reliable and useful. Major challenges are to provide reliable and cost effective test methods for a large frequency range (10 kHz to 40 GHz and, eventually, higher) and for large test volumes. Industrial clients are both manufacturers of electronic equipment, and electromagnetic compatibility and interference (EMC/EMI) test laboratories. NIST research, development, and measurement procedures provide guidelines for the entire U.S. EMC/EMI community.

Current Tasks:

1. Develop radiated immunity metrology

FY 1990	Developed and evaluated a hybrid chamber for broadband immunity measurement.
FY 1991	Developed time-domain method for broadband, radiated-field immunity measurement.
FY 1992	Evaluated the use of injection testing as a substitute for radiated immunity testing; Developed and evaluated the use of the reverberation chamber for cable shield testing.
FY 1993	Analyzed and measured the shielding effectiveness of aircraft cavities; Improved the time-domain method for shielding effectiveness measurements of thin sheets.
FY 1994	Analyzed and measured the crosstalk between transmission lines on printed circuit boards; Developed the time-domain method for measuring the shielding effectiveness of aircraft cavities; Evaluated frequency stirring for reverberation chamber measurements of radiated immunity.
FY 1995	Analyzed and improved the reverberation chamber method for measuring the radiated immunity of printed circuit boards; Surveyed and analyzed measurement techniques for the shielding effectiveness of gaskets; Developed a nested reverberation chamber measurement method for shielding effectiveness of optical fiber bulkhead connector systems.

FY 1996	Developed and evaluated alternative methods (time-domain and stepped frequency domain) for immunity measurements in reverberation chambers; Analyzed a circular aperture for use as a standard in shielding effectiveness measurements.
FY 1997	Developed and evaluated a broadband method for measuring shielding effectiveness of gaskets.
FY 1998	Develop and evaluate new methods for radiated immunity measurements that have the potential to reduce the need for costly facilities such as microwave anechoic chambers; Study in this connection the use of an array of field-sensing elements to differentiate emissions from a test object within the volume defined by the array from stray signals originating outside the volume.
FY 1999	Extend radiated immunity measurements to higher frequencies (above 40 GHz).

2. Develop radiated emissions metrology

FY 1993	Developed and evaluated a three-loop system for low-frequency, radiated-emissions measurements.
FY 1994	Used the NIST spherical radiator to evaluate shielded-room measurements of radiated emissions.
FY 1995	Conducted a successful workshop on EMI/EMC measurement needs for industry; Analyzed and measured printed circuit board radiated emissions in the NIST reverberation chamber.
FY 1996	Correlated reverberation chamber radiated emissions measurements to other facilities.
FY 1997	Developed a spherical scanning theory for characterizing weak sources in the presence of noise.
FY 1998	Determine how to combine radiated emissions from components to estimate total system radiation; Develop broadband methods for radiated emissions measurements.
FY 1999	Extend radiated emissions measurements to higher frequencies (above 40 GHz).

3. Improve measurement uncertainty estimates and methodology

FY 1996	Developed a general framework for evaluating the uncertainties in radiated emissions measurements; Evaluated the uncertainty in field strength and uniformity for alternative mode-stirring methods in reverberation chambers.
FY 1997	Evaluated the uncertainties in field measurements made in anechoic chambers, transverse electromagnetic (TEM) cells, and hybrid TEM-reverberation chambers.
FY 1998	Develop a general framework for evaluating the uncertainties in radiated immunity measurements; Evaluate uncertainties in emissions and immunity measurements due to the configuration of the test object.
FY 1999	Extend uncertainty methodologies to the issue of repeatability from site to site and from facility to facility.
FY 2000	Evaluate the uncertainties of new facilities and methods of emissions and immunity measurements; Extend uncertainty evaluations to higher frequencies (above 40 GHz).

Electromagnetic Properties of Materials

Project Leader: Claude Weil

Staff: 6.0 Professionals, 1.0 Technician

Funding level: $1.3 M

Funding sources: NIST (65%), Other Government Agencies (33%), Other (2%)

Objective: Evaluate existing and new measurement methods for characterizing the complex permittivity and permeability of dielectric and magnetic materials, as well as conductor surface resistance, over the radio-frequency/microwave spectral range 100 kHz to 100 GHz. Provide measurement services, standard reference materials (SRMs) and measurement fixtures to industry and others. Organize and implement measurement intercomparisons.

Background: Dielectric and magnetic materials have wide application throughout the electronics, microwave, communication and aerospace industries. Their applications include printed circuit boards, substrates, electronic and microwave components, sensor windows, antenna radomes and lenses, and microwave absorbers. Improved, low-cost and nondestructive measurement methods of known accuracies, covering a wide spectral and temperature range, plus SRMs, fixtures and services, are needed to support many specific industry needs. Intercomparisons provide quality assessments of national quality of material characterization capabilities.

