AN ASSESSMENT OF THE NATIONAL INSTITUTE OF STANDARDS AND TECHNOLOGY PHYSICAL MEASUREMENT LABORATORY

FISCAL YEAR 2015

Panel on Review of the Physical Measurement Laboratory at the
National Institute of Standards and Technology

Committee on NIST Technical Programs

Laboratory Assessments Board

Division on Engineering and Physical Sciences

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Acknowledgment of Reviewers

This report has been reviewed in draft form by individuals chosen for their diverse perspectives and technical expertise, in accordance with procedures approved by the Report Review Committee. The purpose of this independent review is to provide candid and critical comments that will assist the institution in making its published report as sound as possible and to ensure that the report meets institutional standards for objectivity, evidence, and responsiveness to the study charge. The review comments and draft manuscript remain confidential to protect the integrity of the deliberative process. We wish to thank the following individuals for their review of this report:

Steven M. Girvin, Yale University,
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Although the reviewers listed above have provided many constructive comments and suggestions, they were not asked to endorse the conclusions or recommendations, nor did they see the final draft of the report before its release. The review of this report was overseen by Elsa Reichmanis, Georgia Institute of Technology, who was responsible for making certain that an independent examination of this report was carried out in accordance with institutional procedures and that all review comments were carefully considered. Responsibility for the final content of this report rests entirely with the authoring board and the institution.

Contents

Summary

In 2015, at the request of the Director of the National Institute of Standards and Technology (NIST), the National Research Council (NRC)[1] formed the Panel on Review of the Physical Measurement Laboratory at the National Institute of Standards and Technology (referred to in this report as "the panel") and established the following statement of task for the panel:

> The National Research Council shall appoint a panel to assess the scientific and technical work performed by the National Institute of Standards and Technology (NIST) Physical Measurement Laboratory (PML). This panel will review technical reports and technical program descriptions prepared by NIST staff and will visit the facilities at the Physical Measurement Laboratory. Visits will include technical presentations by NIST staff, demonstrations of NIST projects, tours of NIST facilities, and discussions with NIST staff. The panel will prepare a report summarizing its assessment findings.

NIST specified that the nine divisions of the PML would be reviewed: the Applied Physics Division (APD), Engineering Physics Division (EPD), Office of Weights and Measures (OWM), Quantum Electromagnetics Division (QED), Quantum Measurement Division (QMD), Quantum Physics Division (QPD), Radiation Physics Division (RPD), Sensor Science Division (SSD), and Time and Frequency Division (TFD).

GENERAL OBSERVATIONS

The PML remains an outstanding institution of the highest standards and accomplishments. Broadly speaking, the PML is dedicated to three fundamental and complementary tasks: (1) increase the accuracy of our knowledge of the physical parameters that are the foundation of our technology-driven society; (2) disseminate technologies by which these physical parameters can be accessed in a standardized way by the stakeholders; and (3) conduct research at both fundamental and applied levels to provide knowledge that may eventually lead to advances in measurement approaches and standards.

The scientific staff is of uniformly high quality, but preserving the quality of the staff will be a challenge because of the large number of anticipated retirements of such excellent staff. The physical infrastructure of the PML is heterogeneous and complex but still fundamentally adequate to the tasks at hand. It is generally of a world-class quality, although there remain some weak infrastructure areas in the Radiation Physics Division that need to be addressed immediately.

The PML is a large organization, dispersed on two main campuses, one at Gaithersburg, Maryland, the other at Boulder, Colorado.

It is vital that the excellence of the PML be maintained as the United States faces increasing competition for resources and technology from rapidly advancing countries.

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[1] Effective July 1, 2015, the institution is called the National Academies of Sciences, Engineering, and Medicine. References in this report to the National Research Council are used in a historical context identifying programs prior to July 1.

SIGNIFICANT ACCOMPLISHMENTS

Applied Physics Division

Electron beam lithography has been used by the Applied Physics Division (APD) to pattern nanowires into a thin film made of a heat-tolerant ceramic superconductor, molybdenum silicide, operated at the superconducting transition edge temperature. The new design operates at higher temperatures and bias current. Timing jitter is now 76 picoseconds, and detector quantum efficiencies are 87 percent at wavelengths that are useful in telecommunications.

Quantum Electromagnetics Division

The Quantum Electromagnetics Division (QED) has developed a new type of sensor that can be used to investigate the isotopic composition of plutonium samples, a critical measurement for nuclear nonproliferation efforts and related forensics, as well as for environmental monitoring, medical assays, and industrial safety.

Engineering Physics Division

The Engineering Physics Division (EPD) has developed a system for forensic analysis of spent bullet casings. Use of microscope images of three key markings typically found on spent cartridge cases dramatically reduces the uncertainty levels for the firing pin and breech face markings, which investigators can use to determine their confidence levels about a match.

Office of Weights and Measures

The Office of Weights and Measures (OWM) has proposed a standard for plug-in electric car customers to standardize what they should be charged for their electrical charge, and what requirements operators should meet. This standard, produced by NIST’s U.S. national work group on electric vehicle refueling and submetering, was adopted by the National Conference on Weights and Measures (NCWM) at its 2015 annual meeting.

Quantum Measurement Division

The Quantum Measurement Division (QMD) has performed experimental studies of many-body effects in ultracold atomic systems that are among the best in the world, and the recent test of Bell inequalities, eliminating the remaining loopholes of previous experiments, is a telling example of the synergy between different areas of expertise in Gaithersburg and at JILA, a joint institute of NIST and the University of Colorado, Boulder.

Quantum Physics Division

The work on spin exchange of ultracold molecules is a new testing ground, enabled by tools that have been developed at the Quantum Physics Division (QPD). It will address fundamental questions of molecule–molecule interactions and can be used as a quantum simulator of many-body spin dynamics.

Radiation Physics Division

The Radiation Physics Division (RPD) has implemented a new Co-60 therapy-level calibration facility with state-of-the-art data acquisition and operating capabilities. It is expected to help improve the ability to maintain a number of dosimetric standards essential to the radiation oncology community.

Sensor Science Division

The Sensor Science Division (SSD) has performed work on characterization of hydrogen flow meters for high-pressure refueling of hydrogen-powered vehicles, with reduced uncertainty and rapid response times. A portable field test standard has been developed for use at refueling stations. This work is important as the world seeks alternatives to fossil fuels.

Time and Frequency Division

The Time and Frequency Division (TFD) has generated optical frequency combs through nonlinear wave mixing in optical microresonators. Such microcombs offer dramatic size reduction compared to frequency combs derived from mode-locked lasers, opening the possibility of applications beyond specialized laboratory settings. Researchers have developed new methods for fabricating high-quality-factor optical microresonators at low cost and high speed.

KEY SUGGESTIONS FOR IMPROVEMENT

The quality of work done at the PML and its response to the stakeholders whose interests the PML addresses are excellent. Each division deserves high accolades.

Applied Physics and Quantum Electromagnetics Divisions

The restructuring of the former Quantum Electronics and Photonics Division and the Electromagnetics Division into the Applied Physics Division (APD) and the Quantum Electromagnetic Division (QED) seems to have been accomplished smoothly. However, the decision by the PML to have the panel jointly review the two divisions as one entity has created some confusion and did not allow an in-depth analysis of each division. The APD as a consequence needs to be analyzed in more depth in coming reviews to provide a clearer view of its mission and how it fits into the overall PML effort.

Engineering Physics Division

It will be important that the Engineering Physics Division (EPD) avoid duplication of effort in the area of nontraditional materials conducted by better-funded teams investigating the science or technology of these speculative materials systems.

Quantum Electromagnetics Division

The Quantum Electromagnetics Division's (QED's) optical quantum entanglement work was not at the fundamental leading edge of such work, which is being carried out by many other groups worldwide. It would be worthwhile to focus more on areas where the division has real strengths, such as photon sensors.

The work in nuclear magnetic resonance (NMR) imaging, while strong, needs to be expanded to include the rapidly growing area of functional NMR imaging (fMRI), so that claims made in the literature can be evaluated more carefully.

The Quantum Sensors group has had a significant impact in millimeter wave polarimetry with its detector arrays, but the group serves so many external groups that it runs the risk of becoming oversubscribed.

PML staff suggested that the Gaithersburg and Boulder nanofabrication facilities could support a significantly greater number of NIST projects or outside collaborators. The new facility established at the University of Maryland further disperses the division and could present difficulties for its current cohesiveness and collaborations.

PML staff report that overhead charges on graduate students and on capital equipment are excessive.

Office of Weights and Measures

The effort by the metric program in the Office of Weights and Measures (OWM) to implement the SI units in the United States is lagging. Better quantitative metrics for the effectiveness of the Legal Metrology group needs to be established. The number of accredited and recognized laboratories at the state level for dissemination of mass and volume standards for stakeholders is declining.

PML predicts a large wave of retirements (50 percent of staff) in this office in the coming 5 years, and PML needs to examine the implication of the retirements and determine what replacements, if any, will be required.

Quantum Measurements Division

The partial relocation of the groups working in the Quantum Measurements Division (QMD) to the University of Maryland campus as the Joint Quantum Institute presents both opportunities and challenges and warrants careful monitoring so that the groups do not become isolated.

It will be important that the Synchrometrology Group have sufficient resources to play a role in the upcoming renovation of the national power grid into a smart grid. This effort will have a worldwide scope.

Quantum Physics Division

The powerful Quantum Physics Division (QPD) has successfully evolved new opportunities from initial objectives. The group may be rapidly evolving toward nanotechnology and biotechnology; it may be worthwhile to plan for this evolution rather than expect it to occur organically.

The scientific interests of the division show strong overlap with those of the Time and Frequency Division, but given that both divisions have been extremely successful, this can be viewed as increasing critical mass in areas in which NIST is a world leader.

The activities in biological physics have not been well integrated with those of other efforts within the QPD. PML needs to examine the relationship of biology to other division efforts. The division needs to develop firm guidelines for a consistent and clear approach to the development of intellectual property.

Several staff spoke of a high overhead rate on capital equipment; they suggested that this makes acquisition of expensive equipment very difficult.

Radiation Physics Division

Building 245 in which the Radiation Physics Division (RPD) is primarily housed, is approaching a dangerous and unsafe condition; immediate attention is warranted. In the laboratories of Building 245, where most of the radionuclide standards are prepared for shipment, the rooms are old and lacking in proper heating and ventilation, with consequent inadequate control of humidity and temperature. Neutron source standardization is carried out in a number of shielded, below-grade laboratories in Building 245. Water intrusion during heavy rains has become an issue because the building is no longer watertight. Dispersal of the source material is remotely possible, but the immediate concern is damage and loss of calibration traceability. These events are, at a minimum, distractions to overburdened scientists, and in some cases have threatened to flood sources under test.

The Dosimetry Group primarily works with its large stakeholder community. Providing more opportunity and support to do research would enhance the quality of the staff and the work done.

Lack of funds is resulting in nonreplacement of retiring critical employees and in requiring Ph.D.-level staff to do routine tasks, stealing time from their technical work. Unfortunately, there are examples where dissemination of proper radioactivity standards has not been able to proceed as rapidly as required owing to a lack of funds.

The division needs to strengthen the training program that involves students and postdoctoral researchers in each of the critical standards activities and to foster a program to share equipment and facilities with users at other national laboratories and universities.

Sensor Science Division

One possible caution for the Sensor Science Division (SSD) concerns the increasing emphasis on lower-cost, lower-SWAP sensors for future satellite systems. The division could prepare to calibrate much smaller radiometers for its customers. As microfluidics becomes ever more important, it will be correspondingly important to continue developing noninvasive and inline ways to determine microflows.

While the overarching strategy was well articulated, the division did not describe plans for some of the projects, particularly those that are funded externally; those working on internally funded initiatives seemed to have more concrete plans. The division needs to clarify plans for externally funded projects.

Retirements are being delayed because of difficulties in finding appropriate replacements.

Time and Frequency Division

The NIST-on-a-Chip effort will involve this division, which needs to expand development of its roadmap for this work. The Time and Frequency Division’s (TFD’s) scientific expertise evident during the review was primarily of an experimental nature. As stabilities and accuracies of frequency standards continue to improve, strong theoretical support will be required. The division needs to consider whether the theoretical expertise resident within the division is sufficient to support future experimental efforts.

TFD staff have mentioned the shortage of meeting and collaboration space. Staff also expressed concern about the onerous procurement process, which, they said, incurs substantial delays.

The emphasis on patent preparation does not appear to be stable from year to year. A careful assessment by the division of the value of patenting would be worthwhile. Once the value proposition is in hand, more consistent direction to staff can be provided.

1

The Charge to the Panel and the Assessment Process

At the request of the National Institute of Standards and Technology (NIST), the National Academies of Sciences, Engineering, and Medicine has, since 1959, annually assembled panels of experts from academia, industry, medicine, and other scientific and engineering communities to assess the quality and effectiveness of the NIST measurements and standards laboratories, of which there are now seven,[1] as well as the adequacy of the laboratories' resources.

At the request of the Director of NIST, in 2015 the National Research Council (NRC) formed the Panel on Review of the Physical Measurement Laboratory at NIST and established the following statement of task for the panel:

> The National Research Council shall appoint a panel to assess the scientific and technical work performed by the National Institute of Standards and Technology (NIST) Physical Measurement Laboratory (PML). This panel will review technical reports and technical program descriptions prepared by NIST staff and will visit the facilities at the Physical Measurement Laboratory. Visits will include technical presentations by NIST staff, demonstrations of NIST projects, tours of NIST facilities, and discussions with NIST staff. The panel will prepare a report summarizing its assessment findings.

The context of this technical assessment is the mission of NIST, which is to promote U.S. innovation and industrial competitiveness by advancing measurement science, standards, and technology in ways that enhance economic security and improve the quality of life. The NIST laboratories conduct research to anticipate future metrology and standards needs, to enable scientific and technological advances, and to improve and refine existing measurement methods and services.

NIST specified that the nine divisions of the Physical Measurement Laboratory (PML) would be reviewed: the Applied Physics Division (APD), Engineering Physics Division (EPD), Quantum Electromagnetics Division (QED), Office of Weights and Measures (OWM), Quantum Measurement Division (QMD), Quantum Physics Division (QPD), Radiation Physics Division (RPD), Sensor Science Division (SSD), and Time and Frequency Division (TFD). To accomplish the assessment, the NRC assembled a panel of 26 volunteers whose expertise matched that of the work performed by the PML staff.[2]

On September 9, 2015, a subset of the panel assembled at the NIST facility in Boulder, Colorado, for a two-day assessment, and on September 29 the full panel assembled at the NIST facility in Gaithersburg for a two-and-a-half-day assessment. Each panel member was assigned to one of the nine teams, each of which reviewed one of the PML divisions. The full panel then met to deliberate on its findings and to define the contents of this assessment report.

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[1] The seven NIST laboratories are the Engineering Laboratory, the Physical Measurement Laboratory, the Information Technology Laboratory, the Material Measurement Laboratory, the Communication Technology Laboratory, the Center for Nanoscale Science and Technology, and the NIST Center for Neutron Research.

[2] See the NIST PML website at http://www.nist.gov/pml/ for information on the PML organization and programs (accessed November 11, 2015).

The panel's approach to the assessment relied on the experience, technical knowledge, and expertise of its members. The panel reviewed selected examples of the technical research performed at the PML; because of time constraints, it was not possible to review the PML programs and projects exhaustively. The examples reviewed by the panel were selected by the PML. The panel's goal was to identify and report salient examples of accomplishments, challenges, and opportunities for improvement with respect to the factors suggested above by the director of NIST. These examples are intended collectively to portray an overall impression of the laboratory, while preserving useful suggestions specific to the projects and programs that the panel examined. Given the necessarily broad and nonexhaustive nature of the review, omission in this report of any particular PML program or project should not be interpreted as implying any negative reflection on the omitted program or project.

2

Applied Physics and Quantum Electromagnetics Divisions

INTRODUCTION

The Applied Physics Division (APD) and the Quantum Electromagnetics Division (QED) were recently formed by a restructuring of the former Quantum Electronics and Photonics Division and the former Electromagnetics Division. This restructuring came about as a consequence of the formation of the NIST Communications Technology Laboratory, to which roughly 67 staff members of the two former PML divisions were transferred. Because the two new divisions have considerable overlap of activities and focus, they were assessed together.

These divisions have aligned their activities into five focus areas: quantum information, nano-magnetics, imaging science and technology, sensing, and measurement services and standards.

Applied Physics Division

The APD develops measurement science over broad spans of the electromagnetic spectrum, addressing national priorities that include advanced manufacturing, national security, quantum science, climate change, and biomedical imaging. It consists of seven technical groups: Advanced Microwave Photonics Group, Faint Photonics Group, Fiber Sources and Applications Group, Magnetic Imaging Group, Sources and Detectors Group, Quantitative Nanocharacterization Group, and Quantum Nanophotonics Group.

The Advanced Microwave Photonics Group focuses on microwave generation and detection of quantum information (QI) for both quantum communication and computation. The Faint Photonics Group addresses few-photon generation and detection for quantum communication and secure random number generation. The Fiber Sources and Applications Group addresses high-power lasers and their application to manufacturing. The Magnetic Imaging Group addresses calibration and standardization of magnetic resonance imaging (MRI) and interfaces with an MRI industry standards group. The Sources and Detectors Group develops high-dynamic-range laser power metrology over a broad spectral range. The Quantitative Nanocharacterization Group develops novel optoelectronic scanning probes for a variety of applications, including semiconductor technology, condensed matter physics, biology, and medicine. The focus of the Quantum Nanophotonics Group is on using the entanglement of quantum states to encode information and by applying techniques for manipulation and measurement of the quantum states of atoms, ions, spins, superconductors, and cavity quantum electrodynamics (cavity QED).

Quantum Electromagnetics Division

The QED investigates foundations of techniques for metrology of electronic, magnetic, and photonic technologies. It develops devices, systems, standards, and measurement methodologies to address national needs in these areas of technology. It consists of seven technical groups: Microfabrication Group, Molecular and Bio-Photonics Group, Nanoscale Spin Dynamics Group, Quantum Processing Group, Quantum Sensors Group, Superconductive Electronics Group, and Spin Electronics Group.

The Microfabrication Group runs the recently built microfabrication clean room facility, which houses the molecular beam epitaxy (MBE) epitaxial materials facility, designed for processing the unique materials required for the extensive experimental QI research programs at NIST. The Molecular and Bio-Photonics Group specializes in quantitative medical imaging using a variety of optical methods. The Nanoscale Spin Dynamics Group develops metrology and studies fundamental physics of magnetodynamics in nanoscale magnetic devices and model systems. The focus of the Quantum Processing Group is development of novel materials, devices, and measurements for the integrating quantum systems in information processing architectures. The Quantum Sensors Group develops advanced superconducting photon detectors and amplifiers that are sensitive on the single-photon level over a broad spectral range and applies them to diverse fields such as astrophysics and chemical dynamics. The Spin Electronics Group develops metrology and fundamental understanding of spin currents and their application in nanoscale magnetic devices and hybrid magnetic/superconducting memory devices. The Superconductive Electronics Group develops and characterizes voltage standards based on quantized magnetic flux in superconducting Josephson devices and investigates devices for advanced computers based on superconducting logic and memory.

