Special Publication 980

A Partnership for Advanced Measurement Standards:

The Calibration Coordination Group (CCG)
of the Department of Defense and
The National Institute of Standards and
Technology (NIST)

NIST
National Institute of
Standards and Technology
Technology Administration
U.S. Department of Commerce

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Gerome Reeve and Dr. Raju Datla, Editors

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U. S. Department of Commerce
Donald L. Evans, Secretary

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

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

CCG Participating Military Organizations

Contents

Foreword

Political humor is no stranger to tales of rivalries among Government agencies, including even the military services; stories of voluntary cooperation are rare. But occasionally there are accounts of successful cooperative efforts that have yielded results far greater than expected. This report is about one such effort, which has existed for over three decades. It involves a little-known element within the Department of Defense (DoD), the Calibration Coordination Group (CCG), and the National Institute of Standards and Technology (NIST) of the Department of Commerce.

For over 33 years the CCG and NIST have had a working relationship to provide the military services with required measurement standards and expertise, and to schedule the calibration of military laboratory standards at NIST in the most efficient and cost-effective way. They have also had to anticipate totally new technologies and the measurements that they would require, so that the necessary research and standards development could take place in a timely manner. This benefited not only the military services but also American industry. Yesterday's military technological innovations often become today's industrial products. With the measurement infrastructure already developed, U.S. industry is in a unique position to capitalize on new products and gain a competitive edge in the new world economy.

On the occasion of the one-hundredth anniversary of NIST (and the 33rd of the CCG) it seemed an appropriate time to tell the story of how this partnership came to exist and to provide some highlights of what has been accomplished over these years. Besides coordinating routine calibrations of military standards for the three services at the NIST laboratories the CCG has sponsored close to 500 technical research projects to develop new standards and measurement methods in anticipation of technological advances. Since NIST also serves as the nation's primary civilian standards agency, the results of these projects quickly found their way into the country's commerce. The results, not always easy to document, have in many cases provided the source for new product development and entrepreneurial startups.

In the following pages we have documented some of these engineering projects and their results, not only for archival purposes but also to honor the efforts of the people who had the foresight to recognize the initial problems and generate solutions with far-reaching results.

> This NIST Centennial Special Publication is dedicated to the staff of the National Institute of Standards and Technology and to the members of the metrology organizations of the military services, past and present.

Gerome Reeve, Radio-Frequency Technology Division, NIST retired, and
Dr. Raju Datla, Optical Technology Division, NIST, Editors

Editor's Notes

Certain commercial firms, trade names, equipment, and materials may be identified in this document but only to describe program efforts adequately. Such identification implies neither recommendation nor endorsement by the National Institute of Standards and Technology or the Department of Defense; nor does it imply that these are necessarily the best or only sources or items available.

In regard to the many CCG/NIST projects referenced in the following sections, it has been NIST policy that these metrology projects deal only with unclassified material and aspects of military technology. While specific project reports to the sponsoring military agencies are released to the public only with agency permission, the discoveries and advances in metrological science are broadly published in archival scientific journals and quickly made available in the public domain.

When the projects described in parts 1 and 2 are referred to as CCG sponsored, it should be understood that the CCG itself has no direct funding or contracting authority. All projects are supported by R&D funds contracted out by each service's metrology organization. The CCG is the operational venue for formulating specific requirements, prioritizing, initiating, monitoring, and disseminating the results of the projects within the services.

In the following technical descriptions of the projects, the terms "accuracy" and "uncertainty" are both used interchangeably, and "error" assumes the common meaning of deviation from perfection no matter what the source. The editors are well aware of the correct metrological usages but have chosen to use terms, appropriate to the context, that would be more understandable to those outside the metrology community.

Lastly, for those who dig deeply, a technical note; the symbol K, which appears in some of the project description, particularly in part 2, stands for thermodynamic temperature in units called kelvins. To convert to the more familiar scale of degrees Celsius (° C) subtract 273 from the temperature in kelvins.

The Importance of Metrology to Defense

The Military Need

First one might ask, why are measurement standards and calibrations so important to the military services? For an answer let's turn to a real-life incident as recounted by an Air Force crewman.

The following is from a series of articles entitled "First Person … Singular" from JED, The Journal of Electronic Defense [1]. Although these stories cover the period from WWII to the present they echo many of the same themes. This one was selected for the number of instances in which the accuracy of information presented by instruments was critical to the mission and the lives of service men. It describes a mission aboard an AC-130E, a rather slow transport aircraft that had been converted to a very effective close-in ground support gunship. When faced with enemy fighters, however, the only choice was to run and/or hide. Take particular note of the italicized portions.

First Person … Singular

Jerry Stiles

I will never forget the look on our IR (infrared camera) operator's face when I said that we might have seconds to live. This night our AC-130E was assigned to an armed reconnaissance mission. Our job was to find and destroy military targets. We were on a night mission a few days before Christmas, 1971, but it was far from dark. The moon was full and reflected brightly off the solid cloud undercast obscuring the terrain below us. The glare almost blinded my *night-penetrating, low-light television targeting camera*. The radio code name of our land-based controller was "Cricket." Our code name was "Spectre."

After about two-and-a-half hours we received a radio call. On the universal emergency (or "guard") frequency came a heart-stopping message. "This is Redcrown on Guard. Bandits, Bandits, Blue Bandits." This meant that a friendly radar (Redcrown) had detected North Vietnamese MiG-21 fighters (Blue Bandits). They were undoubtedly looking for a target to engage—perhaps us—and their radar, coupled with the brightness outside, gave them a good chance of success.

Our navigator had also been keeping tabs on the MiGs. Within a heartbeat of the last warning, he called out over the interphone, "Pilot, Nav. Turn south now! Descend! *Minimum safe altitude 9,600 ft*. Those MiGs are coming directly at us!" Our pilot wasted no time. He stood our northbound AC-130 on a wing and pulled hard into the turn; we were running south in a few seconds. Our pilot was motivated, and justifiably so; the MiGs could make mincemeat of our lumbering aircraft. The rapid turn caused my TV camera to swivel and jam inside the aircraft. This, in turn, rendered us three sensor operators *(the IR camera operator, the EWO [Electronic Warfare Operator] and myself—"TV") in the "booth" blind.*

Our situational awareness was limited to observing our flight instruments, and these weren't telling a happy story. *The airspeed indicator had spooled up to 280 knots. The problem was that this was 100 knots above our maximum 180-knot, cargo-door-open airspeed limit. Our AC-130's tail could be torn off because of the loads imposed on our structurally diminished airframe. Equally perilous, my altimeter had unwound to 4,600 ft.–5,000 ft. below the declared 9,600 ft. minimum safe altitude*. Our busy pilot had no time to explain that he was visually skimming along just above the cloud deck, the bright moonlight enabling him to see and avoid the karsts (sharp mountain peaks) looming near and above our gunship. Perhaps four or five minutes crawled by. As more time elapsed, relief began to build with the feeling that, perhaps—just perhaps—we would make it. At our lower altitude, the MiGs may have missed us, and we had avoided the karsts.

But then: "Pilot, this is the IO (the Illuminator Operator: the gutsy, enlisted aviator who physically hung out the open rear door, and who directed our pirouette through flak as it came at us). I can see something! Sir, you won't believe it, but I think I see light reflecting off another airplane. He's higher than we

AC 130 Aircraft

are, but almost directly behind. I think we're being followed!" In all likelihood, the MiGs had slowed and were trying to find us. The interphone buzzed. *"Can't we go faster?"* Another minute or two passed, after which the IO announced that the reflection was no longer immediately behind us. Apparently, the MiG pilot couldn't find us even in the bright moonlight.

We were just starting to breathe a bit easier when our *radar warning receiver (RWR)* began to sing: radar had begun sweeping us. The MiG pilot behind us had begun to search with his radar. If and when the radar locked onto us, we were dead. *Our AC-130's jammers* didn't cover the MiG's radar frequency; it would have been futile to try to jam it. We were sitting ducks.

Time dragged on over the jungle. We now felt that our lives had been extended a few minutes because of our pilot's shrewd action in hugging the cloud tops. This, in turn, required that the MiG pilot look down into the terrain clutter to try to find us—not an easy task with radars of that vintage, but possible. Given our large *radar cross section*, it seemed but a matter of time.

"Call Cricket and tell them to scramble the Papas. Tell him we have a Blue Bandit on our tail and need them to scramble the Papas!" [The "Papas" were several Air Force jet fighters that were kept ready for immediate takeoff from a nearby friendly air base for just such an emergency.]

"Roger, affirmative, Papa. Gate Climb." This meant that Papas One and Two had taken off and were directed to climb to 28,000 ft. on a heading of 10°, with their target on that axis at 50 mi. The instruction to "Gate Climb" was an order to climb in full afterburner, an otherwise less-than-desirable procedure *because it consumed fuel at a prodigious rate. Gate Climb orders were reserved for emergency conditions only*. Finally, someone had recognized the seriousness of our situation, and in less than a minute, two things happened.

First, the copilot announced over the intercom, "I can see the Papas' afterburners in the climb. They're heading our way." Second, the MiG's radar sweep suddenly became silent. The MiG pilot had likely also seen the afterburners and thought it best to head home to Hanoi. The MiG had broken off. We would live another day. But our night was not over. Over our objections, Cricket once again sent us northward above the undercast in another wasted effort to find targets. Once again, the "Blue Bandit" call echoed over the radio, and once again we dropped low and dashed south. This time, however, the bandit didn't even come close. We turned tail and ran at the first hint of a problem. And believe it or not, Cricket tried to send us north again.

On this third attempt to send us into harm's way, *our flight engineer reminded the pilot that we had, in running from the MiGs, exceeded the maximum allowable sustained turbine inlet temperature for our engines for over 40 min. They could now theoretically fail at any minute (a very unlikely event given the robustness of the Allison T-56 engine, but it sufficed)*.

"Ah, Cricket, this is Spectre. Be advised that we have accumulated over 40 minutes of over-temp on our engines. We think it prudent at this time, sir, to RTB [return to base]. Else, we might have to declare an emergency at any moment." The implied threat worked. "Roger, Spectre, Cricket. Understand. You are cleared to RTB. Nice working with you tonight."

The brief, italicized sections that you noted represent instrument readings or physical quantities on which life-or-death decisions depended. For example, what if the engine intake operating temperature sensor system were giving an incorrect reading, due to lack of accurate calibration? Either the engine could have failed while on the mission or, by not pushing it as close to the limit as possible they might not have escaped the enemy fighter. What if the radar warning receiver or their main communications receiver had inadequate sensitivity that had not been detected during routine maintenance, due to improperly calibrated test equipment? The results are easily imagined! The same could be said for any of the equipment highlighted above that supported the mission. The projects sponsored by the CCG at NIST have impacted virtually all of these areas and many more. But before presenting a sampling of these projects, let's find out how the partnership started.

How the Partnership Began

In order to understand the genesis of the CCG and the rest of the story, we must return to the heyday of the cold war. The launch of Sputnik and the subsequent development of missile weapons by the three services demanded unprecedented accuracy of measurements. Comparability of measurements among U.S. manufacturers and the military depots that accepted deliveries of ordnance and other military equipment was now absolutely essential. In the field, precise electrical, mechanical, and optical measurement instruments were needed to ensure that weapons were in a constant state of readiness.

This led to the formation of metrology (the science of measurement) and calibration organizations within the services whose duties were to assure that all such measurements were within the necessary tolerances and were consistent with measurements made in other parts of the organizations and industry. This was addressed by setting up primary service standards laboratories to which all military calibrations were related. These laboratories in turn derived their references from the U.S. national standards at NBS (NIST), to which industrial measurements are also referenced.

By the mid 1960's each of the services had a fully developed metrology program and organization and a designated primary standards laboratory. A brief history of each service's metrology organization is presented at the end of section Part 1. Coincidentally, in the early 1960s an industry-wide association of calibration laboratories was formed under the leadership of NIST and key industry and military metrology engineers. This came to be known as the National Conference of Standards Laboratories, known today as NCSL International. (A short history of NCSL International can also be found at the end of section Part 1). At their annual conferences technical papers on metrology problems were presented, discussions held on how to best utilize the calibration services that NIST provided, and to exchange ideas and experiences in order to develop a nationwide infrastructure of calibration facilities traceable to NIST.

At a luncheon gathering at one of these conferences around 1965, three high level personnel from the services' metrology programs met with a representative from NIST who had been instrumental in the formation of NCSL. Corporate memory has it that the luncheon participants were: Jerry Hayes (Navy), Melvin "Dutch" Fruechtenicht (Army), Ray Bailey (Air Force), and William Wildhack (NIST). The conversation quickly turned to several problems that had developed with NIST's support of the military's primary laboratories. The rapid growth of the DoD calibration workload was straining NIST's capabilities, resulting in the service laboratories vying for priority in having their needs fulfilled. Uncoordinated piece-by-piece scheduling was also driving up the cost of NIST's services.

The answer was fairly obvious. The services needed to coordinate their scheduling of calibrations in a way that would provide a uniform workload throughout the year. In return NIST could then contract at a lower cost for a predetermined number of military calibrations and provide a more defined date for completion of the work. An unofficial committee was formed, called the ANAF Working Group (for Army, Navy, and Air Force), composed of a representative from each service and appropriate NIST staff. But soon, a more formal arrangement was needed to ensure stability as personnel changed over time. This led to the formation of the CCG, which was recognized by the DoD on December 2, 1966. A memorandum of understanding (MOU) was developed between NIST and the DoD that became effective August 22, 1968, and formalized the relationships outlined above. It also allowed for future areas of cooperation in the development of metrology engineering and support. On September 10, 1968 the CCG was taken under the aegis of the DoD Joint Logistics Commanders and became the main component of the Joint Technical Coordinating Group for Metrology and Calibration (JTCG-METCAL), now called the JTCG-CMT (for Calibration and Measurement Technology). Copies of some of the original and current authorizing documents for these groups can be found in Appendix B.

With the emergence of new technologies during the following years, the more important work of the CCG became anticipating requirements that these technologies would force upon the military metrology organizations. A special sub-group of the CCG called the Engineering Working Group was formed for this purpose. As needs were identified, early consultation with NIST determined whether new national measurement standards and techniques would need to be developed. If so, the CCG sought support from the military project offices to fund the development. Eventually this led to the establishment of Engineering R&D budgets in the three services specifically to support development of metrology.

During the peak of the "Star Wars" program, a NIST/CCG Liaison position (filled by a NIST staff member) was established, and for a time this individual had an office in the Pentagon. The purpose of the position was to help the CCG and NIST gather and analyze up-to-date information regarding measurement and standards requirements associated with new military systems while they were still in the R&D phase. This individual also raised the level of awareness of the defense R&D community regarding the importance to defense readiness of accurate measurement capabilities.

Although the R&D funding varied significantly from year to year, the work usually continued at a steady pace. If commercial applications appeared in the offing, a NIST funded research project was sometimes associated with the technical area in which the DoD was interested. This project carried out the more basic research required by the new technology, while the CCG-funded project was concerned with applying the measurement techniques to the military requirement.

Over the years the services used several managerial and funding arrangements. Often the service with the greatest immediate need acted as the project sponsor and provided the required funding. Sometimes the funding was shared by more than one service, with one of them taking the management lead. In a number of instances, basic research had already been initiated at NIST in collateral areas that provided a head start to the CCG projects.

Also with the advent of large military programs that involved all three services the DoD would often establish a central Program Office. When these programs discovered that they needed to develop new metrology standards, methods or equipment, they turned to the CCG and made use of the well-established arrangement with NIST to accomplish the work. These included the MILSTAR Program Office (a satellite communications system) and the Strategic Defense Initiative Organization (SDIO), later known as the Ballistic Missile Defense Organization (BMDO). These organizations would supply funding support for specific metrology development projects while one of the services acted as lead service manager.

Certain advantages to these arrangements should be immediately apparent. Cooperation rather than competition, and the lack of the "not-invented-here" syndrome generated economies not only in metrology research but also in areas not at first foreseen. Sharing in the development of measurement standards and methods at NIST led the CCG to joint service procurements of test equipment in appropriate technologies. Common test procedures were developed and shared by the service laboratories. But these and many other such consequences are beyond the scope of this narrative.

Major advances in microwave, electro-optical, electrical, and physical/mechanical sciences have resulted from these projects. When, often within a few years, commercial applications were developed for these technologies, the measurement infrastructure was already in existence at NIST and could be disseminated quickly to U.S. industry, as needed. The explosive commercial growth in the use of lasers, fiber-optic communication, and microwave cellular radio over the past three decades can be traced, at least in part, to the existence of this infrastructure.

What We Accomplished Together

The following two sections present examples of CCG-sponsored projects chosen by the NIST staff on the basis of technical significance, substantial benefits for the military, and/or related commercial applications. They are but a brief sample of the over 500 projects completed to date. In Part 1, we have selected six that are concerned with subjects that the non-scientist would more easily understand. These descriptions have been written in narrative form with a minimal use of technical terms and jargon, given the nature of the work. Part 2 covers 72 additional projects in more esoteric scientific areas that are described in greater technical detail. Appendix A includes a numerical listing of all the CCG projects since 1968, for which records could be recovered.

Over the last 35 years since the inception of this research partnership almost every area of technology has been represented. During any particular period the current projects naturally reflected the immediate requirements of the military services at that time. As new technologies arose, greater emphasis was placed on developing improved metrology in those areas. In order to reflect scientific timeliness in the presentations, many of the projects described in the following sections are from the last decade. Hence they reflect the technologies requiring the greatest investment during the period of the last ten to fifteen years, namely those related to electro-optics. Previous decades would have shown major investments in areas such as microwave/millimeter wave or physical and mechanical metrology.

Part 1: Highlights

Will my Gas Mask Leak?

One of the major concerns during the Desert Storm conflict was the possible use of chemical warfare, such as nerve agents or biological agents, by the Iraqis. An important element of the individual protective equipment issued to U.S. troops is a gas mask. As anyone who has tried one of these on in a military surplus store knows, it is difficult to get an airtight fit around the face because faces come in all sorts of shapes and sizes. The Army wanted to have a method that could be used in the field to test the fit on individual soldiers. An essential element of such a device is a method of measuring and accurately quantifying the amount of leakage.

Field testing chemical protective equipment.

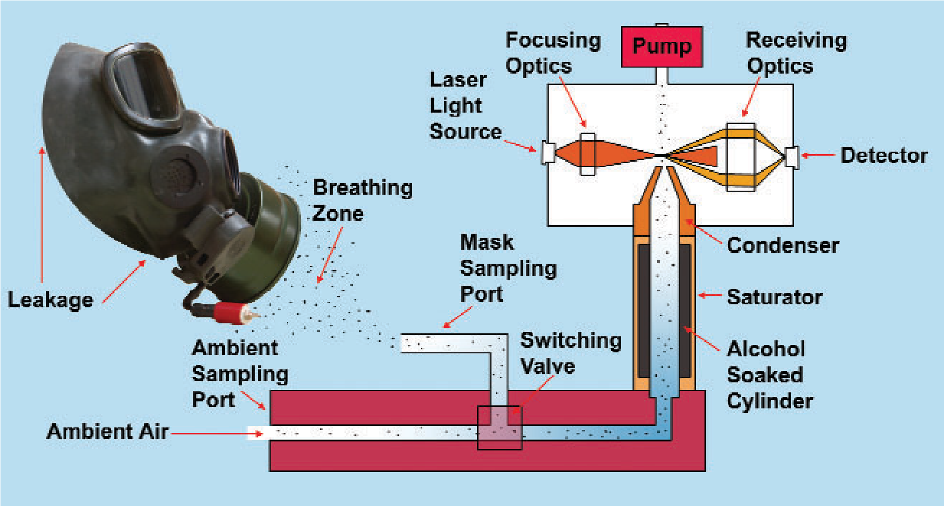
One promising way to determine the quality of gas mask fit is by measuring and comparing the ambient aerosol concentration outside of the fitted masks to the aerosol concentration inside. Small aerosol particles are used as surrogate gas test agents because they behave in a similar manner and have nearly the same fluid-dynamical properties as the airflow streams. The particles can identify both leaks in the mask and inefficiencies in the filters.

The Army, working with TSI, Inc., an aerosol instrument manufacturer, has developed the M41 Protective Assessment Test Systems (PATS) shown here to test and verify the goodness of fit for the gas mask on the individual person that is issued the device. The M41 PATS are tested and verified by the Army Primary Standards Laboratory using specialized fit-test calibration stands, condensation nuclei counters, and laser alignment systems.

The fit test procedure is illustrated below. This technology is believed to provide a complete diagnostic of the integrity of the mask, the filter and the fit to the individual. As illustrated, leakage is measured by means of two condensate particle counters (CPCs) that count both the ambient aerosol concentration and the concentration within the mask.

There are currently no aerosol concentration standards for the CPCs, nor are there certified reference materials available for standardization of aerosol concentration. Traceability is based currently upon consensus methods and standards. To ensure quality, the weakness of the traceability process for aerosols requires extensive process control, proficiency testing, and technical auditing.

The M41 tester connected to gas mask that is mounted on a mannequin head. (Courtesy of TSI, Inc.)



Schematic showing how a small aerosol is used to challenge a gas mask. The M41 is able to sense and count 80 nm particles by using them as droplet nuclei. The droplets grow to sufficient diameter to be detected by laser light scattering and idividually counted. (Courtesy of TSI, Inc.)

Through the CCG an Army-supported project has been initiated at NIST. The objective of the project is to provide measurement assurance to the U.S. Army for their gas mask fit-test method by assuring the accuracy of the aerosol concentration measurement integral to this test method. An aerosol-concentration standard test method, traceable to NIST is needed. This standard method will enable the calibration of Condensation Particle Counters that are currently used to calibrate M41 Protective Assessment Test Systems (PATS) for the Army. This is an ongoing project at NIST; results are expected in 1 to 2 years.

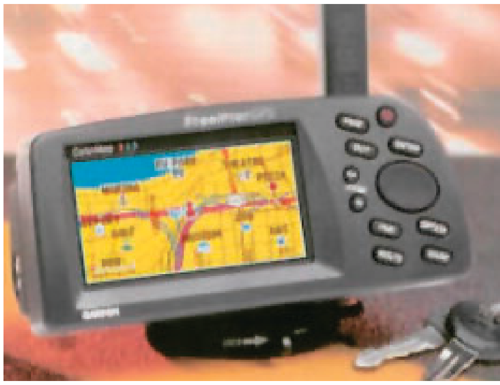
Lest one think that this is a purely military problem, fire fighters and emergency personnel responsible for cleaning up accidental industrial and transport spills of toxic substances also use gas masks. Undoubtedly this technology will be extended to private-sector uses once manufacturing costs can be reduced and a calibration method traceable to NIST established.

This work is being conducted at NIST, Gaithersburg, under CCG project 474.

Where in the World Am I?

GPS (Global Positioning System) receivers have become almost necessities to explorers, campers, sailing enthusiasts, and luxury car owners. It will be only a matter of time until these devices become standard equipment in most automobiles.

GPS receivers work by measuring the differences in timing of signals from several satellites in the GPS constellation. These satellites have ultra-stable atomic clocks that control the timing of the signals and their frequencies. Any small deviations in their signals and orbits are monitored by even more precise systems located at the national standards laboratories of many countries including, in the U.S., NIST and the Naval Observatory. The data from these ground measurements are pooled to generate corrections that, when applied to the data transmitted to a GPS ground receiver, allow its location to be known to within a few feet almost any place on earth.



Commercial GPS receiver. (Courtesy Hammacher Schlemer.)

It should come as no surprise that this system was developed first for the military. Even today, in times of international crisis, the military can add a small amount of "scrambling" to the signal to degrade its accuracy somewhat except for government users.

Commercial phase noise standard licensed by NIST. (Courtesy Femptosecond Systems.)

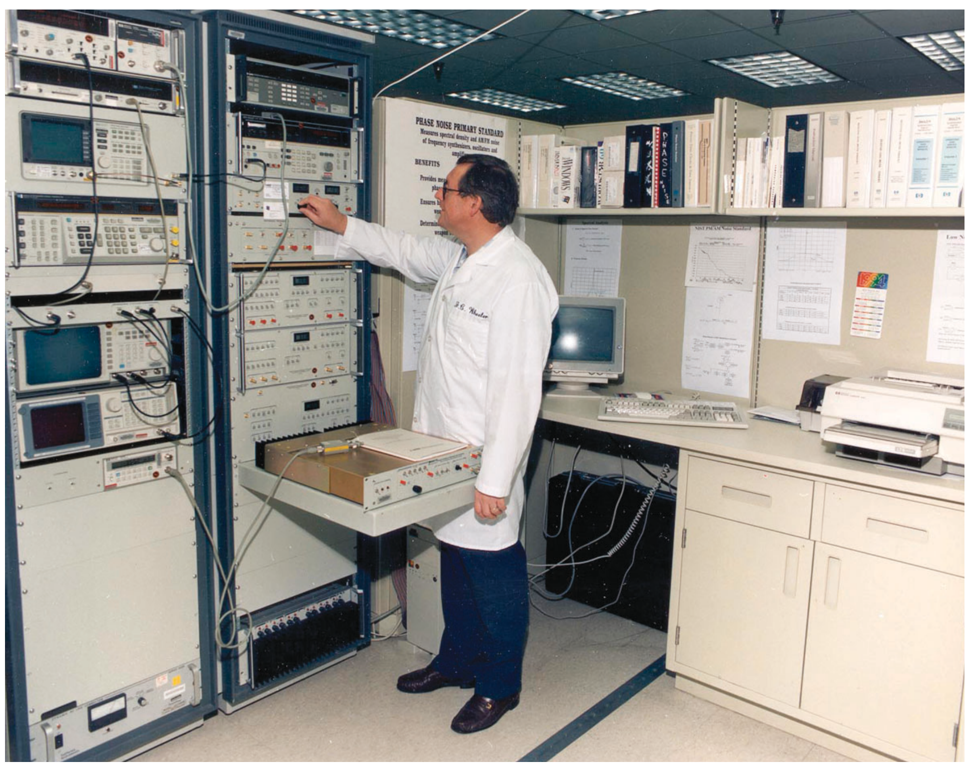
Critical to the operation of the GPS (and many other communication systems) is the ability to determine the purity or lack of noise in the many signals present within the equipment employed. The presence of phase noise on these signals eventually shows up as a time uncertainty, which translates into an uncertainty in the position of the GPS receiver. During the development of the GPS system it became apparent that both a national standard for phase noise, traceable to NIST, and a method of easily comparing such noise to commercial measuring equipment, were needed. Existing methods were so time-consuming that only engineering models and spot tests could be conducted.

In 1984 the CCG contracted with NIST to develop a technical approach and measurement equipment to meet these needs. By 1991 NIST had produced a broadband standard and an automated measurement system to compare other equipment to the standard. Four of these systems were delivered to the military services. During the next six years further work extended the frequency range of the equipment into the millimeter-wave region of the spectrum and produced a portable broadband standard that could evaluate other noise measurement systems and commercial equipment. A patent was obtained for this design and licensed to industry for commercial production. NIST capabilities now exist that will satisfy both military and civilian measurement requirements in this field for the foreseeable future.

Beyond these specific needs, the research conducted under this project resulted in major breakthrough improvements in low-noise solid-state circuits, frequency synthesizers and atomic clocks. But without the initial requirements and support provided by the CCG, NIST is unlikely to have entered this measurement field.

This work was supported by CCG projects 198, 199, 305, and 390.

NIST Phase noise measurement system at the Navy Primary Standards Laboratory, San Diego, CA.