Current Tasks:

1. Develop metrology for medium-to-high loss bulk solids

FY 1995 Published results of intercomparison of dielectric measurements using the 7 mm coaxial air line in journal article; Evaluated the performance of two nontunable stripline resonators for dielectric and magnetic measurements in the frequency range 150 to 2000 MHz; Completed a measurement intercomparison with 6 laboratories using the stripline resonator; Completed intercomparison involving 15 laboratories of dielectric/magnetic measurements of ferrites using 7 and 14 mm coaxial air line technique.

FY 1996 Developed improved full-field solutions for modeling of the 1-port open-ended coaxial probe to include probe lift-off, finite layer thickness and metal backing; Performed measurements of lift-off error using 14 and 35 mm probes and developed new calibration methods; Developed techniques for speeding up numerical integration and wrote PC mountable, user friendly software for industry use; Published theory in journal article; In collaboration with Fields and Interference Metrology Group, developed free-field time-domain techniques for measuring the properties of inhomogeneous honeycomb panels over the frequency range 50-4000 MHz.

FY 1997 Completed development of 2-port open-ended coaxial aperture technique for characterizing dielectric and magnetic properties of thin (250 μm) polymer sheets, using PC-mounted software as adapted from 1-port probe; Measured polymer films using 77 mm coaxial air line system and new 14 mm fixture and published method.

FY 1998 Complete draft of documentation for dielectric SRM service; Begin documentation for SRM service in magnetic materials.

FY 1999 Develop methods for measuring inhomogeneous and anisotropic materials.

2. Develop high-precision resonator techniques for low-loss bulk solids

FY 1995 Completed development of a semi-confocal Fabry-Perot resonator for characterizing thin substrates at 60 GHz. Resonant modes were determined, material measurements performed; Evaluated a split-cylinder (Kent) cavity used for characterizing substrates and printed wiring boards (PWBs); Evaluated split-post dielectric resonator technique for characterizing PWBs and designed four fixtures operating at 1.2, 2.0, 5.6, 10.4 GHz; supplied identical fixtures to industry; Developed measurement capability, using ferrite rod inside dielectric rod resonator, for characterizing the complex permeability tensor of bulk ferrites when biased by a DC magnetic field of up to 8×10^5 ampere-turns/m, obtained tensor data at 10 GHz, as a function of biasing field level.

FY 1996 Completed refurbishment and improvement of the NIST 60-mm diameter TE_{01p} mode cylindrical cavity to provide greater operating frequency range, 6-13.5 GHz, and more accurate loss factor measurements over a wider range of losses; Fixture is critical to planned NIST dielectric SRM service; Fabricated SRM coupons from samples characterized in cavity for industry; Refurbished a tunable coaxial re-entrant cavity covering frequency range 80-250 MHz and characterized PWB samples; Procured two more untuned reentrant cavity fixtures operating at 0.5 and 1 GHz; Developed new full-field solutions for re-entrant cavity and investigating air-gap problems; Developed technique for measuring ferrite complex permeability tensor at low-bias field ($< 8 \times 10^4$ ampere-turns/m) measurements using circularly polarized waves at 2 and 10 GHz; Measured bulk ferroelectric-oxide composites for Army client using 50 mm mode-filtered cavity; also supplied fixture to client.

FY 1997 Completed study and measurements for the Full Sheet Resonance (FSR) method; Documented Circle Fit Routine computer program for FSR measurements; Began development of reentrant cavity technique for characterizing magnetic properties of ferrites in range 150 to 1000 MHz, including new mode-matched field solutions.

FY 1998 Design and fabricate new reentrant cavity fixture for ferrite measurements; Procure new reentrant cavity fixture for dielectric measurements to replace obsolete 80 MHz unit.

FY 1999 Develop fully confocal Fabry-Perot resonator operating at 77 and 94 GHz.

3. Develop metrology for the microwave characterization of high-temperature superconductor (HTS) films and substrates

FY 1994 Developed a cryostat system, which operates over the temperature range of 4 to 120 K to measure both the surface resistance, R_S, of high temperature superconducting films at a frequency of 25 GHz, and the dielectric properties of substrate materials for HTS films.

FY 1995 Completed variable-temperature measurements of yttrium barium copper oxide (YBCO) HTS thin films supplied by the NIST Electromagnetic Technology Division (814) and thallium films purchased from industry; Performed measurements at 77 K of YBCO thick films supplied by industry; Investigated the dependency of R_S properties versus frequency at 77 K in various HTS materials.

FY 1996 Began automation of cryostat system for ease of operation; Began uncertainty and error analysis for dielectric resonator system; In collaboration with Electromagnetic Technology Division, investigated variation of HTS film R_S with film thickness.

FY 1997 Procured very high quality sapphire for dielectric rod fixture and measured losses using whispering gallery mode technique at cryogenic temperatures, applied data to uncertainty analysis; Completed automation of cryostat operation.

FY 1998 Continue measurements on sapphire and other ultra low-loss dielectrics using whispering gallery mode technique.

FY 1999 Develop methods for characterizing semiconductors and demagnetized ferrites at cryogenic temperatures.