ASSESSMENT OF TECHNICAL WORK AND DISSEMINATION OF OUTPUTS

Quantum Information

Quantum Optics and Processing

Quantum optics and processing activities fall under the overall topic of quantum processing, which includes novel measurements and devices for the integration of quantum systems into information processing architectures. On a larger scale, QI is the application of ideas of quantum physics to the area of information sciences.

An important matter being addressed is using the principle of entanglement by encoding information in the quantum mechanical state, which involves the manipulation and measurement of quantum states of atoms, ions, spins, superconductors, and cavity quantum electrodynamics. The group is creating tools for generating, manipulating, detecting, and measuring photons under various conditions.

Transportation of information encoded using quantum states of matter or light has been shown to be desirable by assuring that unauthorized eavesdroppers cannot decode the information. This is often called teleportation of information, which is a subject of intense research activity around the world. The quantum information subgroup within the Faint Photonics Group and the Quantum Nanophotonics Group has demonstrated quantum teleportation over a distance of 100 km of optical fiber, which is approximately four times that of the previous record. This feat was possible because of the high-efficiency single-photon detector capability, which is described in the quantum sensors section of this chapter. Teleportation over optical fibers brings the ability to transmit quantum encoded information into the practical realm.

Application of quantum physics to the area of information sciences involves the use of ion traps that retain the ions for a long time, which requires reduction of anomalous heating that results from surface contamination and ordering. Paying special attention to cleaning of the surfaces reduces heating. The group has attained a 100-fold decrease in ion trap heating rates via in situ cleaning of carbon contamination, which allows the traps to operate with much lower ion height. Quantum computing may have immediate application in the area of true random number generation.

This activity at the Applied Physics Division is among the many similar outstanding activities around the world. The division’s activity is not at the fundamental leading edge of science, but it is taking advantage of the superb photon sensors that the PML has developed. This activity is contributing well toward bringing QI science into practice, even though it may take many years to accomplish that.

Advanced Microwave Photonics

The microwave photonics effort in the QI and measurements project is impressive. The creation of entangled photons is a major challenge for quantum computing. Making use of microwave nonlinearities for generation and detection of QI greatly reduces both fabrication and instrumentation challenges in exchange for carrying out the experiments at much lower temperatures, less than 30 mK. Progress in low-temperature technology over the past decade and readily available, well-established, and extensive microwave instrumentation make this an excellent trade-off, particularly in light of the strong PML expertise in superconductive materials, device design, and characterization.

Creation of controlled-NOT (C-NOT) gates and experimental investigation of QI are impressive. This is part of the more extensive QI project that covers both more conventional photonic and superconducting Josephson junction approaches, so the entire effort is highly complementary and covers a broad range of approaches in this very challenging, long-range program.

Quantum Nanophotonics

The focus of the integrated photonics effort is the development of a quantum repeater for quantum communications. Quantum optical communications requires generation and detection of single photons to produce entangled photon pairs. The project is developing sources and detectors for quantum states of light based on self-assembled quantum dots embedded in high-Q photonic crystal optical cavities for application to single-photon sources, laser diodes, and quantum optical metrology. Integrated quantum dot gain regions in high-Q cavities produce very short radiative emission times, increasing the speed and efficiency of the light source, which are critical enablers for quantum communications.

The Quantum Nanophotonics Group has demonstrated both quantum-dot-based detectors and lasers of single photons that are unique in the compound semiconductor device world. The group recently demonstrated a wavelength bistability phenomenon in a monolithic quantum dot laser. This effort couples well with the efforts of other PML groups in the quantum information program.

Nanoscale Magnetics

Spin Electronics and Nanoscale Spin Dynamics

The projects of the Spin Electronics Group and the Nanoscale Spin Dynamics Group build on their previous work on understanding and measuring the magnetic behavior of microscopic ferromagnetic film devices. These groups continue to demonstrate the world's fastest measurement of magnetization dynamics. The groups also demonstrate microwave ferromagnetic resonance measurement of the smallest magnetic features with the highest dynamic range. It now appears that magnetic switching by use of spin currents will play an important role in future magnetic storage devices. The work of these two groups continues to provide a fundamental understanding of these phenomena. People in industry will use this work for guidance on how to make these extremely difficult measurements, which will be essential for understanding the failure modes of nanoscale spintronics in commercial applications.

Several important investigations push the frontiers of magnetic-based oscillators and of our understanding of dynamic effects (such as magnetic damping during switching). Others provide insight into the thermal stability of microscopic-domain configurations (i.e., stored bits). The data obtained and the techniques perfected are certain to prove useful in the development of future low-power, high-speed computers. This work is entirely in line with the NIST directive to further the national strategic computing initiative.

Imaging Science and Technology

Magnetic Imaging

The biomagnetic imaging program focuses on several issues related to MRI. Central to these efforts is the development of techniques that make it possible to ensure that the images produced with different scanners will reflect underlying pathologies in a consistent manner. At the heart of these efforts is the development of standardized phantoms, nonbiological fabricated artifacts that can be imaged in an arbitrary scanner to identify differences in the images produced by different machines. A particularly good example is a head phantom that contains an array of solutions designed such that each has a well-defined diffusion coefficient for water. Diffusion is often used as a contrast mechanism in MRI, and it can be very important for diagnosing conditions such as traumatic head injury. Diagnosing such injury, however, requires making subtle distinctions that require high levels of standardization in the response of the scanner if results are to be compared from one machine to another. The head phantoms are now being commercialized and are undergoing clinical trials. Another example is breast phantoms that simulate the healthy tissue. It can often be the case that a scanner will produces images with what appear to be morphological anomalies, potentially tumors, that are in fact nothing more than artifacts traceable to imperfections in the MRI scanner. Having a standardized phantom that is known to have no features corresponding to tumors makes it possible to ensure that a particular scanner will not be prone to producing false positive results.

Another area of focus in the biomagnetic imaging program is the study of so-called MRI contrast agents. Historically, contrast agents have been largely limited to injectable substances that, when present, increase the brightness of the MR image. Gadolinium-based compounds, for example, have been very useful for visualizing vasculature. One can imagine, however, contrast agents that provide sensitivity to different biological or chemical characteristics. One PML-developed contrast agent utilizes nanofabricated structures that respond resonantly to radio-frequency (RF) radiation. The resonant frequency of these structures is sensitive to the local pH, making it possible to use MRI to visualize certain details of physiological processes. The approach of using such nanofabricated structures has considerable potential for future applications as well.

Molecular and Biophotonics

The Molecular and Biophotonics Group works to develop methodologies for quantitative optical medical imaging based on several diverse techniques, including optical coherence tomography (OCT), hyperspectral imaging (HSI), photoacoustic imaging, and light scattering methods. They do this by advancing measurement science supporting these techniques and by developing calibration and characterization tools that can make these technologies quantitative and international system of units (SI) traceable. This effort to standardize and develop quantitative tools is of key importance and has the potential for significant impact in laying a foundation for reproducible medical research that can be applied to recognize biomarkers for early disease recognition and to measure short- and long-term response to therapy. Optical imaging methods are advantageous in being mostly noninvasive, utilizing nonionizing radiation, and providing high-resolution, label-free imaging.

Examples of recent technical accomplishments include improvement of OCT resolution to 1 μm, label-free chemical mapping of subcellular molecules at the single-cell level using HSI, and the development of a unique hyperspectral dark field microscope for optical biopsy. This microscope has been deployed in a clinical environment to address a particular deficiency in the rapid, accurate determination of tumor margins in breast cancer, which currently leads to the need for additional surgeries in about half of lumpectomy patients. The rapid-turnaround detection of precise tumor margins available once this instrument is present in the operating room will allow surgeons to make decisions in real time and reduce the likelihood of second surgeries.

Relatively few of the large number (~160,000) of biophotonics-related patents have penetrated the market to become devices approved by the Food and Drug Administration (FDA). Thus, a particular challenge and significant opportunity for external impact is to enable accelerated FDA approval for advanced biophotonic imaging methods. The PML addresses this issue by developing quantitative standards that help to improve measurement quality and lead to faster FDA approval for tools developed by the biophotonics community. Advances toward this goal will be key in maximizing the impact of advanced optical imaging on future delivery of health care. This group has a variety of external collaborators, including academic institutions, instrumentation companies, and other government agencies. Further evidence of the technical quality and success in dissemination of the results of the group's efforts is the output of published papers and invited talks (about five per year of each for the past few years).

Quantitative Nanocharacterization

The Quantitative Nanostructure Characterization Group has developed an advanced optoelectronic probe tip for near-field scanning microscopy that is based on the integration of gallium nitride nanowires with silicon scanning probe cantilevers. They have perfected the growth of these nanowires and demonstrated their use as probe tips for scanning microwave microscopy measurements of carrier concentration and conductivity in semiconductor nanostructures and 2D electronic materials, an application where the exceptional durability of the nanowire tips has enabled more quantitative measurements. The nanowires can also be doped during growth and potentially excited electrically as a light-emitting diode, providing simultaneous force, optical, and microwave susceptibility sensing. This will enable simultaneous detection of changes in electrical properties upon optical excitation directly from the scanning probe, with high temporal and spatial resolution, for example, when applied to characterization of photovoltaic materials.

The realization of this optoelectronic nanowire probe presents a difficult technical challenge. The eventual impact of this technique on advanced manufacturing remains unclear; the demonstration of its application to the solution of a key measurement problem of importance to industry would be a significant advance.

Precision Imaging

The precision imaging facility has impressive capabilities for materials characterization at the atomic and nano scales. These capabilities are primarily used to support the other materials development capabilities, as well as outside clients who have specific metrology needs that can be served by use of these tools. The tools appear to be staffed by highly knowledgeable scientists who publish their work frequently in archival journals and at conferences. Two of the many noteworthy instruments/capabilities are the He ion microscope and the near-field scanning microscope.

The He ion microscope is a new instrument that has been purchased because of its exceptionally large depth of field—an extremely important capability for imaging nanostructures with considerable surface morphology. The second unique capability is a near-field microscope using light-emitting GaN tips. These tips require a considerable degree of expertise to fabricate, but ultimately they allow for the local (at the nano scale) illumination of a sample to observe separate optically active regions. Several other, more standardized pieces of equipment comprise the suite of capabilities in the 3,000 ft^2 facility. The facility appears to be well supported by NIST.

The capabilities and high-quality staffing of the facility play an essential role in supporting both the internal (to NIST) and external materials research communities in the United States.

Sensing

Quantum Sensors

Quantum sensors activities cover precise measurements of the energy carried by photons or particles, the development of sensors, and supporting technology to perform these measurements and apply these sensors to problems with scientific and technological relevance. The core technologies include transition-edge-sensor (TES) calorimeters, superconducting quantum interference devices (SQUID) readouts, and superconducting microresonators.

The photon detection capability developed by the Quantum Sensors Group is now made available for application to practical problems. Application areas include astrophysics, x-ray physics, and laboratory science. The group is among the best in the world in the fabrication of high quantum efficiency integrated transition edge sensors (TES) and ultra-low-noise SQUID readouts for photon detection over a broad range of photon energies. The group expects to reach nearly unity detection efficiency in the future. Upon detection of an incident photon, the signal magnitude is proportional to the photon energy; the TES thus functions as a spectrometer as well as a detector. The TES has shown the capability to reproduce detection of one and more photons. When compared with other gamma-ray sensors the TES sensors show much higher resolution and sensitivity. TES detectors are being integrated into spectrometers deployed in the National Synchrotron Light Source and the Advanced Photon Source. The group also has an x-ray spectrometer under construction for the Stanford Synchrotron Radiation Light Source. A 16 pixel version has been commercialized for semiconductor defect analysis. For analysis of plasma sources, which are very dim compared to the synchrotron sources, the high-resolution, high-efficiency detectors' superconducting x-ray sensors fabricated by the group are ideal for measurements at the 10^{-12} meter scale and the 10^{-12} second time scale for dynamic measurements.

This group is very successful in technology transfer to private industry, to academic and government laboratories, and for astronomy polarimeters, where more than 20 installations of TES/SQUID-based detectors and detector arrays are playing a central role in millimeter wave polarimetry in astrophysical cosmology. PML detectors and/or amplifiers are in almost all millimeter wave polarimeters in the field, because these detectors provide the best performance.

This Quantum Sensors Group and the Quantum Nanophotonics Group have also built a unique tabletop time-resolved x-ray spectrometer based on a femtosecond laser source that is focused into a water jet to generate pulses of x rays. The high sensitivity and quantum efficiency of the TES sensors are a good match to the relatively low x-ray flux, and this is the key enabler that makes this experiment possible without the high x-ray flux of a synchrotron or free-electron laser source. This instrument is used in novel studies of chemical dynamics through time-resolved, x-ray, near-edge spectroscopy and x-ray absorption fine structure.

The PML group deserves congratulations for the success of its TES activity, which has resulted in a uniquely versatile and capable detector technology that has been successfully propagated to many laboratories around the world.

Precision Optical Measurements

The Fiber Sources and Applications Group demonstrated a new technique based on dual frequency comb spectroscopy that can accurately measure amounts of major greenhouse gases. The concept entails sending a laser beam across a 2 km round trip path from NIST to a mirror mounted on the side of a nearby mesa. This provides a test column whereby even trace amounts of methane can be detected with very high sensitivity. The research team has collected data under real conditions and compared the data against data collected at a nearby National Oceanic and Atmospheric Administration (NOAA) point sensor under well-mixed atmospheric conditions.

The PML measurements yielded concentration uncertainties of less than 1 ppm for carbon dioxide, validating the concept. The group has extended this method to differential absorption light detection and ranging (LIDAR) that measures both mass flux and gas content along this volume as a means of obtaining the distribution of greenhouse gases. This allows for pinpointing local sources and perhaps ultimately their remediation. Extension to portable laser systems, which is one focus of this team, will enable its widespread deployment to sites around the United States and worldwide to help in the accurate measurement of greenhouse and other atmospheric contaminants and of their sources. This is a vital precision measurement capability that lies at the core of the NIST mission of determining the trace presence of contaminants and other materials in the environment.

Measurement Services and Standards

Superconductive Electronics

The Superconductive Electronics Group has created and maintains both direct current (DC) and alternating current (AC) voltage standards based on the Josephson effect. The quantization of magnetic flux in a Josephson junction make this device a perfect frequency-to-voltage converter; since frequency is perhaps the most precisely defined quantity, this provides a path to a very precise voltage standard.

Realization of a voltage standard requires synchronous operation of a large number of junctions in series, which is enabled by the excellent microfabrication facilities that are part of the Quantum Electromagnetics Division. The resulting programmable DC voltage standard has demonstrated accuracy to a few parts in 10^{11}, has been disseminated to national metrology institutes (NMIs) around the world, and is available for sale as a certified NIST reference instrument. This group is the best in the world in AC waveform synthesis with quantum-derived accuracy and in the electronic measurement of Boltzmann's constant to 3 ppm accuracy.

The Superconductive Electronics Group also works to develop superconductive logic and memory devices for advanced high-performance computing. This is a national priority area identified in the National Strategic Computing Initiative, and the group is well suited and equipped to make advances in superconducting computing.

Laser Metrology and Applications

The Sources and Detectors Group has performed impressive laser metrology work. Because of the extreme sensitivity of the welding process to the control of laser welder power. PML involvement in setting power measurement standards is important to the U.S. economy.

The work on metrology is very imaginative and impressive. The standard approach is to measure coolant temperature changes from output absorption in metal power-absorbing cells. This method is effective and reasonably accurate; however, it is expensive and does not clearly provide a portable standard that can be used in house by any but the most substantial laser welder manufacturers or users. The new approach being explored by the Sources and Detectors Group is to measure radiation pressure using commercially available scales. The power is measured by determining the change in scale reading in the presence of and the absence of the incident beam. The method is very inexpensive and may provide the accuracy required for many manufacturing needs.

The purchase of a new welding tool is an important addition to the metrology group, which can do real-time experiments to determine the variables that need to be measured and controlled in practical welding applications. The group already has-proficiency in its use.

The Laser Metrology Group is doing excellent work in support of this broad-spanning and crucial component of our national economy. The group holds a global leadership position in high-power laser metrology.

PORTFOLIO OF SCIENTIFIC EXPERTISE

The permanent staff members of the APD and the QED form a talented group, as evidenced by their scientific output, the recognition of 3 of their staff as NIST fellows, and of 14 of them as fellows of scientific professional organizations, and by their recognition as recipients of 8 external awards and 32 NIST or Department of Commerce awards since 2010. They are active and well recognized for their contributions to conference organizations and professional societies. They have averaged about 5 refereed publications per staff member since 2013, for a total of over 250 publications. Their publications were cited 5,335 times in 2014. These scientists exhibited exceptional depth of knowledge and understanding of their fields of expertise.

ADEQUACY OF FACILITIES, EQUIPMENT, AND HUMAN RESOURCES

The MBE laboratories and microfabrication facilities in Boulder and in Gaithersburg are impressive and are designed for the processing of the unique materials and devices required for research, including the extensive experimental QI research programs at NIST.

The MBE systems in Boulder and Gaithersburg are very new and state-of-the-art. Both facilities have excellent capabilities for growth and optical characterization of the unique quantum structures that are being grown to support the quantum device projects on entangled photons and single-photon detectors.

The state-of-the-art Boulder Microfabrication Facility (BMF) provides clean-room facilities and fabrication tools vital to the success of many of the technical groups, such as the Quantum Sensors and Superconductive Electronics Groups. The BMF has impressive capabilities for materials deposition and for sophisticated fabrication of superconductive tunnel junctions and semiconductor quantum well, dot, and nanowire structures.

The precision imaging facility (PIF) offers a variety of microscopy tools, including some relatively uncommon techniques such as local-electrode atom probe and helium ion microscopy.

The Gaithersburg and Boulder nanofabrication capabilities are complementary; the Gaithersburg facilities address Si complementary metal-oxide-semiconductor (CMOS) technology but are unable to meet the demands for the combination of materials grown and processed in Boulder. The processing facilities are state-of-the-art and appear to be staffed by knowledgeable personnel and utilized by a broad range of scientists in the Advanced Microwave Photonics, Magnetic Imaging, Sources and Detectors, Quantitative Nanocharacterization, Quantum Sensors, Superconductive Electronics, Quantum Processing Faint Photonics, and Quantum Nanophotonics groups. The scientists using these facilities publish their work frequently and are active in their respective technical communities.

