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

FISCAL YEAR 2018

Panel on Review of Four Divisions 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

A Consensus Study Report of
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PANEL ON REVIEW OF FOUR DIVISIONS OF THE PHYSICAL MEASUREMENT LABORATORY AT THE NATIONAL INSTITUTE OF STANDARDS AND TECHNOLOGY

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MARTIN OFFUTT, Senior Program Officer

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[1] Member, National Academy of Engineering.
[2] Member, National Academy of Sciences.

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Acknowledgment of Reviewers

This Consensus Study Report was reviewed in draft form by individuals chosen for their diverse perspectives and technical expertise. The purpose of this independent review is to provide candid and critical comments that will assist the National Academies of Sciences, Engineering, and Medicine in making each published report as sound as possible and to ensure that it meets the institutional standards for quality, 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 thank the following individuals for their review of this report:

Ingrid Daubechies, NAS[1]/NAE,[2] Duke University,
Laura H. Greene, NAS, Florida State University,
Paul Kwiat, University of Illinois at Urbana-Champaign,
Jochen Lauterbach, University of South Carolina, and
David Weitz, NAS/NAE, Harvard University.

Although the reviewers listed above provided many constructive comments and suggestions, they were not asked to endorse the conclusions or recommendations of this report nor did they see the final draft before its release. The review of this report was overseen by Arden L. Bement, Jr., NAE, Purdue University. He was responsible for making certain that an independent examination of this report was carried out in accordance with the standards of the National Academies and that all review comments were carefully considered. Responsibility for the final content rests entirely with the authoring committee and the National Academies.

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[1] Member, National Academy of Sciences.
[2] Member, National Academy of Engineering.

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Summary

INTRODUCTION

In 2017, at the request of the Director of the National Institute of Standards and Technology (NIST), the National Academies of Sciences, Engineering, and Medicine formed the Panel on Review of Four Divisions of the Physical Measurement Laboratory of the National Institute of Standards and Technology (the "panel") and established the following statement of task:

> The National Academies shall appoint a panel to assess independently the scientific and technical work performed by four divisions of the National Institute of Standards and Technology (NIST) Physical Measurement Laboratory. This panel will review technical reports and technical program descriptions prepared by NIST staff and will visit the facilities of four divisions of the Physical Measurement Laboratory. The visit will include technical presentations by NIST staff, demonstrations of NIST projects, tours of NIST facilities, and discussions with NIST staff. The panel will deliberate findings in closed sessions of the panel meeting and will prepare a report summarizing its assessment findings.

NIST specified that the following four divisions of the Physical Measurement Laboratory (PML) would be reviewed: Applied Physics Division (APD), Quantum Electromagnetics Division (QED), Time and Frequency Division (TFD), and the Quantum Physics Division (QPD). All four of these divisions are located in Boulder, Colorado, and were visited by the panel on May 1-3, 2018.

GENERAL OBSERVATIONS

Previous Appraisal of PML Enterprise

The Summary of the National Research Council's (NRC's) assessment of the PML in 2015, which included both Gaithersburg, Maryland, and Boulder, Colorado, locations, had general observations that began as follows:[1,2]

> 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.

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[1] National Research Council, 2016, *An Assessment of the National Institute of Standards and Technology Physical Measurement Laboratory—Fiscal Year 2015*, The National Academies Press, Washington, D.C.

[2] Effective July 1, 2015, the institution has been 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, 2015.

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.

Current Appraisal of the Success of PML Enterprise

The present committee fully backs the assessment made in 2015. It is heartening to see the extent to which PML maintains outstanding staff, operating with the highest standards and accomplishments at levels that are often among the best in the world. All divisions within the Boulder group were found to have achieved impressive results and to operate at the highest levels in each of the three tasks listed above. The PML seems to be able to find the expertise they need within their institution or other institutions—universities, private organizations, and other government institutions.

No gaps in PML's scientific expertise were found such as might hinder excellent technical performance of the tasks that PML has chosen to perform, nor were other tasks identified that PML should be performing. PML is fully capable of supporting its technical programs with the ability to achieve its stated objectives. No area of concern was identified with respect to scientific expertise. Dissemination of research results and interaction with relevant external communities are excellent and include work with standards-setting groups, provision of calibration services, and development of industrially and medically useful techniques.