4. Develop low-frequency impedance measurement techniques

FY 1995 Collaborated with MIT-Lincoln Lab (LL) and Genosensor Consortium by developing new automated techniques for DNA hybridization pattern detection; Completed initial permittivity measurements on DNA plus buffer solution and buffer alone, using 14 mm coaxial shielded-open technique, over range 0.3 -100 MHz and found consistent differences in permittivity signatures.

FY 1996 Completed DNA measurements at low frequencies, 0.1-10 kHz using commercial liquid test fixture and NIST designed-fixture intended to overcome electrode polarization effects; Completed theoretical study of low-frequency relaxation in single and double stranded DNA.

FY 1997 Began low-frequency DNA measurements using microelectrode array developed by LL and overcame a number of measurement problems associated with attaching DNA probes to arrays.

FY 1998 Continue measurements with microelectrode array and develop conclusions regarding whether permittivity signature differences are also detectable using array.

5. Develop metrology for characterizing thin-films

FY 1995 With Microwave Metrology Group, derived dielectric properties of thin substrates using coplanar waveguide transmission line structures; Developed low-frequency model for such structures.

FY 1996 Continued coplanar waveguide measurements and developed low frequency corrections to model; Initiated collaborative efforts to fabricate microelectronic test structures with SEMATECH and industry.

FY 1997 Continued collaborative program with industry and NIST Electricity Division for fabricating and measuring coplanaar waveguide test jigs for deriving dielectric properties of overlaid thin-film low-permittivity ("low-k") materials used in microelectronics packaging; Began development of in-situ CPW techniques for characterizing thin ferrite substrates.

FY 1998 Begin development of reentrant cavity techiques for characterizing biased ferroelectric thick films at frequencies in range 150 to 500 MHz.

FY 1999 Investigate methods for measuring thin-film ferrites under both demagnetized and DC-biased conditions at both cryogenic and elevated temperatures.

6. Develop metrology for elevated temperature characterization of bulk solids

FY 1995 Completed survey of high-temperature (to 1500 °C) techniques available for characterizing bulk solids in the range 10 - 1000 MHz; Completed detailed drawings of 1 GHz coaxial reentrant cavity and 14 mm coaxial air line fixtures capable of performing measurements over temperature range -100 to 200 °C.

FY 1996 Published the survey as NIST Internal Report 5045; Fabricated both fixtures at local machine shop and procured third split-post resonator fixture, capable of operating to 150 °C; Procured environmental chamber, capable of operating over range -80 to 300 °C and performed preliminary measurements at 100 °C.

FY 1997 Completed needed laboratory modifications in order to operate environmental chamber at maximum design temperature; Interfaced environmental chamber to PC operation for programmed temperature control.

FY 1998 Conduct material measurements over temperature range from -80 to 300 °C.

FY 1999 Complete fixtures for dielectric measurements at temperatures to 1500 °C.

FY 2000 Measure dielectrics at elevated temperatures using resonant fixture.

ELECTRONIC DATA EXCHANGE

Infrastructure for Integrated Electronics Design

(The former Automated Electronics Manufacturing project has been split into two projects - Infrastructure for Integrated Electronics Design and Infrastructure for Integrated Electronics Manufacturing)

Project Leader: James A. St. Pierre

Staff: 4.0 Professionals

Funding level: $900 K

Funding sources: NIST (100%)

Objective: Develop tools and infrastructure for the electronics industry to facilitate the exchange of product data with a focus on the design phase and the interface to manufacturing. This includes supporting the development of harmonized standards to enable accurate translation of electronic part and product data between standards, developing technology to permit data exchange of electronic component information, and developing certification and conformance testing methods for object oriented software for the semiconductor industry.

Background: To implement new management strategies such as total-quality-management, flexible manufacturing, cooperative development, and concurrent engineering, manufacturers need several types of data in computer-accessible digital formats that can be shared among them, and between them and their suppliers. These product standards and specifications are integral to the electronics industry to enable the design, manufacture, documentation, procurement, and support of modern electronics.

The traditional forums for capturing designs and manufacturing information (engineering drawings and paper specifications) are being replaced by digital formats. This information must be correct, complete, unambiguous, and efficient. According to the Institute for Interconnecting and Packaging Electronic Circuits (IPC), National Technology Roadmap for Electronic Interconnections, "The transfer from design to manufacturing is done by a machine language that was never intended to convey design information." This summarizes a large problem facing the electronics industry today, in that a large amount of time is wasted as manufacturers wrestle with ambiguities in design files. Also according to the roadmap, "Most jobs (upwards of 70%) coming into a printed wiring board fabricator or assembler lack complete information." Among the technical challenges is the development of adequate information models and standards that describe the essential characteristics of electrical and electronic products. In addition, there is a current trend towards the use of virtual components. In order to easily exchange and incorporate these virtual components into commercial products, standards, infrastructure and methodologies are required to support this new paradigm.

As a neutral third party, NIST is uniquely positioned to develop, demonstrate, and test non-proprietary solutions, information models, and emerging standards. Also, NIST's long involvement with voluntary standards organizations permits us to contribute effectively to the development of compatible standards.