As an example of the quality of work in the APD, electron beam lithography has been used to pattern nanowires into a thin film made of a heat-tolerant ceramic superconductor, molybdenum silicide, operated at the superconducting transition edge temperature. The new design operates at higher temperatures and current. Timing jitter is now 76 picoseconds and detector efficiencies are at 87 percent at wavelengths that are useful in telecommunications.[1]

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[1] V.B. Verma, B. Korzh, F. Bussières, R.D. Horansky, S.D. Dyer, A.E. Lita, I. Vayshenker, F. Marsili, M.D. Shaw, H. Zbinden, R.P. Mirin, and S.W. Nam, High-efficiency superconducting nanowire single-photon detectors fabricated from MoSi thin-films, *Optics Express* 23(26), 2015, 33792-33801, doi:10.1364/OE.23.033792.

In the QED, a significant and important advance has been the development of a new kind of sensor that can be used to investigate the isotopic composition of plutonium samples—a critical measurement for nuclear nonproliferation efforts and related forensics, as well as environmental monitoring, medical assays, and industrial safety.

PML staff suggested that the Gaithersburg and Boulder nanofabrication facilities could support a significantly greater number of NIST projects or outside collaborators. These are valuable resources that are not readily available to the growing user community outside NIST.

The Gaithersburg microfabrication facility is older and has been substantially upgraded. A new facility has been established at the University of Maryland.

The recent reorganization of these divisions has balanced the numbers of their staff, with 101 full-time employees and affiliates in the Applied Physics Division and 103 full-time employees and affiliates in the QED, while retaining a distribution across the five focus areas. About a third of the technical personnel in each division are permanent federal employees, with the remainder being mostly affiliates (guest researchers) and federal term employees (postdoctoral researchers). While recent construction has provided new, advanced laboratory space for much of the work in these divisions, the number of postdoctoral researchers has not increased.

It was also noted by the PML that graduate student hiring is substantially hindered by the practice of charging full NIST overhead on the cost of the student, which is then passed to the university, which charges full overhead again on the cost of the student. The resulting concatenation of overheads substantially exceeds 100 percent.

There are few technical support staff members, such as machinists, mechanical designers, instrument builders, and electronics technicians in residence for the areas of applied physics and quantum electromagnetics. This work is divided between external contractors and the special shop facilities personnel at JILA (the joint institute between NIST and the University of Colorado). Continued access to the JILA shops and continued funds supporting work done by external vendors is important for the technical work in these two divisions.

It was also noted by the PML that investments in new capital equipment are charged overhead proportional (approximately 50 percent) to the full amount of the capital cost. This is a serious limitation to the investment in the equipment necessary to maintain the high level of productivity of these two divisions and the PML more generally.

CONCLUSION

The activities in the APD and the QED are well aligned to address the priorities of the PML mission. These priorities are advanced measurement dissemination, photonics, measurement science for future computing devices, quantum information, and physical measurements in biophysics and biomedicine. These divisions excel at advancing the frontiers of measurement science through new technology and at making sure this technology has impact through dissemination of technology and through interactions with key stakeholders in industry and elsewhere. Overall, these divisions are well aligned to contribute to NIST's maintenance of U.S. leadership in metrology that supports advanced optical manufacturing technologies.

3

Engineering Physics Division

INTRODUCTION

The mission of the Engineering Physics Division (EPD) is to promote U.S. industrial innovation through the development of a high-quality physical measurement infrastructure that is specifically relevant to realizing length traceability and that will underpin future electronics. The division has 79 research staff (including 1 NIST fellow), 95 guest researchers, and 20 students. It is responsible for dimensional, nanometer-scale, and surface metrology, accelerometry, acoustic-pressure metrology and standards, and advanced electronics manufacturing, testing, and standards. The division is divided into five groups: CMOS and Novel Devices, Dimensional Metrology, Nanoelectronics, and Nanoscale Metrology, and Surface and Nanostructure Metrology.

ASSESSMENT OF TECHNICAL PROGRAMS

CMOS and Novel Devices

The CMOS and Novel Devices Group has 10 staff scientists, 10 guest researchers, and 6 other affiliated staff. The group advances measurement science to accelerate the commercialization and manufacture of high-performance and reliable electron devices for the electronics industry by developing new characterization techniques, physics-based models, and data analysis methods. The group develops the advanced metrology tools to enable quantitative and mechanistic assessment of reliability issues in emerging electronic devices.

Another thrust is to develop new measurements, physical models, and data analysis techniques to accelerate the development and commercialization of nanoelectronic-device-based medical technology for life sciences and personalized health care. The CMOS and Novel Devices Group has three technical programs—reliability for present and future CMOS; back-end-of-line (BEOL) reliability and metrology; and nanobiotechnology and bioelectronics. The first two programs are closely coupled with the semiconductor industry and are important to this multi-trillion-dollar industry.

CMOS reliability has become more challenging to quantify as dimensions have shrunk. Reliability is an important issue for both consumer and military electronics technology. This PML team has made several major technical achievements that address the reliability issue. They include a probe station that has been modified to make massively parallel current voltage measurement—this tool allows for rapid acquisition of data from which reliability models can be produced; the refinement of a technique for measuring low-level defect concentrations produced in the CMOS device during operation; and the development of a unique high-definition spin resonance tool that allows exploration of the structure of the defects that are being measured electronically. The three projects represent important contributions to the semiconductor industry, where NIST will continue to play an important role. The challenge is that as CMOS scaling comes to its end, the metrology will have to continue to adapt. An exciting application of the spin resonant tool will be in biotechnology. An exemplary contribution of the team is that a tool originally developed to address semiconductor problems will find its main applications in biotechnology.

A second team has focused on BEOL. This team is addressing many of the issues related to 3D integration in semiconductor chips. The semiconductor industry is using more chip volume, which results in expanding the chip vertically. The CMOS and Novel Devices Group has developed several scanning probe and RF techniques for measuring subsurface interfaces and defects and has developed techniques for determining the thermal stress in Cu vias. Stress determination is important because 65 percent of microelectronic failures are stress-related. Three-dimensional (3D) integration will become ubiquitous as the industry pursues multifunctionality in its chip development.

Interaction with the semiconductor industry continues to be important. There may be emerging needs for reliability studies and standards in microelectromechanical systems (MEMS) and nanoelectromechanical systems (NEMS) technology. NIST needs to continue to track developments in this constantly changing environment. A third team addressing bioelectronics is relatively small, with four staff members and two guest researchers. However, the technical results are exciting and lay out a promising biochip development pathway. The researchers have demonstrated biological nanopores on a chip that can distinguish the size of proteins electronically. This is an important research direction that is being followed worldwide. The biggest challenges in the technology will be developing artificial nanopores that can replace the organic pores.

The impressive nanopore work can be used for protein sizing and ultimately could be integrated with a CMOS-based field-effect transistor (FET). The tip-based electron spin resonance equipment was also impressive. This is a unique instrument originally developed for semiconductor characterization, with exciting possibilities in PML’s new initiative in physical measurements on living things. The division’s effort to create a strategic plan to integrate its biological work into this new initiative is commendable.

Nanoelectronics

The Nanoelectronics Group is composed of 11 research staff members and 25 guest researchers. The group conducts basic research to advance the optical and electrical measurement science infrastructure necessary for innovation in nanoelectronic and thin-film devices and their component materials. Within the group are three subgroups that address optical spectroscopy of nanostructures, thin-film electronics, and nanoelectronic device metrology.

The optical spectroscopy of nanostructures subgroup focuses on Raman spectroscopy to access the optoelectronic properties of novel nanomaterials. The focus has been on carbon nanotubes. The emphasis is shifting to graphene and to dichalcogenides. This subgroup has been instrumental in assessing the health and environmental risks of nanomaterials.

The thin-film electronics subgroup develops rigorous measurements and methodology needed for continued U.S. leadership in manufacturing and innovation of emerging electronic devices. An example of the interdisciplinary work done by the Nanoelectronics Group was the development of a standard cleaning technique for graphene. Graphene is particularly difficult to clean because the plasma cleaning normally used to remove photoresist and other polymers will destroy graphene films. The thin-film electronics subgroup is developing metrology for flexible electronic, high-performance heterojunction devices and Li battery technology. An example is the development of internal photoemission spectroscopy to quantify band offsets for gate stacks on alternate-channel FETs. These measurements utilized a NIST-unique test structure incorporating graphene as an electrically and optically transparent electrode.

The nanoelectronic device metrology subgroup seeks to develop measurements that quantify physical processes and electronic properties and to manipulate such processes and properties to enable innovation through entirely new functionality. An example is the projects in is click chemistry, which expands molecular electronics to molecules that do not self-assemble, allowing the build-up of complex molecular layers and electrode variety and adding new functionality at well-designed nanometer distances and concentrations. Another example is the development of eutectic gallium indium electronic junctions, which address the difficult problem of contacts to molecular layers.

Research in nontraditional materials for the purpose of developing the next generation of measurement technologies is a solid rationale for the team's planned direction. However, it will be important that PML avoid duplication of effort conducted by better-funded teams investigating the science or technology of these speculative materials systems.

Surface and Nanostructure Metrology

The Surface and Nanostructure Metrology Group consists of 14 research staff and 12 guest researchers. The group project teams focus on optical methods for 3D nanostructure metrology; nanostructured optics and optical surface metrology; forensic topography and surface metrology; traceable scanning probe nanocharacterization; atom-based metrology; and atomically precise electronic devices.

The team investigating optical methods for 3D nanostructure metrology focuses on resolving critical issues in deep subwavelength line width and defect metrology for the U.S. semiconductor industry. Combining light scattering with algorithms, they are able to extract information from subwavelength line widths. They are reporting the world's smallest multidimensional measurements of objects using optical imaging, providing quantitative information from scattered light images at resolutions previously thought impossible.

The nanostructured optics and optical surface metrology subgroup is developing innovative methods for measurements of ultraprecise flat, spherical, free-form, and nanostructured surfaces and is also developing novel nanostructured optics.

The forensic topography and surface metrology subgroup is developing rigorous metrics and algorithms for forensic firearm and tool mark identification. This work has produced calibration bullets and cartridge cases that serve as laboratory standards. This impressive work illustrates the impact of metrology in non-traditional areas.

The subgroup on traceable scanning probe nano characterization provides fundamental nanoscale length metrology for such applications as semiconductor manufacturing, optics, photonics, and data storage. This group is seeking to understand and characterize tip sample interactions. This is important work; it will be interesting to see how the new efforts on atom-based metrology develop. The subgroup on atom-based metrology is developing the intrinsic metrology needed to enable atomically precise devices at the ultimate scaling limit, applicable to the emerging class of quantum devices.

Dimensional Metrology

The Dimensional Metrology Group realizes and disseminates the SI unit of length, concentrating on dimensional measurements ranging from micrometers to kilometers. The group of 18 full-time staff and 2 guest researchers develops and deliver cutting-edge dimensional metrology technologies, including critical measurement services and standards for industrial manufacturing such as the precise measurement of aircraft and automotive parts to ensure proper mating of parts. The group also collaborates on dimensional metrology tasks relating to NIST research on measuring discrepancies of the value of the universal gravitation constant, G, and evaluation of hip replacement artifacts.

The group has developed the world's best Fabry-Perot refractometer, which will enable a portable, low-cost, and accurate length standard under ambient conditions. The length standard (which, since 1983, has been referenced to the speed of light) is currently limited by the accuracy of the air wavelength, which in this device is known to 5 in 10^{-9} due to the water vapor contribution to the refractive index of air. Further improvement in this accuracy is anticipated when this contribution is corrected for. Because the refractive index in gases depends on pressure, the Fabry-Perot reflectometer can also be used to realize a portable primary standard for pressure. An open question remains: How well can one maintain long-term stability of the mirror reflectivities under ambient conditions? It might be worthwhile to consider whether it is possible to scale this down to make a NIST-on–a-Chip device. NIST-on-a-Chip is an integrated program to develop and deploy NIST-treaceable measurements and physical standards that are deployed in the customer laboratories, factories, devices, and systems; are easily used and integrated; provide a wide range of measurements and standards relevant to the particular customer needs and applications; and are manufacturable.

The group needs to play an important role in the advanced manufacturing initiative for both long-range and short-range metrology. This would draw the group closer to the other groups in the PML. If not currently being done, the group's researchers could benefit from sabbaticals at customer industries. This is particularly relevant for the fast-changing technologies addressed by the group.

Nanoscale Metrology

The Nanoscale Metrology Group provides advanced measurement science, standards, and calibration services for acceleration, shock, and acoustics. The group is an active participant in standards committees in the Institute of Electrical and Electronics Engineers (IEEE), International Organization for Standardization (ISO), and Semiconductor Equipment and Materials International (SEMI) and also provides services for shock measurements for military and sports applications.

The group has revitalized its vibration calibration services activity by opening a state-of- the-art primary calibration system to support U.S. calibration laboratories. They have also refocused their metrology service efforts on developing primary calibration devices aimed at the rapidly growing, multi-billion-dollar MEMS industry for microphones and inertial sensors.

Hearing loss is a major medical issue for millions of Americans and for veterans who have suffered hearing losses as a consequence of combat. The group has created a state-of-the-art capability to measure and calibrate the performance of hearing aids with incorporated adaptive filters. They have also developed test methods to perform the uncertainty analysis of manikin instrumentation during underwater blast testing.

PORTFOLIO OF SCIENTIFIC EXPERTISE

The CMOS and Novel Devices Group is a combination of physicists, biophysicists, and engineers. Many of the investigators have industrial experience and are sensitive to the needs and limitations of the semiconductor industry; this is especially true for the team doing the reliability work. The group expertise strongly supports the responsibilities of the group. Considering the new emphasis on the measurement of living things, it would be useful for the group to add a protein chemist to work with the nanopore team.

The Nanolectronics Group has two Department of Commerce (DOC) silver medal winners and has taken on leadership roles in their respective scientific communities.

The Surface and Nanostructure Metrology Group has received several prestigious awards, including the 2013 research and development (R&D) 100 Award and the 2013 Intel Outstanding Researcher in Metrology Award. In addition, the group has been extremely successful in obtaining both internal and external funding.

ADEQUACY OF FACILITIES, EQUIPMENT, AND HUMAN RESOURCES

The facilities are more than adequate for the technical program described in the CMOS and novel devices area. Some of the equipment developed by the reliability team is unique. The biotechnology team collaborates across NIST and with the National Institutes of Health (NIH) for access to biospecific facilities.

The facilities are adequate to support the work of the Nanolectronics Group and the Surface and Nanostructure Metrology Group. Some of the equipment used by the latter group (particularly for dimensional calibrations) is unique and located inside carefully controlled environments.

DISSEMINATION OF OUTPUTS

The Nanolectronics Group has a solid publication record. In addition to publications the Surface and Nanostructure Metrology Group provides dimensional calibrations in the range from micrometers to 0.1 meter.

4

Office of Weights and Measures

The Office of Weights and Measures (OWM) has a staff of 20 individuals and implements its services through four programs: laws and metric, international legal metrology, legal metrology devices, and laboratory metrology.

ASSESSMENT OF TECHNICAL PROGRAMS

Laws Program and Metric Program

The Laws Program provides "technical information, assistance, and training in the areas of packaging and labelling, methods of sale, uniform laws on legal metrology, net quantity of contents, price verification, and engine fuel quality."[1] The Metric Program "helps implement the national policy to establish the SI (international system of units, commonly known as the metric system) as the preferred system of units for trade and commerce."[2]

To assist U.S. consumers in cost savings, researchers in the Laws Program and the Metrics Program have produced a best practices guide for the layout and design of unit price labels. The guide assists retailers and governments in improving the accuracy and usability of unit pricing.

The Metric Program presents information to stakeholders through yearly attendance at U.S. conferences and provides teacher's metric kits. The use of social media may provide routes to increase the visibility of the OWM's metric outreach program.

The Metric Program has experienced declines in student participation in outreach events. OWM attributes the decline to the decision not to participate in NSF's Science and Technology Education Partnership (STEP) conference in 2014. As a result, OWM decided to attend the 2015 STEP conference and plans to attend STEP in 2016.

International Legal Metrology Program

The International Legal Metrology Program (ILMP) facilitates U.S. participation in the technical work of the International Organization of Legal Metrology (OIML), a treaty organization that develops voluntary standards intended to be used to harmonize national legislation among member states in areas where regulated instruments and measurements are involved."[3]

With the publication in April 2015 of its final two sections, International Recommendation OIML R 117, *Dynamic Measuring Systems for Liquids Other Than Water*, is now considered to be the official

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[1] NIST PML, "Laws and Metric Programs," http://www.nist.gov/pml/wmd/laws/index.cfm, accessed October 28, 2015.

[2] Ibid.

[3] NIST PML, "International Legal Metrology Program," http://www.nist.gov/pml/wmd/ilmg/index.cfm, accessed October 30, 2015.

international standard for almost all dynamic liquid measuring systems, including those used for fuel dispensers, oil pipelines, ship loading, and aircraft fueling.

Legal Metrology Devices Program

The Legal Metrology Devices Program (LMDP) promotes "uniformity at the international, federal, state, and local levels in standards and practices for weighing and measuring devices to facilitate trade and protect U.S. businesses and citizens."[4]

Plug-in electric vehicles make up a growing share of the nation's vehicles and are prompting increased demand for the electrical equivalent of the corner gas station. A standard produced by NIST's U.S. national work group on electric vehicle refueling and submetering was adopted by the National Conference on Weights and Measures (NCWM) at its 2015 annual meeting. The standard details how customers should be charged and the requirements operators should meet.

The OWM is recognized as the experts in the area of legal metrology and devices and is frequently engaged to collaborate with various U.S. national working groups and standards development committees.

The OWM's device-related training has been well received by the states and industry Training effectiveness is assessed at the time the training is completed, and the feedback is used to improve the training methodology. Long-term training effectiveness is assessed by use of a voluntary follow-up to determine how the skills and knowledge acquired are being utilized in the field. It is unclear, however, if the long-term effectiveness of the training is being adequately assessed, and OWM needs to place more emphasis on this aspect. Examples of methods that could be considered are field audits, practical examinations, and partnership agreements.

Laboratory Metrology Program

The laboratory metrology program "provides the basis for ensuring traceability of state weights and measures standards to NIST; conducts fundamentals of metrology, mass, volume; and advances mass training for metrologists working for the states, for industry, and in other countries."[5]

Americans rely on many measurements of mass and volume in their daily lives; the accuracy of the devices used in those measurements must be tested at regular intervals. The degree of accuracy achieved for these devices depends on the competence of the metrologists who calibrate over 350,000 measurement standards per year that are then used by weights and measures officials when testing measuring instruments.[6]

The number of accredited and recognized laboratories has dropped due to inadequate staffing succession at the state levels. Accredited laboratories score highest in proficiency examinations, creating a challenge for OWM as the number of accredited and recognized state laboratories has dropped due to issues with succession planning in some states.

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[4] NIST PML, "Legal Metrology Devices Program," http://www.nist.gov/pml/wmd/lmdg/index.cfm, accessed October 28, 2015.