LBIR absolute cryogenic radiometer.

Selecting the Right Target; or, You Can't Hit It if You Can't See It

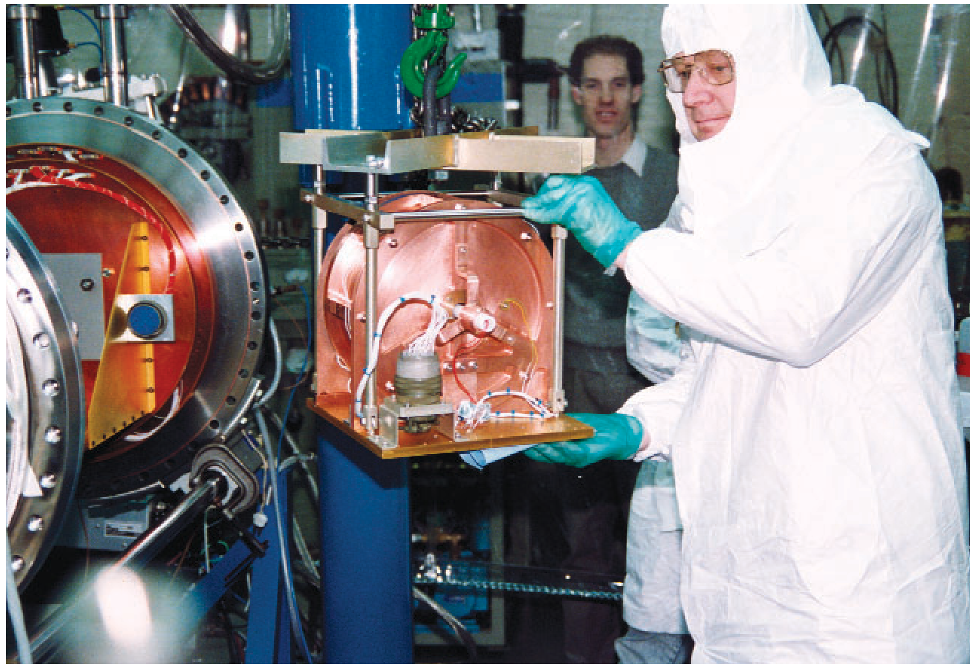
Most readers probably recall the Strategic Defense Initiative (SDI) by the more popular name given to it by the press, the Star Wars Initiative. Although its initial direction has changed significantly since inception, including a name change to the Ballistic Missile Defense Organization (BMDO), the technological challenges remain. Trying to intercept a hostile missile has been likened to "hitting a bullet with a bullet." Interception is possible and has been demonstrated in selective flight tests. However, making an interceptor collide with a warhead, when they are both travelling nearly 16,000 miles per hour in opposite directions, is an extremely challenging task. To complicate matters further, a missile defense system hardly ever gets a chance for a second shot as there is only a small window of opportunity, particularly at mid-course, when the actual warhead is deployed toward its intended target.

Radar of course can do some of the guidance chores, but many missiles have the ability to confuse the defense either by using the remaining deployment debris or specially designed dummy warheads. Early on the need for other ways of "seeing" became evident. The extremely cold backdrop of space, not much above absolute zero, provides a perfect opportunity to "see" the scene with focal-plane-array IR (infrared) sensors. Since there are subtle temperature differences among the various deployed components of the hostile missile, determining which is the real warhead should be possible.

But while there had been great advancements in the sensitivity of IR focal plane sensors, the ability to accurately measure their performance was lacking. In response to this situation, the CCG in 1986 requested that NIST undertake a survey of current and future DoD LBIR (Low-Background Infrared) calibration requirements, and to recommend a program to meet these needs. In this case, "low background" refers to the very cold background found in space, approximately 20 K (423° below zero Fahrenheit).

Based on a NIST survey of military and industrial sites involved in the SDI program, a plan was developed with the following key element: NIST would develop an LBIR calibration chamber with an absolute cryogenic (cooled) radiometer as the standard detector. This would provide primary calibration services for industry and the military so that all subsequent field calibrations would be traceable to NIST. A CCG project was then initiated under Army sponsorship, funded by the SDI program, and subsequently transferred to the Air Force.

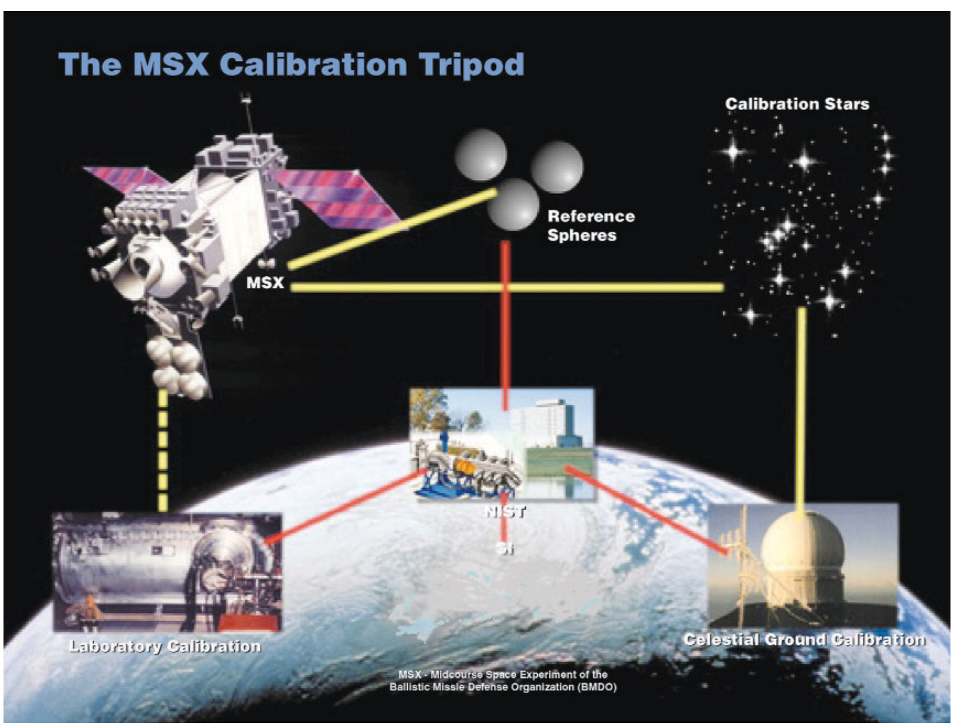
As the SDI transformed into the Ballistic Missile Defense Organization (BMDO) and practical, space deployable IR sensors were built, an experiment to test the capabilities of IR sensing and discrimination in a real missile-defense context was initiated in the early 1990's. The experiment was called the Midcourse Space Experiment (MSX). An IR sensor called the Spatial Infrared Imaging Telescope III (Spirit III) would be deployed in space and measurements made of the radiation from small man-made objects released by the test vehicle. Measurements would be made against different backgrounds such as deep space, auroras, and other phenomena such as the Earth's "limb," that slight halo that surrounds the circumference of the Earth when viewed from space. The data from this experiment, if successful, would be archived to serve as a reference point for future remote-sensing programs. Therefore state-of-the-art calibration of Spirit III became very important.



Loading the calibration fixture for the reference spheres into the LBIR at NIST.

The calibration team devised a scheme, based on three interlocking calibration methods, each independently traceable to NIST standards: ground based, using the LBIR chamber mentioned above; stellar calibration standards; and deployable reference spheres (about the size of a marble and a golf ball). The amount of energy the spheres would radiate at different temperatures was measured at NIST. The stellar (star) calibrations were made at observatories and referenced to standard sources at NIST. Spirit III also made measurements of the stars as a crosscheck of its calibration. Although the experiment may be somewhat difficult to visualize, the following figure may help one to understand the concepts.

The MSX experiment tripod.

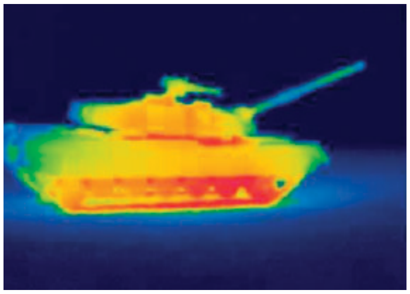


The MSX experiment was conducted in 1996, and all of the careful preparation and calibration effort paid off. Everything worked according to plan and excellent data were obtained. While much additional research and engineering work must occur before a feasible and reliable military interceptor can be developed, the basic data for "looking" at the target with infrared sensors now exist.

This work was conducted under CCG projects 354S, 404S, 410S, and 432S.

To See the Unseen—from Desert Storm to Saving Energy

The acronym FLIR (forward-looking infrared) may not be familiar to many readers, but anyone who has seen James Bond and his high-tech arsenal knows about "night-vision" goggles. FLIR is defined in the Photonics Dictionary [3] as: " … a night-vision device that uses one or more infrared sensors to scan a scene in the 3 to 5, or 8 to 12 µm (micrometer) spectral wavelength region, convert the infrared radiation to electronic data and present the resulting image on a television-like display. The term originally referred to airborne systems but now is used for any real-time thermal imaging system."

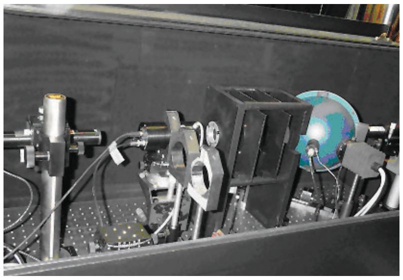


FLIR image of a tank in darkness. (Courtesy FSI Corp.)

The advantage of such a device to the military is obvious and thus not surprising that much of the initial development work was done either for or by DoD laboratories. As the technology improved, it was evident that the existing method of measuring sensitivity of these devices was woefully inadequate. The technique used a photomultiplier, a vacuum-tube device left over from World War II. Besides lacking sensitivity, the device was electrically noisy and unstable at best; an improvement by a factor of 10 was needed. The CCG tasked NIST to develop a method and equipment that could be used to calibrate night-vision goggles by use of new silicon photocell devices that NIST had developed for some very-high-sensitivity radiometers. In response, NIST designed six high-sensitivity transfer-standard detectors, three photometers and three silicon radiometers that are suitable for very-low level-optical radiation measurements. These radiometers and photometers were widely utilized as working standards in the services' primary standards laboratories.

Night-vision device detector standard.

A new radiometric method was developed for calibrating the night-vision radiometric standards and field-level night vision test sets. These test sets are used to calibrate night-vision goggles against NIST-developed detector standards. As a result of this six-year research effort, the safety and reliability of night-vision military operations was dramatically improved.

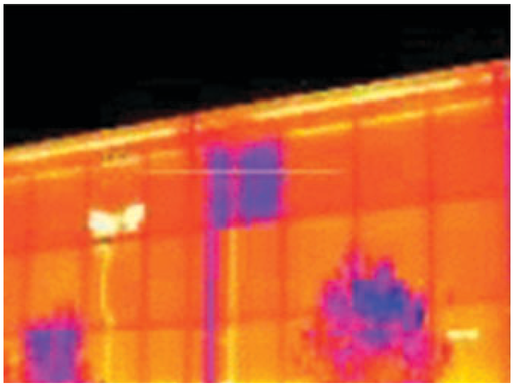


NIST primary calibration facility for night-vision detector standards.

While these particular standards were used exclusively by the military services, industry quickly realized the great commercial potential for night-vision technology. Today, numerous varieties of night-vision devices are available to consumers at reasonable prices. In developing these, manufacturers relied upon the calibration technology developed at NIST for the military.

An example of a common commercial application is shown in the figure below. Energy audits for buildings are easily conducted by observing the sources of thermal leakage, which then can be remedied by various means.

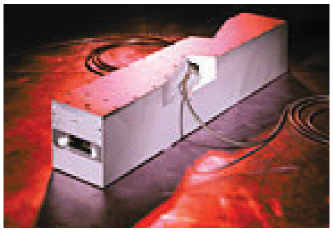
This work was conducted under CCG projects 370 and 404.



Building heat loss imaged by FLIR technology. (Courtesy FSI Corp.)

From Star Wars to Pocket Pointers

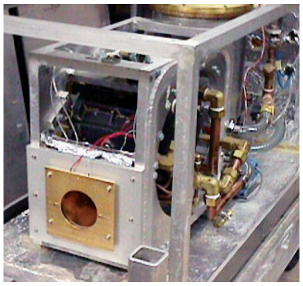
Some research and development efforts conducted by NIST for the CCG cannot be described easily by only one or even a few projects. As rapid advances in a technology took place an almost continual series of projects, each building on the ones before, was required to solve new problems that arose as the military sought to employ these advances in its operations. This is particularly true for lasers. Great scientific strides were necessary to turn what were at first scientific curiosities into the tools of industry, medicine, and military weapons. Each advance required new types of measurements to verify performance and enable manufacturers to produce a uniform product. The military has used lasers for all the applications that industry has, but has additionally developed specialized uses such as target designation and missile defense.



Industrial laser used for micro-machining metal parts. (Courtesy Spectra Physics)

The most common measurement required by laser users is determining the amount of power or energy contained in the laser beam. For almost every laser application, knowledge of the power output is critical for assessment of effectiveness as well as for safety evaluation. This is doubly so for military applications.

However, this was not a simple matter due to certain unique properties of lasers as compared to those of other light sources. These are: (a) the radiation is spatially and temporally coherent, which can create interference problems due to windows or other optics with parallel surfaces, (b) the beams have nonuniform power-density profiles that necessitate measurements across the entire beam, and (c) the energy is contained in a relatively small cross-sectional area. This can lead to very high power or energy densities that can damage or degrade detectors and other optics. If the laser is pulsed, then additional measurement problems are involved.



Front view of NIST BB-Series calorimeter (with the cover plates removed).

The standard device for measuring the power in a laser beam is called a calorimeter. This device converts the light energy into an equivalent amount of heat when the beam strikes a totally absorbing surface inside the calorimeter. There is a consequent rise in the target's temperature, which rise can be converted into an electrical signal and measured. Although simple in principle, months of evaluation are required to determine and evaluate sources of uncertainties in the measurement.

NIST began developing standard calorimeters in the mid-1960's. The CCG began supporting this effort in the early to mid-1970's and, through a series of projects, has continued this support to the present day. This support enabled NIST to develop a suite of electrically calibrated calorimeters for use as primary standards. These are specifically: (a) C-series calorimeters, for low-to-medium continuous-wave (cw) laser power or energy measurements, (b) K-series calorimeters, for high (up to 1 kW) cw laser power or energy measurements, and (c) Q-series calorimeters, for pulsed-laser measurements in the near-infrared wavelength region. (The near-infrared is the wavelength region that military range-finders and target designators use.) Copies of these standard calorimeters were built and installed at the Air Force Primary Standards Laboratory.

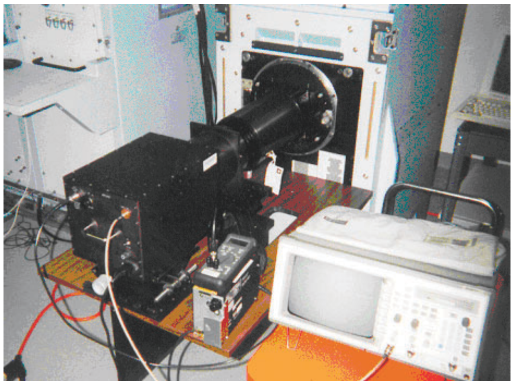
In addition to the above efforts that support both military and civilian laser metrology needs, the CCG also funded NIST to work on projects that were specifically tailored to military applications. One such effort was the development of two large calorimeters called the BB-series. These large (weighing about 400 kg), electrically-calibrated calorimeters were built to measure the outputs of very high-energy lasers (HELs) being developed by the military to be used in defensive weapons systems of the "Star Wars" program. Due to discrepancies in power measurements among different contractors, the CCG, DARPA, and NASA tasked NIST to help resolve the issue.

As a result, the BB-series calorimeters were built in the mid-1970's and transferred to the Air Force Primary Standards Laboratory, where they were used to perform high-power measurements (up to 100 kW) at various HEL sites around the country. These calorimeters are the only such devices in existence anywhere and are still in operation today. The Air Force uses these calorimeters for on-site calibration measurements as well as at remote locations, such as LHMEL (Laser Hardening of Materials Evaluation Laboratory) at Wright-Patterson AFB, Ohio, where they test materials for high-power lasers. Through current CCG support, NIST maintains its collaboration with scientists involved with current HEL work such as the Space-Based Laser and the Airborne Laser and provides consulting support to these efforts.

Sometimes the problem can be just the opposite—too little energy to measure. Military aircraft often use a pulsed laser to target enemy assets and use the return reflections to determine range and velocity. Due to the low reflectivity of most objects and attenuation by the atmosphere, the return signals typically have very small amplitudes. The laser pulses also have very short durations (nanoseconds) as this allows a more accurate range determination. The laser range-finder receiver has to maintain high sensitivity and needs to be checked periodically in the field with a specifically designed optical test set that generates a series of very-low-amplitude pulses simulating reflection from a distant target.

The need by an Air Force contractor to confirm that this type of equipment was being manufactured with the essential specifications motivated NIST's involvement in this work. Later, field performance verification was needed at the Air Force depots that support the repair and calibration of the optical test sets used to calibrate the aircraft laser range-finders. Commercial equipment that could calibrate the low signal levels and measure the relatively fast (nanosecond) pulses at the same time was not available. Through the CCG, the Air Force engaged NIST to develop transfer standards for peak-power and pulse-energy, as well as a 1.06 µm calibration system at NIST.

As a direct result, NIST established a calibration system that measures laser peak-power



The APD-800 pulsed-laser radiometer (black box) being used to calibrate an optical testset.

and pulse-energy at wavelengths of 1.06 µm and is traceable to national standards. A portable instrument called a pulsed-laser radiometer is calibrated and then used as a transfer standard at the customer's site. In this manner, calibration traceabiliy is provided to the military and DoD contractors. Operation within prescribed power levels is vital in order for laser targeting systems to function at their specified range. Early versions of the radiometers were calibrated with an uncertainty of about 12 %. Updated technology and improvements in the calibration system have allowed this uncertainty to be cut in half, depending on the particular instrument.

Later in the early 1990's, Navy aircraft were experiencing problems with their laser targeting receivers, which were more sensitive than those of the previous decade. The manufacturer's field test sets were indicating failure of many of the receivers to meet specifications, but when their receivers were returned to the depot no problems were found. Each unnecessary return cost the Navy $13,000. Through the CCG, the Navy contracted with NIST to develop a new peak-power laser radiometer to calibrate the test set supporting aircraft laser receiver pods. In response NIST developed the APD-800 radiometer, which is 10 times more sensitive than the earlier unit, much easier to use in the field, and does not require cryogenic cooling. Since the initial development, more units have been constructed and this transfer standard has been implemented in several Navy and Air Force facilities around the country. It is estimated that use of this portable transfer standard has saved millions of dollars in unneeded depot returns over the years. Follow-on interest in this radiometer by the Army led to CCG support of the development of an adaptation that can measure pulse energy and peak power in the same instrument. At this time, only the Army fields this version of the radiometer.

Continuing support by the CCG under Navy sponsorship led to the development of a radiometer operating at 1.5 µm to support the next generation of laser receiver systems. New laser range-finder systems being delivered

Air Force F-16 with LANTIRN laser target designator/rangefinder pod.

for the military are operating in the 1.5 µm wavelength region, due to concerns for eye safety. A prototype radiometer is currently under development to provide a field-level instrument to serve as the calibration transfer standard at wavelengths in this region.

And what has all this to do with pocket pointers? The capabilities developed at NIST, as a result of CCG support, provided the necessary metrological equipment and knowledge to support industrial-safety measurements of the energy output of the laser diodes in the popular pointers used by speakers to highlight important points on projection screens.

The importance of this work can be judged by the number of existing airborne platforms supported, including the A-6E Intruder, F/A-18 Hornet, AV-8B Harrier, F-117 Stealth Fighter, and the Hellfire missile.

This work was supported by approximately 19 different CCG projects.

No More Messy Wet Cells for DC Measurements

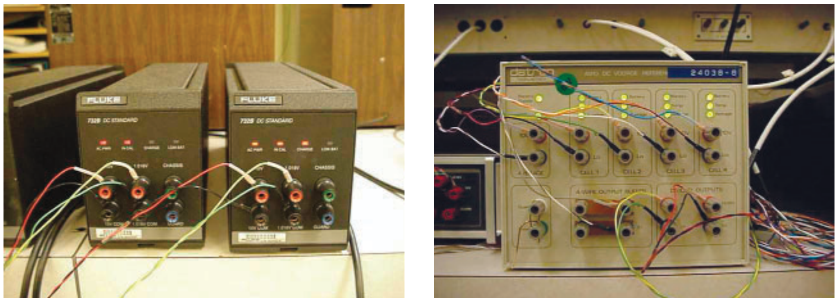
All of us who drive automobiles and use flashlights are familiar with two kinds of chemical batteries that generate DC voltage, although we sometimes misuse the scientific names. Technically the flashlight uses a primary "cell" (or several of them in series). The arrangement used for automobiles (or with a different chemical regime, for laptop computers) is correctly referred to as a battery which is composed of several rechargeable secondary cells. Both primary and rechargeable secondary cells are manufactured in either a dry form, e.g., a flashlight cell, or in a wet form as found in automobile batteries.

For most of the 20th century the standard calibration source of DC voltage for laboratories was a specially designed saturated cadmium sulfate wet cell, commonly called the Weston cell. If properly fabricated and properly handled, it was an excellent source of constant voltage. However, not only did it possess all the problems of any liquid wet cell but, if the best stability were desired, it could not be physically moved from place to place. This might be fine for a high-level standards laboratory but was totally impractical for portable meters, which therefore had limited accuracy.

Two scientific developments were to change this situation. One of the early developments of the semiconductor industry was the Zener or reverse-breakdown diode. If this device is connected to an appropriate current source, a constant voltage is developed across the Zener diode. This voltage to a large degree is independent of changes in current, and in some cases insensitive to modest changes in temperature. While their long-term stability did not match that of the Weston cell, they were useful as short-term transfer standards.

A short while later a major breakthrough occurred in the generation of a known, standard DC voltage. The behavior of this device, called the Josephson junction, is based on rigorous physical laws (see description in the following section, part 2). Many years were required to reduce this device to practice, but it is now used in all of the highest-level standards laboratories. Unfortunately, it requires cryogenic cooling, which limits its portability, and its size is cumbersome (it doesn't fit in your pocket).

Since Weston standard cells did not immediately disappear from secondary-level laboratories, these cells were calibrated against the Josephson junction standard by use of a



Commercial Solid-state voltage standards.
(right - Courtesy Fluke Corp. left - Courtesy Datron Corp.)

Zener-diode voltage source as a short-term, intermediate transfer standard. In performing these calibrations over a six-year period, NIST scientists gained considerable knowledge about the diodes' behavior, leading to their possible use as secondary built-in standards for portable equipment. These data were published in the scientific literature and work was pursued on equipment specifically designed to calibrate Zener diode voltage standards.

As part of a plan to influence manufacturers to incorporate needed capabilities into DC Zener diode voltage performance standards, the Air Force Metrology Program sponsored a CCG project to write NBS Technical Note 1239 [3]. Then, requirements for manufacturers to comply with that publication were incorporated into a solicitation to procure DC Voltage Standards for the Air Force's Precision Measurement Equipment Laboratories (PMELs). From this start Zener diode voltage references came to be incorporated into virtually all portable-voltage-measuring equipment, including meter calibrators and independent voltage standards. And yes, some of them do fit in your pocket!

The uncertainty of these standards represented an improvement of over 37 % as compared to the standard cells that they replaced. This improvement made it possible to support working-level calibration standards and test, measurement, and diagnostic equipment to meet Air Force calibration requirements. These DC voltage standards also permit their use in more efficient calibration methods that save approximately 40 % of the time required by prior standard-cell applications.

Work was conducted under CCG project 372.

Conclusions

The above are just a sample of some of the almost 500 projects that were initiated under this program. Several examples of major cost savings that accrued to military operations as a result of the CCG Engineering Working Group's cooperative program with NIST have been noted. Many more exist that have never been documented.

NIST scientist calibrating a solid-state DC voltage standard.

Two conclusions seem apparent from this long and successful effort over the last 30-plus years. First, a solid and dependable system of cooperation, not only between two federal agencies, but also among the military services, has been established for acquiring the measurement-technology base needed for today's and tomorrow's military operations. As more joint military operations and hardware acquisitions are conducted in the future, the DoD now has a proven mechanism in place for metrology R&D support. Joint program offices such as MILSTAR and BMDO have already discovered this benefit.

Second, it is difficult to estimate the value of the impact that this research has on the U.S. industrial infrastructure. These are the latent benefits to American industry that are realized when the technological areas that were opened by the military's research and development programs later become available to, and are put to use in, commercial applications. With a common metrology base already in place, rapid civilian development of new products results, driving our country's commanding world-market presence in commercial space applications, telecommunications, computers, and semiconductors.

Brief Histories:
The Services' Metrology Programs and Beginnings of the NCSL

The Air Force Metrology and Calibration Program

The United States Air Force calibration program was initiated in January 1952. The Dayton Air Force Depot, located at Gentile Air Force Station, Dayton, Ohio, developed and implemented a plan to ensure traceability to national standards that would apply to all measurements made on any weapon system in the Air Force.

The Dayton Air Force Depot was given the authority to establish a centralized calibration program. Under their plan, the Air Materiel Area Depots were given a set of measurement standards, which were periodically calibrated by the Dayton Air Force Depot using standards traceable to the National Bureau of Standards.

The operational success of a "Test Shop" program set up at March AFB, California, on September 15, 1957, led to establishment of the base-level Precision Measurement Equipment Laboratories, starting with Westover AFB, Massachusetts, on August 3, 1959. By February 1960, there were 136 bases outfitted with Precision Measurement Equipment Laboratories providing the Air Force with a complete calibration system that could handle the increasingly stringent measurement needs of the new missile and aircraft systems.

The Dayton Air Force Depot facilities were becoming inadequate to support the increasing accuracy requirements of the Air Force so the search for a suitable replacement facility was begun in 1958. Air Force Industrial Plant #48 at Heath, Ohio, contained most of the features desired, such as the underground facilities and a stable seismic environment. On February 1, 1959, it was redesignated the Heath Maintenance Annex of the Dayton Air Force Depot. Authorization to begin construction was given by public law on June 9, 1960.

The Dayton Air Force Depot personnel associated with the Air Force calibration program began their moves to the Heath Maintenance Annex in April 1962, and by June, most had been relocated to Heath, Ohio. In June, the name was also changed to the 2802nd Inertial Guidance and Calibration Group under HQ Air Force Logistics Command. By July 1962, the Metrology function was fully staffed. By the end of 1962, the primary calibration labs and the Air Force Measurement Standards Laboratories were completed, consisting of four levels underground containing 20,000 square feet of laboratory area. In November 1962, the facility was named Newark Air Force Station.

In 1965, the Air Force assigned management of the worldwide Precision Measurement Equipment Laboratories certification pro-

Air Force Metrology and Calibration Center, Heath, Ohio.

gram to the Calibration and Metrology Division. In 1968, the 2802nd Inertial Guidance and Calibration Group was deactivated and replaced by the Aerospace Guidance and Metrology Center (AGMC). The Calibration and Metrology Division was changed to the Directorate of Metrology on November 8, 1968. Newark Air Force Station was renamed Newark Air Force Base in June 1987.