Current Tasks:

1. Provide support for International Design Automation Standards to create a consistent method for representation of electronic part/product data

FY 1991	Completed determination of data requirements necessary to manufacture, test, and ship Hybrid Microelectronic Assemblies; Shifted the focus of the activity to developing an Initial Graphics Exchange application protocol as the deliverable.
FY 1992	Participated in a workshop on the harmonization of digital product data sponsored by the American National Standards Institute; Developed a first-draft harmonized model for net list connectivity and defined about 20 terms associated with the model.
FY 1993	Established multi-platform automation testbed to support the development of solutions to interoperability problems among computer aided design tools and electrical/electronic product data exchange standards.
FY 1994	Developed software to exercise the robustness of emerging Application Protocol (AP) 210, "Printed Circuit Assemblies;" Chaired Working Group 5, Test, Validation, Conformance and Qualification Support of Technical Committee 93 of the International Electrotechnical Commission; Completed and delivered draft of "Layered Electrical Products" application protocols to a committee developing the Initial Graphics Exchange specifications.
FY 1995	Contributed to the Electrical/Electronic design team effort of PDES, Inc., to complete Committee Draft version of Application Protocol 210, and submit it for approval as an ANSI standard; Developed automated electronic change control procedure for the components of the Initial Graphics Exchange Specifications and documented procedures in a NIST report.
FY 1996	Convened meetings of International Electrotechnical Commission working group to review existing standards for certification and conformance methodologies and define methodology requirements for all new standards submitted; Developed prototype library of layered electrical product object definitions and relationships; Reviewed compatibility of application protocols in the standard for the Exchange of Product Model Data with other electronic design standards and suggested modifications to resolve interoperability concerns.
FY 1997	Concluded development of the Geometric Dimensioning and Tolerance (GD&T) portion of the application protocol for printed circuit assemblies as it becomes an International Standard (ISO 1303 AP 210); Made significant contributions to the IGES standard for layered electrical products which achieved ANSI standard status; (ANSI US PRO/IPO-111-1996); Led the development of a proposal to establish a new working group on libraries of reusable electrotechnical products for the International Electrotechnical Commission (IEC); Established an IEEE study group on Electronic Commerce of Component Information (ECCI); Convened meetings of the IEC working group on test, validation, conformance and certification of standards related to electronics industry.
FY 1998	Participate in the testing of standards for the Virtual Socket Interface Alliance (industry consortia), to test emerging standards for virtual components. As

chair of the IEC working group on test, validation, conformance and certification, lead the development of guidelines for standards testing, as well as co-chairing the working group on libraries of reusable electrotechnical products; Convene meetings of the IEEE study group on ECCI.

FY 1999 Publish conformance methodologies report to transfer techniques to industry.

2. Develop tools to facilitate Electronic Commerce of Component Information and tools for conformance testing.

FY 1993 Led demonstration project team for the National Initiative for Product Data Exchange to produce proof-of-concept demonstrations showing how the National Information Infrastructure can be used to automate the brokering of electronic component information.

FY 1994 Continued to lead the Electronic Business Reply Card demonstration team, demonstrated software at CALS Expo, November 1993; Investigated use of World Wide Web server and Mosaic client for electronic distribution of the NIST storeroom catalog; Suggested improvements to Internet protocols at the Federal Mosaic Consortium.

FY 1995 Initiated and supported the creation of a Python Software Association to support all industries which use Python programming language.

FY 1996 Completed prototype electronic component dictionary browser and search engine for on-line parts dictionaries; Developed an advanced object oriented dictionary prototype.

FY 1997 Developed an object oriented dictionary browser tool to support ECCI, in collaboration with Silicon Integration Initiative; Developed a specification for a Product Information Viewer and its interface to the World Wide Web, and a phase-one implementation; Co-sponsored a workshop on Design Reuse and Intellectual Property Cores (Virtual Components) with DARPA and the EDA Industry Council.

FY 1998 Demonstrate a prototype ECCI-based design and manufacture methodology in conjunction with IIEM/ICM project; Develop a utility to assist virtual component developers by automatically generating VHDL stub, and EDIF graphical symbol files; Begin development of a process model to allow electronic commerce to be incorporated into an electronic product life-cycle development process; Investigate testing for virtual components.

FY 1999 Conclude development of process model for technical aspects of electronic commerce of component information and publish report.

3. Provide support for the SEMATECH Computer Integrated Manufacturing Framework

FY 1994 Completed first year report to SEMATECH analyzing and documenting cost of certification and conformance testing for computer integrated manufacturing framework to be 27 to 30 work-years.

FY 1995 Developed and documented technical and business model definitions for certification and conformance testing (these models included, for example, plans for how the test suite would be generated, distributed, and executed, and who would pay for certification, maintenance, and dispute resolution).

FY 1996 Developed prototype semi-automated test generator approach; Refined technical and business model definitions; Concluded phase I of task with report to SEMATECH.

FY 1997 Completed extensions to the Java/CORBA based test environment for the SEMATECH CIM Framework, that will allow using this environment for other applications, such as printed circuit board SRFF standard. Task concluded.