[5] NIST PML, "Laboratory Metrology Program," http://www.nist.gov/pml/wmd/labmetrology/index.cfm, accessed October 28, 2015.

[6] NIST PML, "OWM Sees Progress in Proficiency Testing," December 23, 2013, http://www.bldrdoc.gov/pml/wmd/labmetrology/owm-proficiency-testing-success.cfm.

PORTFOLIO OF SCIENTIFIC EXPERTISE

The OWM has a staff of 20 individuals who work as a team. The OWM appears to be adequately staffed to achieve its objectives.

Within the next 5 years approximately 50 percent of the present staff of the OWM will be eligible to retire. The organization has recognized the need for succession planning and has a number of knowledge transfer systems in place to assist with such planning. Continued vigilance is required to ensure there is a transfer of knowledge as retirements take place.

ADEQUACY OF FACILITIES, EQUIPMENT, AND HUMAN RESOURCES

A review of training facilities at NIST determined that the facilities meet the training needs of the OWM. The OWM training facility that is used for mass calibrations training could benefit from improved storage space.

DISSEMINATION OF OUTPUTS

The OWM does an excellent job of disseminating information through its training program, the NIST website, and the publication of technical documents such as handbooks, newsletters, and standard operating procedures. The office conducts proficiency testing and a 45-day follow-up survey with attendees at the OWM training courses.

5

Quantum Measurement Division

INTRODUCTION

The Quantum Measurement Division (QMD) goals and strategic plans are mostly driven by the redefinition of the international system of units (SI), specifically by introducing the quantum SI with a completion target of 2018. This includes redefinitions of the kilogram, ampere, volt, kelvin, and mole. The quantum SI is an approach to implementing the International Committee for Weights and Measures (CIPM) recommendation 1 (CI-205). As a result, this division covers an extraordinary range of activities in fundamental and applied studies. Fundamental work includes research on single atoms and photons, quantum degenerate atomic gases of bosons and fermions, cavity optomechanics, and quantum optics. Spectroscopic work, with its long and distinguished history, includes the atomic spectroscopy database, and metrology covers aspects that include fundamental measurements of mass and force; basic electrical measurements of voltage, ampere, and resistance; and time-synchronized measurements for smart grid applications.

In its plans to physically realize the electrical, mass, and force units, the division focuses on the Committee on Data for Science and Technology (CODATA) recommended values of the fundamental constants of physics and chemistry. With the increasing reliance on quantum-based measurements, the division explores foundational questions directed toward advances in all units, including measurement schemes beyond the standard quantum limit. Another focus is the dissemination of the primary realizations at NIST, illustrated by the *mise en pratique* efforts to introduce a new realization of mass measurement based on electromagnetic levitation.

ASSESSMENT OF TECHNICAL PROGRAMS

Atomic Data and Spectroscopy

The Atomic Spectroscopy Group has an extraordinary record of accomplishments over its multidecade history. Calendar years 2013 and 2014 are typical, with 32 and 25 refereed publications respectively.

The expansion of astronomical spectroscopy into new wavelength ranges is a great opportunity for the group. Mercury cadmium telluride (HgCdTe) detector arrays have opened the infrared (IR), and various orbiting facilities have opened the ultraviolet (UV), vacuum ultraviolet (VUV), and x-ray spectra. Knowledge of the detailed physics and chemistry of the remote universe is gained from spectroscopy. The era of exoplanet studies has started, and the era of exobiology will soon follow.

Although quantum information (QI) processing in the form of a device for factoring large numbers is a major goal of QI research, other applications of QI devices may have commercial significance much sooner (for example, quantum key distribution schemes and early-stage quantum computing products).

Experimental Solid State Quantum Information

Within the field of experimental, solid state QI, a competition is under way between trapped-atom/ion systems and solid-state (SS) systems for QI processing. Trapped-atom/ion systems offer the promise of long coherence times, but SS systems promise greater scalability. This PML group investigating experimental solid-state QI is developing an original and promising concept for a SS system for QI processing, using electromagnetic separation. Isotopic separation efforts in the group could be expanded with a modest investment. Such an expansion would have implications for metrology, e.g., improvements in Avogadro's number, and for technologies such as QI.

Experimental Cold Atoms, Quantum Optics, Nanomechanical Science, and Theory

This is a core enabling component of the PML that provides science drivers and is a powerful innovation engine. It also complements the work of the Quantum Physics Division, located in Boulder, and fits well into PML's NIST-on-a-Chip activities.

As quantum materials become increasingly important, a central goal of this work is to help shed light on these materials by designing and realizing many-body Hamiltonians in ultracold atoms, where exquisite control is available. Another motivation for the work is to investigate the use of quantum many-body systems to make new kinds of measurements. These groups are doing experimental and theoretical research on ultracold atoms, quantum optics, and nanomechanics that is among the best in the world. The researchers produce large amounts of outstanding science and enjoy international recognition. The expertise of the experimentalists covers a broad range of areas, including quantum optics and ultracold atomic physics.

The experimental studies of many-body effects in ultracold atomic systems are among the best in the world, and the recent test of Bell inequalities, eliminating the remaining loopholes of previous experiments, is a telling example of the synergy between different areas of expertise at Gaithersburg and JILA, the extraordinarily successful joint institute of the University of Colorado, Boulder, and NIST.

In the relatively new area of optomechanics, a promising direction is the development of new bridges between quantum physics and sensor development, with promising applications of optomechanics to thermometry. There are also possible applications of single-photon sensing in biological systems.

The theoretical efforts also cover a remarkable range of topics, including many-body physics, quantum optics, traditional atomic physics and collision physics, and QI science. The theorists play an important role in building bridges between different activities, including between other divisions within NIST.

Techniques developed by the PML for precisely placing dopants in silicon may be applicable in more general semiconductor fabrication.

The partial relocation of the groups working in this area to the University of Maryland campus presents both opportunities and challenges. Opportunities include more access to students, the possibility of PML staff seeking funding as University of Maryland adjunct faculty, and additional outreach and education through teaching. At the same time, this geographical separation raises the challenge of maintaining close collaboration and communication with the Gaithersburg NIST campus.

Fundamental Electrical Measurements, Applied Electrical Metrology, Mass and Force, and Synchrometrology

The incremental improvements in the key electrical measurements triangle (voltage, current, and resistance) are demonstrating continued PML leadership in attempting to increase accuracy while reducing uncertainties. The venturing into new materials and the associated quantum phenomena, such as the use of graphene for resistance and the Josephson effect for voltage measurements, is focusing on breakthrough approaches as they become available through new technological developments and improved theoretical understanding.

Further refinement of the CODATA constants is critical for continued efforts of the fundamental electrical measurements, applied electrical metrology, and mass and force work.

The Applied Electrical Metrology Group is maintaining responsibility for well-established AC-DC measurements and is also exploring the AC-DC metrology of the future. A relatively new activity that is primarily focused on smart grids addresses issues of synchrophasor measurements, new sensors, and the associated problems of interoperability and cybersecurity.

In the mass and force research area the general direction of using quantum physics to devise a substitute for artifacts (the watt balance and *mise en pratique*) is a very promising and much needed approach to reducing the cost and increasing the dissemination of calibration references for mass and force. This is an impressive collaboration between two formerly independent groups that merged into the division. The potential to make key contributions to the next SI revision is significant and remains an important focus for NIST. The key challenge may be to achieve the right balance in staffing the various efforts, particularly those with a long history of contributions versus emerging ones.

The PML areas of involvement in the smart grid areas are recognized by industry and users as needing some breakthroughs to serve the potentially huge domain of future commerce (estimated by the Electric Power Research Institute [EPRI/] at almost $500 billion). NIST visibility could be increased by engaging various groups in this area beyond those involved in the Smart Grid Interoperability Panel (SGIP). The choice of where to concentrate and focus already limited resources remains an issue.

The PML could also focus on smart grid sensors other than phasor measurement units (PMUs), with a goal of identifying how to help industry obtain more precise, synchronized, and reliable measurements. In particular, measurements under dynamically changing conditions are widely untapped in the smart grid standardization area, and the PML has an opportunity to position itself as a worldwide leader if it tackles this difficult problem. Development of metrology for assessing effectiveness of standards for the grid cybersecurity and privacy remains a huge challenge.

The ability of the PML to maintain its leading position in what is one of the oldest metrology areas is an accomplishment.

PORTFOLIO OF SCIENTIFIC EXPERTISE

Through its highly productive scientific exchange, with over 150 journal papers published in 2014, numerous awards received in the last 5 years, and the hosting of over 90 guest researchers while maintaining its own staff of 75, the division remains an essential focal point of the world efforts on physical measurement sciences.

ADEQUACY OF FACILITIES, EQUIPMENT, AND HUMAN RESOURCES

Atomic Data and Spectroscopy

The Atomic Spectroscopy Group has unique facilities, including a 2 m normal-incidence spectrometer, a vacuum ultraviolet (VUV) spectrometer, grazing-incidence spectrometer, and tunable single-frequency lasers. Some of the instruments—for example, the research-grade Fourier transform spectrometer (FTS)—are unique in this hemisphere. The shortage of technicians to maintain and upgrade the instruments is very serious, even though the FTS and the data center are staffed by excellent scientific experts.

The Atomic Spectroscopy Group's scientific expertise is in urgent need of strengthening due to the loss of both electron beam ion trap (EBIT) expertise and expertise on highly ionized atoms (HIAs).

The departure and retirement of key atomic spectroscopy staff presents an opportunity to renew the staff and to take the group in new directions.

Experimental Solid State Quantum Information

The group has a combination of high-level theoretical and experimental expertise. The preparation of isotopically pure silicon films using electromagnetic separation is essential to implementation of the SS QI concepts under development by the PML. The productivity of the present electromagnetic (for example, mass spectrometer) separation system could be increased with a modest investment. The group is providing films for other QI research groups.

Experimental Cold Atoms, Quantum Optics, Nanomechanical Science, and Theory

The human resources are excellent, with a number of outstanding recent hires. Following the move to the Joint Quantum Institute (JQI) on the University of Maryland campus, many staff researchers are moving to groups that are more university-like, with three or four graduate students and one or two postdoctoral researchers, instead of relying more heavily on postdoctoral researchers. One advantage is that there is perhaps less pressure to produce fast results with students, who, in contrast to postdoctoral researchers, are under less pressure to accumulate a portfolio of results within a couple of years and may focus more on challenging long-term projects.

A substantial fraction of the activities of this group has been relocated to, or is in the process of moving to, the JQI. The new Joint Center for Quantum Information and Computer Science (QuICS), also located on the University of Maryland campus, is also a joint venture with the NIST Information Technology Laboratory (ITL); this further strengthens intra-NIST collaboration as well as collaboration with the University of Maryland.

Opportunities associated with the move to the JQI and the QuICS on the University of Maryland campus include the benefits of interactions with university faculty, researchers, and students; the possibility of attracting more students to NIST projects; and the opening of new funding avenues. There are also opportunities to disseminate results through teaching.

Fundamental Electrical Measurements, Applied Electrical Metrology, Mass and Force

NIST's ability to maintain high-quality facilities using limited human resources and a relatively limited budget is quite impressive. An example of the PML's ability to maintain its complex facilities is the effort that identified issues with the 4.45 MN force standard machine and helped to expedite its reconditioning. The machine was built several decades ago, and the PML group performed precise modeling of the deterioration phenomena associated with the material galling that developed in key structural components within the stainless steel weight stack.

In the Fundamental Electrical Measurements Group and Applied Electrical Metrology Group, some of the efforts are covered by one or two people only, so staffing may have to be reassessed.

DISSEMINATION OF OUTPUTS

Atomic Data and Spectroscopy

The web-based Atomic Spectra Database (ASD) is a great success. The group has continued to update and modernize the ASD interface to make it increasingly useful.

Spectroscopy will continue to be an important diagnostic for many industrial processes.

Experimental Solid State Quantum Information

The PML research in this area is highly visible through publications and conference presentations.

The need for isotopically pure silicon from multiple research areas is becoming increasingly clear. A modest investment in the small electromagnetic (mass spectrometer) isotope separation system would be valuable. The isotopically pure silicon would be more readily available to internal NIST users and, to the extent that it could be shared with researchers outside NIST, could be used to foster collaborations. It is not necessary to scale up to the large gas centrifuge separation scale that supplies the German Physikalisch-Technische Bundesanstalt (PTB) with macroscopic artifacts of isotopically pure silicon.

Experimental Cold Atoms, Quantum Optics, Nanomechanical Science, and Theory

The results of the research in this area are disseminated in leading journals and at conferences with invited papers and through college courses at the University of Maryland.

In collaboration with JQI and QuICS, teaching presents an opportunity to disseminate results and train future scientists. JILA has a long and successful tradition along these lines, and a similar outcome can be expected from JQI as it further establishes itself.

Fundamental Electrical Measurements, Applied Electrical Metrology, Mass and Force

The dissemination of primary units realizations is an extremely important mission and needs to be supported, with the focus on making the secondary units cheaper but with even more manageable uncertainties. The educational and training efforts for the customers who use the standards are also important.

The PML has provided leadership in smart grid technologies, mainly in synchrophasor measurements and interoperability of metering devices. The PML can leverage its work in the timing standards, atomic clock in a chip, and NIST-on-a-Chip, to develop inexpensive standards for reliable, time-synchronized and interoperable and cybersecure metering standards. For smart grid applications, a timing accuracy of 1 microsecond is acceptable. While the PML has engaged a small section of industry, it is important to increase that engagement.

The dissemination of the work in the new area of smart grid technologies may pose some challenges in balancing the metrology and standards mission of NIST with industrial and commercial interests.

6

Quantum Physics Division

ASSESSMENT OF TECHNICAL PROGRAMS

The Quantum Physics Division (QPD) has a diverse range of programs, including nanotechnology and biological physics, but it continues its firm and unified base in metrology, appropriate for the programs' association with NIST. New advances in measurement science are at the heart of many major scientific advances, and JILA, the joint institute between NIST and the University of Colorado, Boulder (and, therefore, the Quantum Physics Division), is widely recognized as one of the leading research and training organizations in atomic, molecular, and optical (AMO) physics and closely related areas. JILA has been ranked as the nation's top AMO graduate program for decades. JILA scientists are responsible for a long list of breakthroughs in AMO physics, such as the world's first Bose-Einstein condensate, first Fermi condensate, first self-referenced laser frequency comb, first evaporative cooling of molecules, first quantum degenerate gas of polar molecules, and first cooling to the quantum ground state of a macroscopic object (the last-named was accomplished in collaboration with other NIST scientists).

Work on self-referenced femtosecond laser frequency combs was initially pursued as a tool to improve optical frequency standards (atomic clocks), but now laser frequency combs have become one of the most powerful and versatile research and precision metrology tools since the invention of the laser. Laser frequency combs are routinely used across PML laboratories for research and metrology in such areas as remote sensing, chemical analysis and quantification, generation of precision RF and microwave signals, medical diagnostics, length standards, atomic clocks, and references for exoplanet identification and characterization, with new applications appearing continuously. Frequency combs are also ubiquitous in the research laboratories of universities and in national laboratories.

The interplay with and impact on applied physics is also apparent. Improved optical frequency standards will find use in fields that traditionally rely on precision timing (navigation, electronics, communications, and spectroscopy), but in more extreme ways. Such possibilities might include deep space travel and optical-based circuitry and ultraprecision timing for science experiments (e.g., at accelerator centers). The TFD has sent a frequency-comb system to the McDonald Observatory in Texas to aid in the search for exoplanets.

Quantum degenerate gases include Bose-Einstein condensate, Fermi condensates, and molecular gases. In addition to providing a unique laboratory for fundamental physics, scientists across NIST use quantum degenerate gases for quantum information (QI) processing research, quantum simulation, and ultrahigh vacuum standards, with new applications continually evolving.

Division scientists demonstrated cooling to the quantum ground state of a macroscopic object. This system is a promising candidate for quantum information processing, and for ultrasensitive transducers.

Another area of research is observation of spin exchanges in ultracold potassium-rubidium (KRb) molecules inside an optical lattice (a crystal of light formed by overlapping laser beams). In solid materials, such spin exchanges are the building blocks of advanced materials and exotic behavior. Observation of spin swapping could have an impact on future research in such diverse areas as high-temperature superconductivity, energy transport through biomolecules and in chemical reactions, spintronics (a new kind of microelectronics), and the physics of liquids and solids. The work on spin exchange of ultracold molecules is a new testing ground, enabled by tools that have been developed at the division. It will address fundamental questions of molecule–molecule interactions and can be used as a quantum simulator of many-body spin dynamics.

The group of Eric Cornell is using trapped molecular ions to search for a possible electric dipole moment of the electron. This experiment is one of several other ongoing efforts worldwide. The potential for non-point structure of the electron has deep implications for fundamental physics, cosmology, the apparent imbalance between matter and antimatter, and many other issues. The Cornell team has pushed in the 10^{-28} uncertainty range, where possible EDM (electric dipole moment of the electron) effects may be just detectable and is poised to push into the unexplored 10^{-30} range.

There is a strong theory effort in the division. One of the more exciting areas is understanding the realization of quantum Hall states via synthetic gauge fields generated by a spatially dependent optical coupling between internal states of the atoms. One current topic is how to suppress or control collisional relaxation decoherence as well as alternative ways of generating strong Abelian and non-Abelian gauge fields.

Stable laser systems have long been defined by John L. Hall and coworkers. The early days of this work used, for example, locking to the Lamb dip; the work has progressed far beyond the early stages. Work is being conducted on unique ultrastable laser technologies, including the development of an ultrastable reference cavity comprising a monolithic silicon crystal with unique end mirrors and on reducing sensitivity to cavity perturbations. This is used to lock the laser while the signal from an atomic clock is being acquired. Such a device is often called a flywheel because it provides excellent short-term stability to the laser. This work is important in a variety of fields, including experimental relativity and the laser gyro.

Cold atom and stable laser physics is an important area of research. While there are some early-known quantum many-body phenomena with clear impacts (for example, quantum magnetism and superconductivity), the biggest impacts are likely to come from phenomena not yet known or observed. The division strives to play a leadership role in this new frontier, in both experiment and theory, while still leveraging research and measurements using the many important single-body (individual) quantum phenomena.

A fascinating development is the creation of a unitary quantum converter that can interconvert microwave and visible radiation. This advance, while limited by the need for extreme temperatures (40 mK), could eventually have wide-ranging implications for the Internet and other applications. Scientific applications that can eventually benefit from it include clock-signal distribution and QI transfer. As noted in a 2014 commentary,[1] "The potential to transfer QI between optical and microwave photons is especially exciting to the QI processing community. Superconducting microwave circuits have shown great promise for quantum computing, while quantum optics is better at transmission and quantum measurements—combining the two would vastly expand our ability to process and communicate information at the quantum level for computing and security purposes." This effort is at the cutting edge, and it is not known where it will go, but the potential seems large. It is an example of the kind of work one hopes for from JILA.