During the 1990's, privatization took place at Newark AFB. This has resulted in the functions of the Air Force Primary Standards Laboratories, and Technical Order preparation, being performed by a private contractor. The Air Force created the Air Force Metrology and Calibration Program Office (AFMETCAL) at Heath, Ohio, to manage metrology services for the Air Force, retain engineering authority for all calibrations performed in the PMEL labs throughout the Air Force, and manage the contractor operated Air Force Primary Standards Lab. This is the present configuration of the Air Force Metrology program.

The Army Metrology and Calibration Program

The Army did not have a unified calibration program until 1962. Prior to that time, a number of individual programs existed, each designed to meet particular requirements. (The Ordinance Corps used a 1½ ton van carrying about 20 instruments until 1958. The Signal Corps used converted buses for their mobile calibration team operations.)

The missile program in the Ordnance Corps generated a tremendous increase in calibration requirements and, by 1959, the Ordnance School at Aberdeen Proving Grounds, Maryland, was conducting a 19-week calibration course to train military, civilian, and NATO personnel in measurement techniques. The Ordnance Corps established Frankford Arsenal, Philadelphia, Pennsylvania, as a Primary Standards Laboratory for the east coast, and Benecia, California, as a primary facility for the west coast. Five Ordnance Depots had been designated as secondary reference laboratories and were certified by the primary facilities. Each of these five depots had mobile calibration teams to support their area of responsibility.

In 1962, the initial AR 750-25 was published delineating a single Army Calibration Program. Frankford Arsenal was designated the Army Metrology and Calibration Center, and included the Army Standards Laboratory primary facility. In 1967, the Army Metrology and Calibration Center and the Army Standards Laboratory were moved to their present location, Redstone Arsenal, Alabama, the home of the U.S. Army Missile Command (MICOM).

From the late 1970's through the mid-1980's the Army consolidated and relocated virtually all Army test, measurement, and diagnostic equipment (TMDE) activities and management functions to Redstone Arsenal, Alabama. All Army calibration laboratories and support centers were placed under a common command and control structure. The new U.S. Army TMDE Activity (USATA) included all military and civilian calibration teams and laboratories worldwide. It also included the Army's Test Equipment Modernization program (TEMOD), the Army's general purpose Integrated Family of Test Equipment (IFTE) program, the Army's acquisition program for calibration sets (Cal Sets), and the Army's radiation and dosimetry programs.

During the 1990's, the metrology and calibrations program's structure continued to evolve. The Army Aviation Command was moved to Redstone Arsenal and combined with MICOM to form a new command, Army Aviation and Missile Command (AMCOM). TMDE acquisition programs were centralized

U. S. Army Primary Standards Laboratory Complex, Redstone Arsenal, Alabama

(top photo) Army Primary Physical and Electrical Standards Laboratory (Building 5435).
(bottom photo) Army Radiation Standards and Dosimetry Center (Building 5417).

in a formal program management structure within the new AMCOM. Some USATA field calibration laboratories were closed, others were consolidated, and military presence was reduced. USATA was consolidated with AMCOM, even though USATA's director remains the Army's Deputy Executive Director for TMDE.

Among the military services, the Army remains the only straight-line hierarchy with a single Senior Executive Service director responsible for all operational aspects of calibration and metrology, military and civilian. The Army is also the only service to have its primary laboratory and one of its support centers accredited to ANSI/ISO/IEC 17025.

Today, the U.S. Army metrology, calibration, and TMDE support program is poised to respond to the Army's global missions, which stretch from the Middle and Far East to the Pacific, Europe, and throughout the continental United States. This support mission extends from the modern battlefield to the nation's weapons laboratories, and ranges from the two-person calibration and repair team to the Army's highest-level calibration laboratory.

The Navy Calibration and Metrology Program

The Navy's formal program began back in 1956 with its Bureau of Ordnance (BuOrd). In part, its creation resulted from the problems the country was having with missile failures in a scramble to counter Soviet military and space developments. In the case of the Navy, a high percentage of TERRIER, Tartar, and TALOS ship-to-air missiles that were accepted at contractor's plants were being rejected when they reached BuOrd's ammunition depots. A study was commissioned by BuOrd and performed by the Missile Evaluation Department of the Naval Ordnance Laboratory, Corona, California. This study revealed that a lack of test, measurement, and calibration controls common to both contractor and Navy facilities was the principal cause.

This inability of the measurements of one activity to agree with those of another when testing identical items had serious consequences in development, design, and evaluation efforts at the factory, depot, and fleet levels. These incompatibilities resulted in undue rework and shipping costs as well as serious doubts as to the validity of the measurements leading to designs and subsequent factory specifications, emanating from development activities. As a result, action was undertaken by BuOrd to assure the following: that common tests and tolerances were specified at the factories and depots, that calibration systems were available to control the uncertainties of the test equipment being used, and that all measurements were controlled and traceable to one common source, the National Bureau of Standards.

The formal program to centralize the engineering aspects of metrology and establish a hierarchy of Navy laboratories originally covered only the ammunition depots. The newly formed Metrology Branch at the Naval Ordnance Laboratory, Corona, California, was assigned as the central engineering group to define the requirements of a program, acquire and distribute measurement equipment for laboratories, prescribe calibration methods and procedures, identify calibration recall intervals, and train personnel.

Prior to 1955, some standards laboratories and calibration facilities existed in prime contractor plants and the depots of the Bureau of Aeronautics (BuAir), Bureau of Ships (BuShips), and BuOrd. These were primarily focussed on dimensional measurements, but included some capability for electrical measurements. BuOrd had a prime interest in gaging of ordnance such as shells and gun barrels, BuShips in dimensional measurements of shipbuilding materials, and BuAir in mechanical and electrical measurements for aircraft construction and rework equipment.

With the merger of BuOrd and BuAir, which became the Bureau of Weapons (BuWeps), the program included aviation depots. BuShips "joined" the program around the same time. The Navy's Special Projects Office, responsible for developing the Fleet Ballistic Missile program, was included in the same time frame as was the Marine Corps. Thus, a Navy-wide calibration program emerged. The Office of Naval Material (NavMat) formalized this when, on March 20, 1959, it released SECNAV Instruction 4355.11 and, in July 1959, released a document called the Standards Laboratory Information Manual (SLIM). It was prepared at the request of the FBM Special Projects, for use by Navy field activities as well as Navy contractors. With this action, the Navy Calibration Program has been tied historically and closely to its fleet and field activities as well as its prime and subcontractors.

The NOL (Naval Ordnance Laboratory) Measurement Standards Branch was relocated in January 1957 to the Naval Industrial Reserve Ordnance Plant in Pomona, California, which included the Navy Gage and Primary Standards Laboratories. In the early 1960's, this was designated as the Navy Metrology Engineering Center. Soon after, the responsibility for providing primary laboratory services was transferred to the Naval Air Rework Department of the North Island (San Diego, California) Naval Air Station, and to the Navy Yard, Washington, D.C. In 1993, the Navy Yard in Washington was closed and the facility at North Island took over sole responsibility. Now known as the Navy Primary Standards Laboratory, Engineering Directorate, Naval Air Systems Command, it provides the highest level of calibration to the Navy and its supporting contractors.

Unlike the case in the other two services, the Navy Metrology Engineering R&D work was not co-located with its primary calibration laboratory, but situated first at Pomona, California, as noted above. In the late 1970's this work was organizationally transferred to the Naval Weapons Station, Seal Beach, California. Beginning in 1986 the component organizations began a physical relocation to the Corona, California, facility, designated the Naval Warfare Assessment Center, and established as an independent command. While there have been minor reorganizations during the 1990's, the group's metrology and gage missions have remained intact. Recently they acquired a weapons test certification function and currently form the Measurement Science Directorate of the Naval Surface Warfare Center (NSWC) at the Corona, California, site.

U.S. Navy Measurement Science Directorate, Corona, California.

NCSL International

The idea for an organization such as the National Conference of Standards Laboratories (NCSL) International was first proposed in 1960 by Harvey Lance of the National Bureau of Standards in Boulder, Colorado. At that year's Conference on Electronic Standards and Electronic Measurement, he delivered a paper entitled "Where Do We Now Stand?" His provocative paper posed six very significant problems concerning Measurement Standards Laboratories and suggested that the solution might be found in establishing an organization whose charter would include a method for dealing with those types of problems.

The suggestion met with resounding approval and, in 1961, with the backing of a group that was a veritable "Who's Who" of major U.S. corporations, the objectives of the organization were put forward. With the authorization of NBS Director Dr. A.V. Astin, the Bureau assumed a sponsorship role for the new organization and assigned William A. Wildhack as the first NBS liaison to the NCSL.

Over the years, the original NCSL organization has expanded to include international members. Its frame of reference has expanded from the Standards Laboratory to all elements of measurement, and the corporate membership roster is over 1400 organizations strong and growing. Since 1985, NCSL International has operated independ-

Navy Primary Standards Laboratory, North Island, San Diego, CA.

ently from its original NBS sponsor, but continues to maintain a formal liaison and close working relationship with them. (NBS is now known as the National Institute of Standards and Technology, or NIST.) In 2000, the name of the organization was changed to NCSL International to reflect its continuing and expanding role in the international metrology community.

Acknowledgements

The editors acknowledge the technical assistance of the many NIST staff members both in Gaithersburg, Maryland, and Boulder, Colorado, too numerous to name individually, who contributed information on the projects portrayed in this history. Thanks are also due to the following individuals, past and present, in the metrology and calibration organizations of NIST and the three military services who provided guidance and background material that otherwise would not have been available.

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Naval Surface Warfare Center,
Corona, California

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Navy Primary Standards Laboratory
North Island, California

Mike Cruz
(Retired), Past Director,
Navy Primary Standards Laboratory,
North Island, California

Jerry Hayes
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Naval Metrology Engineering Center,
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Dr. Brian Belanger
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Past NIST-DoD Liaison

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Part 2.

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Part 2: Digest of Selected Projects by Technical Area

Electrical/Electronic

1. NIST 100 ampere Transconductance Amplifier, and AC-DC Transfer Shunts.

CCG Project 425, Air Force sponsorship

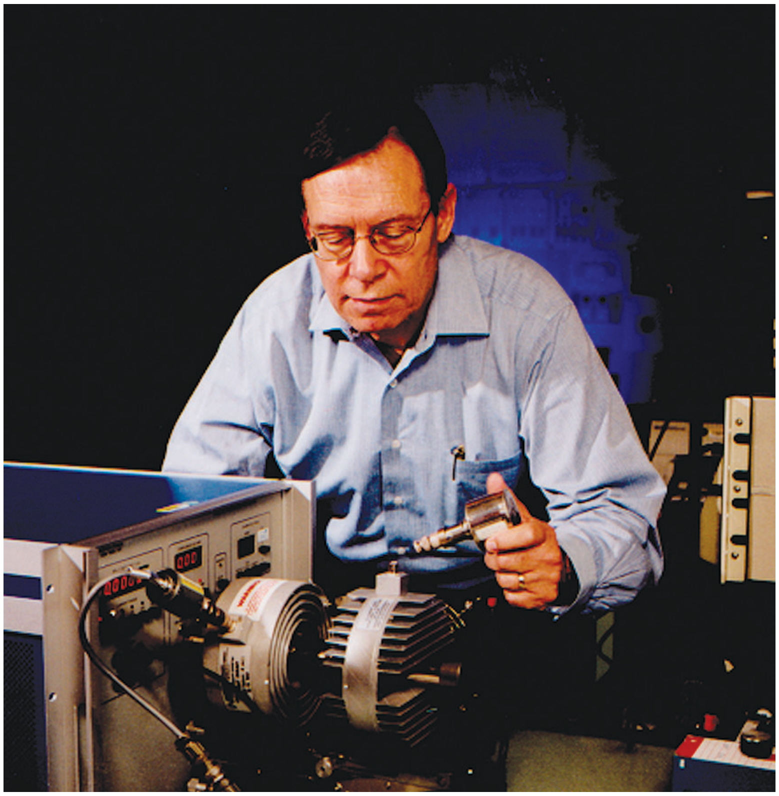
Industrial and Air Force needs developed in the early 1990's for AC high-current/high-frequency traceability in such applications as high-frequency welding techniques, harmonic power measurement by the utilities, and accurate measurement of current in high-current switching supplies by manufacturers of power supplies. There was also the requirement for NIST traceability of current shunts to support a new 100 A, 100 kHz transconductance amplifier coming into use in the U.S. Air Force's calibration system. Addressing these needs for NIST broadband calibration services for electrical current required the development of calibration sources and stable calibration reference standards. CCG project 425 was established to develop these capabilities.

A new high-current, wide-band transconductance amplifier was designed and built that provides an unprecedented level of output current at high frequencies with exceptional stability. It is capable of converting an applied signal voltage into a ground-referenced output current up to 100 A rms over a frequency range from dc to 100 kHz with a usable frequency extending to 1 MHz. The amplifier has an output capability of 1000 W, a compliance of ±10 V, and can deliver up to 400 A of pulsed peak-to-peak current. The amplifier design is based on the principle of paralleling a number of precision bipolar voltage-to-current converters. It incorporates a unique ranging system controlled by opto-isolated switches that permit a full-scale range from 5 A to 100 A. This design is the basis for a commercial product, the Clarke-Hess Model 8100 transconductance amplifier, which is extensively used in the Air Force primary and secondary laboratories.

To support this new amplifier, NIST developed new high-current, ac-dc transfer shunts using a three-terminal, coaxial design, including wide-band, two-stage current transformers as working standards for the NIST calibration service. Candidate, prototype devices from commercial sources were evaluated, but most of the designs submitted were found to exhibit very large AC-DC differences of the order of 30,000 μA/A at 100 kHz. Such large AC-DC differences can be measured; however, the measurement uncertainty would become quite large. As might be expected from shunts with such large frequency coefficients, these sample shunts generally exhibited poor stability, making them unsuitable as reference standards.

Early work at NIST found that a four-terminal shunt of surprisingly high quality could be obtained by paralleling a large quantity of low-power metal film resistors between two copper plates and connecting the potential terminal at the center of the resistor matrix.

Testing a Model EL-9800, 100 A, transfer shunt using the NIST 100 A, transconductance amplifier and NIST 100 A, transfer shunt.



These shunts of NIST design have small inductance and low skin effect. Their large, distributed structure allows good thermal contact to heat sinks. These characteristics make it possible to calibrate the shunt at low current against existing standards and then use the device at higher currents at a reasonable level of uncertainty. These NIST shunts are the basis for commercially made ac current shunts, the Model EL-9800 made by Precision Measurements, Inc., and are used by the Air Force as calibration standards for the Model 8100 amplifier.

2. NIST Wideband Sampling Voltmeter

CCG Project 328, Air Force Sponsorship

Alternating voltages and currents (AC) are easy to measure when they have a pure sinusoidal waveform. In this case, there are exact mathematical relationships among the peak, peak-to-peak, average, and RMS (root-mean-square) voltage values of the waveform. However, due to distortion from various sources, sometimes the signal is not sinusoidal.

When the RMS value (which represents the heating value of the current) of such a signal is desired, engineers used to resort to calorimetric determinations, where the signal under test was used to create heat, and the rate of heat production was assumed to be proportional to the RMS value. Besides being very time-consuming, the measurement has uncertainties of its own.

Modern solid-state electronic circuitry can be devised to measure the instantaneous value of the waveform at closely spaced intervals in time, creating a digital reproduction of the waveform from which other parameters can be accurately calculated. When commercial RMS voltage instruments started entering the military test inventory, the CCG contracted with NIST to develop a wide-band sampling voltmeter that would fulfill a number of requirements at lower uncertainties and be traceable to national basic standards.

NIST had already begun work on sampling circuitry. A method and instrumentation for accurately sampling and digitizing repetitive waveforms was developed in the mid-1980's and known as a sampling voltage tracker (SVT). This sampling method is capable of making state-of-the-art, equivalent-time measurements for signals with frequency components up to 2.5 GHz. The rf voltage measurement accuracy of the SVT has been shown to be comparable to that of thermal voltage-converter standards.

The key element in the SVT circuit is a strobed analog comparator, the design of which is critical to the closed-loop performance that can be realized using this sampling method. Although the NIST SVT circuit was shown to have excellent performance characteristics, a more convenient form of this sampling method was implemented with a successive approximation feedback loop for establishing the reference voltage. This was referred to as a Sampling Comparator System (SCS).

Combining the above with the development of a timebase that could be accurately synchronized to the input signal frequency, this CCG Project resulted in the realization of an accurate wide-band sampling voltmeter (WSV) that can span the frequency range from 10 Hz to 200 MHz. This instrument has a number of unique capabilities, including the feature of an update rate of at least one measurement per second, even for input signals at 10 Hz. The time base has been further enhanced with an improved gated-oscillator design and an internal calibration algorithm.

With the ability to utilize SCS-based input probes having different bandwidths, input signal levels, frequency flatness, settling time, and uncertainty levels, this instrument can be used for a variety of measurement applications. For example, the WSV can be used to support the calibration of the rms voltage outputs from various commercial multifunction calibrators, such as the Fluke 5700 and 5702A. It can be used as well for the calibration of the rms voltage measurements made by commercial instruments such as the Fluke 5790 AC Measurement Standard, the Wavetek 4290 AC Measurement Standard, and the Wavetek 4950 Multifunction Transfer Standard. In conjunction with calibrated attenuators, the WSV can be used to provide a convenient, cost-effective means for calibrating the wide-band (30 MHz) option of these commercial instruments. Several instrument manufacturers have indicated an interest in developing a commercial product based on the design of the NIST WSV.

3. NBS/NIST Phase-Angle Standard

CCG Project 112, Navy, Air Force Sponsorship

Commercial digital phase-angle meters began appearing on the market in the 1970s, requiring the development of a convenient, efficient calibration method. Obtaining a meaningful and comprehensive coverage of all-possible input phase angles, frequencies, and signal levels made manual testing very labor-intensive and prone to errors. About 1980, with their earlier analog Phase Standards also becoming obsolete and with a need to calibrate the higher-accuracy, distortion-sensitive, digital phase meters entering their equipment inventories, the services contracted with NBS to develop the NBS Phase-Angle Standard.

This standard is a digitally synthesized, dual-channel signal source that generates a pair of sinusoidal waveforms whose relative phase angle is determined from digital memories, 18-bit digital-to-analog converters (DACs), and an auto-zero phase feedback circuit. Several additional improvements were later made, such as extending the frequency range coverage up to 50 KHz.

NIST wideband sampling voltmeter comparing RMS voltage readings with a thermal voltage converter standard.

The development of the NBS/NIST Phase Standard was recognized by an R&D 100 award in 1985, and has been the basis for commercial products, particularly the Clarke-Hess Model 5000 and 5500-2 phase standards, both of which the Air Force now maintains in its electronic equipment inventory. These and similar instruments are now the nominal standards used to calibrate audio-frequency phase meters in laboratories around the world.

NIST offers a routine calibration service for commercial digital phase-angle meters and phase-angle bridges using the Phase Standard as a known source. Its performance is characterized by means of a precision sampling phase-meter developed at NIST,

Testing the performance of the NBS/NIST phase angle standard.

which has been documented to have a relative uncertainty of less than ±0.010° up to 50 kHz. The recent development at NIST of the wide-band sampling voltmeter described above has reduced this uncertainty to less than ±0.003°.

The Air Force's procurement of the Clarke-Hess commercial version, mentioned above, for their Precision Measurement Equipment Laboratories (PMELs) resulted in an improvement of about 50 % in efficiency for phase-meter calibrations. PMEL technicians favored the user-friendly digital version over their predecessors, and their computer interfaces will permit more planned productivity gains once future automation implementations are completed. These Phase-Angle Standards calibrate phase meters and other test, measurement, and diagnostic equipment that support many weapons systems, including the F-15 Strike Eagle.

4. Josephson-Junction DC Voltage Standards

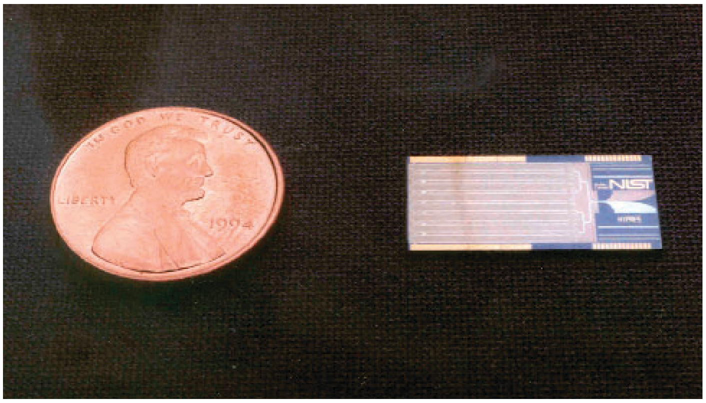
CCG Projects 191, 245, 284
Army, Navy Sponsorship

Direct current (DC) voltage is perhaps the most fundamental and basic electrical quantity and it is also the foundation of many other measurements. The output of many types of sensors that measure other physical quantities is often in the form of a DC voltage. The development of modern solid-state instrumentation that operates at voltage levels about 10 times lower than those of vacuum tube circuits created an imperative need for a more precise absolute voltage reference for a national standard.

The Josephson effect, discovered in 1962 by Brian Josephson and earning him a Nobel Prize, provided the answer. A Josephson junction is constructed of a superconductor-insulator-superconductor "sandwich" that is cooled to below the superconducting point with liquid helium. When such a junction is radiated with microwave energy in the millimeter-wavelength region, the relationship between the voltage across the junction and the current through it changes drastically. The normally linear relationship between voltage and current is quantized into a "staircase" function, with the voltage having discrete values that are a function of the frequency and a proportionality constant called the Josephson constant. Only fundamental constants of nature are involved in this relationship, thereby creating an ideal basis for a voltage standard.

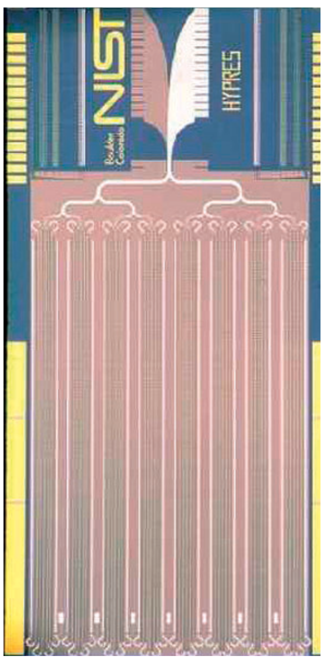
Implementing this method of generating a voltage standard was not easy. Since the voltage steps are very small, over 20,000 perfect junctions connected in series must be fabricated to produce a 10 V standard. Also, since the exciting wavelength is extremely short the structure must also be very small in order to avoid unwanted circuit effects. Fabrication of the circuit made use of the latest in integrated-circuit manufacturing technology to achieve these goals.

The military services saw that this new type of standard, based on a fundamental law of nature, offered advantages over standard



(top) A JJA containing thousands of Josephson junctions fabricated on a single integrated circuit.

(bottom) Enlarged view of a JJ array.



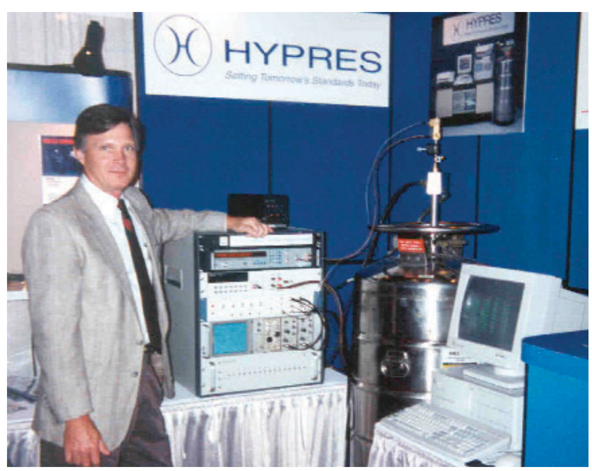
cells. Any such standard is as accurate as another identical standard, meaning fewer intercomparisons with NIST might be required, with consequent monetary savings. The CCG contracted with NIST during the 1970's and 1980's to perfect this technique, which resulted in the Josephson Junction Array (JJA) becoming the new national DC voltage standard at NIST. The only disadvantage was that this standard could not in any sense be considered a portable unit, because it required continuous cryogenic cooling in liquid helium.

In 1992, the Advanced Technology Office of the U.S. Army TMDE Activity, parent organization of the Army Primary Standards Laboratory (APSL), initiated a program to pull together the results of many years of CCG research projects in Josephson-Junction Array applications. The goal was to develop the technology necessary to eventually construct a portable JJA voltage standard cooled by cryogenic refrigeration and rugged enough to be deployed to Army calibration facilities in remote locations.

At the time of project initiation, Dr. Clark Hamilton of NIST, Boulder, Colorado, constructed JJA chips and hand-selected those that operated satisfactorily from each batch. His laboratory was the only source in the world for these semiconductor chips. A research team was put together that included Dr. Hamilton plus engineers and scientists from a commercial company, HYPRES, which had experience in fabricating cryogenic devices. Additional participants included the Army Research Laboratory and the Army Primary Standards Laboratory. Funding was provided through a variety of means, including a Small Business Innovative Research grant and direct Army research and development dollars. NIST participation was funded by the CCG under project 284.

The first technical challenge was to reliably produce all-niobium JJA integrated circuits (ICs). APSL used its operating JJA system as a test bed for prototype ICs. (This JJA system was developed and funded through CCG projects.) Using transferred NIST technology, HYPRES quickly produced batches of JJA

Transportable commercial Josephson junction voltage standard.



chips, and based on test data coming back from APSL was able to render the NIST design in all-niobium, and to do so in a production environment. This advance made commercialization of JJA technology possible for the first time. HYPRES first produced and marketed a commercial JJA system in 1994.

Today, many government agencies and private companies throughout the world own and operate JJA voltage systems, which give them the ability to operate with part-per-billion uncertainties that would have been unimaginable only a few years ago. The JJA voltage standard is an intrinsic (fundamental) standard that has revolutionized the field of precision voltage measurement.

Physical/Mechanical

Interim Testing System for Coordinate Measuring Machines

CCG Projects 318, 379, 394, Air Force Sponsorship

Coordinate Measuring Machines (CMMs) are used to determine the physical dimensions of complex manufactured parts. Tens of thousands of CMMs are employed in U.S. industry, including DoD maintenance and repair facilities. They are rapidly becoming the dimensional measurement tool of choice because of their speed, accuracy, and flexibility. CMMs fulfill both the traditional function of rejecting "bad" (out-of-specification) parts, as well as supplying "process-control information" that can be used to improve the manufacturing process. Consequently, CMMs must consistently measure parts accurately. If they do not, both safety and cost issues may be compromised. This program was initiated when a military facility discovered that an unacceptably large number of CMMs were failing the annual recalibration procedure. Hence the need was established for development of a rapid and thorough testing procedure that could be used between the regular calibration intervals.