4. Develop prototype framework to integrate design tools for Microwave and Millimeter-wave Advanced Computational Environment program

FY 1993 Organized and conducted four-day technical meeting to discuss MMACE requirements; Converted supporting documents to World Wide Web format for interactive electronic distribution.

FY 1994 Developed Python language module to simplify creation of Common Gateway Interface (CGI) scripts for implementation of a control panel for the advanced computations environment on the World Wide Web.

FY 1995 Acted as Contracting Officers' Technical Representative, guiding two software developers in creating the final control panel; Completed control panel demonstrated; Investigated Khoros and Fresco programming languages for use in this application.

FY 1996 Finalized creation of industry-supported Python Software Association to support use of Python in this computational environment.

FY 1997 Provide additional technical guidance related to the use of object-oriented software for the MMACE framework as requested. Task concluded.

Infrastructure for Integrated Electronics Manufacturing

(The former Automated Electronics Manufacturing project has been split into two projects - Infrastructure for Integrated Electronics Design and Infrastructure for Integrated Electronics Manufacturing)

Project Leader: Barbara L. M. Goldstein

Staff: 3.0 Professionals

Funding level: $0.5 M

Funding sources: NIST (100%)

Objective: Work with industry to develop tools and standards to enable a "plug and play" manufacturing software environment for the electronics industry. This includes methodologies and standards for linking Manufacturing Execution Systems (MES) to Enterprise Resource Planning (ERP) applications, across to design, down to equipment control, and across to suppliers and dispersed sites. This project will also help the industry adapt to an electronic commerce business paradigm.

Background: As outlined in the 1996 National Electronics Manufacturing Technology Roadmaps, electronics manufacturers face tremendous pressures in today's global manufacturing environment, where being first to market is often the chief determinant of market share. Customers expect to pay increasingly lower prices for increasingly more sophisticated products; i.e., custom products at mass-volume prices. Business competition pressures manufacturers to cut costs throughout the manufacturing process, instead of raising end-unit prices. Increasing product complexity forces manufacturers to maintain flexible factories of high-capital equipment and best-of-breed software applications. Globalization of the customer base is driving the need for globally distributed manufacturing facilities and suppliers, and international manufacturing partnerships. The complexity of and speed with which information must cross corporate barriers makes it virtually impossible for prime subcontractors to impose their software choices on their subcontractors, much less on an equal partner in a joint undertaking.

Meeting these challenges requires not only the available of manufacturing automation software, but the ability to rapidly integrate and customize those tools within a facility, and among key partners and suppliers. Such ease of integration will only be possible through the development of industry standards and enabling technologies. NIST has the opportunity to assist the electronics industry to reach consensus on common information exchange practices and standards, and to encourage collaborative research on integration technologies.

Current Tasks:

1. Support industry roadmapping and needs analysis efforts

   FY 1997 Co-chaired National Electronics Manufacturing Initiative (NEMI) Factory Information Systems (FIS) Technical Working Group (TWG), which published a roadmap in the 1996 National Electronics Manufacturing Technology Roadmaps; Co-chaired NEMI FIS Technical Implementation Group (TIG), which created a technology gap analysis, five-year plan, and initial project portfolio, Chaired manufacturing integration strategy session with key industry participants; Chaired SPIE Conference on "Plug and Play Software for Agile Manufacturing" and published proceedings.

FY 1998 Publish document correlating NEMI FIS Roadmap to objectives of NIST Advanced Technology Program awardees; Work with industry through NEMI to publish 1998 FIS Roadmap; Assess needs of Contract Manufacturing community.

FY 1999 Assess industry needs through workshops and industry meetings in order to support roadmapping efforts.

FY 2000 Work with industry through NEMI to publish 2000 FIS Roadmap

2. Encourage and perform collaborative research with industry and academia in manufacturing software integration, electronic commerce and Internet-based manufacturing

FY 1997 Worked with industry to develop plan for NEMI "Plug & Play Factory" project and obtained NEMI executive council support; Developed plan for multi-lab "Internet Commerce for Manufacturing (ICM) project"; Planned the development of an Object Oriented Printed Circuit Repository specification (this would allow the transfer and querying of intelligent object-oriented electronic product descriptions).

FY 1998 Initiate NEMI FIS Plug & Play Factory project: help establish interoperability testbed and research state-of-the-art integration approaches; Develop architecture and establish demonstration scenario and business case for Internet Commerce for Manufacturing (ICM) project; Develop an Object Oriented Printed Circuit Repository specification and a working simulation of the printed circuit repository on the virtual factory floor.

FY 1999 Conclude NEMI FIS Plug & Play Factory project; Provide demonstrations and make recommendations for NEMI-endorsed integration approach; Demonstrate use of open standards to contract electronics design and analysis services, and prove feasibility of contracting assembly services, in Internet Commerce for Manufacturing project; Conclude the development of a printed circuit repository with published specification of operation and demonstration model; Develop a process model to allow electronic commerce to be incorporated into an electronic product life-cycle development process; Establish NEMI Extended Enterprise Integration project, responsive to needs of contract manufacturing community.