Biological physics in the division has had a varied path, including the development of technologies to probe the real-time dynamics and kinetics of large, single biological molecules such as proteins, enzymes, and nucleic acids, to better understand normal physiology and disease processes. These are large areas of science being conducted worldwide. There are technical barriers that can arise and that need innovative measurement science, to which the division has been a contributor. Historically there are examples of the application of measurement science within the field of biological physics, one of which is described below, but there are new capabilities emerging that will broaden the scope if further encouraged.

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[1] M. Tsang, 2014, Microwave photonics: Optomechanics sets the beat, *Nature Physics* 10:245-246.

As a historical example in biological physics, targeted chemotherapy often exploits a genetically engineered monoclonal antibody (mAb) that is chemically attached to an agent that can kill tumor cells. Monoclonal antibodies are designed to attach to specific antigens (e.g., proteins) that are predominantly found on the surfaces of malignant cells, and mAb's can be engineered to bind to them. Once research determines that a certain cell-surface molecule indicates cancer, then mAb's can be designed to target that molecule and hence the cell that it is on. One way to target therapy is to conjugate radioactive atoms to the mAb's, using the radiation to treat the tumors. This radioimmunotherapy received FDA marketing approval in 2009. However, before FDA could approve the marketing of radioactive materials (e.g., yttrium-90) there needed to be a measurement system in place to ensure that the intended dose of radiation was delivered. The PML Radiation Physics Division was instrumental in getting this done, holding workshops so that the relevant stakeholders agreed on what procedures were needed, and providing an anchor in the quality system—a yttrium-90 radioactivity standard solution. This is an excellent example of how research crosscutting physics and biology is being carried out at NIST.

Another example in biological physics has been the development of the world's most stable atomic force microscope (AFM) for biophysical applications, such as exploring the folding landscape of biological macromolecules in solution or in biological membranes. Because the measurements are in aqueous environments at physiologically relevant temperatures, the 100- to 1,000-fold gain is relevant for the biology. While the division's AFM technology is currently aimed at following the complex behavior of proteins and nucleic acids in real-world biological systems, it is also available for a broad range of physical measurements. It is significant that one of the leading laboratories is seeking to duplicate the instrument, and the division is helping it to do so.

AFMs are also being developed for the study of structure–energy relationships in biological macromolecules and membranes. When biological macromolecules are synthesized, they are linear polymers that must fold to make specific compact structures before they can function in cells. There has been limited work to optimize AFM methods to follow the energetics and intermediate states of protein folding. This has presented an opportunity for a laboratory focused on metrology to pick apart the technique, identify the weaknesses, and fix them. The result is an orders-of-magnitude improvement in stability and sensitivity that opens up new capabilities and is likely to allow new explorations of protein folding, a missing conceptual link in the expression of genetic information. In the fields of biological membranes and macromolecular folding, energy landscapes can now be explored as a set of equilibrium measurements that were inconceivable before the JILA advances. The current results on the folding of a membrane protein are particularly interesting and are unmatched by those in any other laboratory in the world.

The world's fastest system for measuring and separating individual living cells with unique properties revealed by ultrafast optical studies has been demonstrated for activities such as quickly identifying algal cells with the highest biofuel production and rapidly identifying optimal fluorescent proteins used to monitor real-time processes in living cells. Practical uses of biological systems are often assisted by finding the optimal organisms in a diverse population, so this technology will find important applications.

PORTFOLIO OF SCIENTIFIC EXPERTISE

In terms of its core strengths, the QPD includes an elite collection of scientists—so elite that it is a constant problem to protect the Fellows from recruitment by other organizations. Unfortunately, the salary of NIST employees is often not able to compete with salaries at academic institutions.

Along with recruitment by other organizations will be the problem of replacing the senior JILA Fellows as they retire. The division is moving strongly into research and measurements on quantum many-body phenomena as the key thrust of the second century of quantum mechanics. Single-body (individual) quantum phenomena have been enormously successful and powerful.

The division does not seem to have a consistent and clear approach to the use of intellectual property. In some fields, the use of a patent by a research organization can be to facilitate new companies that can be protected in their exploitation of the kinds of technology developed at the division. It appears that there has been no consistent view, and that the expertise to guide a technology transfer effort is not in place. Division investigators are, understandably, confused, asking, “Are we patenting this year?” An organized position needs to be thought through for the future—either intellectual property is useful and important or not, in the areas represented. A serious effort is a large expense, so the division will need to seek support from PML if the decision is to protect the intellectual property.

ADEQUACY OF FACILITIES, EQUIPMENT, AND HUMAN RESOURCES

JILA has a very slow turnover rate, perhaps because it recruits excellent faculty and make them happy. Faculty hired more than a decade ago are still referred to as new, and the slow turnover makes the initiation of new areas, such as biological physics, challenging. There will probably be, it seems, a tension between maintaining current directions and creating new ones. The following findings confirm those of the previous (2010) review of the division[2]:

- The new JILA X-Wing provided the space needed to expand present crowded laboratories and make vibration-free areas and, hopefully, clean rooms available for ultrafast and other experiments. The JILA shops provide service that is unmatched in pure university environments in the design and construction of various types of mechanical and electronic equipment, and it is critical that they be maintained at that high level.
- The current size of JILA is nearly optimal, given expectations for future financial resources and space and in recognition of the challenges of maintaining a coherent organization as the organization’s size increases. JILA does not expect to grow appreciably in the foreseeable future. Instead, it will focus on improving the balance of various research areas through replacements as fellows retire or otherwise leave JILA.

DISSEMINATION OF OUTPUTS

The following findings confirm those of the previous (2010) review of the division[3]:

- The impact of the QPD is outstanding as measured against its stated goal and mission of making important advances at the frontiers of science that enable future precision measurement technology and producing graduates who form a talented pool of scientists who are now dispersed throughout the NIST laboratories and elsewhere. These researchers are also having significant impact through applications of their technology outside NIST—for example, in sensitive, high-resolution frequency comb spectroscopy for trace detection and molecular fingerprinting and in the development of technology for multiplexed low-temperature detector arrays for astronomy.
- The division is a premier laboratory that favorably competes, in most of the fields of research that it pursues, with the best academic and federal research institutions in the world, and the graduate school of the University of Colorado was recently ranked in a national rating as number one in atomic physics. The laser frequency comb work and the cold atom and now the new cold molecule research are among the best in the world. The division has attracted

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[2] National Research Council, *Assessment of the National Institute of Standards and Technology Physics Laboratory: Fiscal Year 2010*, The National Academies Press, Washington, D.C., p. 52.

[3] Ibid., p. 50.

applicants with competing offers from top-five U.S. institutions in areas identified for expansion, such as biological physics and nanoscale physics.

JILA alumni have started about a dozen high-tech companies in such areas as optical components, medical diagnostics, and gravity meters. These companies provide innovative technologies and good jobs, commensurate with the NIST mission to facilitate economic growth and new technologies. JILA alumni are key scientific and innovation leaders in industry laboratories, in universities, and in national laboratories (beyond NIST). They contribute broadly to U.S. economic growth and technology development, and they expand the active network of collaborators for NIST.

CONCLUSION

The Quantum Physics Division has had a spectacular run of success over the past 20 years, and long-range planning will be needed to guide continued success. The move into quantum many-body phenomena with strong theoretical support is important so that the division will remain at the frontier of quantum physics. However, the role that quantum-nano biological physics plays in the division needs to be carefully considered. The biological physics effort presently has very little quantum physics. While the current faculty are outstanding, biological physics will need additional hires if it is to become on par with the level of effort of other areas in this division.

Given the promising developments such as those described above, it seems that some expansion is warranted, subject to the reality of budget constraints.

7

Radiation Physics Division

The primary mission focus of the Radiation Physics Division (RPD) is ionizing radiation physics metrology. As part of NIST, a national metrology institute (NMI), it is required to establish, disseminate, and ensure the proper utilization of standards in regard to all aspects of ionizing radiation. In addition to the responsibility to maintain state-of-the-art radiation physics metrology, there is a recurring requirement to develop novel standards to meet current and future needs as the state of radiologic sciences advances.

The division prioritizes its efforts based on input from a variety of outside stakeholders, which include the Council on Ionizing Radiation Measurements and Standards (CIRMS). CIRMS is an independent, nonprofit council that draws together experts involved in all aspects of ionizing radiation to discuss, review, and assess developments and needs in this field.[1] Drawing on expertise from government and national laboratories, agencies, and departments, from the academic community, and from industry, CIRMS issues periodic reports on the needs in ionizing radiation measurements and standards.[2] Such needs are delineated in measurement program descriptions (MPD's), which indicate the objective, state background information, define needed action items, and estimate resource requirements in terms of personnel and facilities. Through dialog at CIRMS meetings and workshops, the appropriate subcommittees (currently industrial applications and effects, medical, and homeland security/radiation protection) independently determine the needs in their respective communities.

In addition, there is organized input from professional groups such as the Radiological Society of North America (RSNA); Society of Nuclear Medicine and Molecular Imaging (SNMMI); and the American Association of Physicists in Medicine (AAPM). These groups provide clinical input, a real-world perspective that helps maintain relevance of division activities from a clinical and scientific perspective. There is additional strong input from industry, with direct interaction that impacts the quality control and regulatory compliance of American business and supports international leadership in radiation treatment machines, scanners, radioactivity measurement devices, and dosimeters. Through intragovernment committees, there is direct input to specialized radiation and regulatory needs that positively impacts mandated responsibilities of the Food and Drug Administration (FDA), Nuclear Regulatory Commission, Department of Energy (DOE), Department of Homeland Security (DHS), and the National Institutes of Health, among other agencies.

The RPD is also responsible for maintaining liaison with international agencies that have parallel radiation metrology functions in other parts of the world. There is key exchange of both information and standards with groups from the United Kingdom, Japan, and Germany and from other official government bodies on both a routine and emergency basis, to ensure global standardization and uniformity of measurement and reporting of quantitative radiologic activities and radiation use.

Within the RPD there are three groups: the Dosimetry Group; the Neutron Physics Group, and the Radioactivity Group, each with clearly defined core functions.

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[1] Council on Ionizing Radiation Measurements and Standards, "Welcome," http://www.cirms.org, accessed November 24, 2015.

[2] The latest needs report was updated following the CIRMS 2015 meeting and can be accessed at the CIRMS website (http://www.cirms.org).

The Dosimetry Group performs work in the following areas: radiation source standardization, chemical interaction studies and reporting, dose from medical imaging procedures, radiation protection dosimetry for the nuclear engineering field, international liaison, determination of biological effects of ionizing irradiation, science and technology of radiation for the DHS, high-dose calibrations, gamma- and x-ray calibrations, and brachytherapy calibrations. A key mission of the Dosimetry Group is to develop and maintain national air kerma and absorbed dose standards (kV and MV x rays, Co-60 and Cs-137 gamma rays, and Sr-90 and Kr-85 beta beams) based on the derived SI unit—the gray—for homeland security, medical, radiation processing, and radiation-protection applications.

The Neutron Physics Group performs work in the following areas: fundamental neutron physics, neutron interferometry, neutron source calibration, neutron imaging, neutron instrumentation calibrations, neutron instrument development, and special calibrations.

The Radioactivity Group performs work in the following areas: basic radionuclide metrology, low-level radionuclide metrology, imaging studies and standards, calibration services, measurement quality assurance, development of nuclear forensic standards and methods, investigation in international and national developments in technology, and production of standard reference materials (SRMs). The key mission of the Radioactivity Group is to develop and maintain state-of-the-art high- and low-level radioactivity detection methodology, including gamma, beta, and alpha counting and spectroscopic capabilities, often based on first-principles methodology that directly measures key radioactive emissions by multiple cross checks and approaches in order to maximize confidence in assay accuracy. The group is also required to develop relevant standards and methods of assay for common radionuclides used in industry and medicine, including calibration services for radioactivity dosimeters utilized in nuclear medicine. The group defines protocols for radioactivity measurement on the national and international level. In addition, other government agencies such as the Nuclear Regulatory Commission and the FDA may mandate linking of radioactivity measurements to NIST-maintained standards.

ASSESSMENT OF TECHNICAL PROGRAMS

Dosimetry Group

Among the recent accomplishments of the Dosimetry Group are the 320-kV W-anode x-ray tube replacement, establishment of an air-kerma standard for electronic brachytherapy using a miniature x-ray tube (50 kV, 300 μA), development of the Lamperti free-air chamber, and implementation of a new Co-60 therapy-level calibration facility with state-of-the-art data acquisition and operating capabilities.

The quality of the work by the group is excellent. It demonstrated competence in maintaining existing radiation dosimetry standards and in developing new ones as needed by the user community. In 2015, a new Co-60 irradiator is being installed to replace an older unit. This work is expected to improve the ability to maintain a number of dosimetric standards essential to the radiation oncology community. According to the Task Group report 51, issued by the American Association of Physicists in Medicine (AAPM),[3] therapeutic-level clinical x-ray dosimetric standards are based on Co-60 sources.

The work in the Dosimetry Group appears to be largely in services rather than innovative research. The group does have a list of potential research projects that can be pursued if funding is available.

Research in advanced computing (such as Monte Carlo simulations) could enhance existing capabilities in radiation measurement and dosimetry. It would be advantageous to strengthen the training program that involves students and postdoctoral researchers in each of the critical standards activities and foster a program to share equipment and facilities with users at national laboratories and universities.

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[3] Dosimetry of interstitial brachytherapy sources, AAPM Task Group Report 51, reprinted from *Medica Physica* 22(2).

Neutron Physics Group

In addition to its core activities, there is a unique basic-research program in the fundamental properties of the neutron. This program is synergistic with the core elements, because the stringent demands of the physics measurements call for a steadily advancing art of calibration and instrumentation.

The fundamental neutron science program is carried out at the NIST Center for Neutron Research (NCNR) and in Building 245. With the new guide hall now in full operation, neutron beam intensities are up by a factor of 5 or more. The additional capacity in flux and in the number of available ports represents a substantial improvement. The guide hall is the world's most modern and places the neutron program in a class with other world-leading reactor neutron programs, such as the one at the Institut Laue-Langevin in Grenoble, the Gatchina reactor in St. Petersburg, Russia, and the high-flux isotope reactor (HFIR) at Oak Ridge.

The basic neutron physics research program by PML scientists at the NCNR has led to advances in metrology. For example, the continuing work to refine the lifetime of the free neutron has led to a recent major advance in neutron flux determination at the 0.1 percent level. This makes possible a new level of precision in neutron cross sections.

The Neutron Physics Group standardizes neutron sources (^{252}Cf, AmBe, etc.) for users around the world in industry, government, and academia. The RaBe photoneutron source at NIST, called NBS-1, is the national reference standard, which has been determined to 0.85 percent.

The Mn bath method is used at NIST and at four other laboratories around the world to calibrate source strengths relative to NBS-1. The Bureau International des Poids et Mesures (BIPM) discontinued its calibration service and sent its three standard sources to NBS-1, and all were found to agree well within the combined uncertainties.

The group also provides spectral reference measurements from a room constructed with boron-loaded walls having a very low return. A scintillation and He-3-based detector has been constructed as a new methodology for higher-energy neutron spectra.

Neutron imaging is another important service provided by the group. It has wide application, in industry particularly; new technologies such as fuel-cell and battery development need it. In the imaging program there are opportunities for new advances in technology, and NIST is an international leader in this area. Phase-contrast methods are used for high-definition density measurement. A unique new instrument that uses Wolter optics to obtain micrometer spatial resolution is under construction and in limited operation; full capability will be in operation by 2018.

The Neutron Physics Group, in cooperation with external collaborators, has been successful in obtaining DOE support for a strong program in fundamental physics. Within the constraints of its limited budget, the Neutron Physics Group has managed to develop new technology in support of the core program—for example, a scintillator-proportional counter array for the measurement of high-energy neutron spectra such as cosmic-ray secondaries.

Radioactivity Group

The work of the Radioactivity Group appears to be largely in services rather than innovative research. The group has a list of potential research projects that can be pursued if funding is available.

Some of the recent accomplishments of the Radioactivity Group include maintaining continuous standardization of approximately 30 distinct radionuclides as primary standards linked to nuclear medicine. A suitable standard for accurate measure of the alpha emitter radium-223, a recently introduced therapeutic radionuclide for prostate cancer treatment, is under development. The group is collaborating with professional societies such as the AAPM in the development and publication of ^{90}Y protocols for radiation brachytherapy. The group's new measurement of the half-life of ^{209}Po has resulted in substantial revision of the accepted half-life.

Dose calibrators are used in nuclear medicine tens of thousands of times each day in the United States, and they depend on NIST-determined calibration factors for more than 20 different radionuclides. Some recent examples include ^{18}F, ^{68}Ge, ^{111}In, ^{123}I, ^{125}I, ^{133}Ba, ^{177}Lu, and, as mentioned, ^{223}Ra. Future work focuses on ^{64}Cu and ^{227}Th.

The quality of the work by the Radioactivity Group is excellent. They demonstrated competence in maintaining existing radionuclide standards and in developing new ones identified by the user community. In addition, as part of a grant from the DHS, they have developed key nuclear forensic standards to be used for investigations of stolen radioactive materials destined for use in radiologic devices such as dirty bombs.

PORTFOLIO OF SCIENTIFIC EXPERTISE

Most of the counting equipment is state-of-the-art, and the specialized expertise of the staff is related to the unique experience needed to maintain the standards. Positions of staff members and technicians in the Radioactivity Group who have resigned or retired recently were either filled or reprogrammed. However, if these actions have not resulted in a sufficient number of technicians, this creates an undesirable situation whereby Ph.D.-level staff are required to perform routine sample preparation, including weighing and pipetting of radioactive solutions, packaging, and shipment. The time of these highly trained and dedicated individuals would be better utilized for research into state-of-the-art issues such as radioactivity metrology and dissemination of knowledge on proper use of modern equipment for accurate assay.

Some of the unique equipment can be operated optimally only by a highly expert single individual, and there is relatively little time to train more junior staff in the proper use of certain specialized equipment and counting devices. A stronger training program that involves students and postdoctoral researchers in each of the critical standards activities would help fill the personnel gap that now exists, and it would provide intelligent, willing workers who learn on the job in the unique NIST environment. Another area to explore could be alliances with medical physics training programs at regional universities, to provide internships of varying length that would be sponsored through NIST internal resources. Budget plans that project the expansion of such programs could be considered for the future.

Management can further encourage the pursuit of cutting-edge radioactivity research projects with external funding from DHS, NIH, DOE, and private-sector industry. An example would be the development of positron emission tomography (PET) and computed tomography (CT) and PET/MRI devices in Gaithersburg as part of a secondary standards laboratory devoted to nuclear medicine quantitation. One element of this is the growing emphasis on the theranostics, in which the same radionuclide may be used at the tracer level for dosimetry and detection and, by scaling up to radiotherapeutic doses, could be used for therapy. There will be important standardization issues in the radioactivity measurement as well as tissue dosimetry as the range of dose is expanded over orders of magnitude. A strong presence in this field of the experienced NIST metrology experts would likely give U.S. industry and medicine an important competitive advantage.