Challenges to PML's Achieving Its Goals

The 2015 NRC report noted concern for possible staff turnover due to retirements. The staff at the divisions reviewed this year has met this challenge very successfully. Unexpectedly large turnover was partly caused by the unanticipated death of a very successful researcher. However, no projects were dropped or diminished, primarily because of the interactive group structure in the research laboratories. Unusually large turnover in the administration has caused minimal disruption, because staff stepped up to address PML needs and met the unexpected challenges.

PML did report considerable turnover, much of it due to the short-term nature of many technical appointments, including graduate fellowships, visiting faculty, and other short-term visitors. Retirements occur as usual, but it seems that many professional staff who leave do so for other technical opportunities.

Discussions with several women staff suggested that it would be important for the PML to investigate analytically whether the excellent technical support that is provided to the women is complemented by support for their career goals, including promotion, and for the PML to act upon the results of that analysis as appropriate. The PML reported that they have an acceptably good record in recruiting women early in their careers, but promotions have not kept up with the norms for other institutions. Data can be collected to establish whether there is indeed basis for concern, and to identify the issues in which possible inequitable treatment manifests itself.

There appears to be a need for a human resources professional resident at the Boulder campus—someone who can get to know the staff and respond to career considerations in a timely manner. A resident human resources professional could monitor promotional norms and assure that they were the same across the institution for equivalently performing individuals, independent of their gender, age, race, or other relevant demographic variables. The PML staff have appointed one woman to take on the retention of women as her task, but she apparently has no specific training or experience in this role. It is not clear how much difference she can make without authority. A further possible approach might be to establish a review group of NIST and non-NIST scientists who could establish the appropriate analytics for management to track on a longitudinal basis to monitor this issue and advise on any new policies.

The weak infrastructure highlighted in the 2015 report persists in some areas. NIST responded to this challenge by bringing on board the new Katharine Blodgett Gebbie Laboratory Building, which is devoted to research. Some fortunate PML staff have excellent research space in that new building. At the same time, however, some staff laboratories are in a building that has not been upgraded since the 1960s. The environmental controls in the laboratory space need to be improved. While the ability of PML researchers to operate in less-than-optimal physical space was impressive, they are rapidly reaching the day when the decaying infrastructure will limit their ability to perform their necessary duties, continue the accuracy of the standards that PML researchers have developed, and show the applicability of their research to ever-advancing high-tech industry.

Recommendation 1. The PML should develop with NIST management a plan to remodel and upgrade, as soon as possible, the infrastructure utilized by the PML and should perform an assessment to determine which PML infrastructure assets are weakest in supporting the scientific mission.

Global Challenges

The researchers at PML are aware of the competition they have throughout the world. Fortunately, they have been allowed to travel when needed to conferences and workshops, giving papers and talks. This keeps them abreast of breakthroughs in their respective fields. They seem admirably up-to-date technically. Their technical and scientific awareness is at the level of the highest educational institutions in the United States and considerably more than in many government laboratories. It is urgent that the government continues to fund this travel. Similarly, access to a variety of library resources is critical. Portions of PML have the good fortune to be located on the University of Colorado, Boulder (CU) campus, and researchers have access to their state-of-the-art libraries.

The ability to purchase or have access to state-of-the-art equipment is also crucial to maintaining a world-class effort. Researchers expressed faith that continued funding would be available through the Department of Commerce (DOC). This faith is crucial to maintaining forward-looking researchers with ambitious plans—the kind that have made PML world-class in many areas. NIST in Boulder is fortunate to have the backing of both current Colorado senators. Nonetheless, the funding profile in recent years does not suggest long-range stability of the funding of PML. Funding for JILA—a joint organization of NIST and the University of Colorado, Boulder (CU), established in 1962 and located on the CU campus—has recently benefited from being awarded an additional 5 years from the National Science Foundation, but nothing is guaranteed after that. The management at PML, in collaboration with NIST upper management, needs to do long-range planning about what to do if the funding dips. PML is hiring a person to market PML to private entities, with the plan to ultimately cover any loss of government funds. This is an essential endeavor.