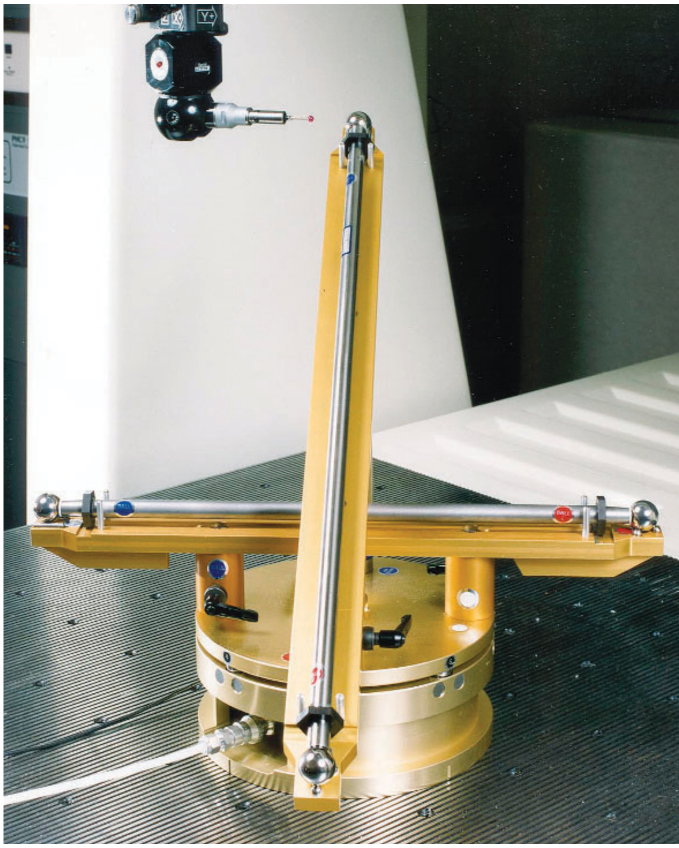
In 1994, the CCG contracted with NIST to develop what has become known as the interim testing system. Prior to this, existing technology to evaluate CMMs was either expensive ($25,000), time-intensive (many hours), difficult to establish and maintain calibration, or failed to test important subsystems of the CMM. The interim testing system, shown in the following figure, behaves as if it were a large three-dimensional (3-D) calibrated ball plate. The system achieved the following objectives:

1. Comprehensive: provides a check of all CMM components, sampling a large volume of the CMM work zone in 3-D, and is sensitive to common CMM failure modes.
2. Relatively inexpensive: the system costs less than $10,000.
3. Fast: performs the test in under 30 min. (typically 15 min.).
4. Calibration: provides traceability to the SI quantity of length, and is inexpensive to recalibrate.
5. Light weight and robust: under 15 kg and physically robust to allow regular use.
6. Versatile: can be used on many different sizes and styles of machines.
7. Easy: no special training or special care needed; easy to move and set up.

A key design point is the use of kinematic mounting, which creates an important "division of labor," isolating the calibrated standard from all distorting forces and other structural requirements. Consequently, the calibrated ball bars are designed for high dimensional stability and accuracy without concern for rigidity, while the underlying support frame is freed from metrology requirements, allowing it to be constructed from inexpensive materials such as aluminum extrusions. Additionally, the calibrated ball bars can be rotated by a pneumatic indexing system allowing these simple one-dimensional standards to sweep out a large three-dimensional work zone. Furthermore, this mounting method allows the calibrated ball bars to be easily removed for storage or replacement by a different length selected from a range of 300 mm to 1500 mm; this provides great flexibility to accommodate a wide variety of CMMs.

The CCG-funded CMM interim testing system is now a commercial product manufactured and sold by the Bal-Tec Corporation. The system is in use in numerous industrial and military facilities, including Kelly Air Force Base (prior to closure), Pensacola Naval Aviation Depot, Caterpillar, Inc., and Boeing; its success is due in part to the cooperative nature of its design. Early prototype systems were sent to Air Force Bases for critiques, resulting in numerous design improvements. To provide sufficient metrology capacity for the calibration of ball bars, the Department of Energy's Y12 Oak Ridge Metrology Center has made available several high-accuracy calibration instruments for use by government and industry.

Initial applications of the interim testing system identified several defective CMMs that were being used to inspect parts on the factory floor; once these faulty CMMs were repaired, the interim testing system has maintained the "health" of the CMM population. The system provides more exhaustive testing in less than half the time of previous methods. Consequently, its frequent application has allowed the intervals between full calibrations to be significantly extended. Since a full calibration is a lengthy process in terms of machine "down time," the interim testing system represents a significant cost saving. This reduced testing time was particularly useful when an earthquake rolled through Boeing's Seattle facility; by use of the interim testing system, critical inspection CMMs were rapidly validated and returned to service without delaying production.



The CCG interim testing system with a CMM evaluation in progress.

Thanks to the CCG program, CMM interim testing methodologies are now becoming accepted as standardized metrological practices. The most recent (1997) edition of the ANSI B89.4.1 standard on CMM performance evaluation now includes a chapter on CMM interim testing taken directly from methods developed under the CCG program. Finally, interim testing procedures are starting to reach the international level and the CCG interim testing system will provide measurement assurance that is required for quality assurance standards such as ISO (International Standards Organization) 9000 and ISO 17025.

RF and Microwave

1. Radar Cross Section (RCS) Measurements and Standards

CCG Projects 355, 466, 466F, Air Force and Navy Sponsorship

Stealth technology is the ability to make our military platforms, such as airplanes, helicopters, missiles, tanks, and ships, nearly invisible to enemy radar, and depends on measuring a quantity called radar cross section or RCS (a measure of the radar reflectivity of an object). Each of the services has developed its own capability for measuring RCS for its particular needs.

In general, RCS is measured on a range, traditionally outdoors, where the measurement may be static (object mounted on a non-reflecting pedestal) or dynamic (object in motion such as an airplane). More recently,

An aircraft prepared for RCS measurement on a Navy range.

indoor ranges (compact ranges) are being used for static RCS measurements. In addition, many of the major aerospace defense contractors have built their own RCS ranges to develop and test new radar absorbing materials and stealth technology.

RCS measurements taken at various ranges on the same targets must agree with each other within estimated uncertainties to justify confidence in the results. Although the sources of uncertainty are well known, a comprehensive determination of uncertainties in RCS calibrations and measurements at government or industrial ranges has only recently been undertaken. Such studies are essential at every RCS measurement range if the U.S. RCS industry is to maintain its world leadership well into the new millennium. To satisfy this requirement there need to be well-formulated procedures that measurement ranges can use to determine the uncertainties in their system calibrations and target measurements. Development of standard artifacts, to be used uniformly at all RCS ranges, would greatly enhance the reliability of measurements in the RCS community.

Thus, in the late 1980's several government RCS ranges formed an association and contracted with NIST to develop a plan and specific procedures for range evaluation which could be undertaken by the individual ranges on their own schedule. NIST would provide critiques of the evaluations, technical assistance, and, if required, artifact RCS test standards to insure measurement consistency. Since the work involved all three services, the CCG assumed a portion of the support.

In the context of a DoD RCS Self-Certification Program, the framework of a RCS Range Book has been proposed to ensure community wide compliance. A DoD Demonstration Project is in progress to assess the feasibility and usefulness of such a program.

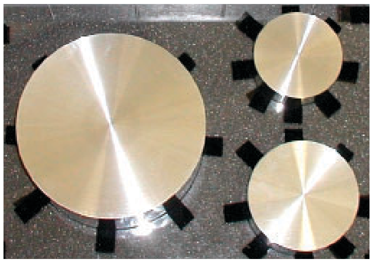
Currently, NIST is actively engaged in the following areas of research to improve the reliability of RCS measurements:

1. Development of a new set of calibration artifacts to assess and improve calibration accuracy.
2. Implementation of defendable range specific uncertainty analyses throughout the RCS industry.
3. Establishment of an RCS interlaboratory comparison program and the corresponding technology to enhance confidence in uncertainty analyses, in calibration of RCS artifacts, and in measurements of unknown targets.

The standard-cylinder set adopted by the RCS community for calibration of their measurement systems is an excellent candidate for the NIST SRM (Standard Reference Materials) program. The results of inter-laboratory comparison programs among the RCS ranges would be more reliable using these standard-cylinder sets. Currently, NIST is manufacturing a standard cylinder set for in-house use.

To calibrate an RCS measurement system, we need to know the computed RCS values of the calibration artifacts. NIST is planning to implement a computational effort to determine the cross section of calibration artifacts with known uncertainties. After a national review of the computational procedures and results, NIST will recommend that such data be adopted for Standard Reference Data sets.

NIST has published a standard table of sources of uncertainties known to exist in RCS calibrations and measurements and has recommended that such a table be adopted as the industry standard for specifying RCS measurement uncertainties. NIST already follows this recommendation in its current research in this area. The RCS community is examining and implementing various versions of this basic table for their own use. The development of this standard-uncertainty table for use in RCS measurements increased awareness for the need to thoroughly understand the estimation of uncertainty in all other areas of research in this technology.



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

Recently, several of the industrial owners of RCS ranges have become interested in the progress of this work, in particular the methodology developed by NIST for self-evaluation of range performance. Significant cost savings are expected to ensue from this effort, as better and more repeatable calibration and measurement results will obviate the need to repeat costly and time-consuming measurements.

2. Thin-Film Coaxial Microwave Power Detector

CCG Project 393, Navy Sponsorship

During WWII and many years beyond, waveguide was the "conductor" of choice to convey signals and transmitter power from one piece of equipment to another at microwave frequencies above 10 GHz. It was not until the 1970's and 1980's that low-loss cables, and more importantly, well matched connectors that were usable to 40 GHz and beyond became available. While waveguide is still required for higher powers, miniature coaxial components and cables are now commonly used in low-power receivers, signal processors, and measuring instruments.

Newer electronic equipment, in particular Naval and Air Force avionics and EW systems, are now incorporating smaller 3.5 mm and 2.4 mm coaxial connectors and cable, even in the lower-microwave region, in order to save both weight and costs. This makes it essential that critical RF measurements, particularly power, be made with nearly the same accuracy as in the larger type N connector size or waveguide. Prior to this project, measurements traceable to primary standards at NIST could be made in these smaller connector sizes only by using adapters, which significantly degrades the accuracy of the measurements.

To solve this problem the CCG contracted with NIST to develop a new, all-coaxial standard transfer power detector, usable from 10 MHz to 50 GHz. This device would avoid any use of adapters, and have the lowest uncertainty in transferring the national standards for microwave power from NIST to the services'

NIST 2.4 mm transfer power detector (shown next to dime).

primary laboratories. This required a totally new construction approach that used integrated-circuit techniques borrowed from the semiconductor industry and the cooperative assistance of a major industrial metrology laboratory.

In researching approaches, NIST discovered that Hewlett-Packard (HP) had developed an experimental device that with significant modifications might be used to accomplish the project's goal. HP had earlier decided the device was not commercially feasible and had shelved it. Using data and a set of design requirements from NIST, HP manufactured a number of customized devices that were shipped to NIST for further evaluation. Using modified Type IV Bridge circuitry, formerly developed at NIST, and later adapted for military use, a Direct Comparison measurement system based on the 2.4 mm coaxial connectors was built, tested, and supplied to the Navy Primary Standards Laboratory (NPSL) in 1999. Additional copies of this system are currently being built for the Air Force and Army Primary Standards Laboratories.

NIST direct comparison 2.4 mm power measurement system at NPSL.

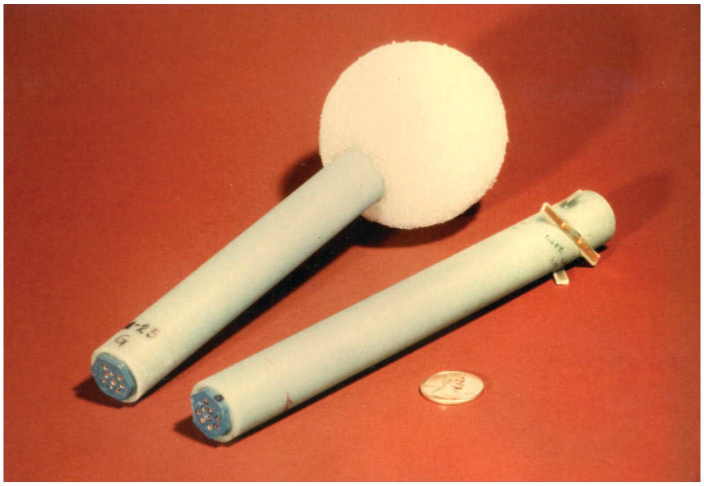
The use of the new 2.4 mm primary standards, which are directly calibrated in the NIST microcalorimeter, now allows NPSL to measure power over a larger frequency range at improved levels of uncertainty. Also, the use of the NIST-developed Direct Comparison Measurement System has greatly reduced the time needed to make these measurements. The combination of the 2.4 mm standards and the Direct Comparison System at NPSL has resulted in reduction by order of magnitude in cost over the previously used dual six-port systems.

Development of the 2.4 mm power standard and the Direct Comparison System also made it possible for NIST to greatly expand its microwave power measurement services for industry. 2.4 mm devices can now be directly calibrated against a primary microcalorimeter standard, and 3.5 mm device measurements have been greatly enhanced. In addition, NIST added a capability to measure thermoelectric power standards, which are becoming much more important in the millimeter-wave region.

3. Measurements of Electromagnetic Field Strength

CCG Projects 206, 231, 389, 437, Navy, Army, Air Force Sponsorship

While we are all continuously bathed in very weak electromagnetic (EM) fields from sources such as distant radio and TV stations, and even energy from outer space, with no undue effects, high-strength EM fields are a major concern. These may be hazardous to people required to work near high-power shortwave or radar transmitters. While all of



NIST three orthogonal dipole electric field intensity probe.

the military services have such high-power equipment, the problem is particularly vexing on Navy ships, since there is so little space available above deck to avoid areas of high field intensity.

NIST has long been involved in measurement research and standards for EM field strength resulting from public safety issues concerning microwave ovens. Also the ability to generate an accurately known EM field in a given space is a requirement of some antenna-gain measurement procedures and for calibration of EM hazard probes.

Over the years, as the military services strove to improve the safety conditions for those service personnel working in potentially high-level fields, the CCG contracted with NIST to provide improved accuracy for instruments used to measure potentially hazardous EM fields. The first effort produced a set of design criteria for anechoic chambers designed for calibrating EM Hazard meter probes including broad-band "omnidirectional" EM field-level transfer probes. (While there is no physical implementation of a truly omnidirectional or isotropic probe, we can independently measure the three orthogonal E or (H) field vectors, and by summing the squares of their values, we can compute the energy density at a point in space. Many, although not all, EM hazard survey probes use this technique.) The Army, and later the Navy, used this chamber information to construct EM probe calibration facilities at their primary standards laboratories.

The Air Force tasked NIST, through the CCG, to develop a special millimeter-wave probe for EM field measurements. These measurements were necessary to protect pilots and service technicians from being exposed to moderately high EM field levels from aircraft-mounted MILSTAR satellite communication transmitters.

Calibrating EM hazard probe at the Navy Primary Standards Laboratory anechoic chamber facility.

For many years the electric (E) field component of EM fields was the major interest of medical safety personnel. More recently concern has also been voiced about the magnetic (H) field component, particularly at mid-to-lower RF frequencies. While we can generally compute the H field from the E field, if one is far enough away from the radiating source, this is not possible on Navy ships where exposures can take place in close proximity to the radiating antennas. The CCG recently contracted with NIST to develop a specialized EM field probe capable of monitoring both electric and magnetic ambient fields.

NIST fiber-optic-coupled E and H probe.

This new combination probe will use fiber-optic "connections" between the sensing probe and the data recording equipment instead of wire cable. Hard-wire connections to such probes often distort the fields being measured and pick up extraneous noise; this is particularly so where near-field conditions exist. Work on this probe system is currently under way with delivery to the Navy slated for late 2002.

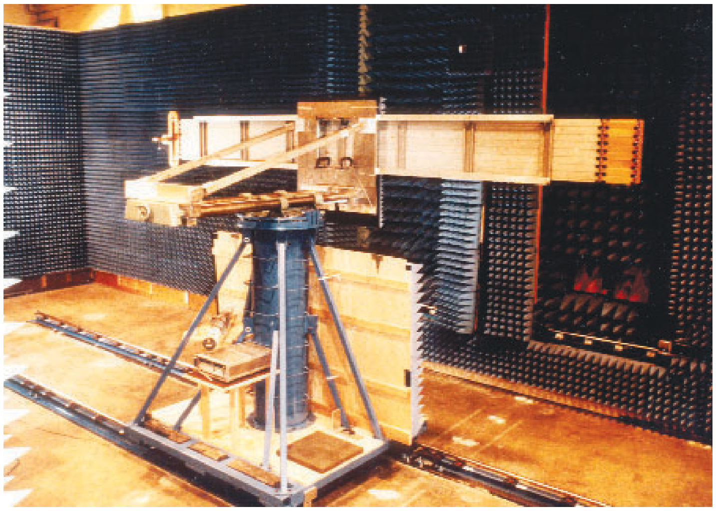
4. Automated Near-Field Antenna Measurement Capability

CCG Projects 196, 196M, 253S, 302, 303, Army, Air Force, MILSTAR, and SDIO Sponsorship

The development of space satellites and their use in long-distance communications created the need to more accurately determine the radiation pattern of large microwave antennas. For example, to optimize customer service and conserve satellite power, the radiation patterns of U.S. satellite TV transmitting antennas are shaped so that the energy falls only on the land mass of North America. The same is true respectively of satellites that cover European, Asian and African countries. The satellite contractors are paid premiums (or conversely penalized) for how closely they do or do not meet such specifications.

When an antenna is physically very large with respect to the wavelength being used, the true "far-field" pattern can be observed only at a point far distant from the antenna. For modest microwave antennas this might be a few thousands of meters away, but for extremely large, deep-space antennas this point could be over 10 million meters away (a physical impossibility to measure on the Earth's surface). Even distances of over 100 meters usually require outdoor ranges where varying atmospheric conditions and interference can contaminate the data.

AWACS antenna on NIST near field range.



In the mid 1950's NIST developed a method (both theory and implementation) that can determine the true far-field pattern of a highly-directive antenna from data obtained by measuring the antenna's radiation in a plane a few meters in front of the antenna. A small probe antenna samples the amplitude and phase of the radiation field at points on an imaginary rectangular grid, located on this plane. Since the sample points must be closely spaced, relative to a wavelength, thousands of data sets must be obtained. All this can be accomplished indoors in a fully anechoic chamber, immune from the effects of weather.

A complex spatial Fourier-transform method converts the raw data, which may show little directivity, into the highly directional pattern expected from a properly designed and functioning space antenna. Before the advent of modern computers, this method would have remained in the theoretical realm.

The military services were quick to take advantage of this capability and, under direct contracts, NIST provided measurements to the military services of several specialized antennas such as the AWACS and Firefinder. This led the CCG to contract with NIST to further develop its capabilities to meet upcoming military requirements. Prior to this CCG-funded work, NIST was unable to provide measurement services for antennas operating above 30 GHz and had very limit-

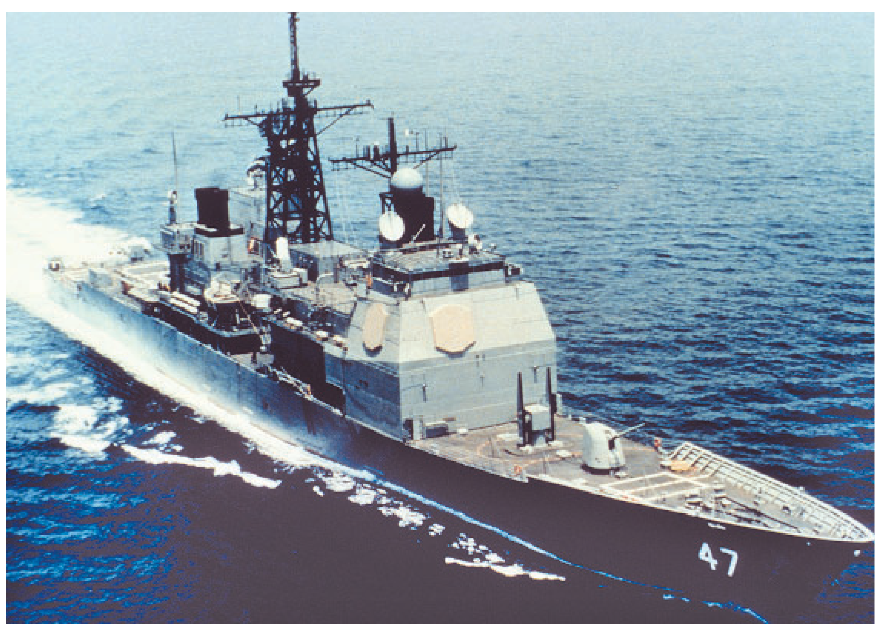
Army mortar firefinder array antenna.

ed capability for measuring circularly polarized antennas. One of the main results of this effort was to provide measurement services for evaluating antenna performance for the MILSTAR program at 20, 44, and 60 GHz. NIST was also able to evaluate the performance of a 60 GHz prototype Ballistic Missile Defense phased array. These early efforts later led to the development by NIST of a method for correcting for the effects of probe position errors at higher frequencies. The automation of the near-field range under this project later permitted quick evaluation and repair of PASS sub-arrays used in the Gulf War in 1991. Repair times were reduced from nine months to a few days.

The Navy's Aegis program to provide a class of destroyers with a total three-dimensional, real-time radar coverage, called the SPY 1 radar, made use of NIST capabilities. The SPY 1 antenna is a phased array composed of hundreds of individual radiating elements. By changing the relative amplitude and phase of the signal fed to each of the elements, the narrow antenna beam can be instantly pointed in any direction without physically moving the antenna. This allows the radar system to keep track of a huge number of objects in a threat environment.

However, any failure of individual elements is not easily discovered since the overall performance of the antenna degrades only slowly. A unique feature of the near-field scanning method, which was later implemented by the Navy with NIST consultation, is its ability to determine faulty elements in an array. An Aegis destroyer can now have its antennas tested using a mobile scanning unit in port.

This technology is an example of a more symbiotic relationship compared to many of the others described earlier. In this case the original theory and implementation were developed at NIST under civilian funding. The military services then augmented this capability to enable NIST to provide specialized support for military platforms. In the future the expanded capabilities developed for the military will also be used by industry as communication satellites move up into the millimeter frequency range. The long-term cost savings to DOD and industry on present programs is estimated to be in the ten-million-dollar range.



Aegis destroyer with SPY 1 radar.

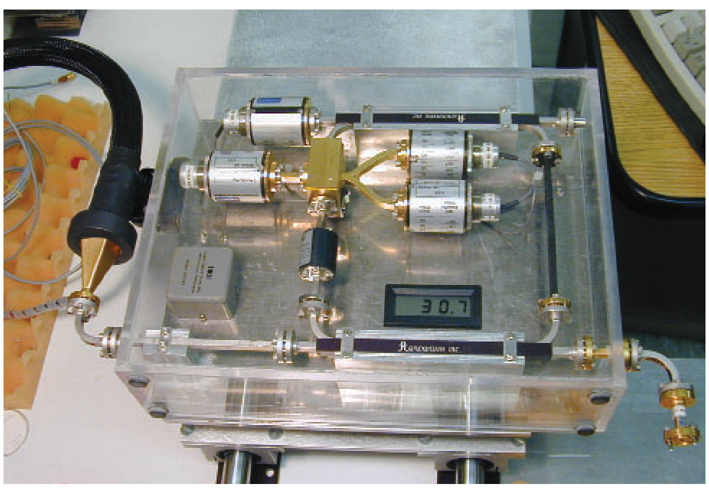
5. Dual Six-Port Vector Network Analyzer Development

CCG Projects: 15 total, Army, Navy, Air Force Sponsorship

Precision measurements of impedance, reflection coefficient, and attenuation of microwave components have always been difficult, particularly if both the magnitude and phase components are desired. Individual measurement set-ups of specific equipment were necessary, and because the measurement devices were imperfect themselves, tedious adjustments were necessary to cancel out possible errors introduced by the measurement apparatus.

During the 1960's, the advent of automated test equipment running under computer control made possible a new approach to the problem. Using microwave circuit theory, some of which was developed at NIST, measurements of the errors introduced by the measurement equipment and corrections to the raw test data, for the device under measurement, became possible. Second-order residual errors still remained, but these could be accounted for in the estimation of uncertainty.

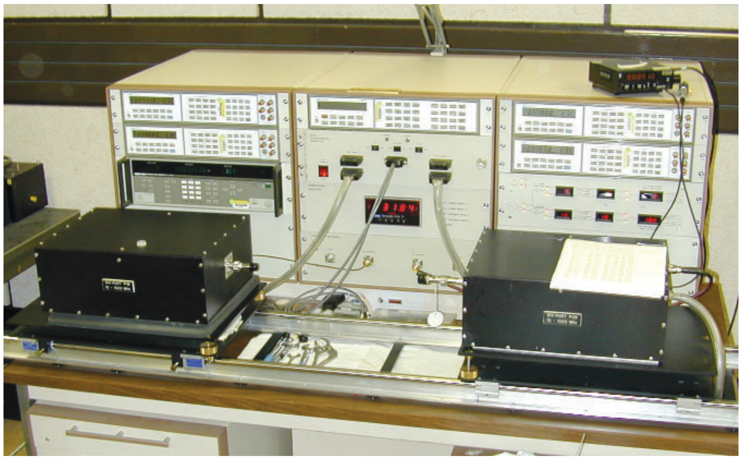
NIST waveguide (WR 15) six-port head.



As computer processors and equipment interfaces became faster and more efficient, specific test instruments for general microwave parameters became possible, allowing for many measurements of previously unimaginable sensitivity to be made in a very short time. The generic name given to these new microwave measurement sets was "vector network analyzers" or VNAs.

Two different technologies were used in their development. NIST chose to implement a dual six-port scheme that uses precision DC substitution microwave power detectors as the data-gathering devices (Type II and Type IV Power Bridges). These instruments, which were developed at NIST, had been thoroughly studied and evaluated for many years. Their use also facilitated measurement traceability to SI derived units. Industry chose another technique involving direct measurement of amplitude and phase using a microwave receiver. While still based on the microwave network theory developed at NIST, this technique allowed much faster operation, which was considered critical for industrial production-line use. Evaluation of the measurement uncertainties in the industry-developed instrument was more difficult.

When the military primary-standards laboratories first decided to transition to VNAs, for several reasons they chose to use the six-port method developed at NIST. Firstly, they were concerned that commercial versions were in their infancy and that the market was rapidly evolving. The services also wanted to be able to call upon the long-term support and consultation of NIST, assistance that might or might not be available from the commercial sector. The CGG contracted with NIST to provide pre-assembled six-port systems, software, and training in their use and application. These systems are still in



Complete six-port calibration system at NIST.

use even though commercial VNAs are used sometimes for more routine measurements.

Over the last three decades, at least 15 six-port projects were initiated as measurement requirements evolved across the frequency range from 0.1 MHz to 110 GHz. Improvements and software upgrades were made over time as new, improved components and faster computers came on the market.

All vector network analyzers need to be calibrated in order to have their imperfections quantified and necessary correction terms for the raw data determined. Various standards such as a known load or termination impedance, short or open circuits, and precision transmission line sections must be used for these determinations. There are different methods of employing these standards. Research conducted during these CCG-sponsored projects resulted in optimizing several sets of standards and methods to minimize uncertainties. One of these methods, known as the TRL (through-reflect-line) method, is now widely used in government and industrial laboratories, and in production testing, for all types of vector network analyzers.

6. Cryogenic Microwave Noise Standard

CCG Projects 200, 200M, Air Force and MILSTAR Support

Amplitude noise, sometimes called white noise, is the ultimate limiting factor in reception of radio signals. (The effects of phase noise discussed earlier in Part 1). Such noise originates from a multitude of sources, including outer space, the sun, and actually any object that is not electrically lossless and whose temperature is greater than absolute zero. Such noise is also generated by the electronic circuitry at the input of sensitive radio receivers. (This does not include impulsive noise, created by digital circuits and electrical equipment, which often can be suppressed at its source by adequate filtering.)