Strategic projects that align closely with the priority areas of the PML—in particular, medical imaging—would seem to be a natural component of such an approach, and there is already a good basis for this in terms of expertise and facilities. Enhanced research in areas of collaboration where NIST excels, such as advanced computing (for example, in Monte Carlo simulations), would augment existing capabilities in radiation measurement and detection.

ADEQUACY OF FACILITIES, EQUIPMENT, AND HUMAN RESOURCES

Most of the equipment is state-of-the-art, and staff expertise is related to unique experience needed to maintain the standards. However, in the laboratories of Building 245, where most of the radionuclide standards are prepared for shipment, the rooms are old and lacking in proper heating and ventilation, with consequent inadequate control of humidity and temperature. Neutron source standardization is carried out in a number of shielded, below-grade laboratories in Building 245. Water intrusion during heavy rains has become an issue, because the building is no longer watertight. These events are, at a minimum, distractions to overburdened scientists and in some cases have threatened to flood sources under test. Dispersal of the source material is remotely possible, but the immediate concern is damage and loss of calibration traceability. Repair and renovation of building 245 are urgently needed. These conditions, along with the requirement for researchers to perform technician chores due to a lack of manpower and technical support, are severely compromising the ability of the staff to perform key tasks. The neutron metrology staff has decreased in number to a level causing concern, and efforts are needed to add technical support in this area.

The resilience of the core program against the loss of a single individual is no longer assured. Many core activities are supported by a single scientist, without the assistance of a technician. Scientists are spending time on functions that are inappropriate and wasteful for highly qualified personnel. They must handle packing and shipping, compliance issues, contract generation, purchasing, and budget analysis. This is having an increasingly corrosive effect on the entire core metrology function in the division, and especially on the neutron physics program.

The fundamental neutron research program has a high profile in the U.S. nuclear physics program, as delineated in the long-range plans periodically released under the auspices of DOE and NSF, most recently in 2015. This profile has allowed NIST to recruit outstanding talent for the neutron program. These individuals are also responsible for the neutron metrology services, and they carry them out with the same goal of leadership and excellence.

Nuclear medicine is more and more reliant on a combination (fusion) of instruments whereby a CT scanner and a positron emission tomograph are combined into a single gantry for imaging use. This approach to nuclear medicine is essentially quantitative; accuracy and precision of measurement would be greatly benefited by involvement of the Radioactivity Group in developing standardized phantoms and appropriate radioactivity standards. As part of the future relevance of NIST to medical practice, a PET/CT scanner was purchased and installed in the Radioactivity Group. Unfortunately, funding was insufficient for a proper maintenance contract, and at the time of this review, the PET/CT had been out of action for several weeks. Attention to proper maintenance and support for such a valuable program is important. Management could further encourage conjoint programs to share equipment and facilities with users at national laboratories and universities, to enlist whenever possible outside facilities to bolster the NIST mission.

The positions of staff members in the Dosimetry Group who have retired recently have been filled or reprogrammed. However, some of the critical standards for diagnostic x rays, Cs-137/Co-60, and high-dose industrial applications are maintained by a single staff member. At least one critical staff member is close to retirement, and if the position is not filled with a qualified individual, the quality of the program will suffer.

DISSEMINATION OF OUTPUTS

Members of the Dosimetry Group are active in various professional societies—for example, the AAPM, the American National Standards Institute (ANSI), and the Health Physics Society (HPS)—which helps to disseminate the work at NIST. The group also interacts with CIRMS, DOE, and the FDA. Members of the Dosimetry Group also publish in journals The group supports three AAPM-accredited dosimetry calibration laboratories as well as other secondary calibration laboratories through its calibration services.

For the Neutron Physics Group, the program output is disseminated in many ways and is effective. In addition to published research papers and conference presentations, the calibrations and the distribution of standard reference materials are universally recognizable products. Many guest researchers come to NIST to take part in the fundamental neutron physics program and to collaborate with personnel in the Radiation Physics Division. There is also abundant cross-fertilization between disciplines because so many disparate sciences are practiced at the NCNR. An example is the development of the small-angle neutron scattering (SANS) device at the NCNR, with polarized neutrons for the study of magnetic ordering in materials. A major step toward this new capability came from the helium-3 polarizers and analyzers first devised for fundamental neutron physics by an RPD scientist.

The Radioactivity Group does an excellent job in disseminating its work through interactions with CIRMS, AAPM, SNMMI, DOE and FDA and in providing calibration standards for many common radionuclides used in nuclear medicine. In some cases they interact with groups who provide a secondary standard service that is traceable back to NIST. The advantage of this approach is that a very a large demand for radioactivity measurement standards can be met by expanding through secondary standards that will still relate to the NIST-prepared primary standards.

Members of the Radioactivity Group are active in various professional societies such as AAPM, SNMMI, and HPS, which helps disseminate the work of NIST, and they also publish journal papers. These services include the dissemination of technical reports such as Technical report series 454, *Quality Assurance for Radioactivity Measurement in Nuclear Medicine.*

Unfortunately, there are examples where dissemination of proper radioactivity standards has not been able to proceed as rapidly as required owing to a lack of funds. Because medical imaging and nuclear medicine increasingly depend on short-lived radionuclides such as F-18 (110-minute half-life) or C-11 (20-minute half-life) there is recognition that specialized and accurately calibrated detection devices need to be sent between institutions in the United States to serve as the standard of measurement, since it is physically impossible to ship the radionuclides themselves.

One such device uses the triple-to-double coincidence ratio (TDCR) method. As explained on the website of the Laboratoire National Henri Becquerel,[2]

> . . . TDCR is an absolute activity measurement method specially developed for pure beta- and pure EC-emitters activity determination, in which the detection efficiency is calculated from a physical and statistical model of the photon distribution emitted by the scintillating source. As the signals delivered by the photodetectors are affected by the thermal noise of the photocathode, a coincidence method is used to remove that noise. There is not enough information in a two-photodetector system to determine the experimental detection efficiency without an additional reference source. The TDCR method uses a three-photomultiplier detector, allowing the observation of 3 kinds of double coincidences (2 photodetectors) and triple coincidences (3 photodetectors).

The Portable TDCR is a portable version of one of the primary measurement systems for activity measurements of beta emitters, positron emitters, and electron-capture decay radionuclides. There is concern that, because of the lack of manpower for calibration and testing of these TDCR devices at NIST within the Radioactivity group, U.S. hospitals have difficulty taking proper advantage of these specialized devices for on-site measurement to establish proper radioactivity standards. Meanwhile, foreign standards laboratories such as the Physikalisch-Technische Bundesanstalt (PTB), the European Association of Nuclear Medicine (EANM), and others, funded through a European Union investment in metrology, have working instruments.

8

Sensor Science Division

INTRODUCTION

The Sensor Science Division (SSD) of the PML conducts an extremely broad set of technical activities. The division creates and produces devices and articles as primary and secondary standards for dissemination, creates standards, and does fundamental science in a diverse set of technical fields. These fields include optical, temperature, and pressure measurement, as well as imaging and flow. Size scales range from a few atom widths to many meters and system complexity ranges from photonic devices to satellites and smokestacks. The division comprises a division office (6 staff and 3 associates), overseeing the work of six groups: Thermodynamic Metrology (16 staff and 3 associates), Fluid Metrology (10 staff and 1 associate), Optical Radiation (16 staff and 3 associates), Infrared Technology (10 staff and 9 associates), Laser Applications (9 staff and 1 associate), and Ultraviolet Radiation (10 staff and 1 associate). However, the review of the division was conducted along the lines of programs, as carried out in various facilities. The high degree of collaboration within the division results in the fact that a given program is almost always supported by staff from more than one group; however, it was not always clear which groups, and how many staff from each, supported each program. The panel therefore conducted its assessment on the basis of the facilities it had the opportunity to observe, and the thematically coherent programs conducted within them, rather than attempting to assess the groups themselves.

ASSESSMENT OF TECHNICAL PROGRAMS

Vision Science Laboratory

The research work presented in the vision science laboratory is mature, and its results are ready to be introduced as a worldwide standard. The team working in this area is exploring solid-state lighting from a psychological point of view. The results of this study are important because they will impact the replacement rate of incandescent lighting. Lighting comprises a significant fraction of the nation's total electricity usage, and solid-state lighting has the potential to reduce electricity usage for lighting by a factor of 10 or more. One big difference between incandescent and solid-state lighting is the ability to control the color of the light. Currently, solid-state lighting is specified by the light output (lumens) and the color temperature. The vision science team has added a third factor, chromaticity or tint, and has found that people prefer a pinkish tint. The desired tint depends to some extent on the cultural background of the subject. This finding is likely to broaden the appeal of solid-state lighting, accelerating the transition, saving energy, and reducing CO_2 emissions.

Optical Properties of Materials and Spectroradiometry

The research in the areas of optical properties of materials and spectroradiometry appears to involve excellent personnel and equipment with accuracy over a prodigious spectral range from 4 nm to 100 µm. This team conducts a significant portion of the division's measurements for customers and has a wide and deep outreach program, participating in standards organizations, training personnel from other national measurement laboratories (NMLs), conducting short courses, performing phantom development, and generating publications.

The reflection measurements are being automated to save customers time and money and to reduce the workload of highly trained personnel, allowing them to pursue more creative activities.

The reflection measurements were not conducted or stored in a clean and dry area. This could be acceptable if it were an experimental setup or if the measurements did not require the accuracy of samples free of a small amount of dust.

Photonic Sensors and Standards

An overarching theme at the division is the development and deployment of NIST-traceable measurements and standards that are reliably produced in low size, weight, and power (low-SWaP); low-cost (low enough to enable broad customer deployment, or even embedded applications), integrated packages producing one or more measurements. At an institutional level, this initiative is known as NIST-on-a-Chip, where the overall goal is to develop and deploy SI-traceable measurements and physical standards that are deployed in the customer's environment. The desired attributes are usability (small size, low power, rugged, easily integrated and operated); flexibility (broad range of SI-traceable standards, possibly including a few to many measurements from an single small and affordable package); and manufacturable (low cost for broad deployment or acceptable cost for high-value applications). Within the SSD, there are numerous examples of this theme in development. An example of particular significance is the development of a dynamic pressure standard based on wavelength modulation spectroscopy. Two significant aspects of this project are these: (1) dynamic pressure measurements are particularly difficult and inaccurate using current approaches, most of which are designed to measure static, or slowly varying pressures, so that some important, highly dynamic situations, such as shocks, are measured with significant inaccuracy; and (2) there are many extremely important application areas that require relatively inexpensive, broadly deployed (or especially embedded) measurement systems. A prominent example with both high economic and policy impact is the phenomenon of traumatic brain injury occurring in sports and in military combat. The potential for sensors in this context is recognized by the PML, and that application is guiding some aspects of the current program. As the research progresses, it will be important to assure that measurement of acceleration and "jerk "(the third derivative of distance with respect to time) is being considered, with the objective of developing an integrated accelerometer/dynamic pressure sensor.

Low-Background Infrared Facility

The low-background infrared (LBIR) facility specializes in low-power infrared measurements with wavelengths from 2 to 30 µm, and it does so at a physical scale sufficient to test actual sensors used in astrophysics and missile defense. The LBIR receives significant support from the Missile Defense Agency (MDA) and is used extensively by some of the MDA's major contractors. The NIST traceability of radiometric measurements is one of the singularly defensible (technically) aspects of MDA's programs of record, which have undergone significant programmatic upheavals.

The LBIR's strong customer focus leads to several issues and uncertainties concerning its future. The underlying research program, focusing on high-sensitivity electrical substitution radiometers, solid-state trap detectors, fluid bath cryogenic vacuum blackbody sources, and carbon nanotube sources and detectors, does not seem as closely coupled to customer needs; evidence of such coupling was not presented during the assessment. The LBIR needs to ensure that one of the MDA contractors, Johns Hopkins University (JHU) Applied Physics Laboratory, is not essentially duplicating the NIST capability. The extreme politicization of missile defense over the past 6 years makes the MDA program highly unstable and has led in the recent past to significant management and programmatic upheavals. The LBIR needs to undertake scenario-based planning to seek a broader customer base, aligning the research program to the needs of other customers, such as the National Aeronautics and Space Administration (NASA) and to minimize disruption that might occur with a significant, unpredictable change in MDA support.

SIRCUS/Satellite Sensor Calibration/Ocean Color/Space Weather

This program and its primary facility, the spectral irradiance and radiance responsivity calibrations using uniform sources (SIRCUS) facility, underpin optical metrology in terms of power, irradiance, and radiance for a broad range of important measurement systems with high operational and scientific significance, such as weather satellites, land and ocean color sensing, stratospheric aerosols, Earth's radiation budget, and corresponding ground truth artifacts. The range of customers is impressive: NASA, NOAA, the National Geospatial-Intelligence Agency (NGA), and the Department of Defense (DoD).

Given the ever-increasing importance of hyperspectral measurements and imaging, the increasing emphasis of SIRCUS on calibration methods and standards for such systems is admirable.

One possible caution concerns the increasing emphasis on lower-cost, lower-SWaP sensors for future satellite systems, following the National Polar-orbiting Operational Environmental Satellite System (NPOESS) programmatic debacle, and the later cancellation of the DoD-focused Defense Weather Satellite System (DWSS). The SIRCUS team could explore (and perhaps partner in development of smaller radiometric sensor systems for satellites. It is possible that the upcoming NASA preaerosol, clouds, and ocean ecosystem (PACE) mission, if awarded competitively, could provide an opportunity for disruptive developments in radiometers that would effectively displace the Visible Infrared Imaging Radiometer Suite (VIIRS). At a minimum, the division could prepare to calibrate much smaller radiometers for its customers.

Pressure and Vacuum Measurement Program

These efforts are important and will particularly impact semiconductor manufacturing, where molecular-level control of pure environments is critical. Photonics measurement will replace, among other measurement methods, a 3-m mercury column and will enable a route to faster measurement that can be more easily deployed to a field environment by means of handheld devices usable at room temperature. This effort to integrate the standard and the sensor is consistent with the priorities of NIST-on-a-Chip. There are also significant efforts to automate calibration and testing to improve service for customers, including reduced turnaround time and lower cost.

Members of the team are amongst the best in the world in their activities to reinvent pressure measurement, having won several awards within their communities, published papers, and pursued numerous patents. Overall, the efforts of this program are commendable and on a good trajectory.

Fluid and Flow Metrology

This program has provided best-in-the-world capability to realize flow measurement over 11 decades for gas flow and 5 decades for liquid flow. The team has won several awards and honors recently for its efforts in these areas. A notable effort is the characterization of hydrogen flowmeters for high-pressure refueling of hydrogen-powered vehicles with reduced uncertainty and rapid response times. A portable field test standard has been developed for use at refueling stations. This work is impressive and important as the world seeks alternatives to fossil fuels. Other flow metrology efforts include use of microwave resonances to measure large volumes and efforts to develop methods for measuring microscale flows.

Acknowledging the challenge of quantifying small-scale flows, it would be worthwhile for the team to continue developing other noninvasive and in-line ways to determine microflows that can be readily integrated into devices. The development of measurement methods for multiphase flows is also worthwhile. These are challenging areas that are becoming increasingly important with the growth and use of hydraulic fracturing methods.

Smokestack Simulator Laboratory

As the world places a higher cost on emissions of CO_2 from coal-burning power plants, the need for more accurate measurement of these emissions increases. In response to this need, a new, first-in the-world, 1:10 scale model of a swirling smokestack is being built and tested. The challenges lie in the very rapid, turbulent, 3D, swirling nature of flows in smokestacks, and in the need to accurately measure transport of CO_2 within this type of flow, in very harsh environments. The PML is at the forefront in developing tools and calibrations to address these needs, emphasizing accurate, systematic, and appropriate use of long-wavelength acoustic flowmeters. Though still in early stages, these efforts are excellent and hold significant promise for aiding national efforts to limit environmental release of greenhouse gases.

Synchrotron Ultraviolet Radiation Facility

The Synchrotron Ultraviolet Radiation Facility (SURF III) is a nationally unique facility providing NIST traceability for (most) solar-observing and space sensors operating in the UV and extreme UV part of the spectrum. These instruments underpin the current understanding of solar variability and its potential contribution to global climate change. SURF III also underpins the current understanding of parts of space weather, and its potential impact on critical national and international infrastructure in space. Its customer set includes NASA, NOAA, and the DoD. The facility is under active development to provide NIST-traceable irradiance measurements from 2 nm to 500 nm with less than 1 percent absolute uncertainty (current capability is 4 to 400 nm). The facility also calibrates approximately 25 photodiodes per year to disseminate the radiometric scale over SURF's spectral regime.

The quality of the work done at SURF supports broad international collaboration, despite the relative decrepitude of the radiation physics building (building 245). Notwithstanding the challenges of operating in this building, this was the one facility within the SSD that was not meeting the standards for neatness and order that characterized the rest of the facilities visited; this building needs attention.

Conclusion

The division's general strategy of moving metrology from pristine laboratory contexts to more complicated real-world environments associated with applications is commendable. The division appears well coupled to the communities it serves and strives to solve their problems with the goal of better, safer, and more useful products. The emphasis on low-cost, portable, photonic, and potentially embedded standards is particularly relevant and consistent with the theme NIST-on-a-Chip.

While the overarching strategy was well articulated, the division did not describe plans for some of the projects, particularly those that are funded externally; those working on internally funded initiatives seemed to have more concrete plans.

PORTFOLIO OF SCIENTIFIC EXPERTISE

The SSD is a large division created several years ago by combining a number of disparate activities with multiple areas of expertise and capabilities. The division is now synergistically very productive; this is a testament to good management. It is a division of outstanding and very capable people who cover a large spectrum of technology and science.

Despite the impressive breadth of technical areas, the SSD appears to be leaders in all their activities, in measurement and, in many cases, the underlying science. They participate in and lead national and international standards committees in their fields of interest, and they have generated numerous publications and patents. Many of the world's other leading standards laboratories send staff to be trained at this division and ask for their staff to visit and transfer technology. The division is asked for help by many leading organizations with exacting requirements for measurement accuracy such as NASA, DOE, and DoD laboratories.

The staff seemed very knowledgeable in the domains related to their activities, in terms of their specific work and in terms of worldwide scientific and technological developments. Many of the staff are leaders in their fields. There is a general expectation of excellence and objectivity and very good alignment with the public service mission of NIST. The division conducts a large fraction of the NIST calibrations and dissemination of secondary standards, but staff expressed little objection to doing routine measurements or supplying multiple samples. In fact, members of the division expressed pride in the number of samples they produced and expressed desire to find ways to make them cheaper and to find ways to automate the measurements for faster and better service.