Patents and Intellectual Property

The 2015 NRC report noted that NIST procedures and policies relating to patents and intellectual property (IP) were not clearly defined for technical staff. The present panel revisited this issue and found, for example, that JILA—the host institution of the QPD—is mostly engaged in basic scientific research not compatible with patent protection and licensing. Protecting some of the work would allow its translation into the commercial sector. Without IP protection, companies will not want to invest the time and money to complete translation to market. Incentives for JILA researchers could be constructed that reward IP development, compatible with government restrictions, in a manner that does not distort the basic scientific effort but promotes technology transfer.

At the conclusion of the committee's site visit, the chair of the committee and National Academies staff met with the Director of NIST, who explained that a priority for him was developing and regularizing workable procedures and policy positions on patents and IP for all parts of NIST. The Director reported this year that he is addressing this matter throughout the DOC, so that all DOC staff, including those at NIST, will be afforded a clear understanding of IP procedures and policies. NIST researchers need to be part of the conversation. The prospect of changes in patent and IP procedures and policies, being developed by the NIST Director, is encouraging and represents an opportunity for PML to regularize these procedures.

Recommendation 2. The PML should maintain awareness of changes in patent and intellectual property procedures to encourage and more efficiently enable the movement of PML discoveries into commercial space.

Collaboration Across Organizational Boundaries

Divisions in PML are meeting the needs of stakeholders in other laboratories of NIST. Within PML itself, there is an opportunity for greater interaction and dissemination of results between the Time and Frequency Division and the Quantum Physics Division, which are located on different campuses.

SIGNIFICANT ACCOMPLISHMENTS

Applied Physics Division

The seven groups of the APD are broadly concerned with measurement of electromagnetic radiation and address stakeholder needs in a range of applications, including magnetic imaging in health care, quantum communication and computing, brain network cognitive processes simulation, single photon detection, gas sensing, and other areas.

The APD has responded to a global need to standardize and calibrate magnetic resonance (MR) imaging and spectroscopy systems used in clinical medicine and medical research by successfully fabricating phantoms that allow not only physical system calibration but also allow evaluation of slight differences in pulse sequences, including radio frequency (RF) and gradient protocols. A major innovation from the Magnetic Resonance Group is the development of new micro- and nanoparticle-based contrast agents for new MR imaging and sensing schemes. The high-moment synthetic antiferromagnet nanoparticles provide enhanced contrast in T2-weighted studies for in vivo cell-tracking and remote sensing of biological tissue mechanical stresses in human physiology research.

The success of atmospheric horizontal and vertical path assessment of gases (e.g., carbon dioxide and methane) using fiber-based optical comb technology opens new and highly accurate methodologies for monitoring a large volume of three-dimensional air space by remote and flexible systems. This technology has the potential for a significant improvement in environmental monitoring.

Quantum computation relies on fast and high fidelity coupling between quantum information-holding systems. The Advanced Microwave Photonics Group has developed a parametric-based architecture that dramatically increases the connectivity between qubits, thereby advancing significantly the practicality of quantum computing.

Three groups in this division are engaged in development of neuromorphic systems designed to simulate circuit functions of the human brain's memory and data processing functions by utilizing superconducting single flux quantum (SFQ) and spintronics devices that will measure spatial and temporal correlations in high-density networks to understand memory and data processing. The group has developed a stochastic model of magnetic Josephson junctions suitable for high-density neural simulations. The circuits allow simulation of most known neurophysiology functions, including inhibition.

One of the groups is extending atom probe tomography to include laser-assisted tomography and extreme atom probe tomography and is extending this work to the extreme ultraviolet (EUV) regime and adding in situ transmission electron microscopy analysis. This work has the potential to significantly advance the practical utility of atom probe tomography.

Quantum Electromagnetics Division

The QED's interdisciplinary program of research focuses on high-performance computing; superconductive electronics, quantum sensors, nanomagnetic measurements, and spin electronics; and molecular photonics and biophotonics. The division is also responsible for the Boulder Microfabrication Facility, utilized by NIST-Boulder and its direct collaborators.

The QED develops highly precise measurements and instrumentation using a range of techniques and phenomena such as Josephson standards and millimeter-wavelength detectors. The division maintains a programmable DC voltage standard with current demonstrated accuracy to a few parts in 10^{11}. This has been disseminated to national metrology institutes (NMIs) in other countries and is available for sale as a certified NIST reference instrument.