FY 2000 Continue to build the Internet Commerce for Manufacturing infrastructure and services; incorporate simulation and board assembly; Conclude development of process model for electronic commerce and publish report; Conclude NEMI Extended Enterprise Integration project.

3. Support standards development efforts and provide tools to case standards conformance

FY 1997 Completed development of a prototype testing environment for the SEMATECH CIM Framework, and published a web-based report demonstrating the work.

FY 1998 Build on testing environment developed in 1997 to develop an initial conformance software tool for Standard Recipe Format Files (SRFF) files;

	Support the development of the Standard Recipe Format File specification; Work with electronics manufacturers to provide a conformance testing mechanism for the Generic Equipment Model (GEM) standard.
FY 1999	Conclude GEM conformance testing mechanism; Conclude SRFF conformance testing tool.

LAW ENFORCEMENT

Enabling Technologies for Criminal Justice Practitioners

Project Leader: Kathleen M. Higgins

Staff: 3.0 Professionals, 1.0 Technician, 2.0 Support staff

Funding level: $4.3 M

Funding sources: Other Government Agencies (100%)

Objective: To apply science and technology to the needs of the criminal justice community (including law enforcement, corrections, forensic science, and the fire service) by utilizing the resources of EEEL, other NIST laboratories, and external contract support as necessary. While the primary focus is on the development of minimum performance standards, which are promulgated by the sponsoring agency as voluntary national standards, studies leading to technical reports and user guidelines are also undertaken. To accomplish its objective, the Office of Law Enforcement Standards (OLES): (1) develops methods for testing equipment performance and for examining evidentiary materials; (2) develops standards for equipment and operating procedures; (3) develops standard reference materials; and, (4) performs other scientific and engineering research as required.

Background: The Office of Law Enforcement Standards was established in 1971 through a Memorandum of Understanding between the Departments of Commerce and Justice, and was based upon the recommendations of the President's Commission on Crime. The areas of research investigated by the Office include clothing, communication systems, emergency equipment, investigative aids, protective equipment, security systems, vehicles, weapons, and analytical techniques and standard reference materials used by the forensic science community. The composition of OLES projects, which are sponsored by the National Institute of Justice (NIJ), the National Highway Traffic Safety Administration (NHTSA), and the Office of Management and Budget (OMB), varies depending upon the priorities of the criminal justice community at any given time.

The objectives of NIJ include improving Federal, state and local criminal justice systems and related aspects of the civil justice system; preventing and reducing crimes; and fostering programs that offer a high probability of improving the functioning of the criminal justice systems. Science and technology are among the tools utilized by NIJ to further these objectives and OLES renders support to NIJ in that program area. The projects that comprise OLES's program for NIJ are based upon the recommendations of the Law Enforcement and Corrections Technology Advisory Council and the needs for specific research expressed by the criminal justice community.

The NHTSA program is concerned with three types of speed-measuring devices: (1) conventional radar units; (2) the automated speed enforcement system, or photoradar; and, (3) laser speed-measuring systems. The projects that comprise NHTSA's program are based on input from both NHTSA and the International Association of Chiefs of Police. The projects reflect the needs of state and local law enforcement agencies for not only equipment standards, but also for permanent, self-sustaining testing programs to assure the reliability and accuracy of all radar units following the initial approval of a device.

OLES has been funded by OMB to facilitate the development of interoperability standards for ballistic imaging systems. Through the efforts of a team composed of staff members from EEEL and ITL, the first part of a proposed three-part standard was issued in FY 1996. Support for this program is expected to continue through the laboratory and field evaluations.

Current Tasks:

1. Develop quality assurance program for soft body armor

FY 1986	Published revision to NIJ Std. 0108.01, Ballistic Resistant Protective Materials and NBSIR 86-34444, Ballistic Tests of Used Soft Body Armor.
FY 1987	Revised body armor standard.
FY 1990	First year of multi-year effort to establish realistic quality control procedures for ballistic fabric used in body armor.
FY 1992	Completed and published the results of a limited experiment to investigate whether the physical size of body armor samples influences ballistic tests; Developed test methods to evaluate the resistance of armor to sharp instrument slashing and thrust attack.
FY 1993	Assisted NIJ in establishing the National Armor Advisory Board (NAAB).
FY 1994	Supported the NIJ Compliance Testing Program.
FY 1995	Discovered a flaw in the proposed aluminum plate test method for defining ammunition as armor-piercing; Assisted DARPA in the development of concealable military body armor.
FY 1996	Assisted DARPA in the development of concealable military body armor (continuation of program initiated in FY 1995); Tested and reported results on DARPA body armor.
FY 1997	Established working group within the NAAB to develop requirements for a quality assurance program.
FY 1998	Develop critical review of statistical quality assurance (QA) protocols used with ballistic resistant materials; Propose specific recommendations for performance assurance of ballistic resistant materials; Incorporate the QA program into the revision of the 0101.03 body armor standard.