Semiconductor manufacturers have striven to develop devices with higher gain and lower internal noise. Customers are willing to pay premium rates for the lowest-noise devices. Measuring the amount of internally generated noise, which is defined by a term called noise figure (or noise temperature), is vitally important to manufacturers of semiconductors and communications equipment.

Noise figure measurement requires two different external sources of noise whose levels are accurately known. One of these can be a termination at room temperature. For the other source, the earliest noise standards used either a temperature-limited diode vacuum tube, or a common (miniature) fluorescent light (called a gas tube). The output of these tubes is coupled to a RF termination, either directly, or through a section of waveguide or coaxial line. By turning the tube on and off, the level of available noise at the output of the device can be changed. More recently a special type of zener diode that generates high noise levels, and which can also be turned on and off easily has been substituted for tube sources in coaxial systems. However, since the output noise levels produced by these zener diodes cannot be theoretically predicted, they must be calibrated against a standard, whose output can be predicted theoretically.

Waveguide cryogenic noise source.

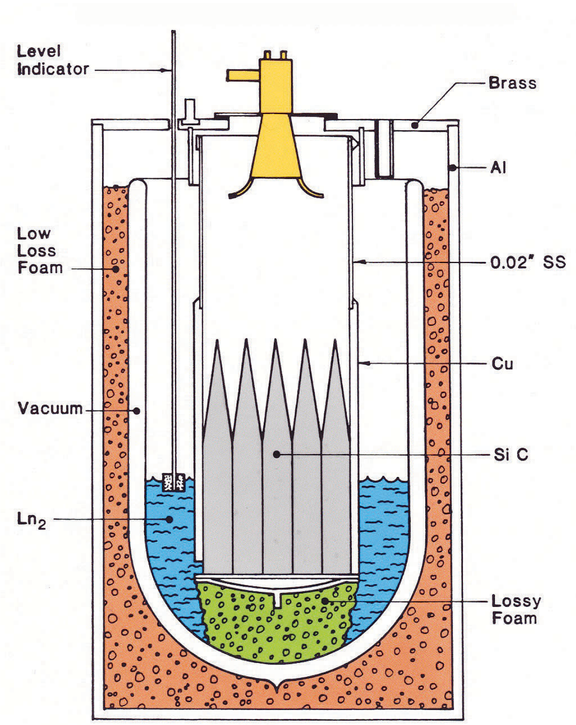
Fortunately, there is an exact theoretical relationship between the absolute temperature of a lossy element such as a waveguide or coaxial termination and the available noise power it produces. Since one termination can be at room temperature, we only need heat another termination to a temperature where its available noise would be sufficiently greater than that for the one at room temperature. However for the best calibration results, the ratio of the two temperatures, not the absolute difference, should be large enough to accurately determine any nonlinearities in the measurement system, for the device being measured. In the early implementations using heated waveguide terminations, this meant that the high-temperature source was operating between 800 K and 900 K, almost hot enough to glow. While excellent results were obtained, operation at this temperature led to metal oxidation and mechanical stress. This meant that the primary standard was only used intermittently to calibrate intermediate gas tube or solid-state noise standards resulting in greater uncertainties.

For this reason, NIST had not extended its microwave calibration services above X band (10 GHz). As the MILSTAR program ramped up, aerospace contractors and the Air Force metrology organization realized that national noise reference standards would eventually be required. With the support of the MILSTAR Program Office, the CCG contracted with NIST to develop national noise standards and calibration services for the 20, 44, and 60 GHz frequency ranges.

Knowing the difficulties encountered with the former hot waveguide standard, NIST decided to design and build a set of waveguide, liquid-nitrogen (LN2)-cooled, radiating absorber units for the non-room-temperature sources. While cryogenic noise sources were available in coaxial structures for frequencies below 4 GHz, none, and particularly radiant ones, had been previously used as waveguide standards in the millimeter-wave region.

Detailed research was required into the electrical and thermodynamic properties of materials, and a computerized ray-tracing program was written to assist in evaluating the losses in the cooled chamber walls, as the radiation from the LN2-cooled load propagated to the output waveguide horn.

As shown in the following cross-sectional diagram, a microwave "load" fabricated of porous silicon carbide wicks up liquid nitrogen, which evaporates at its top surface, thus establishing an exactly known temperature for the material. Radiation from the material is captured by the horn and is available at the output waveguide. Detailed analyses were made of the residual losses from inter-



94 GHz cryogenic noise source: A cross-sectional view.

nal reflections and in the output waveguide in order to establish a total uncertainty for the source temperature.

When the project was completed, calculations revealed that the cryogenic sources produced lower uncertainties in customer calibrations than corresponding hot ones would have done. NIST continues to use a full set of these sources in the microwave and millimeter wave region above 18 GHz.

Due to the difficulty in constructing and evaluating this type of standard, they have not been installed in the service laboratories, nor have they been commercially produced except on special order. A few have been specifically made for use at national standards laboratories in other countries. Nevertheless this endeavor is an example of how support from a CCG/NIST research project successfully solved a critical development and production problem in a major national defense program.

Electro-Optics

1. The Foundations and Infrastructure of Electro-Optical Metrology

(CCG Projects Listed Below)

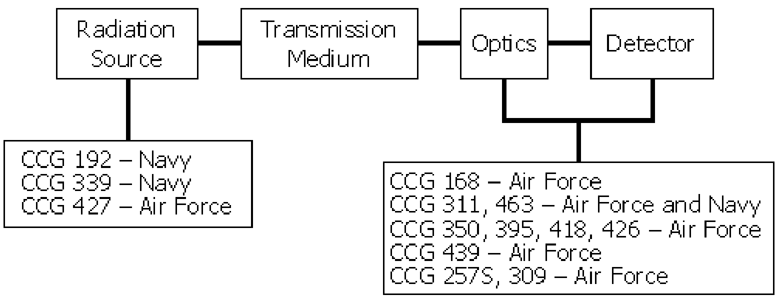
Behind all of the seeming magic of lasers and fiber-optics there exists a metrology derived from the basic quantities of nature: optical power, electricity, and thermodynamic temperature. Electro-optical metrology relies on instruments such as cryogenic radiometers, optical pyrometers, and black bodies. From all of these comes the ability to accurately measure the brightness of a common light bulb or the sensitivity of the night vision systems.

Not surprisingly, the explosive growth of high-technology military equipment in the last few decades required massive upgrades in NIST's capability to support basic optical measurements; thus, the CCG had a vested interest in their support. As in other technology areas, the military requirements were at the time unique, but metrological advances soon supported growth in civilian applications as the technology was adopted by industry.

Before we describe some of these projects, we will present relevant background information in order to assist the reader. The key scientific quantities, and the calibration standards and instruments that NIST uses to measure them, need to be defined. We will first attempt to provide the reader with the what, why, and how of optical measurements and standards. This information should clarify the project descriptions that follow.

Optics deals with light—its creation, propagation, and detection. Optics is not limited to the visible part of the electromagnetic spectrum; the many principles that apply to visible light also apply equally to the ultraviolet

and infrared regions. Instruments called radiometers and photometers are used to measure the intensity of light. The term radiometer is used to identify the instrument that measures the intensity of light at any part of the electromagnetic spectrum, whereas the term photometer refers to the



A functional diagram for a typical electro-optical system and the projects that will be reviewed.

instrument that measures the intensity of visible light, as seen by the human eye. Descriptive terms such as infrared radiometer, ultraviolet radiometer, or microwave radiometer are used to specify the particular wavelength region in which these instruments function.

In general, the term spectroradiometer refers to an instrument that measures the intensity of radiation at any selected wavelength region. Optical metrology uses radiometers and photometers to measure the intensity of optical radiation. Therefore, in optical metrology, we are concerned with electro-optical systems that are used to measure optical radiation and with the materials that transmit or convert optical radiation to electrical signals. The basic building block diagram of such an electro-optical system is shown in the following figure.

The *radiation source* is an object that emits or reflects light. Common emitters are blackbodies, gray bodies, and lasers. In reality, an object could be a reflector as well as an emitter. For example, an enemy airplane could be located by laser-ranging, where the airplane's reflection of the laser light is viewed by the electro-optical sensor to determine its location, speed of travel, etc. In an alternative method, a thermal imager that creates an image of the airplane using emitted infrared light from the airplane could also identify it.

The *transmission medium* that transmits the light from the source to the optics could be the atmosphere, a vacuum, or an optical fiber, etc. In any case, the optical properties of the medium, such as absorption, influence the amount of light that is transmitted to the optics assembly. The optics assembly is generally used to analyze the light in terms of its wavelength, intensity, and polarization. Optical components such as lenses, mirrors, filters, gratings, or interferometers form the optics assembly designed to meet the requirements in the optical spectrum of interest.

The *detector* detects the light output of the optics assembly, converting the optical signal into an electrical signal. It could be a photomultiplier, a photodiode, or a multipixel solid-state device. An electro-optical sensor combines the optics and the detector modules into a single unit.

Calibration of an electro-optical sensor could be accomplished by using a standard source or a standard detector. Traditionally, a standard source such as a blackbody at a set temperature is used for calibrations. Calibrations following this scheme are called source-based calibrations. Over the past 15 years, absolute standard detectors called cryogenic radiometers have been developed that improve the stability and accuracy of calibrations. Calibrations based on using the cryogenic radiometer as the standard detector are called detector-based. The CCG projects mentioned in the above figure have greatly helped NIST to become a world leader in developing standards for electro-optical sensor calibrations. The CCG projects that enabled NIST to improve the source-based calibrations and the detector-based calibrations are reviewed separately below.

A. Source-Based Radiometry

Imaging Infrared Systems Support

CCG 192, Navy Sponsorship

Forward-Looking Infrared (FLIR) Basic Support Standards

CCG 339, Navy Sponsorship

High-Temperature Blackbody Calibration

CCG 427, Air Force Sponsorship

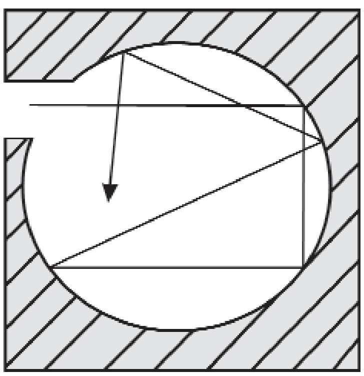


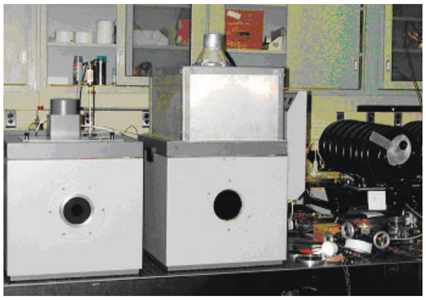
Diagram of a blackbody.

Although their titles differ, all the three CCG projects listed above are concerned with the development of blackbodies for different purposes. The Photonics Dictionary [3] defines a blackbody as "an ideal body that completely absorbs all radiant energy striking it and therefore appears perfectly black at all wavelengths. The radiation emitted by such a body, when heated, is referred to as blackbody radiation. A perfect blackbody has an emissivity of unity."

A laboratory approximation of such a device " … consists of a cavity, generally spherical, made of an opaque material and insulated from thermal effects, with a small aperture for entering radiation, which is absorbed by multiple internal reflection and absorption … ." It can be used " … as a reference source to supply radiation of a given intensity and spectral distribution … ."

As absorbers, blackbodies are used to measure the power of laser beams by noting the rise in temperature caused by the beam's radiant energy being dissipated inside the sphere. As a source, it is considered a standard since there is an exact physical law, Planck's law, from which we can calculate the power at a specific wavelength that is radiated by a perfect blackbody at a given thermodynamic temperature.

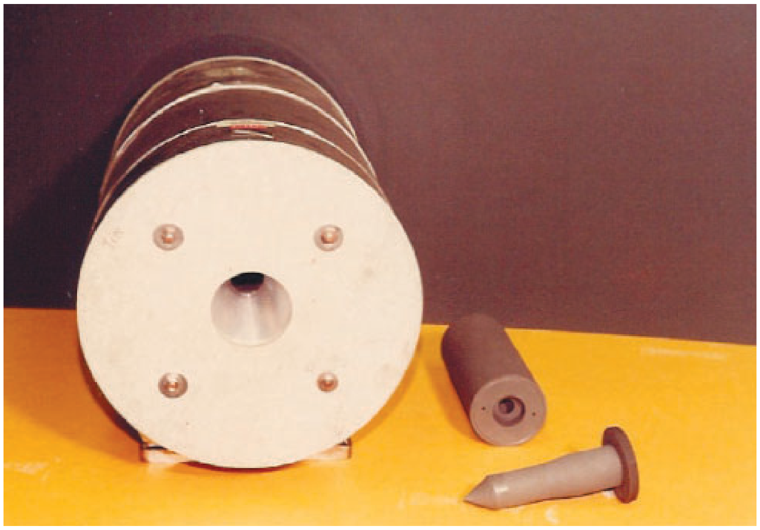
CCG project 192 was created to solve a specific problem for the military. They had commercial blackbodies with large areas that were used to test infrared imaging devices. Getting these calibrated at NIST was difficult to do with existing small-aperture blackbody standards. NIST developed a variable-temperature water bath blackbody with a large (10 cm diameter) aperture that has a minimum resolvable temperature of 10 mK in its operating temperature range of 288 K to 363 K. The availability of this blackbody greatly increased the accuracy and reduced the turnaround time for NIST calibrations.



NIST standard water-and oil-bath balckbodies.

CCG project 339, in support of Forward-Looking Infrared (FLIR) technology, improved the performance of the water-bath blackbody by improving its short- and long-term radiometric stability. A companion oil bath unit was also constructed to extend the available temperature range for large-aperture blackbodies up to 446 K.

While blackbodies have been, and still are, used as radiant standards, their uncertainties



NIST constructed, high-temperature blackbody (zinc melting point).

are larger than desired particularly when operated at very high temperatures such as 3000 K. NIST has moved to a detector-based calibration method to determine the radiance temperature of such sources. The NIST implementation, supported by CCG project 427, has resulted in a tenfold reduction in uncertainties over commercial radiance temperature sensors (pyrometers).

B. Detector-Based Radiometry

Photodetector Transfer Standards, HACR and HACR 2
Primary Standard Cryogenic Radiometer

CCG 168, 311, 463, Air Force, Navy Sponsorship

Development of Radiometric and Photometric Standards

CCG 350, 395, 418, 426, Air Force Sponsorship

UV and IR Spectral Responsivity Calibration Facility

CCG 257S, 309, SDIO, Air Force Sponsorship

Calibration Facility for Spectral Irradiance and Responsivity with Uniform Sources (SIRCUS)

CCG 439, Air Force Sponsorship

The primary goal of the projects listed above is to establish capabilities at NIST for calibrating radiometers and photometers at high accuracies and to develop the methods and standards necessary to transfer these calibrations to various defense applications. CCG projects 311 and 463 supported the development of the Primary Standard Cryogenic Radiometer. The first such radiometer that was developed at NIST, HACR (High-Accuracy Cryogenic Radiometer), is the basis for the radiometric measurement chain established at NIST. The HACR uses electrical substitution to determine optical power with an absolute uncertainty of 0.02 %. Optical power is a derived quantity of the International System of Units (SI) for radiometric, photometric, color, and optical pyrometric measurements. The need for a more accurate measure of power prompted the CCG to fund this project. NIST was an early adopter of the cryogenic radiometer technology, although most National Measurement Institutes presently use cryogenic radiometers as their primary standard for measurements of optical power.

The HACR maintains the measurement scales of detector spectral power, irradiance, and radiance responsivity, and improves the radiometric accuracy throughout the Optical Technology Division at NIST. HACR ultimately reduces the uncertainty of the measurement chain to DoD's primary standard laboratories. Currently, an improved next-generation version called HACR-2 is under development.

One of the main CCG electro-optical efforts is to switch from traditional source-based calibrations to detector-based calibrations of higher accuracy. The uncertainty of the new detector primary standards is about an order of magnitude smaller than that of traditional source standards. In turn, a NIST goal is to minimize the measurement traceability chain between the primary detector standard and field-level calibrations. Generally, the more steps in the chain, the higher the measurement uncertainty. Prior to the CCG-sponsored detector projects, the measurement uncertainty was in some cases more than three orders of magnitude higher (e.g., source-based calibrations of night-vision goggles). As a result of CCG-funded research and development, the previous uncertainties decreased on average by about an order of magnitude. This improvement translates to better-quality radiometric instrumentation and measurement systems in the U.S.

The improved measurement uncertainty of the primary radiometer standard affects the overall radiometric calibration chain of the Optical Technology Division. The accuracy of the two base SI quantities maintained by NIST (luminous intensity and thermodynamic temperature) in the region above the melting point of silver (1235 K) have improved by about a factor of 5. This improvement has been transferred to both military and civilian measurement systems.

CCG Projects 350, 395, 418, and 426 have supported the development of photometric and radiometric standards at NIST. In general, silicon detectors are used in the visible-wavelength radiometers because of their superior linearity, sensitivity, and spatial uniformity. The photometers and radiometers developed under project CCG 350 have improved the accuracy of scale realizations and field level measurements. The simple-to-use, small field-of-view photometers were primarily developed for field-level photometric source and detector calibrations. These new devices don't require specialized laboratory hardware to operate and are therefore less expensive to use than traditional photometric devices.

In addition to the silicon radiometers and photometers, near-infrared and infrared radiometers were developed within the CCG 395 project. The developed radiometers are used as working standards for high-accuracy radiant power, irradiance, and radiance measurements between 1 μm and 5.2 μm in the DoD Primary Standard Laboratories. High-performance electronics and detectors were selected and/or developed for the radiometers. Filters, diffusers, apertures, room-temperature or cold field-of-view limiters, and photocurrent meters were applied and optimized to accurately measure the most important radiometric quantities. Indium-antimonide irradiance meters with very high sensitivity are utilized in the CCG 418 project to calibrate field-level infrared target simulators on a standard detector-base. The detector-based calibration will simplify the present (traditional) source-based target-simulator calibration procedure and will improve the irradiance calibration accuracy by nearly a factor of five.

Radiometers developed at NIST with CCG support.

Ambient temperature, long-wavelength infrared (LWIR), working-standard radiometers were developed within the CCG 426 project. Large-area, single-element, photovoltaic mercury-cadmium-telluride (HgCdTe) detectors, and integrating-sphere HgCdTe radiometers were developed as working standards. Also, linear photocurrent measuring circuits were developed to increase the range of radiant power measurements. These radiometric systems will maintain the spectral responsivity scale between the wavelengths of 5 μm and 20 μm.

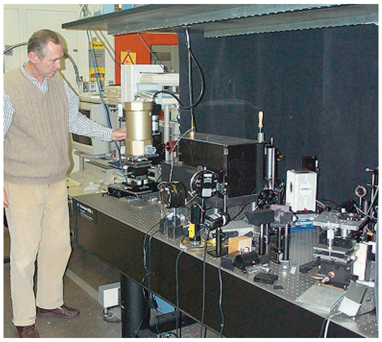
High-accuracy working standard radiometers developed at NIST are the calibration standards used in all DoD laboratories. Use of the improved standards results in more reliable and more accurate measurements in the field and in the military's primary laboratories.

As a result of these projects, frequent replacement and recalibration of traditional lamp standards are not needed (lamps are still needed but they are not standards anymore). Color-temperature lamps are sources that are still issued to the DoD's Primary Standards Laboratories.

UV spectral calibration facility.

The new photometric and radiometric standards are better than previous standards because of higher accuracy, better stability, shorter calibration and measurement times, and less-frequent recalibrations. As a result of these new NIST photometric and radiometric developments, a large number of transfer and working-standard photo/radiometers are used in different NIST projects where calibrations are based on detector standards.

CCG projects 257 and 309 helped the development of the Ultraviolet (UV) and Infrared (IR) Spectral Responsivity Calibration Facilities at NIST. The UV Spectral Comparator Facility (SCF) is a monochromator-based system that uses the detector substitution method to calibrate photodetector responsivity from 193 nm to 500 nm. Absolute spectral responsivities are determined with measurement uncertainties ranging from 0.4 % to 4 %, dependent on wavelength.



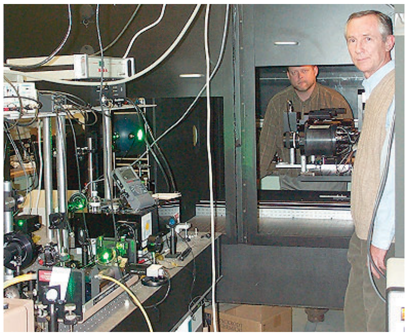
Ambient IR spectral calibration facility.

An Ambient Background Infrared Detector Calibration Facility (IRDC) was developed for Project 309. This facility can calibrate detectors and radiometers for spectral power responsivity in the infrared wavelength range. The transfer standard of the facility is a cryogenic bolometer which holds the infrared spectral power responsivity scale with an uncertainty of 0.8 % between 2 µm and 20 µm. The cryogenic bolometer was calibrated against HACR by means of transfer standard detectors.

As a result of the projects mentioned above, the measurements with detector standards of the DoD primary standard laboratories are now directly traceable to the HACR. NIST uses the detector comparator facilities for DoD calibrations on a regular basis. Additionally, U.S. industry and other government laboratories receive their detector characterizations from the SCF and IRDC facilities.

CCG project 439 helped to establish a new laser-based facility, the facility for Spectral Irradiance and Radiance Responsivity Calibrations using Uniform Sources (SIRCUS) at NIST. This facility was developed to reduce the uncertainties in detector power, irradiance, and radiance responsivity measurements. For example, using the new facility, the uncertainty in irradiance responsivity calibrations have been reduced from 0.5 % to 0.1 % in the visible wavelengths. This improvement will propagate to the two base SI units maintained by the Optical Technology Division of NIST. Future work at this facility will provide calibration support for detector arrays requiring spatially uniform sources.

Working standard detectors calibrated on the SIRCUS facility along with lower transfer uncertainties will increase the accuracy of radiometric and



SIRCUS for UV, visible and near-IR.

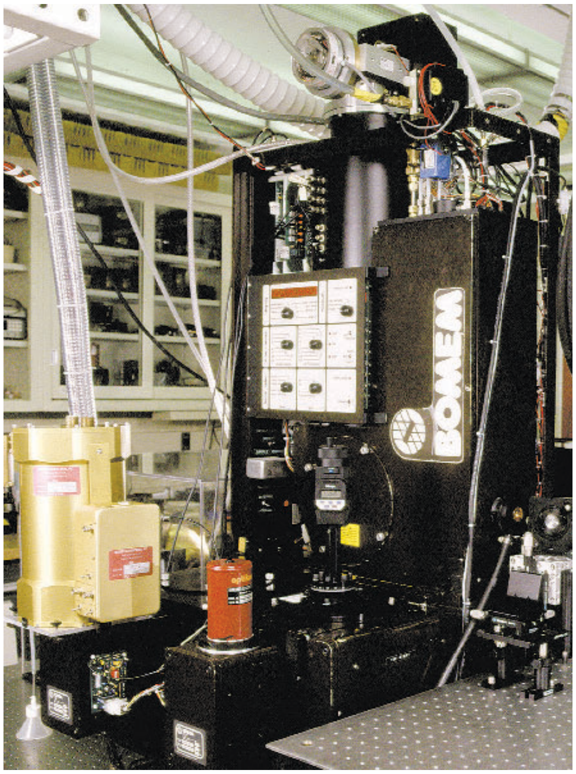
photometric measurements at DoD. The SIRCUS facility will continue in the tradition of the Spectral Comparator Facilities by facilitating the transfer of the new high-accuracy detector-based calibrations to the military, academia, and industry.

Beyond the military requirements, the new capabilities afforded by SIRCUS enable other NIST projects to achieve higher radiometric, photometric, color, and optical temperature measurement accuracy. Other government projects, such as NASA's Earth Observing System (EOS), use the higher radiometric calibration accuracy offered by SIRCUS.

2. Optical Filters and Fourier-Transform Infrared Spectrophotometry

CCG 408S, 414S, 432S, BMDO Sponsorship
CCG 348, Army Sponsorship

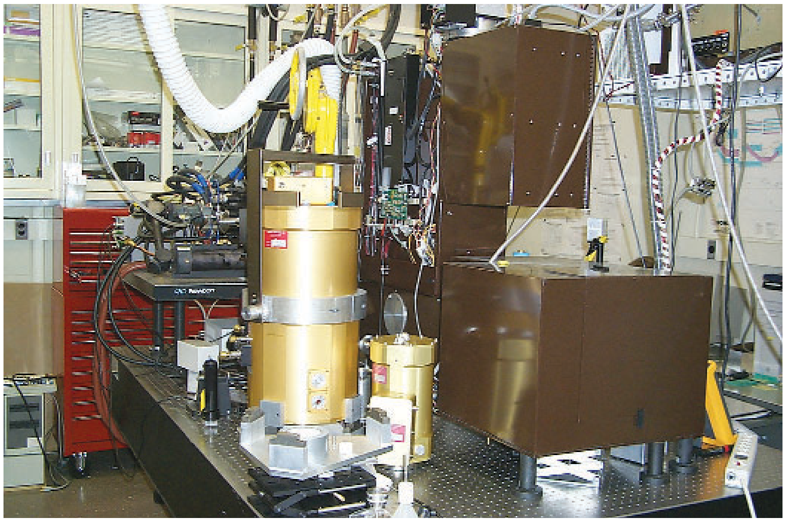
The Ballistic Missile Defense Organization (BMDO) needed accurate characterization of filters that are used to reject high levels of radiation lying outside a narrow transmission band in the infrared (IR). The exact spectral character of the blocking must be known to effectively use the filters with the sensor systems. Since the filters will be deployed in deep space, the transmittance values are required at low temperatures. The BMDO also employs sensors that use array detectors for imaging in a wide variety of systems. These detector arrays are often packaged with filters for spectral selection. For accurate imaging, the filters need to be spatially uniform. Some of the filters are designed with small-scale structure. Required detailed spatial mapping of filter transmission is not generally available from filter manufacturers. Finally, many BMDO systems employ refractive and reflective infrared optical components that need to be well characterized to predict the performance of their associated sensor systems. The CCG initiated contracts with NIST to improve metrology in this technical area.



Fourier-transorm infrared spectrophotometer with cryostat for reflectance and transmittance.

Monochromators have traditionally been used at NIST for spectrophotometry. However, use of interferometers has become more prevalent, especially in the IR, because of the throughput and speed advantages. These interferometers are called Fourier-transform spectrometers (FTS). They also provide much higher resolution than do monochromators.

CCG support for the projects cited above helped to establish the Fourier-transform (FT) Infrared Spectrophotometry Laboratory at NIST, and to develop many of its new and diverse capabilities for optical component characterization. Among these new capabilities are temperature-dependent transmittance and reflectance from 10 K to 600 K, and characterization of infrared index of refraction. Techniques were developed for narrow-band filter characterization, both within- and out-of-band, at the temperatures and beam geometry of use. Also, instrumentation for small-area, spatially resolved transmittance



Equipment for evaluating nonlinearities in the Fourier transform infrared spectrophotometer.

capability for filter characterization has become available. Unique methods are employed for determining window transmittance and emittance, and mirror reflectance and emittance with high accuracy.