The division did not describe a strategy for maintaining its spectrum of excellence and diversity (age, gender, ethnicity, and expertise) of human capital to maintain the division's preeminence over the long term. Flat funding exacerbates this problem, but addressing the problem is very important and worthy of effort and a definitive plan. In particular, the presumption that a practical solution will be achieved by a likely delay in senior staff retirement is neither constructive nor forward-looking, even if that pattern is based on experience. Very few people maintain high creativity for decades, and simply delimiting the desired spectrum of staff attributes by length of experience seems to fall short of desired management principles in an institution with a critical mission.

ADEQUACY OF FACILITIES, EQUIPMENT, AND HUMAN RESOURCES

The division appears to have excellent facilities, and the work spaces are generally well maintained. The one exception was the SURF area. Division management acknowledged that this building needs a refurbishment, but much can be done to improve the situation in the short term with a clean-up and attention to making the area safer.

Quality Management System in the Sensor Science Division

Support of the QMS in the Sensor Science Division is viewed as supportive of the overall PML mission, and not a system populated by checkers. The PML is to be congratulated on this approach. The

NIST PML mission of maintaining and improving the U.S. (and, through consultative committees, the international) SI system of physical measurements requires exacting standards and the implementation of quality control throughout its divisions. The standing of the PML as gauged by international comparisons, customer feedback, and interaction with stakeholders speaks to the effectiveness of the overall quality management system (QMS). It appears that the QMS is implemented in a way that maximizes efficiency and minimizes staff requirements. In other contexts, including those of the International Organization for Standardization (ISO) and national standard regimes, such as AS9100, quality assurance is envisioned as requiring a completely parallel staff system, which is frequently viewed by customer-facing staff as redundant, threatening, and contributing to overhead. The PML apparently implements its QMS using staff who themselves have customer-facing and customer-supporting responsibilities This leads to a constructive team dynamic and endows the staff implementing the QMS with moral authority when inevitable problems arise. QMS in the Sensor Science Division is viewed as supportive of the PML mission and not a system populated by checkers. The PML is to be congratulated on this approach.

9

Time and Frequency Division

INTRODUCTION

The Time and Frequency Division (TFD) is located in Boulder, Colorado. The division consists of approximately 125 technical personnel, including federal employees and NIST associates. The majority of the staff works on the NIST Boulder campus. One TFD staff member has an appointments in both the Time and Frequency Division and the Quantum Physics Division. The TFD carries out an extensive technical program in virtually all areas of time and frequency. While the majority of division funding comes directly from the NIST appropriation, a significant amount of its support is received from the DoD and members of the national intelligence community. The breadth, depth, and impact of this program are unmatched by any similar foreign metrology organization.

ASSESSMENT OF TECHNICAL PROGRAMS

The current TFD technical program is well aligned with the strategic goals of the organization. These goals have three interrelated components: realization of the official U.S. time scale (Atomic Standards Group), dissemination of time and frequency information (Time and Frequency Services Group), and conduct of the research that underpins the quality of products today and ensures advances of these products in the future (Ion Storage, Optical Frequency Measurements, and Atomic Devices and Instrumentation groups) This is a solid strategic approach. Its results have produced state-of-the-art time and frequency products today with a firm foundation for future improvements in place. The TFD effort expended in developing and addressing a strategic perspective is in keeping with recommendations provided by the 2010 National Research Council review of the NIST Physics Laboratory.[1] The recommendation calling for more thorough strategic planning has been addressed in an excellent manner by the TFD.

The quality of TFD products employed in realizing official U.S. time and frequency is outstanding. Central to this is the national frequency standard NIST-F2. This standard, based on a cesium atom hyperfine transition, is internationally recognized as the most precise and accurate national standard[2] in the world. Consistent with a technical program that addresses current and future time and frequency needs, NIST-F2 is the cryogenic extension of the NIST-F1 standard. The latter standard was the first United States standard to employ cold atoms in a cesium fountain, while NIST-F2 now places the microwave interaction region in a cryogenic environment, dramatically reducing the frequency uncertainties resulting from the blackbody radiation of the standard housing. The TFD accomplishment of developing the cryogenic, cesium fountain clock as the national standard of the United States has improved national and international timekeeping.

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[1] National Research Council, 2010, *Assessment of the National Institute of Standards and Technology Physics Laboratory: Fiscal Year 2010*, The National Academies Press, Washington, D.C., Chapter 1.

[2] T.P. Heavner, E.A. Donley, F. Levi, G. Costanzo, T.E. Parker, J.H. Shirley, N. Ashby, S.E. Barlow, and S.R. Jefferts, 2014, First accuracy evaluation of NIST-F2, *Metrologia* 51(174).

The actual U.S. timescale is maintained by an ensemble of about 10 hydrogen masers whose frequencies are periodically steered by NIST-F2 and NIST-F1. This information is a major contributor to coordinated universal time (UTC), the international time scale maintained by the BIPM,[3] the French equivalent of NIST. Complementing the time scale is the exceptional progress the TFD has shown in the development of ultrastable radio-frequency (RF)/microwave signals. Employing laser comb signals, TFD laboratories have improved the stability of microwave signals from 100 to 10,000 beyond that obtained from other methods of generation. This is reflective of a technical program producing products of the highest quality.

The TFD has accomplished its goal of disseminating its time and frequency information in an exemplary manner. The TFD is a major contributor to national and international time scales. Beyond this, the TFD actively distributes its expertise domestically and internationally, providing training opportunities to guest researchers, maintaining a strong commitment to publication and conference participation, and conducting a variety of instructional events.

Underlying time scale maintenance and dissemination is the research portion of the TFD technical program. The program seeks to advance the state of the art to meet the needs of stakeholders in the future and to improve the quality of current time and frequency products. An example of applied research improving products in the near term is the effort to operate a new primary frequency standard (such as NIST-F1 or -F2) in a nearly continuous manner. This new approach to maintaining a time scale allows a single-hydrogen maser to be almost continuously steered by the primary standard, replacing the 10-maser ensemble that is only periodically adjusted by information from NIST-F2. The result will be a more stable time scale realized in a more cost-effective manner.

Looking further into the future, TFD laboratories are exploring new standards based on optical transitions. With operating frequencies approximately 100,000 greater than those of microwave transition standards, optical standards are already orders of magnitude more stable and accurate than their microwave analogs. The new generation of standards can be divided into two general categories based on atoms and ions. The atomic standard being investigated employs optical transitions in ytterbium (Yb) atoms. Currently the TFD Yb standard is the most stable in the world. Its stability is on the order of 2×10^{-18}. This can be compared to the accuracy and ultimate stability of NIST-F2, whose accuracy reaches approximately 1×10^{-16}. The ion standards employ either single mercury (Hg) or aluminum (Al) ions held in electromagnetic traps. Again, these devices have accuracies in the upper 10^{-18} range. The TFD research into trapped ion standards improved the performance of these devices and provided a foundation for significant accomplishments in the area of QI and processing. Evidence of the significance of accomplishments in this area is the Nobel prize awarded to David Wineland, a TFD staff member. A further accomplishment of the research effort is the recognition and demonstration that combining optical standards with optical frequency combs allows relating their frequencies in an extremely precise manner to lower, electronically accessible values that are more easily manipulated. The research aspects of the TFB technical program are also at the state of the art internationally.

Members of the TFD continue to work at the forefront of optical frequency combs. One area of particular accomplishment focuses on generation of microwave signals with ultralow phase noise and timing jitter through photodetection of optical frequency combs. In this so-called optical frequency division process, the already low optical phase noise associated with individual comb lines that are referenced to ultrastable resonators and atomic frequency references is divided down by the ratio of the optical to microwave frequency. Through optical frequency division TFD scientists have now demonstrated generation of 10-GHz microwave signals with the best low-frequency phase noise ever reported, substantially below what is available with the best electronic oscillators. This work is pushing technological performance and is advancing scientific understanding. One notable example involves the understanding of shot noise, a fundamental noise process in photodetection that arises because photons arrive as discrete and randomly spaced energy packets. A standard expression for shot noise has been

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[3] Bureau International des Poids et Mesures, Time Department, “Staff of the BIPM Time Department,” http://www.bipm.org/en/bipm/tai/members.html, accessed September 14, 2015.

known for decades and is widely applied. TFD researchers showed that when short pulse laser sources such as those from optical frequency combs are used for microwave generation, the standard shot noise formula associated with continuous-wave laser excitation is modified, allowing generation of microwave signals with phase noise and timing jitter below the limit that the conventional shot noise formula would predict.

Another notable area of accomplishment within the last 5 years is in the generation of optical frequency combs through nonlinear wave mixing in optical microresonators. Such microcombs offer dramatic size reduction compared to frequency combs derived from mode-locked lasers, thereby opening the possibility of applications beyond specialized laboratory settings. TFD researchers have developed new methods for fabricating high-quality-factor optical microresonators at low cost and high speed and have used these microresonators as a platform for investigating comb generation physics and noise processes. The TFD is among about a half dozen of the most active and visible groups worldwide, and it is at or very near the top of this group in terms of application of microcombs for optical metrology and low-phase-noise signal generation. The TFD accomplishments in optical frequency division for low-phase-noise microwave generation and in microcombs have attracted a series of grants from other government agencies.

There are also interactions with companies that want to commercialize the compact Ca clock developed at the TFD. This system would serve as an ultrastable microwave source for a variety of applications, including very long baseline telescopes and radar detection of slow-moving objects. Clock-based relativistic geodesy is an intriguing possibility that challenges contemporary physics to find applications where gravitational potential is the critical quantity.

TFD activities on chip-scale atomic clocks, which originated a little more than a decade ago under funding from the Defense Advanced Research Projects Agency (DARPA), are a major success story. By employing modern microfabrication techniques and miniature lasers, the NIST group was the first to realize an atomic clock at chip scale. This effort was relatively new at the time of its inception but has now grown into a subject pursued by many groups worldwide. A commercial version of the chip-scale atomic clock was introduced in 2011 by a U.S. company, Symmetricon (now Microsemi), and is being used for applications with modest timing requirements (modest in comparison to NIST's state-of-the-art frequency standards) such as telecommunications networks, GPS receivers, and seismic exploration. The development of the chip-scale atomic clock has impact from both a research and a dissemination perspective.

The frontier of trapped ion physics and technology is defined by Wineland's Ion Storage Group in the TFD. Indeed, the early days of atomic cooling were pioneered by, for example, Wineland and nearly simultaneously by Dehmelt at the University of Washington. They pioneered various aspects of laser cooling of atoms, and they are theoretically and experimentally showing how the kinetic energy of a collection of resonant absorbers can be reduced by irradiating these absorbers with near-resonant electromagnetic radiation. Their process is closely related to anti-Stokes spontaneous Raman scattering. At present the use of ion traps is ubiquitous in many areas of physics, including quantum computers and atom-field matter interactions.

Over the last few years, work on chip-scale atomic sensors has been broadened to include other sensing applications. In one example, TFD researchers demonstrated the first chip-scale magnetometer. This device, which operates near room temperature, achieved performance equivalent to that of SQUID, which requires cooling to below 1 K. TFD scientists partnered with medical researchers to demonstrate sensing of weak biomagnetic fields, enabling, for example, precision measurements of fetal heart activity without the need to implant electrodes. New programs aimed at using atomic sensors for sensing of other fundamental quantities (for example. length and temperature) are now under way as part of the NIST-on-a-Chip initiative.

The dramatic progress in laboratory demonstrations of optical clocks, both in the TFD and in the Quantum Physics Division, brings them to the point where they demonstrate world-record stability of 2×10^{-18}, nearly two orders of magnitude better than the NIST-F2 cesium clock (currently at $\sim 1 \times 10^{-16}$ accuracy). Several different matter systems for optical clocks are being explored (for example, various ions in the TFD Ion Storage Group, Yb atoms in the TFD Optical Frequency Measurements Group, and Sr atoms in the Quantum Physics Division at JILA). Optical clock technology shows promise to take over as the new primary frequency standard in the years ahead. The opportunity and challenges confronting NIST researchers and researchers worldwide is to continue this progress, to develop optical clocks to the maturity needed, and to chart the evolution of optical clock technology to become a primary standard.

The performance of the best optical clocks is now at a level where even minute changes in the gravitational field, such as those associated with a few centimeters change in elevation, become observable. On the one hand, this brings new opportunities for applying such clocks to sensing. On the other hand, it raises the question whether optical clocks are nearing their accuracy limit, since with further improvements they may become dominated by the local microgravitational environment.

TFD research related to the NIST-on-a-Chip initiative appears to center on incorporation of multiple atomic sensors, such as those introduced in the previous, highly successful chip-scale atomic clock work, interconnected via on-chip waveguides with in-plane light propagation. The general idea of scaling to a larger number of sensors and exploiting waveguide photonics to enable more sophisticated device architectures is appealing. Further development of their roadmap for this work will be beneficial.

PORTFOLIO OF SCIENTIFIC EXPERTISE

The scientific and technical expertise resident in the TFD is outstanding. Developing this internationally recognized level of excellence is a significant accomplishment of the TFD. The achievements outlined in the preceding section result directly from the excellence of the scientific expertise resident in the division. This excellence is further confirmed by the numerous awards TFD staff members have received, including a 2012 Nobel prize in physics. Additionally, TFD staff members have received multiple external awards, such as the Benjamin Franklin Medal from the Franklin Institute, the Rank Foundation Prize, the IEEE Sensor Technical Achievement Award for chip-scale devices, the IEEE Rabi Awards for time-scale establishment and oscillator development, and the National Conference of Standards Laboratories International (NCSLI) Wildhack Award for remote time-measurement services. Staff members have also received many NIST and DOC awards. These include multiple Arthur S. Flemming Awards, Gold and Silver and Bronze DOC awards, and NIST's Rabinow, Condon, and Slichter awards. The award subjects span a wide variety of TFD areas of investigation and effort. Within NIST a prestigious position is that of fellow, a rank achieved by only 2 percent of staff members. While the TFD represents 2 percent of the NIST technical staff, fellows within the TFD comprise 10 percent of the NIST population of Fellows.

The TFD scientific expertise evident during the review was primarily of an experimental nature. One consideration is whether the theoretical expertise actually resident within the TFD is sufficient to support the experimental efforts into the future. As stabilities and accuracies of frequency standards continue to improve, strong theoretical support will be required. Of course, NIST staff does collaborate closely with staff of JILA, where theoretical expertise resides. The adequacy of this expertise and ensuring continuing close interaction deserves ongoing attention.

With the current excellence of TFD scientific expertise comes the challenge of maintaining the same high level into the future. This will require ongoing effort on the part of NIST researchers and management. Not surprisingly, many current junior staff members have outstanding qualifications. Confirming this are the multiple forms of recognition already received. Examples include the International Union of Pure and Applied Physics (IUPAP), the Young Scientist Award, European Frequency and Time Forum Young Scientist Awards, and the Humboldt Foundation's Fyodor Lynen Research Fellowship. This bodes well for ongoing excellence of the scientific expertise within the TFD.

ADEQUACY OF FACILITIES, EQUIPMENT, AND HUMAN RESOURCES

Most of the buildings on the NIST Boulder campus are about 60 years old. These older buildings do not provide the environmental controls (for example, temperature and humidity) necessary for modern precision measurement central to the TFD mission. The new precision measurement laboratory building, which was completed in 2012, represents a major improvement. The laboratories visited are well equipped. Such performance improvements in physical facility are essential to the division's ability to maintain its scientific leadership. Challenges associated with shortage of meeting and collaboration space have also been voiced by TFD staff.

The unique facilities associated with the TFD provide remarkable synergy, enabling research that could be accomplished at few other institutions. As one example, research of optical frequency combs can draw on cold atom and ion frequency standards programs and use these highly stabilized frequency references for stabilization of the comb. Optical frequency comb research can also access maser signals associated with the U.S. primary clock for stabilization or measurement of the comb repetition rate. Conversely, the highly stabilized comb enables comparison of optical clocks based on different matter systems.

Of approximately 130 TFD personnel, 42 percent were NIST permanent employees. The remaining 58 percent were guest researchers, consisting of graduate students, postdoctoral researchers, contractors, and foreign visitors. A benefit of the large pool of guest researchers is that the division work force is being constantly refreshed. The guest researchers also provide a pool from which permanent hires can be made when openings arise. As noted above, several of the more junior TFD researchers have won awards from external bodies. Such recognitions provide evidence of the TFD's ability to attract excellent new talent to its workforce.

Because of its unique strengths and capabilities, the TFD has enjoyed continued success in attracting funding from other government agencies. This has allowed it to broaden its research portfolio in important ways beyond its core activities. Some of this work has been sufficiently successful that it led to some of the division's highest impact programs—for example, chip-scale atomic clocks, quantum information (QI) processing, and low phase noise signal generation from optical frequency combs.

TFD staff have voiced concerns that there are major institutional challenges associated with administrative processing in accepting funding from other agencies.

Concerns were also raised with respect to an onerous procurement process with substantial delays. Several staff spoke of a high overhead rate on capital equipment; they suggested that this makes acquisition of expensive equipment very difficult.

DISSEMINATION OF OUTPUTS

The products of the TFD program are various and are disseminated in many ways. The division distributes not only scientific expertise and findings but also technologies for measuring and maintaining precise time and frequency; it disseminates internationally as well precise time and frequency information. The dissemination efforts and their resulting impacts are outstanding, meeting the needs of both internal and external stakeholders. While there are opportunities and a limited number of areas of potential improvement, the levels of excellence in all aspects of product dissemination are at the state of the art, displaying international leadership.

The dissemination of scientific expertise and products proceeds along two primary paths. Fifty-eight percent of the division staff is composed of guest researchers, primarily graduate students, postdoctoral fellows, and visiting researchers. The ratio of permanent to guest staff is the result of a strategy that seeks to disseminate scientific expertise to scientists throughout their careers. The ongoing training of nearly 60 researchers in a field as specialized as the measurement and maintenance of extraordinarily precise time and frequency is an accomplishment worthy of note. The scale of such efforts may be compared to those of similar organizations such as BIPM. One of the BIPM's responsibilities is the maintenance of international time through the collection of information from timekeeping institutions around the world. Its time department lists 8 permanent staff members[4] compared to the approximately 50 permanent NIST staff members in the Time and Frequency Division. By inference, the BIPM's outreach through visiting researchers will in no way match that of the TFD.

Beyond direct training, the TFD publishes the results of its scientific investigations regularly, and its staff participates in numerous domestic and international conferences. Over the period 2010 through 2014 the TFD averaged 58 publications per year. In 2014 the BIPM Time Department produced 12 publications.[5] In 2014 also, the time and frequency department of the German equivalent of the NIST, the Physikalisch-Technische Bundesanstalt, produced 5 publications.[6] Similarly, in 2012, the Division of Time and Frequency of the Chinese National Institute for Metrology produced 10 publications.[7] In terms of its publications, the TFD is therefore a unique institution on an international scale.