2. Characterize oleoresin capsicum (OC) further in support of the less-than-lethal technologies program

FY 1988	Initiated three-year project to monitor the U.S. Army development effort to design and implement appropriate chemical delivery systems.
FY 1991	Began to identify the performance characteristics and requirements appropriate for inclusion in NIJ standards for less-than-lethal weapons to be established in FY 1992/93.
FY 1992	Initiated development of standard for less-than-lethal weapons delivery systems.
FY 1994	Initiated study to characterize oleoresin capsicum (OC).

FY 1995	Published NIJ Report 100-95, Preliminary Investigation of Oleoresin Capsicum; Provided technical assistance and administrative support to program.
FY 1996	Analyzed the contents of several cans of OC in connections with an incident involving the Baltimore County Police Department, where an individual exposed to the OC spray exhibited no significant reaction; prepared official "report of analysis".
FY 1997	Conducted preliminary tests for evaluation of the contents of 100 canisters of OC spray used by the Los Angeles County Sheriff's Department.
FY 1998	Complete evaluation of 100 canisters described above; Prepare statistical analysis of resulting data to determine whether any measured quantities correlate with the failure pattern observed; Publish findings.

3. Investigate DNA profiling technologies further and develop additional SRMs as applicable

FY 1988	Developed preliminary standard for DNA reporting formats.
FY 1989	Initiated two-year project to refine reporting standards, standard materials for molecular weight quality assurance, and even more sensitive detection and non-isotropic probes.
FY 1991	Synthesized and characterized several potential standard reference materials; Examined DNA coding systems and advanced and emerging DNA instrumental techniques; Completed the development of a standard reference material (SRM) for DNA genetic typing.
FY 1992	Issued SRM 2390 for DNA quality assurance testing.
FY 1993	Completed initial round robin tests of prototype SRMs for DNA profiling, employing the polymerase chain reaction (PCR) technique.
FY 1994	Re-certified SRM 2390, the restriction fragment length polymorphism profiling standard; Validated the proposed components of SRM 2391; Developed new electrophoretic methods for STRs.
FY 1995	Issued SRM 2391, the PCR profiling standard; Investigated method for typing mitochondrial DNA; First phase of a mitochondrial interlaboratory study was completed; Developed new approach to PCR amplification (i.e., "Long PCR"); Implemented laser-induced fluorescence detection for rapid detection of electrophoretically separated PCR products.
FY 1996	Implemented Long PCR technology to aid in the rapid determination of human identity; Conducted several interlaboratory studies; Revalidated SRM 2390 and 2391.
FY 1997	Started the production and certification of a set of well-defined DNA standards for mitochondrial and general DNA sequencing; Meetings held to consider the formation of a consortium of DNA chip manufacturers.
FY 1998	Finalize the production and certification of a set of well-defined DNA standards for mitochondrial DNA sequencing; Complete recertification of SRMs 2390 and 2391; Develop interlaboratory study to examine issues of DNA quantification; Evaluate the impact of NIJ grants to state laboratories; Begin studies on commercial mitochondrial DNA chip; Investigate the use of matrix-assisted-laser-desoprtion and ionization time-of-flight mass spectrometry in accurate and rapid DNA testing.

4. Prepare Digital Intercept Standard for digital telephone systems

FY 1992	Initiated a project to assist the FBI in the development of a digital intercept system for integrated services digital network (ISDN).
FY 1995	Prepared ten of the final sixteen parts of the draft standard; Continued to provide programmatic and technical support to the FBI; Witnessed first article testing and critically reviewed test data; Reviewed and commented in 14 other program documents.
FY 1996	Prepared final six parts of the requirements documentation and began to develop test methods document.
FY 1997	Completed draft of test methods.
FY 1998	Integrate test methods with requirements documents to produce a unified standard; Submit standard to outside and WERB review; Incorporate reviewers' recommendations and deliver standard, in camera-ready or electronic file format, to NIJ for promulgation.

5. Review and revision of standards

FY 1982	Three communication standards were revised to improve test methods and to change the classification system to achieve common transmission band identification; Revised metallic handcuff standard.
FY 1983	Additional two communication standards revised as above; Revised body armor standard.
FY 1984	Revised crash helmets standard.
FY 1985	Revised standards for riot helmets and face shields, body armor and personal FM transceiver standards.
FY 1987	Revised fixed and base station FM transmitters and mobile digital equipment standards.
FY 1988	Revised fixed and base station receivers standard.
FY 1989	Revised 9mm/45 caliber autoloading pistols and mobile antennas standards.
FY 1990	Revised body-worn FM transmitters standard.
FY 1996	Initiated collaboration with Canadian General Standards Board, CEN and ISO on soft body armor; Established contract with ITS for review of two NIJ communication standards and a FIPS on land mobile radio.
FY 1997	Published revisions of communication standards (0204.01 and 0205.01); Prepared statements of work and funding proposals for emergency vehicle sirens (0501.01), walk-through and hand-held metal detectors (0601.00 and 0602.00), and kits for preliminary identification of drugs of abuse (0604.00 and 0605.00); Continued support of land mobile radio effort.
FY 1998	Prepare drafts of body armor standard (0101.03), ballistic resistant protective materials (0108.01), metallic handcuffs (0307.01), ballistic helmets (0106.01), and autoloading pistols (0112.02); Monitor progress and provide support to revise standards for chemical spot test kits and color reagent for preliminary identification of drugs of abuse (0604.00 and 0605.00), walk-through and hand-held metal detectors (0601.00 and 0602.00), and X-ray systems for bomb disarmament (0603.00); Prepare draft guideline document on emergency vehicle sirens (0501.00), antennas (0204.02 and 0205.02), video surveillance equipment and batteries.