While FT-IR instruments have many advantages over grating or prism instruments, one important disadvantage is measurement error due to nonlinearities. This error is difficult to quantify and is often overlooked by instrument users. The resulting unrecognized inaccuracies in the data will propagate through the application or technology. CCG-supported project 348 enabled NIST to carefully study and obtain an understanding of nonlinearly error mechanisms. This has resulted in the development of techniques for eliminating, or otherwise identifying and quantifying, nonlinearly and other sources of error. As a result, NIST has established improved measurement uncertainties for infrared spectral transmittance and reflectance for both specular and diffuse materials. The FT Spectrophotometry facility has benefited a number of DoD/BMDO programs including HALO, SBIRS-Lo, SBIRS-Hi, and EKV.

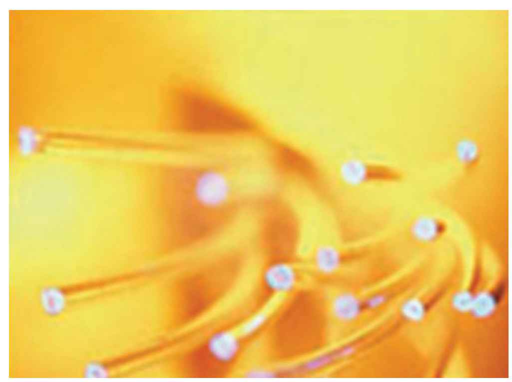
Civilian applications include improved infrared detector standards, infrared radiometer development, boiler chamber window performance, and characterization of critical components in support of a number of NASA and NOAA programs such as GOES, EOS, and SIRTF.

3. Fiber-Optic Power Measurements

CCG 272, 440, Navy, Air Force Sponsorship

The metrology that supports the field of fiber optics is another case where the number of CCG projects at NIST is too large (over 25) to cover individually. Therefore this section will deal with only one narrow aspect; fiber-optic power measurements.

With the rapid growth of optical fiber-based telecommunications systems in the mid-to-late 1980's, the military discovered a concurrent need for establishing metrological support for calibration equipment such as optical-fiber power meters. Optical-fiber power measurements differ from typical laser power measurements in that the radiation is emitted from the end of a fiber and then diverges as it propagates rather than being

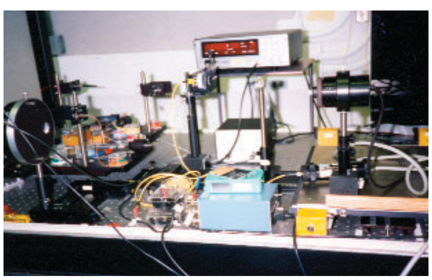


Optical fibers for communications. (Courtesy of Corning Corp.)

contained in a narrow beam. Recognizing the special needs inherent in these measurements, the CCG funded several projects at NIST to develop a fiber-based optical power measurement system.

NIST uses this measurement system to provide accurate optical fiber power meter calibrations to the military as well as to other government agencies, and industrial and academic research laboratories. Improvements to the NIST optical-fiber power measurement capabilities have also been funded by the CCG, such as the development of a detector linearity system and the development of new improved optical fiber power detectors. NIST has provided the Air Force and Army Primary Standards Laboratories (PSLs) with these NIST-built optical fiber power measurement systems. In addition, all three service PSLs have NIST-built detector linearity measurement systems that they use for performing accurate calibrations of optical fiber power meters.

To provide higher-accuracy measurements of optical fiber power, the CCG funded NIST to develop a cryogenic radiometer for use as a high-accuracy power standard. The result of this effort is the Laser-Optimized Cryogenic Radiometer (LOCR). The LOCR serves as the primary standard for NIST's optical fiber power measurements and as a result now provides measurements to the DoD and others with a measurement accuracy twice that of previous systems. A current CCG project strives to reduce the associated measurement uncertainty even more by developing new standard detectors that enable an improved transfer from the LOCR to the actual calibration system.



NIST optical fiber power measurement system.

The explosive growth of optical telecommunications in the past 10 years has generated new and critical metrology needs that are of vital importance to the rapid pace of technology development. Because of CCG support, NIST has been one of the few metrology laboratories to keep pace with these fast-changing needs. CCG-sponsored systems such as those described above have enabled NIST to provide to this industry the most comprehensive and accurate measurement services anywhere in the world.

4. Other Optical Properties

A. Optical Scattering Metrology

CCG 152, Army, Navy, Air Force Sponsorship

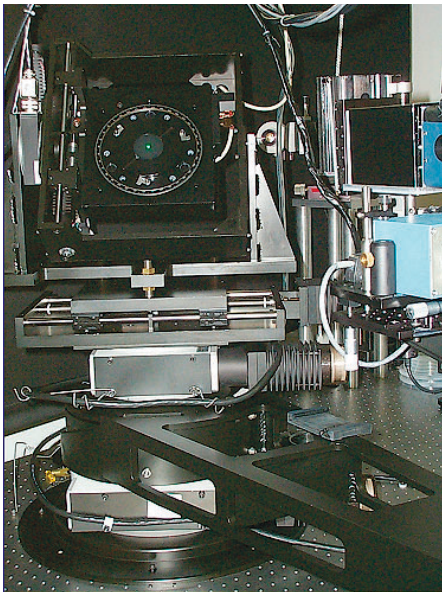
CCG 289, Navy Sponsorship

CCG 295, Air Force Sponsorship

CCG 481, Air Force Sponsorship

When light strikes a surface, some is absorbed and some is specularly reflected in a direction determined by the laws of optics. Depending on the nature of the surface, some light will be scattered in other directions. Every reflecting surface, even a mirror, will scatter light to some extent. Sometimes the effects are pleasing to the eye, such as diffuse reflection when light is scattered from a wall painted with a "flat" textured paint; but in optical devices scattering is usually detrimental. As an unwanted effect, scattering must be measured and quantified to specify the performance of equipment.

The bidirectional reflectance distribution function (BRDF) quantifies the directional dependence of optical scattering from a material surface. BRDF metrology was initially driven by the designers of large optical systems used for national defense. The BMDO has a need for specifying and evaluating large low-scatter mirrors to be used in ground- and space-based sensors as well as energy directed weapons. Prior to the acceptance of BRDF by the affected communities, polished mirrors were commonly characterized with surface profilers, and those measurements were used to infer optical scatter performance. The ultimate scatter performance of a part, however, can be evaluated with certainty only by direct measurement of its scatter distribution. BRDF was identified as a significant figure of merit for specifying mirrors, but there was no standard calibration throughout the measurement community.



NIST goniometric optical scatter instrument.

Realizing its importance to our defense effort, the Secretary of the Air Force, Office of Research (SAF/OR), began funding the development of a low-level BRDF program at NIST in 1988, with the objective of establishing a world-class optical scattering facility, extending and refining BRDF measurements, and unifying the BRDF measurement metrology. This was transferred to CCG funding under Air Force sponsorship in 1993.

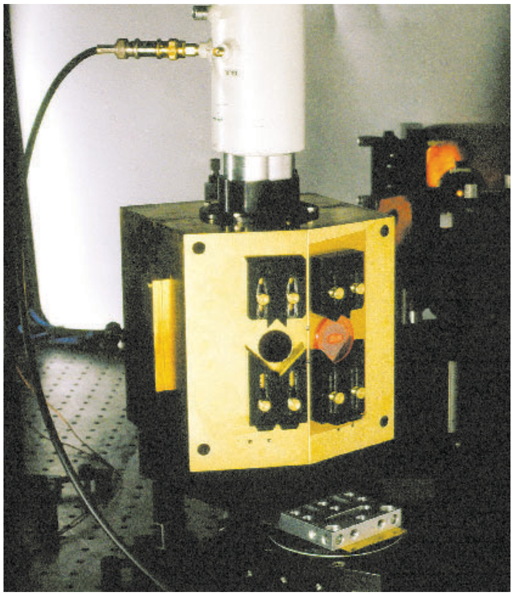
The approach was to develop a high-accuracy BRDF instrument and methods for transferring the accuracy of the measurement through standard artifacts and techniques. In subsequent years the facility has provided DoD with needed support for surface topography profiling, BRDF comparisons among laboratories (round robins), and development of BRDF calibration standards. By supporting NIST contributions to the development of an ASTM standard test practice, DoD stimulated the emergence of BRDF as a widespread metrology tool used throughout the optics manufacturing and testing communities.

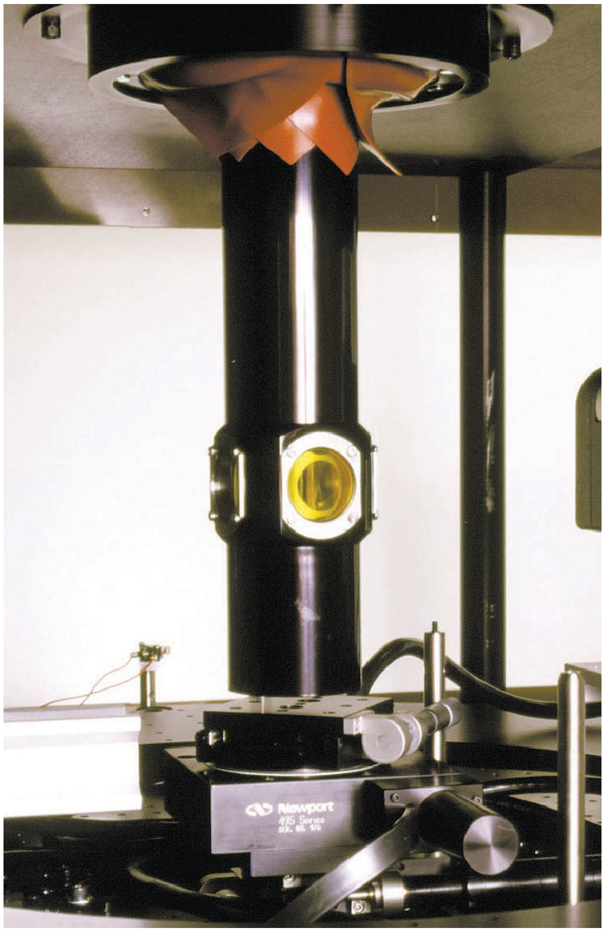
The Goniometric Optical Scatter Instrument (GOSI) that resulted from DoD funding is a world-class facility, featuring full hemispherical mapping of the BRDF, full polarimetric capabilities, high angular resolution, a dynamic range of about 16 orders of magnitude, and a Rayleigh-scatter-limited instrument signature. The unique capabilities of this instrument have enabled NIST to play a leadership role in the development of polarized-optical-scatter methods that enable distinction among different scattering sources.

Thus, NIST's BRDF measurements and research have had significant impact on a broad industrial community representing manufacturers of optical instrumentation and materials development, semiconductor inspection, remote sensing instruments, astronomical telescopes, medical imaging optics, consumer optical devices, and textiles, paper, paint, and finishes. In addition the DoD will continue to reap benefits from this research through its applications in target detection and remote sensing.

The light (radiation) we observe from a surface is a combination of light originating from various sources and reflecting from the surroundings and light emitted from the surface itself. For numerous applications, including target discrimination, both the

Integrating sphere for measurement of diffuse reflectance.





Cryostat for sample temperature control, 10 K to 600 K (for studying temperature dependence of emittance).

reflectance and emittance properties of the target must be understood. Most materials and surfaces will scatter to some degree. For these materials all the reflected light must be collected to determine the reflectance. This is known as "diffuse" or "total" reflection. Emittance is a measure of how well any material emits light (due to its temperature) in comparison to a perfect blackbody emitter.

Under an earlier CCG-funded project, 289, NIST established diffuse reflectance standards for the infrared spectral region. This included a facility for the calibration of DoD sample material, commercially available standards in the form of Standard Reference Materials (SRMs), and new measurement instruments and methods. (SRMs are sample materials available from NIST that have had their pertinent characteristics carefully measured so other laboratories and industry can use them to assure proper performance of their instruments and traceability to national standards.)

This project was a cooperative effort between NIST and the Naval Research laboratory (NRL) in Washington, D.C. Instrumentation developed by NIST was delivered to NRL and the Navy Primary Standards Laboratory in San Diego, California.

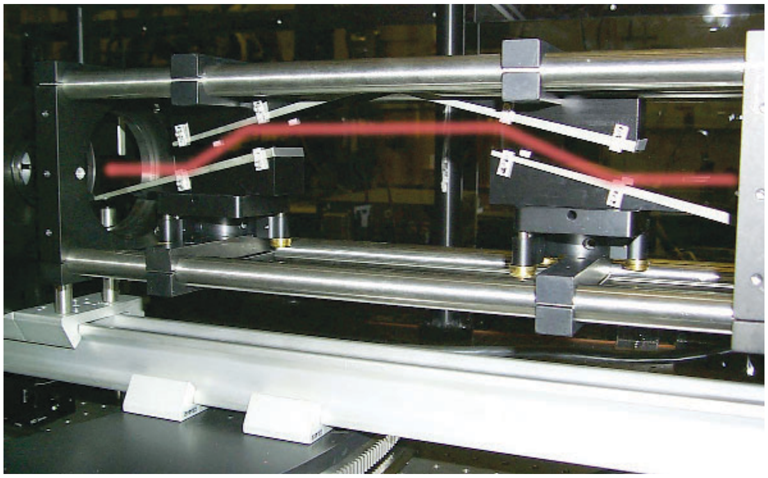
Very recently, the CCG has funded NIST under Project 481 to develop measurement standards and methods for angular and temperature dependence of emittance for target discrimination. This project will expand upon current indirect emittance characterization capabilities at NIST to include temperature and angle dependence. New instrumentation to be developed will include a facility for measurement of direct emittance for materials at temperatures up to 1273 K.

Civilian applications for diffuse reflection metrology include the study of flame-retardant building materials and the development of protective fire-fighting clothing, while developments in emittance measurements will benefit manufacturers of aluminum moldings and semiconductor fabrication through improvements in noncontact thermometry and thermography.

B. Infrared Polarization Standards and Metrology

CCG 400, Navy Sponsorship

Another characteristic of light common to all electromagnetic (EM) waves is a property called polarization. EM waves move through space with electric and magnetic fields that are orthogonal both to each other and to the direction of propagation. Polarization is



NIST-developed high contrast IR polarizer.

defined as the angle between the direction of the electric field and some arbitrarily chosen direction, usually in the medium of propagation.

A very commonly encountered use of polarization is in certain types of sunglasses. These utilize a material that rejects visible light of certain polarizations, thus reducing unwanted glare. In the military area on the modern battlefield, target discrimination from clutter and decoys becomes more important as these areas expand into more efficient countermeasure capabilities. New ways to provide this discrimination require examining other properties of light such as polarization and applying it to the infrared sensors so important to modern warfare.

Recent investigations have shown plumes and natural clutters to be mostly unpolarized. Since light detected from a man-made target is often partially polarized, polarization could be an effective discriminator for targets. Polarization imaging using a focal-plane array could discriminate between the natural background and a camouflaged target. Performance of a polarimetric sensor system depends on the quality of polarizers, retarders, and other optical components used. In addition, polarization measurements greatly extend the optical analysis of materials via spectroscopic ellipsometry, polarimetry, and the Kerr and Faraday effects. Other applications are optical computing, magneto-optical data storage, and pharmaceutical quality control.

Real polarizers, known as diattenuators, do not completely extinguish the orthogonal polarization component. Real retarders (phase shifters) may not project the correct retardance and may have a different attenuation for the two orthogonal polarization components. Undesirable near-specular scattering (NSS) degrades not only the polarimetric performance, but also the image quality of an optical system. A polarimetric component can be characterized by the parameters of diattenuation, NSS, and retardance. These parameters must be quantified and corrected for the optimal performance of an optical polarimetric system.

Realizing the importance of this metrology area the CCG, under Navy sponsorship, funded NIST to develop these measurement capabilities. As a result NIST was able to establish a new capability for spectral calibration of polarization components (linear polarizers and retarders) in the infrared. This new capability has been used to produce calibrated standard polarizers for Navy Laboratories including the Naval Warfare Center in China Lake, California, and the Naval Research Laboratory in Washington, D.C. A critical component specifically developed for the new calibration facility is a nearly ideal "master" standard linear polarizer. Two of these polarizers were delivered to the China Lake facility to improve their own polarimetric capabilities.

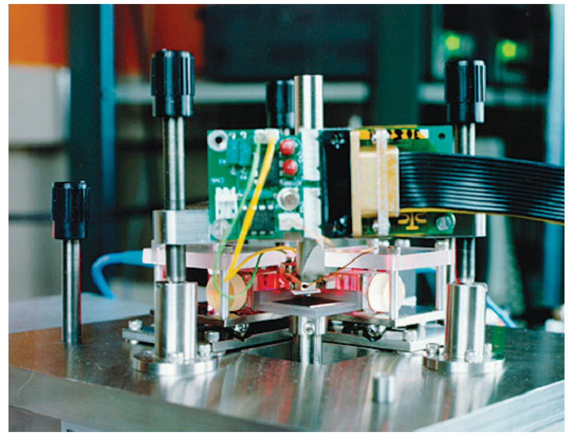
C. Surface-Finish Metrology

CCG 254S SDIO Sponsorship

Although less relevant to electro-optical metrology, surface finish of mirrors is an extremely important matter to the Strategic Defense Initiative and Ballistic Missile

Defense programs. In a technology where a mere thumbprint on a mirror can absorb enough heat to destroy the mirror when irradiated by a very-high-energy laser beam, imagine what a tiny bit of roughness in the mirror's surface could do. In the 1980's, the BMDO required measurements of mirror roughness to an accuracy previously unavailable. The CCG supported NIST to develop new measurement techniques and calibration artifacts that could satisfy this need. Previously, optical interferometry and physical stylus methods were the profiling techniques principally used to test optical surfaces. The resulting profiles and topographic images generally have dimensions on the order of 1 nm (nanometer) or more. The vertical resolution of these techniques was as low as 0.1 nm or better, but the lateral resolution was much more limited. It was 0.1 mm (micrometer) at the very best and typically 0.5 mm or more.

NIST turned to new profiling techniques of scanning tunneling microscopy (STM) and atomic-force microscopy (AFM), which had been used in the semiconductor industry for profiling the miniature structures of transistors, etc. It also had been used successfully to produce rastered-profile maps of surfaces with sub-nanometer lateral resolution and 0.1 nm vertical resolution or better. A principal limitation of these techniques for optical surface metrology was the short scan length and hence the small area size that could be measured. Very little work had been done at the time for profile lengths of 10 mm or more on optical surfaces by use of these techniques [4]. Therefore, there was a gap between the short profile, high-resolution STM and AFM methods and the surface profiling techniques predominantly used for optics at the time. Important properties of optical surfaces could be missed until the gap was bridged.



NIST's calibrated atomic-force microscope with direct traceability to the SI quantity of length in all three axes of motion.

After extensive development work the following objectives were achieved:

- A long-range scanning tunneling microscope with traversing capability of 500 µm x 500 µm, lateral resolution of about 1 nm, and vertical resolution of 0.1 nm.
- A calibrated atomic-force microscope (C-AFM) with traceability to the wavelength of light for all three axes of motion used in an ongoing test service primarily for calibration of specimens used to calibrate other atomic-force microscopes. Specifically, the instrument is used to calibrate pitch, step height, and linewidth specimens, and to measure roughness. It has a lateral traversing capability of 50 µm x 50 µm, a lateral resolution of about 1 nm for measurement of smooth surfaces, and a vertical resolution of about 0.1 nm.
- ASTM F1811-97, Standard Practice for Estimating the Power Spectral Density Function and Related Finish Parameters from Surface Profile Data.

As a result NIST's capability for surface calibrations has improved the state of the art of step-height calibrations to DoD's metrology laboratories. This enables NIST to provide traceable roughness measurements at extremely high levels of spatial resolution and atomic vertical resolution for optical surfaces used in DoD optics projects.
This capability has also been beneficial to the semiconductor industry, the data storage industry, and their suppliers. Specifically, calibrations and special tests have been performed for metrology companies supplying those industries and the optics industry. In addition, the C-AFM has been used to settle a question arising from systematic differ-

ences observed between measurements of linewidth by electrical methods and by scanning electron microscopes. In addition, the C-AFM has been used to provide an independent traceable measurement of prototype single-atom step-height standards.

Chemical, Biological, Radiological (CBR)

Alpha and Beta Calibration Source Traceability

CCG Projects 321, 371, 376, 435, 459, Air Force Sponsorship

CCG 475, 492, Army Sponsorship

ADM 300 radioactivity measurement probes.

The Department of Defense has used many thousands of ionizing-radiation-detector meters since the beginning of the Cold War to monitor potential radiation contamination resulting from weapons tests, spills or leakage of radioactive materials, facility decommissioning, and even peacetime applications such as radioisotopic medicines. The meters are typically used at military bases by bio-environmental personnel, by disaster preparedness teams, and by civil-defense groups. The vast majority of these ionizing-radiation survey meters must be calibrated periodically. Precision calibration for surface-contamination alpha and beta particles has long been a challenge, and the DoD-NIST partnership has made great strides to solve these calibration problems.

Emissions of alpha and beta particles are fundamentally difficult to measure. Calibration traceability to a national standard that simulates the "real world" of surface contamination has been the chief obstacle. Nine projects, in fact, have been initiated over the last 10 to 15 years to help establish real traceability for accurate detector calibrations.

Air Force Primary Standards Laboratory calibration range for calibrating ionizing-radiation detectors.

The problem was first recognized during intercomparison measurements of a series of large-area plutonium-239 (Pu-239) calibration sources known by the military part number AN/UDM-7. NIST discovered that the sources varied significantly in thickness and were easily damaged and generally unstable. They decided to investigate the possibility of replacing these sources with anodized-aluminum Pu-238 sources, which are more rugged and uniform. The application had to accommodate Pu-239, however, so it was necessary to develop the calibration apparatus and appropriate correction factors for converting the response of the instruments to Pu-238 to their response to Pu-239. This led to the development of a special calibration "jig" or fixture for holding a detector close to the calibration source. The fixture also had to be adaptable to the various surface monitors used by the three services. This objective has been accomplished.

The traceability problem for beta-particle calibrations was even more profound. The standards had to be developed, but even before that could happen the behavior of beta particles had to be better understood. The first CCG beta-particle project resulted in a published paper detailing a beta-particle model that has gained international acceptance. Ionizing-radiation projects are ongoing, and large-area calibration standards are being developed for distribution to the military laboratories.

Appendix A.

A List of all CCG Projects as of FY 2002

The following is a list of CCG metrology engineering projects. It is as complete as possible, going back to the beginning of the CCG in the 1960's, and continuing through 2001. In some cases the information in the table is incomplete, but we have chosen nevertheless to present what was available.

The table is arranged by project number, which approximates a chronological order. As a time reference, project 100 was assigned in 1975, project 200 in 1985, project 300 in 1990, and project 400 in 1995. Project 500 should be designated in 2002.

The next three columns, (1), (2), and (3), under the heading "SUFFIX," contain letter suffixes that were occasionally appended to the project number. Column (1) contains letter designators that were used to denote projects with very similar subject matter. These projects were assigned the same number and a letter suffix indicating that another service was providing support for a different frequency range or configuration. The letters have no special meaning other than as a differentiator. This project naming practice was abandoned for many years after project number 225 with the institution of the "Lead Service" arrangement (see below).

Column (2) is used to designate projects that were supported by one of the joint service program offices. Here the letter M stands for the MILSTAR Program Office and S stands for either SDIO, the Strategic Defense Initiative Office, or later for its successor, the Ballistic Missile Defense Office (BMDO). In these projects one of the services, usually the Air Force, acted as the lead-service project manager.

Starting with project number 444, when reduced budgets sometimes required the use of joint service project funding, a project naming practice similar to that formerly used was resumed. Column (3) contains a letter suffix used with projects with identical numbers. In these cases, however, the letter A stands for Army, F for the Air Force, and N for the Navy.

The major column, "Project Title," contains the title assigned at the time of project initiation. In some cases the names are self-explanatory, while in others they are so abbreviated that they admittedly appear cryptic.

The column labeled "NIST Facility" designates where the work was conducted, with G standing for the Gaithersburg, Maryland, and B for the Boulder, Colorado, facilities of NIST. Oak Ridge National Laboratory (ORNL) also led the research on a few projects as indicated in this column. IH stands for In-house, meaning that a service laboratory undertook the majority of the work.

The next column, "Technology Area," lists the name of the CCG Engineering Working Subgroup currently responsible for the scientific area of the project. The names of these subgroups have changed over the years, and the present name may not correspond to the name of the sub-group cognizant at the time of the project.

The last column, "Sponsoring Organization," designates which service(s) funded and/or had oversight over each project. Until project 190, it was not uncommon for the services to contribute equally to the support of projects, indicating they all had an equal stake in the projects' results. In some cases only one or two service(s) had a requirement that was addressed by a project as evidenced in the table.

However, in the mid-1980's, the DoD Joint Director of Laboratories recommended that projects be managed and funded by use of a "Lead Service" concept in order to simplify management responsibility. Using this approach, all funding and oversight responsibilities for each project now belong to a single service. It is still true that typically more than one service has an interest in most projects. The sub-groups of the CCG Engineering Working Group decide the division of project responsibilities among the services with a project's lead-service position being filled by the service having the most pressing requirements in the project's technical area.

The practice of project funding by a single service continued until project 444 when once again, on occasion, more than one service might fund a single project. The method of designating these projects, using suffix column (3), is explained above. The service listed as the sponsoring organization on the first entry of the project number fulfills the role of lead service project manager.

Table A-1. List of CCG projects by number.