In the dissemination of time and frequency technology the TFD has excelled in a number of areas. The most accurate primary atomic frequency standard contributing to UTC is the cooled cesium fountain clock, NIST-F2. The scientific and technical excellence embodied in this device set the state of the art in 2009 when it was brought into operation, with continuing improvement through 2014, at which point it became the official primary frequency standard of the United States,[8] along with the continuing NIST-F1. To distribute the unique expertise within this standard, a copy was provided to the Italian National Metrology Laboratory, Istituto Nazionale di Ricerca Metrologica, in 2009.[9] Today this is the second-most-accurate standard contributing to UTC. The research that NIST conducts currently in the field of optical frequency standards will result in the next generation of primary national standards. Eventually this will significantly improve the performance of the UTC time scale. Progress in this area is disseminated through publications and participation in international conferences.

Continuing its efforts related to chip-scale devices, the TFD is applying its expertise related to small gas cell frequency standards to a new generation of extremely compact magnetometers. Such devices have the potential to make laboratory-quality magnetic field measurements available to a broad range of applications in various environments. Progress in this field is conveyed to the international community through publications.[10,11,12] Of particular note is the introduction of such technology to the

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[4] Ibid.

[5] Bureau International des Poids et Mesures, Time Department, Director's Report on the Activity and Management of the International Bureau of Weights and Measures (January 1, 2014–December 31, 2014) Supplement: Time Department, http://www.bipm.org/en/publications/directors-report/, accessed September 14, 2015.

[6] Physikalisch-Technische Bundesanstalt, Time and Frequency Department Publications, http://u99132.bs.ptb.de/cms/de/ptb/fachabteilungen/abt4/fb-44/44-literatur.html, accessed September 14, 2015.

[7] Chinese National Institute of Metrology, Division of Time and Frequency Publication Summary, http://en.nim.ac.cn/ncmc/845, accessed September 14, 2015.

[8] T.P. Heavner, E.A. Donley, F. Levi, G. Costanzo, T.E. Parker, J.H. Shirley, N. Ashby, S.E. Barlow, and S.R. Jefferts, 2014, First accuracy evaluation of NIST-F2, *Metrologia* 51(174).

[9] F. Levi, C. Calosso, D. Calonico, L. Lorini, E. Bertacco, A. Godone, G. Costanzo, B. Mongino, S. Jefferts, T. Heavner, and E. Donley, 2009, "The Cryogenic Fountain ITCsF2," pp. 769-773 in *Frequency Control Symposium, 2009, Joint with the 22nd European Frequency and Time Forum*, IEEE International, doi:10.1109/FREQ.2009.5168289.

[10] R. Jiménez-Martinez, S. Knappe, and J. Kitching, 2014, An optically-modulated zero-field atomic magnetometer with suppressed spin-exchange broadening, *Review of Scientific Instruments* 85:045124.

[11] R. Jiménez-Martinez, D.J. Kennedy, M. Rosenbluh, E.A. Donley, S. Knappe, S.J. Seltzer, H.L. Ring, V.S. Bajaj, and J. Kitching, 2014, Optical hyperpolarization and NMR detection of 129Xe on a microfluidic chip, *Nature Communications* 5:3908.

[12] P.J. Ganssle, H.D. Shin, S.J. Seltzer, V.S. Bajaj, M.P. Ledbetter, D. Budker, S. Knappe, J. Kitching, and A. Pines, 2014, Ultra-low-field NMR relaxation and diffusion measurements using an optical magnetometer, *Angewandte Chemie Internationale Edition* 53(37):9766-9770.

field of medical imaging.[13] This is an example of the TFD disseminating its time and frequency expertise to fields outside its core areas of responsibility. The TFD continues to demonstrate exceptional breadth of expertise in its dissemination.

Another aspect of time and frequency technology is related to the high-precision measurement of the phase noise of electromagnetic signals. The TFD excels at an international level in this field and disseminates its state-of-the-art expertise through numerous publications. For example, a recent article identified a weakness in the accepted means of measuring phase noise. The failure of these measurement techniques under certain conditions can lead to errors in phase noise magnitudes on the order of 20 dB.[14] The TFD engineers are also extending the range of frequencies over which precise phase noise measurements can be made, again disseminating information about this technique through publication.[15] Finally, research in the generation of ultrastable RF signals based on the use of optical transitions and optical combs is laying out a path to the future of ultralow-phase noise microwave signals.[16]

Complementing its publications, the TFD presents a series of seminars and workshops addressing various aspects of precise timekeeping. The best known of these is the annual NIST time and frequency metrology seminar. Now in its fortieth year, this is the most comprehensive introductory seminar on the field of time and frequency in the world.

The final component of dissemination is the actual distribution of precise time information. For many years, the TFD has very successfully distributed time and frequency information in a number of ways. These include providing calibration services at the NIST Boulder campus, precise time distribution via various forms of radio transmissions, and, more recently, the distribution of time via the Internet. In recent years there have been several noteworthy accomplishments in the area of dissemination. The TFD contributions of ultraprecise time and frequency information to UTC and its recent improvement through NIST-F2 have already been noted. The TFD led the formation of a near real-time international time scale among members of the Sistema Interamericano de Metrologia (SIM), a regional metrology organization whose members are nations of the Organization of American States.[17] The SIM Time Network is based on GPS common view intercomparisons between member state primary standards. Today the timing laboratories of 23 SIM member states participate in the SIM time network, and further expansion to more SIM members is planned. Timing information for the SIM Time Network is disseminated at the +/- 100 ns level. A unique, recent accomplishment of this time scale is its real-time nature enabled by the Internet-based exchange of intercomparison information. In contrast, UTC is a backward-looking time scale with intercomparison information delayed two to four weeks. The real-time nature of the SIM time scale is an international first and is driving UTC to a more frequent dissemination of information. The TFD SIM time-scale efforts disseminate high-quality time throughout the western hemisphere and also influence the global UTC scale.

At a lower level of precision, NIST, under TFD leadership, continues to broadcast precise timing information from high frequency and low frequency radio stations in Colorado and Hawaii to the continental United States and Pacific waters. With proper adjustment for propagation time and atmospheric conditions, this system can provide time information at the ±100 μsec level. Broadcasting in Colorado since 1965, the transmission system modified its transmission waveform in 2012, resulting in

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[13] O. Alem, A.M. Benison, D.S. Barth, J. Kitching, and S. Knappe, 2014, Magnetoencephalography of epilepsy with a microfabricated atomic magnetrode, *Journal of Neuroscience* 34(43):14324-14327.

[14] C. Nelson, A. Hati, and D. Howe, 2014, A collapse of the cross-spectral function in phase noise metrology, *Review of Scientific Instruments* 85:024705.

[15] A. Hati, C. Nelson, and D. Howe, 2014, PM noise measurement at W-band, *IEEE Transactions on Ultrasonics, Ferroelectrics and Frequency Control* 61(12):1961-1966.

[16] S. Diddams, J. Li, X. Li, H. Lee, and K. Vahala, 2014, Electro-optical frequency division and stable microwave synthesis, *Science Magazine* 345(6194):309-313.

[17] J.M. López-Romero, M.A. Lombardi, N. Diaz-Muñoz, and E. de Carlos-Lopez, 2014, SIM time scale, *IEEE Transactions on Instrumentation and Measurement* 62(12):3343-3350.

better coverage in areas that prior to the upgrade had poor reception.[18] The formal dissemination of time and frequency information has been markedly improved through this recent upgrade.

NIST TFD time dissemination efforts are also looking toward the future. The network-based dissemination of timing information is of growing importance to a variety of industries, including telecommunications and financial services. To meet growing needs the TFD is exploring the use of the precise time protocol in optical networks.[19] These steps forward in the dissemination of timing information are distributed to the national and international technical communities through publications. GPS common view techniques for time transfer, along with those enabled through communication satellites, have been in operation for many years. The TFD is now investigating more precise time transfer that could be enabled through use of a hydrogen maser on the International Space Station (ISS). The ever-improving operational time dissemination services, along with research in this field, demonstrate a robust time dissemination program at the TFD. This program is at the leading edge of international activities in this field.

The emphasis on patent preparation does not appear to be stable from year to year. A careful assessment by the division of the value of patenting would be worthwhile. Once the value proposition is in hand, staff can be given more consistent direction.

The product dissemination efforts of the TFD are at the state of the art in this field and in many cases define it. The TFD has opportunities to advance the state of the art in several areas. These include improved global time transfer through use on an atomic standard on board the ISS and further improvement of network time transfer using the precision time protocol (PTP). The primary challenge to TFD progress is maintaining adequate funding for its diverse efforts in time and frequency and the ensuing dissemination of those products.

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[18] Y.Liang, O. Eliezer, D. Rajan, and J. Lowe, 2014, WWVB time signal broadcast: An enhanced broadcast format and multi-mode receiver, *IEEE Communications Magazine* 52(5):210-217.

[19] M. Weiss, L. Cosart, J. Hanssen, S. Hicks, C. Chase, C. Brown, C. Allen, P. Johnson, G. Wiltsie, and D. Coleman, 2014, Ethernet time transfer through a U.S. commercial optical telecommunications network, pp. p. 214-220 in *Proceedings of Annual Precise Time and Time Interval Systems and Applications Meeting*, Institute of Navigation, Manassas, Va.

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Key Suggestions for Improvement

The quality of work done at the PML and its response to the stakeholders whose interests it addresses are excellent. Each division deserves high accolades, which are discussed at length in previous chapters. This chapter highlights key suggestions for improvement.

Applied Physics and Quantum Electromagnetics Divisions

The restructuring of the former Quantum Electronics and Photonics Division and Electromagnetics Division into the Applied Physics Division (APD) and the Quantum Electromagnetic Division seems to have been accomplished smoothly. However, the decision by the PML to have the panel jointly review the two divisions as one entity created some confusion and did not allow an in-depth analysis of either division. The APD as a consequence needs to be analyzed in more depth in coming reviews to provide a clearer view of its mission and how it integrates into the overall PML effort.

Engineering Physics Division

It will be important that PML avoid duplication of effort in the area of nontraditional materials conducted by better-funded teams investigating the science or technology of these speculative materials systems.

Quantum Electromagnetics Division

This optical quantum entanglement effort at the PML is among the many similar outstanding activities around the world. PML activity is not at the fundamental leading edge of science, but it is taking advantage of the superb photon sensors that the PML has developed. This activity is outstanding toward bringing QI science into practice, even though it may still take many years to accomplish that.

The work in nuclear magnetic resonance (NMR) imaging, while strong, needs to be expanded to include the rapidly growing area of functional NMR imaging (fMRI), so that claims made in the literature can be evaluated more carefully.

The Quantum Sensors Group has had a significant impact in millimeter wave polarimetry with its detector arrays, but the group serves so many external groups that it seems somewhat oversubscribed.

PML staff suggested that the Gaithersburg and Boulder nanofabrication facilities could support many more NIST projects or outside collaborators.

The new facility at the University of Maryland further disperses the division and could challenge current cohesiveness and collaborations.

PML staff reported that overhead charges on graduate students and on capital equipment are excessive.

The number of technical staff needs to be increased.

Office of Weights and Measures

The effort by the Metric Program to implement SI units in the United States is lagging. Better quantitative metrics for the effectiveness of the Legal Metrology group needs to be established. The number of accredited and recognized laboratories at the state level for dissemination of mass and volume standards for stakeholders is declining.

PML predicts a large wave of retirements (50 percent of staff) in this office in the coming 5 years, and PML needs to examine the implication of the retirements and determine what replacements, if any, will be required.

Quantum Measurements Division

The partial relocation of the groups to the University of Maryland campus as the Joint Quantum Institute presents both opportunities and challenges that warrant careful monitoring so that the groups do not become isolated.

It will be important that the Synchrometrology Group have sufficient resources to play a role in the upcoming renovation of the national power grid into a smart grid. This effort will have a worldwide scope.

Quantum Physics Division

The Quantum Physics Division is likely to become increasingly involved in nanotechnology and biotechnology, broad areas in which careful planning will help to establish productive PML niches.

The scientific interests of the division show strong overlap with those of the Time and Frequency Division; this represents complementary activities in areas in which NIST is a world leader. The activities in biological physics have not been well integrated with those of other efforts within the Quantum Physics Division. PML needs to examine the relationship of biology to other division efforts. The division needs to develop firm guidelines for a consistent and clear approach to the development of intellectual property.

Several staff mentioned that a high overhead rate on capital equipment makes acquisition of expensive equipment very difficult.

Radiation Physics Division

Building 245 in which the Radiation Physics Division is primarily housed is approaching a dangerous and unsafe condition; immediate attention is warranted. In the laboratories of Building 245, where most of the radionuclide standards are prepared for shipment, the rooms are old and lacking in proper heating and ventilation, with consequent inadequate control of humidity and temperature. Neutron source standardization is carried out in a number of shielded, below-grade laboratories in Building 245. Water intrusion during heavy rains has become an issue, because the building is no longer watertight. Dispersal of the source material is remotely possible, but the immediate concern is damage and loss of calibration traceability. These events are, at a minimum, distractions to overburdened scientists, and in some cases have threatened to flood sources under test.

The Dosimetry Group primarily works with its large stakeholder community, providing more opportunity and support to do research would enhance the quality of the staff and the work done.

Lack of funds is resulting in non-replacement of retiring critical employees and in requiring Ph.D. level staff to do routine tasks, stealing time from their technical work. Unfortunately, there are examples where dissemination of proper radioactivity standards has not been able to proceed as rapidly as required, owing to lack of funds.

The division needs to strengthen the training program that involves students and postdoctoral researchers in each of the critical standards activities and to foster a program to share equipment and facilities with users at other national laboratories and universities.

Sensor Science Division

One possible caution concerns the increasing emphasis on lower-cost, lower-SWAP sensors for future satellite systems. The division could prepare to calibrate much smaller radiometers for its customers.

As microfluidics becomes ever more important, it will be correspondingly important to continue developing noninvasive and in-line ways to determine microflows.

While the overarching strategy was well articulated, the division did not describe plans for some of the projects, particularly those that are funded externally; those working on internally funded initiatives seemed to have more concrete plans. The division needs to clarify plans for externally funded projects.

Retirements are being delayed because of difficulties in finding appropriate replacements.

Time and Frequency Division

The NIST-on-a-Chip effort will involve this division, which needs to expand development of its roadmap for this work.

The division's scientific expertise evident during the review was primarily of an experimental nature. The division needs to consider whether the theoretical expertise resident within the division is sufficient to support future experimental efforts.

Challenges associated with shortage of meeting and collaboration space have been voiced by TFD staff. Staff also expressed concerns with respect to an onerous procurement process that incurs substantial delays.

The emphasis on patent preparation does not appear to be stable from year to year. A careful assessment by the division of the value of patenting would be worthwhile. Once the value proposition is in hand, more consistent direction to staff can be provided.

Acronyms

AAPM	American Association of Physicists in Medicine
AC	alternating current
AFM	atomic force microscope
Al	aluminum
AMO	atomic, molecular, and optical
APD	Applied Physics Division
ASD	Atomic Spectra Database
BEOL	back-end-of-line
BIPM	Bureau International des Poids et Mesures
BMF	Boulder Microfabrication Facility
cavity QED	cavity quantum electrodynamics
CIPM	International Committee for Weights and Measures
CIRMS	Council of Ionizing Radiation Measurements and Standards
CMOS	complementary metal-oxide-semiconductor
C-NOT	controlled-NOT
CODATA	Committee on Data for Science and Technology
CT	computed tomography
DARPA	Defense Advanced Research Projects Agency
DC	direct current
DHS	Department of Homeland Security
DOC	Department of Commerce
DoD	Department of Defense
DOE	Department of Energy
DWSS	DoD-focused DoD-wide strategic sourcing
EBIT	electron beam ion trap
EDM	electric dipole moment of the electron
EPD	Engineering Physics Division
EPRI	Electric Power Research Institute
FDA	Food and Drug Administration
FTS	Fourier transform spectrometer
GaN	gallium nitride
HFIR	high flux isotope reactor

Hg	mercury
HgCdTe	mercury cadmium telluride
HIA	highly ionized atom
HPS	Health Physics Society
HSI	hyperspectral imaging
IEEE	Institute of Electrical and Electronics Engineers
ILMP	International Legal Metrology Program
IR	infrared
ISO	International Organization for Standardization
ISS	International Space Station
ITL	Information Technology Laboratory
IUPAP	International Union of Pure and Applied Physics
JHU	Johns Hopkins University
JILA	joint institute between NIST and the University of Colorado, Boulder
JQI	Joint Quantum Institute
KRb	ultracold potassium-rubidium
LBIR	low-background infrared
LIDAR	light detection and ranging
LMDP	Legal Metrology Devices Program
low-SWaP	low size, weight, and power
mAb	monoclonal antibody
MBE	molecular beam epitaxy
MDA	Missile Defense Agency
MEMS	microelectromechanical system
MRI	magnetic resonance imaging
NCNR	NIST Center for Neutron Research
NCSLI	National Conference of Standards Laboratories International
NCWM	National Conference on Weights and Measures
NGA	National Geospatial-Intelligence Agency
NIH	National Institutes of Health
NIST	National Institute of Standards and Technology
NMI	national metrology institute
NML	national measurement laboratory
NMR	nuclear magnetic resonance
NOAA	National Oceanic and Atmospheric Administration
NPOESS	National Polar-Orbiting Operational Environmental Satellite System
NRC	National Research Council
OCT	optical coherence tomography
OIML	International Organization of Legal Metrology
OWM	Office of Weights and Measures

PACE	preaerosol, clouds, and ocean ecosystem
PET	positron emission tomograph(y)
PIF	precision imaging facility
PML	Physical Measurement Laboratory
PMU	phasor measurement unit
PTB	Physikalisch-Technische Bundesanstalt
QED	Quantum Electromagnetics Division
QI	quantum information
QMD	Quantum Measurement Division
QMS	quality management system
QPD	Quantum Physics Division
QuICS	Quantum Information and Computer Science
R&D	research and development
RF	radio frequency
RPD	Radiation Physics Division
RSNA	Radiological Society of North America
SANS	small-angle neutron scattering
SEMI	Semiconductor Equipment and Materials International
SGIP	Smart Grid Interoperability Panel
SI	international system of units
SIM	Sistema Interamericano de Metrología
SIRCUS	spectral irradiance and radiance responsivity calibrations using uniform sources
SNMMI	Society of Nuclear Medicine and Molecular Imaging
SQUID	superconducting quantum interference device
SS	solid state
SSD	Sensor Science Division
SURF III	Synchrotron Ultraviolet Radiation Facility
TDCR	triple-to-double coincidence ratio
TES	transition edge sensor
TFD	Time and Frequency Division
UTC	coordinated universal time
UV	ultraviolet
VIIRS	visible infrared imaging radiometer suite
VUV	vacuum ultraviolet
Yb	ytterbium