6. Furnish technical support and assistance in key areas

FY 1990	Published report on lithium batteries, hands-free communication systems, and technical assessment of portable explosives vapor detection devices.
FY 1991	Prepared reports on handgun accuracy, trunked radio systems, body armor test fixtures, field strength measurements of high power transceivers, performance of dialed number recorders, and a standard for rechargeable transceiver batteries; Developed procedure for the analysis of residues of explosives and gunshots; Developed a guide to video surveillance equipment; Developed a computer program supporting the economical disposal of police vehicles.
FY 1992	Drafted report on instrumentation to measure forces on a holster when gun is withdrawn; Issued AutoBid, a computer program used by police departments for automobile fleet management.
FY 1993	Drafted standard for flammability of mattresses for detention and corrections facilities; Updated AutoBid; Published reports on locks for corrections facilities, trunked radio systems, a test procedure of handgun accuracy, a guide to voice privacy for law enforcement radio communication systems, and a standard for dialed number recorders.
FY 1995	Updated AutoBid; Served as DOC representative for law enforcement to the Technology Reinvestment Program.
FY 1996	Updated AutoBid; Initiated protective glove project; Assisted in establishment of program to produce guidelines for forensic laboratory design; Authored interagency agreement with FBI to develop automobile paint database in conjunction with RCMP; Lend support to BFRL in conjunction with U.S. Fire Administration to re-evaluate traditional "arson indicators".
FY 1997	Updated AutoBid as interactive web site; Prepared preliminary test requirements for protective gloves; Published guidelines for forensic laboratory design; Continued support of paint database development project; Published findings from test burns; Prepared findings from 2 drugs-of-abuse studies; Continued support of concealed weapons detection project within EEEL; Supported two programs within the Office of Applied Economics, i.e., minimizing costs of the Life Safety Code for Corrections Facilities and cost-effective decisions for police patrol vehicle disposal (auto rank).
FY 1998	Continue update of AutoBid as interactive web site; Prepare draft standard for protective gloves; Publish "Forensic Science: Status and Needs" document; Continue support of projects (i.e., automobile paint database development; terahertz-wave concealed weapons detector; detection of electronic bomb detonators; computer database of Raman spectra of energetic materials; scientific study of body armor trauma plates; development of standards for knife/puncture resistant armor, concealed weapons detectors, and explosives detectors; non-eradicable marking(s) of firearms; and, development of Standard Reference Material for ballistic imaging systems); Publish findings from continued work on burn pattern analysis and four drugs-of-abuse studies; Continue support of two programs within the Office of Applied Economics as described above; Provide technical input and support to the rechargeable batteries testing program.

7. Support the quality assurance program for police traffic radar/lidar

FY 1991	Completed revision of model minimum performance specifications for radar units; Assisted independent laboratory with tests to determine compliance with specifications.
FY 1992	Initiated project to develop standard for laser based units (lidar); Initiated project to develop standard for photoradar.
FY 1994	Revised the Model Minimum Performance Specifications for Police Traffic Radar Devices; Supported the test program; completed preliminary laboratory and field tests of photoradar systems.
FY 1995	Supported the quality assurance testing program of the International Association of Chiefs of Police; Draft standard for laser speed-measuring devices completed and submitted to NHTSA; Model specifications published by NHTSA; Participated in reference speed comparison study with the Transportation Research Center, East Liberty, OH; Selected and equipped UC/Davis as IACP lidar test site; Prepared draft standard and submitted it to outside reviewers.
FY 1996	Presented and obtained approval for proposed revisions to conventional radar performance specifications; Published lidar standard.
FY 1997	Supported conventional radar and lidar test programs; Prepared draft of photoradar standard, undergoing outside review; Revised radar performance specifications to include approved changes.
FY 1998	Support conventional radar and lidar test programs; Assist in establishing a second lidar test site; Submit draft of photoradar standard to NHTSA for promulgation.

8. Development of Interoperability Standards for Ballistic Imaging Systems

FY 1996	Published NISTIR 5855, "Specification for Interoperability Between Ballistic Imaging Systems; Part 1 - Cartridge Cases".
FY 1997	Developed test procedure for Part 1 of the standard; Developed ballistic data file conformance tester; Acquired cartridges for interoperability test.
FY 1998	Conduct laboratory and field evaluations of part 1 of the standards; Continue to support interoperability effort as directed by sponsor.