CCG #	(SUFFIXES) (1)	(2)	(3)	PROJECT TITLE	NIST FACILITY	TECHNICAL AREA	SPONSORING ORGANIZATION
3				Flow Project	G	phys/mech	
4				Improved Transfer of Standard Voltage	G	electrical	
5				Resistance Scaling Techniques	G	electrical	Army
6				EPR Magnetic Standards	G	electrical	Navy
8				Thermal Voltage Converter Improvement	G	electrical	Army
9				Low Field Magnetic Calibration System	G	electrical	Navy
12				DC Ratio by AC Ratio Techniques	G	electrical	Army
13				Automated Vibration Calibration System	G	phys/mech	
15				Absolute Vibration Calibration System	G	phys/mech	Air Force
16				Infrared Standards of Radiance	G	electro-optical	Air Force
21				CW High Power Measurement	B	microwave	Navy
23				RF Peak Pulse Power Measurement	B	microwave	Navy
25				Signal Detection Systems	B	microwave	Army
27				EM Field Intensity Standards Frequency Extension	B	microwave	Navy
33				Standards Waveform Generator	G	electrical	Air Force
34				Vibration Monitoring System	G	phys/mech	
37				Systematic Study of Vibration Transfer Standards	G	phys/mech	Air Force
38				Josephson Effect Voltage Standards	G,B	electrical	Army, Navy, Air Force
40				Two Stage Inductive Voltage Divider	B	electrical	Army
41				Interlaboratory Transfer of Units of Resistance and Capacitance	G	electrical	Army
42				Development of High Resonant Frequency Accelerometer	G	phys/mech	
44				30 MHz Attenuation Measurement System	B	microwave	Navy
46				Noise Figure Meter Calibrator	B	microwave	Air Force
47				Microwave Phase Measurement	B	microwave	Navy
48				High Frequency Vibration Measurement	G	phys/mech	Navy, Air Force
50				Survey of Wave Sampling Systems Limitations	B	microwave	Army
51				Gadby System Resolution Improvement			Army, Air Force
52				Freq. Domain Measurement - Baseband Instrumentation Systems	B	microwave	Army
56				Specification and Measurement of Frequency Stability	B	microwave	Army
57				Stable Pressure Transducers	G	phys/mech	Army
70				CW Signal Systems Standards - Field Intensity Measurements	B	microwave	Army, Air Force
72	A			Improved EM Impulse Field Measurements	B	microwave	Navy
72	B			RF Adapter Evaluation/Measurement Data Base	B	microwave	Air Force
72	C			Cryogenic RF Attenuation Measurement	B	microwave	Navy
72	D			Cryogenic RF Power Measurement	B	microwave	Navy
77				EM Power Density Meter Calibration System	B	microwave	Army, Navy
79				Automated Systems Standards	B	microwave	Army
79	A			Meas. Assurance Program (MAP) for Automatic Network Analyzer	B	microwave	
81				Transportable DC Voltage Standard	G	electrical	Army
82				Laser Calorimeter Standards	B	electro-optical	Air Force
83				Ultrasonic Interferometer	G	phys/mech	Air Force
87				VOR Aircraft Navigation Standards	B	microwave	Army, Navy, Air Force
88				Low Light Level Standards	G	electro-optical	Army
89				Interlaboratory Comparison of Infrared (IR) Standards	G	electro-optical	Army, Navy, Air Force
90				Infrared (IR) Detector Standards	G	electro-optical	Army, Navy, Air Force
91				Interlaboratory Comparison - Laser Standards	B	electro-optical	Army, Navy, Air Force
92				Laser Q-Switched Power/Energy Measurements	B	electro-optical	Air Force
95				Automated Standard Cell Comparator	G	electrical	Air Force
96				Automated AC Voltage Measurement	G	electrical	Air Force
97				EM Field Measurement and Analysis	B	microwave	Navy, Air Force
98				Calibration Services for Accelerometers	G	phys/mech	
99				Six Port Measurement Techniques	B	microwave	Army, Navy, Air Force
100				Automated Bolometric Calibration System	B	microwave	Army
101				Millimeter Wave Standards	B	microwave	Air Force
102				Thermal Coefficients	G	phys/mech	
103				Low Velocity Primary Standard	G	phys/mech	Navy
104				CW Signal Generator	B	microwave	Air Force
105				Pulse Power Signal Generator Calibrator	B	microwave	Air Force
106				Spectral Radiometry	G	electro-optical	Army
107				Laser Standards Measurement Assurance Program	B	electro-optical	Air Force
108				Laser High Power Metrology	B	electro-optical	Army, Navy, Air Force
109				Laser Beam Characterization	B	electro-optical	Army, Air Force
111				Low Frequency RMS Voltmeter	G	electrical	Army, Navy, Air Force
112				Phase Angle Standard and Measurement Methods	G	electrical	Navy, Air Force
113				Support of New Power Standards	B	microwave	

Table A-1. List of CCG projects by number.

CCG #	(SUFFIXES) (1)	(2)	(3)	PROJECT TITLE	NIST FACILITY	TECHNICAL AREA	SPONSORING ORGANIZATION
117				Radiac Round Robin	G	radiological	Army, Navy, Air Force
118				Radiac Handbook	G	radiological	Army, Navy, Air Force
120				Laser Target Designator Metrology	B	electro-optical	Army, Navy, Air Force
121				High Frequency Automatic AF Admittance Bridge	G	electrical	Army, Air Force
123				Automated AC/DC Thermal Voltage Converter	G	electrical	Army, Air Force
124				Pulse Transition Time Measurement Assurance Program	B	microwave	Air Force
125				Auto Test System for AC Voltage Calibration	G	electrical	Army, Navy, Air Force
126				DoD Laboratory Independence, Power and RF Voltage	B	microwave	Army, Navy, Air Force
127				Temporal Characterization of Pulsed Lasers/Laser Devices	B	electro-optical	Army, Navy, Air Force
128				Future DoD Laser Metrology Requirements	B	electro-optical	Army, Navy, Air Force
129				Laser Rangefinder/Receiver Metrology	B	electro-optical	Army, Navy, Air Force
130				Improved AC High Voltage Divider	G	electrical	Army, Air Force
131				Optical Fiber Standards for Communications	B	electro-optical	Army, Navy, Air Force
132				Modern Electro-Optical (EO) Technology	G	electro-optical	Army, Navy, Air Force
133				Forward Looking Infrared (FLIR) Radiance Standard	G	electro-optical	Navy, Air Force
134				Sidewinder/Intermed. Wave IR Transfer Radiometer Character	G	electro-optical	Navy, Air Force
135				DoD Infrared /Electro Optical Metrology Requirements	G	electro-optical	Army, Navy, Air Force
136				Fundamental Radiometry	G	electro-optical	Army, Navy, Air Force
137				Dynamic Electrical Measurements	G	electrical	Army, Navy, Air Force
138				Millimeter Wave Standards	B	microwave	Army, Navy, Air Force
139				Kilogram Standard Improvement	G	phys/mech	Army, Navy
140				Waveguide Transmission Line Standards: WR-42, WR-28	B	microwave	Navy
141				Microwave Antenna Coupler Standard	B	microwave	Navy
142				Satellite Controlled Clocks	B		Navy
146				Improved Modeling of Diode Detectors	B	microwave	Army, Navy, Air Force
148				NBS Self Study Manual on Optical Radiation Measurements	G	electro-optical	Army, Navy, Air Force
151				Tunable Laser Source	B	electro-optical	Army, Navy, Air Force
152				Optical Scattering Standard	B	electro-optical	Army, Navy, Air Force
153				IR High Accuracy Spectrophotometry	G	electro-optical	Army, Navy, Air Force
154				Improved Standards for Wide Ranging Environments	G	electrical	Army, Air Force
155				Automated Capacitance Bridge	G	electrical	Army, Navy, Air Force
156				1.25 MHz IF Standards	B	microwave	Army, Navy, Air Force
157				Automatic Test Equipment Metrology	G		Army, Navy, Air Force
158				Fast Laser Pulse Metrology	B	electro-optical	Army, Navy, Air Force
159				Laser Beam Divergence/Profile Measurements	B	electro-optical	Army, Air Force
160				Type N Line Standards for Six-Port Calibration	B	microwave	Army, Navy, Air Force
161				Quality Control for Six-Port Systems	B	microwave	Army, Navy, Air Force
162				Solid State Thermal Converters	G	electrical	Army, Navy, Air Force
163				Quantum Hall Effect Resistance Standard	G	electrical	Air Force
165				Extend Dynamic Range of Six-Port to 80 dB or Higher	B	microwave	Army, Navy, Air Force
166				Construct/Evaluate Directional Couplers (10-1000 MHz)	B	microwave	Army
167				Long Wavelength Infrared Spectrophotometry	G	electro-optical	Army, Navy, Air Force
168				Low Background Infrared Standards	G	electro-optical	Air Force
169				Precision Arbitrary Waveform Generation Methods	G	electrical	Air Force
170				Std. for Oscilloscope Waveform Recorder	B	electrical	Army, Navy, Air Force
171				Standards for 3.5 mm Connectors, 18-26 GHz	B	microwave	Army, Navy, Air Force
172				Transportable 10 Volt DC Standard	G	electrical	Army, Navy, Air Force
175				New DC Resistance Metrology	G	electrical	Army, Air Force
176				Low Level Germanium Transfer Standard	G	electro-optical	Army, Navy, Air Force
178				Broadband Isotropic Probe Std, 0.01-6 GHz	B	microwave	Army, Navy, Air Force
179				Broadband Isotropic Probe Std, 4-18 GHz	B	microwave	Navy
179	B			Field Intensity Transfer Standards, 18-26.5 GHz	B	microwave	Navy
180				Improved Manometry Capability	G	phys/mech	Army, Navy, Air Force
181				Jet Engine Temperature Measurement	G	phys/mech	Army, Navy, Air Force
183				Calibration of Alpha Radiac Calibration Test Set	G	radiological	Air Force
185				Automated Temperature Measurement	G	phys/mech	Army, Navy
186				DoD Liaison Support	G/B	other	Army, Navy, Air Force
187				New Impedance Metrology	G	electrical	Army, Air Force
190				Improved Transportable Capacitance Standard	G	electrical	Air Force
191				Josephson Array Voltage Standard (1 Volt)	B	electrical	Navy
192				Imaging IR Systems Metrology	G	electro-optical	Navy
193				Infrared Detector Standards	G	electro-optical	Army
194				LWIR Detector Characterization Facility	G	electro-optical	Army
195				Millimeter Wave (MMW) Meas. System for Power & S-parameters	B	microwave	Air Force

Table A-1. List of CCG projects by number.

CCG #	(SUFFIXES) (1)	(2)	(3)	PROJECT TITLE	NIST FACILITY	TECHNICAL AREA	SPONSORING ORGANIZATION
195	A			MMW Meas. System for Power & S-parameters WR-42	B	microwave	Air Force
195	B			MMW Meas. System for Power & S-parameters WR-28	B	microwave	Air Force
195	C			MMW Meas. System for Power & S-parameters WR-22	B	microwave	Air Force
195	D			MMW Meas. System for Power & S-parameters WR-15	B	microwave	Air Force
195	E			MMW Meas. System for Power & S-parameters WR-10	B	microwave	Air Force
195	M			Interim MILSTAR - Power and S-parameters	B	microwave	MILSTAR P .O.
196				Nearfield Antenna Measurement Automation	B	microwave	Army
196	M			Interim MILSTAR - Nearfield Antenna Measurement Automation	B	microwave	MILSTAR P.O.
197				Precision Coax. Step Attenuator Check Standard (below 26 GHz)	B	microwave	Navy
197	A			Precision Coax. Step Attenuator Check Standard (26-50 GHz)	B	microwave	Navy
198				High Accuracy Phase Measurement	B	microwave	Air Force
199				Phase Noise	B	microwave	Navy
199	A			Phase Noise Measurement Standard (5 MHz-26.5 GHz)	B	microwave	Navy
199	M			Interim MILSTAR - Phase Noise Measurement Standard	B	microwave	MILSTAR P.O.
200				Noise Temperature Measurement Support	B	microwave	Air Force
200	M			Interim MILSTAR - Noise Temperature Measurement Support	B	microwave	MILSTAR P.O.
201				Monolithic Construction for Six-Ports	B	microwave	Army
202	A			Standards for Microwave Power at 10 mW	B	microwave	Navy
202		M		Interim MILSTAR - Standards for Microwave Power at 10 mW	B	microwave	MILSTAR P.O.
204				Transportable Calibration Chamber	B	microwave	Navy
206				Broadband Isotropic E-field Probe (10 MHz-26.5 GHz)	B	microwave	Navy
206	A			Broadband Isotropic E-field Probe (26.5-110 GHz)	B	microwave	Navy
207				Piston Gage Metrology	G	phys/mech	Navy
208				Dynamic Pressure, Temperature & Shock Measurements	G	phys/mech	Army
209				Laser Peak Power Standards	B	electro-optical	Air Force
210				Photoconductive Switch for Reference Waveform Generator	G	electrical	Army
211				Non-Destructive Test Research	G	phys/mech	Air Force
213				Prototype DC Voltage Measurement System	G	electrical	Navy
214				Multi-range Thermal Converter System	G	electrical	Navy
215				Aerosol Science and Technology	G	phys/mech	Army
216				Space Based Weapons and Measurements	G	phys/mech	Army
218				Gas and Liquid Flow	G	phys/mech	Air Force
219				AC Voltage Standard and Measurement Methods	G	electrical	Navy
220				Modular Calibration Interface	G	electrical	Navy
221				Temperature Sensors	G	phys/mech	Navy
222				Near Infrared Radiometer	G	electro-optical	Navy
223				Study of Environmental Criteria for Standards Laboratory			Air Force
225				High Power CW Measurements	B	microwave	Navy
225	B			High Power CW Measurements to 1 GHz	B	microwave	Army
225		M		Interim MILSTAR - High Power CW Measurements	B	microwave	MILSTAR P.O.
226				30 MHz Attenuation Standard	B	microwave	Air Force
227				Sensor Research	G	phys/mech	Army
228				Vision Intelligent Calibration	G	phys/mech	Army
229				X-ray Counting System	G	chem/bio/rad	Air Force
230				MMW Meas. System for Power & S-parameters 2.4/3.5 mm	B	microwave	Army
231				Anechoic Chamber Facility	B	microwave	Army
232				Advanced ANA Impedance Standards Characterization	B	microwave	Navy
233				Superconducting Thermometer for Bolometric Applications	G	electro-optical	Army
234				Standard Detector for X-ray Sensors	G	chem/bio/rad	Air Force
234		S		XUV Spectrometer/Detector Calibrations	G	electro-optical	SDIO
235				Primary Liquid Flow Standard	G	phys/mech	Navy
236				Precision Arbitrary Waveform Standards	G	electrical	Navy
237				High Current Wideband Transconductance Amplifier	G	electrical	Air Force
238				Cryogenic Power Measurement System	B	microwave	Navy
239				Fiber Optic Calorimeter	B	electro-optical	Navy
240				Single Mode Fiber Optic Test Procedure Analysis	B	electro-optical	Navy
241				Imaging IR System Support	G	electro-optical	Navy
242				High Resolution Optical Reflectometry	G	electro-optical	Navy
243				Fast Optical Sampler	G	electro-optical	Navy
244				New Tech IR Imaging Support	G	electro-optical	Navy
245				Josephson Array Voltage Standard (10 V)	B	electrical	Navy
246				Dissipation Factor Measurements	G	electrical	Navy
247				Digital Synthesis/Measurement of Waveforms	G	electrical	Air Force
248				Dynamic Pressure	G	phys/mech	Army

Table A-1. List of CCG projects by number.

CCG #	(SUFFIXES) (1)	(2)	(3)	PROJECT TITLE	NIST FACILITY	TECHNICAL AREA	SPONSORING ORGANIZATION
249				Fixed Point Pressure Standards	G	phys/mech	Army
250				Capacitance Bridge Evaluation	G	electrical	Army
251				Automatic Test Equipment (ATE) Calibration Strategies	G	electrical	Air Force
252		S		Advanced Angle Metrology	G	phys/mech	SDIO
253		S		60 GHz Probe Position Correction	B	microwave	SDIO
254		S		Surface Finish Metrology	G	phys/mech	SDIO
255		S		Environmental Effects on Optical Fabrication	G	phys/mech	SDIO
256		S		Precision Optical Grinding	G	phys/mech	SDIO
257		S		Ultraviolet Radiometry	G	electro-optical	SDIO
258		S		Megawatt Laser Calorimeter	B	electro-optical	SDIO
259		S		XUV Optics Characterization	G	electro-optical	SDIO
260		S		Dimensional SEM Standard	G	phys/mech	SDIO
261		S		Superconducting Bolometer	B	electro-optical	SDIO
262				Coaxial Connector Gauges and Tools	B	microwave	Army
263				Six-Port at 18-40 GHz	B	microwave	Army
264				Low Level Laser Measurements	B	electro-optical	Air Force
265				Optical Time Domain Reflectometer (OTDR) Support Facility	B	electro-optical	Navy
266				Laser Heterodyne	G	electro-optical	Navy
267				DC Resistance Standards	G	electrical	Air Force
268				NMR Based Voltage Standard	G	electrical	Air Force
269				Unbalanced Bridge for Resistance Measurements	G	electrical	Navy
271				High Current AC Measurement Standard	G	electrical	Navy
272				Fiber Optic Standard Detector	B	electro-optical	Navy
273				Temporal Pressure/Temperature Phenomena	G	phys/mech	Army
274				Automated Physical Measurements	G	phys/mech	Army
275				Gas Mask Leakage Testing	G	phys/mech	Army
276				Fast Pulse Measurement System	G	electrical	Army
277				Thermal Resolution Targets	G	electro-optical	Navy
278				Contactless Liquid Flow Standard	G	phys/mech	Navy
279				AC Voltage & Current Standards	G	electrical	Navy
280				Night Vision Imaging System Measurement/Calibration Support	G	electro-optical	Army
281				Measurement of Low Loss Adapters	B	microwave	Army
282				Coaxial Transfer Standard for Microcalorimeter Calibration	B	microwave	Army
283				Microwave Power at 1 GHz - 1 mW	B	microwave	Air Force
284				Transportable Josephson DC Voltage Standard System	G	electrical	Army
285				Multi-Junction Thermal Converters	G	electrical	Army
286				Salinity/Conductivity Measurements	G	phys/mech	Navy
287				Interferometric Optical Time Domain Reflectometer (OTDR) Tech.	B	electro-optical	Navy
288				Single Mode OTDR Standard	B	electro-optical	Navy
289				IR Diffuse Reflectometer and Standards	G	electro-optical	Navy
290				Optical Fiber Geometry	B	electro-optical	Navy
291				MIMIC Consortium	B	microwave	Navy
292				Gage Block Interferometric Measurements	G	phys/mech	Air Force
293				Multimode Optical Fiber Standard	B	electro-optical	Air Force
294				Optical Power Measurement	B	electro-optical	Air Force
295				Bidirectional Reflectance Distribution Function (BRDF)	G	electro-optical	Air Force
296				Spectral Responsivity	G	electro-optical	Air Force
297				3.5 mm Coaxial Power Standard	B	microwave	Air Force
298				Coaxial Six-Port (18-40 GHz)	B	microwave	Air Force
299				Noise Calibration Efficiency Improvements	B	microwave	Air Force
300				Noise Calibration Accuracy Improvements	B	microwave	Air Force
301				Coaxial Noise Calibration (10 MHz through 1 GHz)	B	microwave	Air Force
302				Swept Frequency Antenna Meas (WR22, WR-15)	B	microwave	Air Force
303				Dual Circularly Polarized Probes (WR-42/22/15)	B	microwave	Air Force
304				Gravimetric Hygrometer Primary Standard	G	phys/mech	Navy
305				Phase Noise Standard	B	microwave	Army
306				Advanced AC/DC Difference Metrology	G	electrical	Air Force
307				Improved Film Multijunction Thermal Converters	B	electrical	Air Force
308				AC Resistance Frequency Dependence Measurement	G	electrical	Air Force
309				IR Detector Characterization	G	electro-optical	Air Force
310				Signal Analyzer Measurement System WR-3	B	microwave	Air Force
311				Photodetector Transfer Standard	G	electro-optical	Air Force
312				Kilowatt CO2 Laser Measurement Assurance Program	B	electro-optical	Air Force
313				Built-In Calibration for Fiber Optic Sensors	B	electro-optical	Navy

Table A-1. List of CCG projects by number.

CCG #	(SUFFIXES) (1)	(2)	(3)	PROJECT TITLE	NIST FACILITY	TECHNICAL AREA	SPONSORING ORGANIZATION
314				Fiber Optic Pulse Measurement System	B	electro-optical	Navy
315				High Power RF Transfer Standard	B	microwave	Navy
316				Millimeter Wave Source Stabilization	B	microwave	Army
317				Accelerometer Super Shaker	G	phys/mech	Air Force
318				Interim Testing of Coordinate Measuring Machine	G	phys/mech	Air Force
319				Primary/Transfer Pressure Standards	G	phys/mech	Air Force
320				Infrared Transmittance & Specular Reflectance Standards	G	electro-optical	Air Force
321				Traceability of Radiac Standards	G	chem/bio/rad	Air Force
322				Extended Frequency Impedance Standard	G	electrical	Air Force
325				Interferometric Measurement of Short Optical Fibers	B	electro-optical	Air Force
326				850 nm Multimode Reference Fibers	B	electro-optical	Air Force
327				Spectrally Flat Detectors with Low Noise Equivalent Power (NEP)	B	electro-optical	Air Force
328				Wideband Sampling Voltmeter	G	electrical	Air Force
332		S		Bidirectional Reflectance Distribution Function (BRDF) Standards	G	electro-optical	SDIO
333		S		Dimensional Stability of Materials	G	phys/mech	SDIO
334		S		Aspheric Optics Metrology	G	phys/mech	SDIO
335		S		Argus Calibration Support	G	electro-optical	SDIO
336				Noise Figure Measurement Program	B	microwave	Air Force
338				Research and Testing of Ceramic Gage Blocks	G	phys/mech	Air Force
339				Imaging IR System Support	G	electro-optical	Navy
340				Spectral Radiometric Support	G	electro-optical	Navy
346				High Reliability 10 V Josephson Voltage Standards	G	electrical	Army
348				Non-Nonlinearities in Infrared Fourier Transform Spectroscopy	G	electro-optic	Army
350				Photometric Standards and Procedures	G	electro-optical	Air Force
351				Multiple Wavelength Standard for Lightwave Communications	B	electro-optical	Air Force
352				Diffraction Corrections	G	electro-optical	Air Force
353				Standard Leak Calibration System	G	phys/mech	Navy
354		S		Low Background Infrared (LBIR) Calibrations	G	electro-optical	BMDO
355				Metrology Support for RCS Measurements	B	microwave	Air Force
357				Fiber Optic Linearity Standard	B	electro-optical	Navy
358				Fiber Optic Polarization Standards	B	electro-optical	Navy
359				Thread Gage Measurement Standard	G	phys/mech	Navy
360				Salinity Measurement / Calibration System	G	phys/mech	Navy
361				Large Diameter Gas Piston Gage Primary Standard	G	phys/mech	Navy
362				High Pressure Gas Calibration	G	phys/mech	Navy
363				NIST Consortium for MMIC Metrology	B	microwave	Air Force
364				Dynamically Applied Torque Measurements	G	phys/mech	Air Force
365				Fast Electrical Pulse Calibration & Standards	G	electrical	Air Force
366				High Accuracy and Sensitive Pyroelectric Radiometer	B	electro-optical	Air Force
367				High Intensity IR Source	G	electro-optical	Air Force
368		S		IR Detector Transfer Standards	G	electro-optical	BMDO
369		S		Infrared Spectral Emittance	G	electro-optical	BMDO
371				Beta Traceability	G	chem/bio/rad	Air Force
372				Investigation of Solid State Volt. Ref. Performance Parameters	G	electrical	Air Force
374				Calibration Support for Type N Connectors above 18 GHz	B	microwave	Army
375				Optical Fiber Group Index Measurement Standard	B	electro-optical	Navy
376				Alpha Traceability	G	chem/bio/rad	Air Force
377				Microwave High Power System	B	microwave	Air Force
378				Laser Power/Energy High Accuracy Standard	B	electro-optical	Air Force
379				Calibration Methodologies for Coordinate Measuring Machines	G	phys/mech	Air Force
380				Mathematical Modeling of Standard Calibration Parameters	G	electrical	Air Force
389				U-Band MILSTAR Hazard Probe	B	microwave	Air Force
390				Phase Noise Implementation	B	microwave	Navy
393				Thin-Film Detector Standard	B	microwave	Navy
394				Uncertainty Modeling for Coordinate Measuring Machines	G	phys/mech	Air Force
395				Radiance & Irradiance IR Transfer Standard Radiometer	G	electro-optical	Air Force
396				Absolute Fiber Optic Wavelength Values	B	electro-optical	Air Force
400				Polarization Standards	G	electro-optical	Navy
401				Cryogenic Fiber Optic Power Standard	B	electro-optical	Navy
402				Laser Power Standard (1.5 µm)	B	electro-optical	Navy
403				Dynamic IR Scene Projector Standard	G	electro-optical	Navy
403				Laser Power Standard (1.5 µm)	B	electro-optical	Navy
404				Calibration of Night Vision Detectors	G	electro-optical	Navy
404		S		LBIR Detector Primary Standard Improvement	G	electro-optical	BMDO

Table A-1. List of CCG projects by number.

CCG #	(SUFFIXES) (1)	(2)	(3)	PROJECT TITLE	NIST FACILITY	TECHNICAL AREA	SPONSORING ORGANIZATION
406		S		Optical Meas. of Blackbody Aperture Area/Diffraction	G	electro-optical	BMDO
407		S		IR Scene Projector Metrology	G	electro-optical	BMDO
408		S		Filter Out-of-Band Blocking	G	electro-optical	BMDO
409		S		IR Spectral Transmittance	G	electro-optical	BMDO
410		S		IR Imaging System/FPA Metrology	G	electro-optical	BMDO
411		S		Ballistic Missile Defense Optics Metrology	G	phys/mech	BMDO
412		S		Ground Based Radar Support	B	microwave	BMDO
413				Rapid Blackbody Calibrator	G	electro-optical	Air Force
414		S		Bandpass Filter Spatial Uniformity	G	electro-optical	BMDO
415		S		Optical Materials Sub-Surface Damage	G	phys/mech	BMDO
418				Infrared Target Simulator Calibration	G	electro-optical	Air Force
420				Enhanced Electrical Substitution Radiometer.	G	electro-optical	Air Force
421				Tunable Lasers for Radiometry	G	electro-optical	Air Force
422				Display Measurement Standards	G	electro-optical	Air Force
423				Conical Field Generation System	B	microwave	Air Force
424				Phase Noise Software	B	microwave	Air Force
425				100 Amp AC Current Shunt	G	electrical	Air Force
426				Ambient Long Wavelength IR (LWIR) Working Std. Radiometer	G	electro-optical	Air Force
427				High Temperature Blackbody Pyrometer	G	electro-optical	Air Force
428				Fiber Optic Chromatic Dispersion Standard	B	electro-optical	Navy
430				Laser Tracker Standard	G	phys/mech	Navy
431				Micro Electromechanical Sensor (MEMS) Standards	G	phys/mech	Navy
431			F	Micro Electromechanical Sensors (MEMS)	G	phys/mech	Air Force
432				Infrared Chamber Support	G	electro-optical	Air Force
432		S		National Missile Defense Infrared Chamber Support	G	electro-optical	BMDO
433				Frequency Response Characterization of Capacitors	G	electrical	Air Force
435				Large Area Radiation Source Metrology	G	chem/bio/rad	Air Force
436				High Energy Laser Calorimeters @ 1.06 µm	B	electro-optical	Air Force
437				E&H Nearfield Probe	B	microwave	Navy
438				High Power Measurement System Upgrade	B	microwave	Air Force
439				Spectral Irradiance & Radiance Calibration	G	electro-optical	Air Force
440				Tunable Diode Lasers for FO Metrology	G	electro-optical	Air Force
441				Improved Thin Film Multijunction Thermal Converter	G	electrical	Air Force
442				Vector Network Analyzer Six-port Verification Standard	B	microwave	Air Force
443				Full Scale Conical Chamber	B	microwave	Air Force
444				Transfer Standard for Fiber Optic Power	B	electro-optical	Navy
444			F	Transfer Standard for Fiber Optic Power	B	electro-optical	Air Force
444			A	Transfer Standard for Fiber Optic Power	B	electro-optical	Army
445				3.5 mm Microwave Power Calibration	B	microwave	Navy
446				Prototype 1.54 µm Pulsed Laser Standard	B	electro-optical	Navy
446			F	Prototype 1.54 µm Pulsed Laser Standard	B	electro-optical	Air Force
447				Army Dimensional Calibration Hierarchy	G	phys/mech	Army
448				Improved Temperature Calibrations Improvement	G	phys/mech	Army
449				Wind Tunnel Characterization and Modification	ORNL	phys/mech	Air Force
449			A	Wind Tunnel Characterization and Modification	ORNL	phys/mech	Army
450				DoD Metrology R&D Support	G/B	other	Air Force
451				Target Simulator Radiometer	G	electro-optical	Air Force
452				Avalanche Photodiode Det. Improvement - Uniform Scan System	B	electro-optical	Air Force
453				Direct Comparison Power Calibration System	B	microwave	Air Force
454				2.92 mm Power Calibration System	B	microwave	Air Force
455				High Power Mismatch Error Improvement	B	microwave	Air Force
456				Enhanced Wideband Oscilloscope Characterization	G	electrical	Air Force
457				Next Generation Sampling Comparator Probe	G	electrical	Air Force
457			A	Next Generation Sampling Comparator Probe	G	electrical	Army
458				Sampling System for Precision Wideband Measurements	G	electrical	Air Force
459				Large Area Beta Sources	G	chem/bio/rad	Air Force
460				Low Level Dosimetry Traceability	G	chem/bio/rad	Air Force
461				Domain Engineered Pyroelectric Detector	B	electro-optical	Air Force
462				Contrast Measurement Standard	G	electro-optical	Navy
463				High Accuracy Cryogenic Radiometer (HACR II)	G	electro-optical	Navy
463			F	High Accuracy Cryogenic Radiometer (HACR II)	G	electro-optical	Air Force
464				Tunable Laser System for Laser Metrology	B	electro-optical	Navy
465				Calibration for Fiber Optic Bragg Gratings	B	electro-optical	Navy
465			F	Calibration for Fiber Optic Bragg Gratings	B	electro-optical	Air Force

Table A-1. List of CCG projects by number.

CCG #	(SUFFIXES) (1)	(2)	(3)	PROJECT TITLE	NIST FACILITY	TECHNICAL AREA	SPONSORING ORGANIZATION
466				Radar Cross Section Standards	B	microwave	Navy
466			F	Radar Cross Section Standards	B	microwave	Air Force
467				8-12 μm Infrared Imaging System	G	electro-optical	Navy
468				High Energy Laser Metrology Support	B	electro-optical	Air Force
469				NIST Joint Service R&D Centennial Review	G/B	other	Navy
469			F	NIST Joint Service R&D Centennial Review	G/B	other	Air Force
470				Sampling/Synthesis System for Precision Wideband Meas.	G	electrical	Army
472				Quality Assurance Methods for Vector Network Analyzers	B	microwave	Army
473				50 GHz Direct Comparison Power Measurement System	B	microwave	Army
474				Gas Mask Tester Calibration System Project	G	phys/mech	Army
475				Wide Area Planar Beta Standard Development	G	chem/bio/rad	Army
476				Software for 10-Volt Josephson Voltage Standards	B	electrical	Army
477				Prec. Low-Freq. Probe for NIST Wideband Sampling Voltmeter	G	electrical	Army
478				Techniques for Scaling & Frequency Ext. of Impedance Calib.	G	electrical	Army
479				Hydrazine Detector Calibration Support	ORNL	phys/mech	Air Force
480				Low Gas Flow Measurement Assurance Program	G	phys/mech	Air Force
480			A	Low Gas Flow Measurement Assurance Program	G	phys/mech	Army
481				Angle/Temperature Dependence of Emittance/Reflectance	G	electro-optical	Air Force
482				High Accuracy Pyrometry to 3200 K	G	electro-optical	Air Force
483				Power Delivery System for Co-conical chamber	B	microwave	Air Force
484				High Accuracy Flow Standard	G	phys/mech	Navy
484			A	High Accuracy L-H Flow Calibration Facility	G	phys/mech	Army
485				IR Wavelength Calibration Standard	B	electro-optical	Navy
486				Fourier Transform IR Spectrometer Project	G	electro-optical	Navy
487				Six-Port Vector Network Analyzer Upgrade	B	microwave	Navy
488				Internet Based Calibration	G	analytical	Navy
489				1.064 μm Laser Source Update	B	electro-optical	Navy
490				Portable Variable Frequency Capacitance Standard	G	electrical	Navy
491				Fourier Transform MW Sp. Quantitative Anal. Chem. WF Agents	G	chem/bio/rad	Army
492				Wide Area Beta Calibration Standard	G	chem/bio/rad	Army
493				Reverb. Chamber for Microwave/Millimeter Wave Probe Calib.	B	microwave	Army
494				Software Upgrade for Optical Fiber Power Meter Calib. System	B	electro-optical	Army
495				Pulse-Driven AC and DC Josephson Voltage Standard	B	electrical	Army
496				30 MHz Comparison Receiver	B	microwave	Army
497				Deployable Dosimetry Laboratory	Army IH	chem/bio/rad	Army

Appendix B.

The Charter Documents and Present CCG Organization

The First DOC-NBS/DoD (DDR&E-ASD-I&L) Memorandum of Understanding (MOU)

August 22, 1968

MEMORANDUM OF UNDERSTANDING

SUBJECT: Procedure for Determining, Estimating the Cost of and Arranging for the Radio and Electronic Calibration Services that Department of Defense Activities Obtain from the National Bureau of Standards

1. General

This memorandum establishes an agreement between the Department of Defense (DDR&E-ASD(I&L)) and the Department of Commerce (National Bureau of Standards) regarding calibration requirements and services pertaining to radio and electronic standards except for Time and Time Interval Standards covered by DoD Directive 5160.51.

2. Purpose

The purpose of this agreement is to establish a uniform procedure for: (a) determining DoD requirements for calibration and calibration engineering services; (b) a joint DoD/NBS review of these requirements to identify those services NBS can provide and to estimate their cost; and (c) planning to budget and fund the estimated cost of the services that by mutual agreement are to be provided by NBS.

3. Basis for Agreement

(a) The services and facilities of the National Bureau of Standards in radio and electronic standards are essential for the support of DoD operations.

(b) An effective NBS/DoD relationship requires a continuing exchange of information regarding requirements, capabilities, and costs.

4. Procedures

(a) A DoD Calibration Coordination Group (DoD/CCG) consisting of representatives from the Military Departments and DSA will be the DoD requirements that describe (i) DoD calibration requirements for the next two fiscal years (ii) DoD calibration engineering requirements for this two year period and the following three fiscal years.

(b) The Director, NBS, will review the schedule of DoD requirements and prepare a cost estimate before 15 November.

(c) A final schedule of requirements will be prepared by the DoD/CCG in cooperation with the Director, NBS by 1 January. The DoD will plan to budget and fund the estimated cost of the requirements that have been mutually agreed upon between the DoD/CCG and NBS. NBS will plan to provide a calibration and supporting services program to meet these requirements.

(d) Prior to 1 July, each of the Military Departments will submit to NBS a formal work order. The Military Departments will transfer advance funds to NBS at the earliest time possible.

(e) For workloads in addition to those already covered by work orders, NBS will charge the Military Departments the same fees or hourly rates as are charged to the public. Such additional workloads can be covered either by amendment of the original work orders or by new work orders.

(f) To facilitate transition to the above described procedure, the DoD will plan to provide for funded work requested during FY 68 and FY 69 at a level at least equal to the level of funding for calibration services in FY 67, subject to the availability of funds.

6. <u>Revisions</u>

This agreement may be reviewed at the request of the DoD or the NBS and revised as mutually agreed between the two agencies.

Concurrence [signature] Date 19 Jan 1968
Allen V. Astin, Director, National Bureau of Standards

Concurrence [signature] Date 2? August 1968
Assistant Secretary of Defense (Installations and Logistics)

The First JLC Charter for the CCG

DEPARTMENT OF THE ARMY
HEADQUARTERS UNITED STATES ARMY MATERIEL COMMAND
WASHINGTON DC, 20315

DEPARTMENT OF THE NAVY
HEADQUARTERS NAVAL MATERIAL COMMAND
WASHINGTON, DC, 20360

DEPARTMENT OF THE AIR FORCE
HEADQUARTERS AIR FORCE LOGISTICS COMMAND
WRIGHT-PATTERSON AFB, OHIO 45433

10 September 1968

DEPARTMENT OF THE AIR FORCE
HEADQUARTERS AIR FORCE SYSTEMS COMMAND
ANDREWS AFB, WASHINGTON, DC, 20331

JOINT AMC/NMC/AFLC/AFSC COMMANDERS CHARTER FOR THE
JOINT TECHNICAL COORDINATING GROUP FOR METROLOGY AND CALIBRATION

1. PURPOSE: A Joint Technical Coordinating Group for Metrology and Calibration (JTCG-METCAL) is hereby established for the purpose of providing management of the DOD calibration and metrology program.

2. MISSION: The mission of the JTCG-METCAL is to (a) provide interservice coordination on matters within the responsibilities of our Commands and (b) make such recommendations as necessary to insure the viability of the Program.

3. GUIDANCE: The JTCG-METCAL will assure accomplishment of interservice coordination on:

a. Interservicing of calibration support.
b. Calibration engineering (metrology).
c. Calibration Training.
d. Calibration procedures, methods and related documentation.
e. Measurement agreement audits.
f. Calibration interval establishment and changes.
g. Need for present or additional calibration facilities resources.
h. National Bureau of Standards calibration and engineering services.

4. REQUIREMENTS: The JTCG-METCAL will (a) within 30 days develop and submit operating procedures (b) formalize the CCG (Calibration Coordinating Group) as the principal subgroup of the JTCG-METCAL, and (c) provide guidance and direction to assist in accomplishing interservice coordination. The CCG was established as a result of a Joint ASD(I&L)/DDR&E memorandum of 2 December 1966.

5. ADMINISTRATION: Each of us will provide at least one member to the JTCG and responsibility may not be delegated. The JTCG-METCAL will report to us in accordance with Operational Instructions issued by the Joint Secretariat. Sufficient priority and resources will be afforded to pursue its assigned responsibilities.

F. S. BESSON, JR.
General USA
Commanding General
U. S. Army Materiel Command

I. J. GALANTIN
Admiral, USN
Chief of Naval Material
Naval Material Command

JACK G. MERRELL
General USAF
Commander
Air Force Logistics Command

JAMES FERGUSON
General, USAF
Commander
Air Force Systems Command

The Current JLC charter for the CMT (Calibration and Measurement Technology Group)

DEPARTMENT OF THE ARMY
HEADQUARTERS US ARMY MATERIEL COMMAND
5001 EISENHOWER AVE., ALEXANDRIA, VA. 22333-0001

DEPARTMENT OF THE NAVY
DEPUTY CHIEF OF NAVAL OPERATIONS (LOGISTICS)
WASHINGTON, DC 20350-2000

DEPARTMENT OF THE AIR FORCE
HEADQUARTERS AIR FORCE LOGISTICS COMMAND
WRIGHT-PATTERSON AFB, OHIO 45433-5001

DEPARTMENT OF THE AIR FORCE
HEADQUARTERS AIR FORCE SYSTEMS COMMAND
ANDREWS AFB, WASHINGTON, DC 20334-5000

JOINT TECHNICAL COORDINATING GROUP

FOR

CALIBRATION AND MEASUREMENT TECHNOLOGY

The enclosed charter dated 30 October 1989 for the Joint Technical Coordinating Group for Calibration and Measurement Technology (JTCG-CMT), Subgroup on Test Measurement and Diagnostic Equipment (TMDE) Metrication is approved.

CLIFFORD GEIGER
Deputy Chief Engineer for
Logistics for the Navy
Naval Sea Systems Command

ROBERT DUBOIS
Deputy Executive Director
of Test Measurement and
Diagnostic Test Equipment
for the Army

LARRY RYAN, COLONEL, USAF
Assistant Deputy Chief of
Staff for Maintenance
Air Force Logistics Command

RUSSELL L. FLINT, COLONEL, USAF
Director, Acquisition and
Logistics
Air Force Systems Command

DATE: 3 November 1989

30 October 1989

JOINT TECHNICAL COORDINATING GROUP
FOR
CALIBRATION AND MEASUREMENT TECHNOLOGY
(JTCG-CMT)
SUBGROUP ON TEST, MEASUREMENT, AND DIAGNOSTIC EQUIPMENT (TMDE)
METRICATION

I. PURPOSE. A JTCG-CMT Subgroup on Test, Measurement, and Diagnostic Equipment (TMDE) Metrication is hereby established to plan and implement a metrication program for DOD TMDE and metrology standards.

II. SCOPE. The actions and recommendations of the TMDE Metrication subgroup are applicable to all DOD elements who own or maintain TMDE and metrology standards.

III. OBJECTIVE.

a. To establish a joint work group of metrology experts and TMDE managers to work with the National Institute of Standards and Technology and industry in developing a plan of action which will serve to facilitate the implementation of the DOD Metric Transition Plan, Task 11, TMDE.

b. To determine the resource impact on TMDE and the metrology program driven by conversion to the metric system.

c. To serve as the DOD focal point for technical matters concerning TMDE/Metrology metrication, to develop and provide TMDE metrication data as required to meet the needs of the Joint Services and the Office of the Secretary of Defense.

IV. MISSION.

a. Review types of metrology standards and TMDE required for electrical, electromagnetic, physical, radiation, and all other areas of measurement.

b. Determine numbers of existing TMDE in field organizations and metrology standards in DOD laboratories, logically grouped by measurement categories and capability.

c. Assess the present status of TMDE metrication in DOD, and conduct market investigations to determine commercial availability and related costs of required metric metrology standards and software products that will be necessary for metric augmentations or conversions.

d. Assess the economic feasibility of metrication of metrology standards and TMDE in the laboratories and field organizations examined in mission area b, above; determine the type (hard, soft) of metrication required; and set priorities and establish milestones for metric augmentations or conversions determined to be feasible and necessary.

e. Identify the impact on facilities, operations and training incident to the execution of the TMDE Metrication Subgroup mission.

V. REQUIREMENTS. The TMDE Metrication Subgroup will:

a. Develop and submit a plan for mission accomplishment, including milestones, to the JTCG-CMT within 30 days after receiving the approved charter.

b. Meet at the call of the chairperson, who will convene meetings as required to respond to OSD requirements and meet milestone schedules. Meeting locations will be rotated to spread the TDY costs among the services. Teleconferencing will be used to the maximum extent possible consistent with mission accomplishment.

c. Submit written quarterly progress reports signed by the chairperson and coordinated with all members to the JTCG-CMT within 15 days prior to the end of each fiscal quarter. Report status of milestone objectives, a summary of the subpanels activities during the quarter, and planned activities for the following quarter.

d. Provide briefings at the request of the JTCG-CMT chairperson.

VI. ADMINISTRATION.

a. The TMDE Metrication Subgroup will report to the JTCG-CMT. Written reports will be addressed to Chairperson, JTCG-CMT with information copies to each JTCG-CMT member.

b. Chairperson of the TMDE Metrication Subgroup will be a representative of the Army Materiel Command, since DOD has designated the Army as Office of Primary Responsibility. Members of the TMDE Metrication Subgroup will be provided by the Army, Navy and Air Force. The Marine Corps will be an invited participant.

The Latest DOC-NIST/DoD (ASD-P&L) MOU

MEMORANDUM OF UNDERSTANDING
BETWEEN
THE DEPARTMENT OF DEFENSE
(THE ASSISTANT SECRETARY OF DEFENSE FOR PRODUCTION AND LOGISTICS)
AND
THE DEPARTMENT OF COMMERCE
(NATIONAL INSTITUTE OF STANDARDS AND TECHNOLOGY)

John W. Lyons
Director
National Institute of Standards and Technology

March 9, 1992
Dated

Donald J. Yockey
Under Secretary of Defense for Acquisition

26 MAY 1992
Dated

MEMORANDUM OF UNDERSTANDING
BETWEEN
THE DEPARTMENT OF DEFENSE
(THE ASSISTANT SECRETARY OF DEFENSE FOR PRODUCTION AND LOGISTICS)
AND
THE DEPARTMENT OF COMMERCE
(NATIONAL INSTITUTE OF STANDARDS AND TECHNOLOGY)

1. INTRODUCTION

This Memorandum of Understanding establishes an agreement between the Department of Defense (DOD), the Assistant Secretary of Defense for Production and Logistics, and the Department of Commerce, National Institute of Standards and Technology (NIST), to define interagency working relationships on matters of liaison, and technical cooperation and support. It is based on the premises that:

a. Since high technology military hardware requires high quality measurement and evaluation standards, the services and facilities of NIST are essential for the support of DOD operations and readiness.

b. It is a part of NIST's stated mission to support DOD requirements relating to measurement standards, calibration support, and metrology related research, development and engineering.

c. An effective NIST/DOD relationship requires a continuing exchange of management and technical information regarding requirements, capabilities, and the costs of supporting the DOD metrology base.

This agreement specifically includes procedures for identifying, estimating the cost of, and arranging for the calibration services and the metrology research, development and engineering (RD&E) services that DOD activities obtain on a regular basis from the National Institute of Standards and Technology. This Memorandum of Understanding supersedes a Memorandum of Understanding signed in 1978 by Ernest Ambler on behalf of NIST and by Robert Pirie, Jr. and Dale W. Church on behalf of DOD.

2. PURPOSE

The purpose of this agreement is to establish points of contact and procedures for:

a. The interchange of information on technical requirements and unique research programs and capabilities that would mutually benefit the achievement of each agency's mission.

b. Coordinating and submitting DOD requirements for calibration and metrology RD&E services to NIST. Calibration service typically is calibration of DOD measurement standards by

NIST. Metrology RD&E services typically are metrology research, development, and engineering projects performed by NIST for DOD that result in improved or new measurement services, techniques, or equipment.

c. NIST review of these requirements to identify those services which can be provided and to estimate their cost.

d. Budgetary planning for the funding of the services that by mutual agreement are to be provided to DOD by NIST.

3. IMPLEMENTATION PROCEDURES/SCHEDULE

a. DOD and NIST recognize the need for effective communications at the policy-making level in both organizations in order to implement this Memorandum of Understanding. Both organizations will strive to maintain and improve effective DOD-NIST coordination. The following sections set forth specific procedures for achieving the above stated purposes.

b. The principal DOD point of contact for policy matters between NIST and DOD, including Federal Government-wide programs coordination, will be the Chief of the Industrial Quality and Productivity Division. Other DOD points of contact will be:

(1) For DOD military services requirements planning--Chairman of the Joint Technical Coordination Group for Calibration and Measurement Technology (JTCG-CMT). The Chairman, JTCG-CMT, also will be the action point of contact (policy matters excepted) for DOD participation in the coordination of Federal Government-wide metrology and calibration programs.

(2) For technical and/or financial matters relating to metrology RD&E services--The Calibration Coordination Group (CCG), Engineering Working Group (EWG) of the JTCG-CMT, consisting of representatives of the Army, Navy, and Air Force.

(3) For technical and/or financial matters relating to calibration services--the NIST Scheduling Subgroup, Laboratory Operations Working Group of the CCG.

c. The principle NIST point of contact with DOD for policy, planning, or Federal Government-wide coordination matters will be the Physical Measurement Services Program (PMSP) of the Office of Measurement Services (OMS), Technology Services (TS). Other NIST points of contact will be:

(1) For financial matters--Advances and Reimbursements, Office of the Comptroller.

(2) For technical matters relating to particular calibration and/or metrology RD&E services--the appropriate NIST technical division.

(3) For overall technical coordination--the NIST/DOD Liaison (appointed by, and at the discretion of, the Director of NIST).

d. NIST will communicate promptly with JTCG-CMT whenever changes in programs or support levels are anticipated which will impact calibration services or metrology RD&E support to the DOD. NIST will endeavor to coordinate such changes with the JTCG-CMT in order to minimize the impact on DOD programs, and to assist affected DOD elements in seeking alternative sources or methods to meet continuing DOD requirements.

e. The CCG NIST Scheduling Subgroup of the CCG will assemble and submit to NIST on or before 1 July of each year a schedule of requirements that describes quantitative DOD calibration services requirements for the next two fiscal years.

f. NIST will review the list of DOD calibration services requirements and submit a cost estimate to the NIST Scheduling Subgroup before 15 August of each year, for the fiscal year beginning 1 October. NIST will provide to each subgroup member an itemized list of fees for each calibration service requested. NIST will charge the DOD fees no greater than those charged other government agencies for similar calibration services.

g. To facilitate joint program planning and promote technology transfer:

(1) The CCG shall provide NIST a long range forecast, updated at reasonable intervals (The Joint Service Metrology Research Development and Engineering Plan) of anticipated metrology requirements and related technology development.

(2) NIST shall provide the CCG, on an annual basis, with information on other DOD funded metrology research, development and engineering projects and shall endeavor, through meetings with the CCG Engineering Working Subgroups and the Services Metrology Requirements Conference, to keep the CCG informed of new metrology developments which may affect its programs and mission.

h. In response to metrology RD&E requirements identified by the CCG, appropriate NIST staff will meet with the respective CCG Technical subgroups at a regularly scheduled meeting to discuss proposed metrology RD&E projects. During these discussions the following points shall be considered in selecting projects for consideration:

(1) Measurement technology needed to meet DOD operational requirements.

(2) Whether the projects under consideration are appropriate to NIST's mission or might better be accomplished by private industry.

(3) The availability of NIST resources required to meet DOD requirements in a timely and efficient manner.

In collaboration with the subgroup members, NIST will draft work statements and prepare cost estimates for appropriate projects under consideration. Based on these discussions, the subgroups will establish priorities and forward their recommendations to the Engineering Working Group.

i. The military services will plan to budget and fund the estimated cost of the projects that have been mutually agreed upon. NIST will plan to perform the required RD&E project work.

j. The CCG will attempt to insure that adequate funds are available to cover the cost of all services and projects requested of NIST for the next fiscal year. CCG statements of work will identify the CCG member who is to provide the funds for each metrology RD & E project. When the CCG is not authorized sufficient funds to cover all requested NIST services, the CCG will immediately review the requirements, and in consultation with NIST, adjust project priorities and/or make mutually agreeable adjustments to the project work statements. After work has commenced, the CCG will notify NIST informally as soon as possible of any potential decreases in funding and will attempt to give at least 30 days notice of decreases in funding for CCG metrology RD&E projects with the understanding that this time period will be used to negotiate and adjust the NIST program to the change.

k. By 1 September the CCG or CCG/EWG chairman shall forward to NIST a list of the metrology RD&E projects that have been authorized for the following fiscal year and the funding allocated to each by each service. As soon as possible after the beginning of the fiscal year each service shall either transfer the allocated funds (or a pro-rated portion thereof on a quarterly basis) or shall furnish a Letter of Intent specifying the funding to be provided and authorizing charges to be accrued for work performed on the projects funded by that service. Work will not begin on any project until such funding or authorization has been received and accepted by NIST.

l. NIST will not accept from DOD components requests for calibration services or metrology RD&E services to be performed under CCG funding that are not on the submitted lists in 3(e) and 3(k), or approved amendments to those lists. This does not preclude DOD components from requesting other related metrology RD&E or calibration/special measurement services at NIST, providing the requesting organization separately funds such services.

m. Following the authorization of funds by each NIST Scheduling Working Group member organization for NIST calibration services, each organization represented on the Working Group will also submit to NIST a quarterly advance, at a minimum for calibration services for that organization. If funds are advanced quarterly, the last quarterly advance will ensure there are adequate funds to cover all authorized calibration services for that fiscal year.

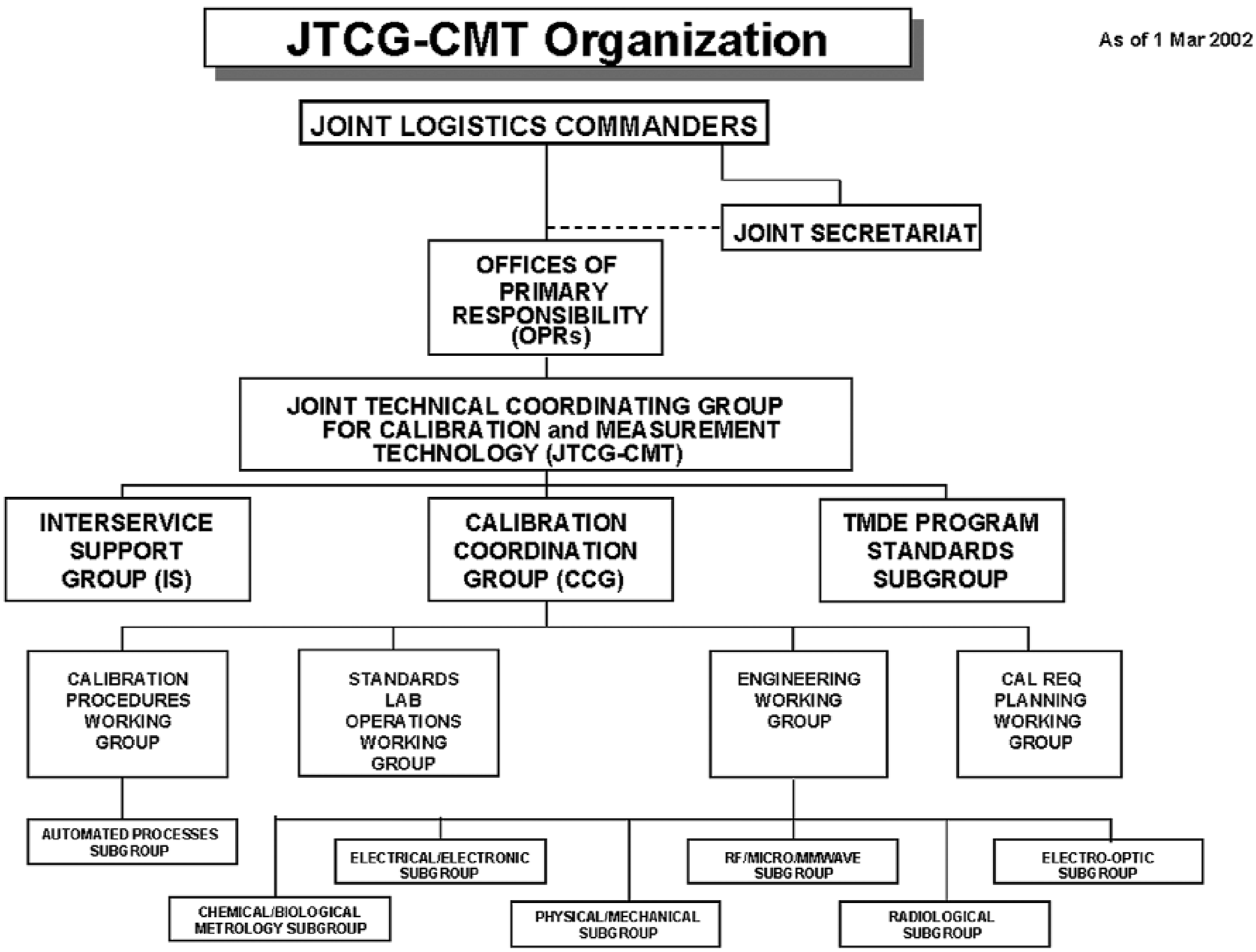
n. Projects authorized after the start of the fiscal year not already covered by approved work statements will be covered either by amendments to the original work statements or by new statements. Estimates of costs associated with the additional projects shall be provided by NIST to the cognizant CCG member organization, and the required funding provided to NIST prior to the performance of the work. Thirty days prior to the end of each fiscal year, NIST will provide to each CCG member organization an estimate of the total cost of each funded requirement of that fiscal year.

o. NIST will provide to the NIST Scheduling Working Group members cost information on reimbursable calibration services NIST provided DOD. This information will be:

(1) Monthly statements of all calibration services provided to each NIST scheduling Subgroup member (Air Force, Army, and Navy) due as soon as possible after the end of the month during which the calibration services were provided. Unless services were paid for in advance, this statement will be accompanied by a Form SF 1080 covering the cost of these services.

(2) A report containing the estimated cost of calibration services remaining to be performed during the last month of the fiscal year. This report is to be sent to each NIST Scheduling Working Group member prior to the first day of the last month of each fiscal year.

The Current Organization of the JLC-CMT



US ARMY MATERIEL COMMAND

UNITED STATES NAVY CHIEF OF NAVAL OPERATIONS

AIR FORCE MATERIEL COMMAND

MARINE CORPS METROLOGY / CALIBRATION PROGRAM METCAL