The QED has maintained the microfabrication facility's impressive capabilities; adding an e-beam lithography tool has allowed greatly enhanced resolution (below 10 nm), essential for magnetic sensors and devices. The new clean room has been key in enabling production of the large (150 mm) wafers that are essential in current and future astronomy projects.

Time and Frequency Division

The mission of the TFD is to provide official U.S. time and frequency, entailing not only their accurate realization but also their dissemination through various devices and services. A measure of the value of the service NIST provides in dissemination is the 40 billion Internet synchronization requests it serves each day. Additionally, the TFD performs state-of-the-art research in time and frequency and related technologies. As an example, two independent ytterbium lattice frequency standards were constructed within the TFD, which demonstrated agreement to better than one part in 10^{18}, nearly a factor of five beyond the previous state-of-the-art research in atomic clock. The division has also made important contributions to research in optical frequency combs, quantum information/computing, and chip-scale atomic clocks and sensors.

Quantum Physics Division

The QPD is the NIST component of JILA and operates within a cooperative agreement between NIST and CU. The QPD/JILA cooperative addresses measurement science, including focus areas of quantum many-body physics, quantum technologies, and more recently, biophysics. The division's optical lattice clocks have a precision of approximately 10^{-19}, with the further promise to reach 10^{-21}, owing to development of a fermionic atomic lattice clock. A further accomplishment is the realization of a superradiant laser that is 500,000 times less sensitive to cavity length than conventional stable lasers. In biophysics, QPD utilized biological atomic force microscopy (AFM) for membrane protein studies and achieved record time resolution (~1 μs) and low noise.

ADDITIONAL CONCLUSIONS AND RECOMMENDATIONS

Applied Physics Division

Instrumentation and space resources are excellent for most of the groups, but the Magnetic Resonance Imaging group is badly in need of a clinical-class magnetic resonance imaging (MRI) scanner so that appropriate phantom design, as well as initial testing, can be readily accomplished without going to other sites. NIST has access to nearby clinical commercial MRI systems, but nonetheless might evaluate whether a clinical system of its own might not improve productivity by eliminating wait times, providing opportunities for CRADAs and other partnerships that might offset costs, and decreasing costs it would otherwise occur using other clinical scanners in the area. In its work on quantitative nanostructure characterization, APD may benefit from broader collaborations on different materials systems. APD's work on advanced microwave photonics applied to quantum computing and its stakeholder community would benefit from experimental validation or the development of theoretical manuscripts describing the proposals.

> **Recommendation 3. PML should study the costs and benefits of acquiring a clinical-class magnetic resonance imaging machine that would assist in phantom design and enable testing onsite.**

Quantum Electromagnetics Division

The QED would benefit from increased guidance on the value to NIST of patent activity vis-à-vis journal publications and other metrics. (See Recommendation 2 above.) The environmental controls in the laboratory space need to be improved. The aging facilities have problems with the building envelope, such as the observed roof leaks. (See Recommendation 1 above.)

Time and Frequency Division

The problem of transmitting time signals and comparing frequency standards in this new regime of precision poses a serious scientific and technical challenge for the TFD. Comparisons in the same laboratory are relatively straightforward, but the problem of comparisons at large distances remains to be solved.

> **Recommendation 4. PML should continue its work to develop methods for distributing time over long distances at the newly attainable levels of precision.**

Quantum Physics Division

QPD/JILA has strong overlapping interests with other PML divisions, such as the TFD. Because QPD/JILA is housed in a CU facility and not at NIST Boulder, there is little trickle down to QPD/JILA of technical improvements in TFD.

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. 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 standard's needs, enable scientific and technological advances, and improve and refine existing measurement methods and services.

At the request of the Acting Director of NIST, in 2017 the National Academies formed the Panel on Review of Four Divisions of the Physical Measurement Laboratory at the National Institute of Standards and Technology (the "panel") and established the following statement of task for the panel:

> The Panel on Review of Four Divisions of the Physical Measurement Laboratory at the National Institute of Standards and Technology will assess the scientific and technical work performed by the National Institute of Standards and Technology (NIST) Physical Measurement Laboratory. The panel will review technical reports and technical program descriptions prepared by NIST staff and will visit the facilities of the NIST laboratory. The visit will include technical presentations by NIST staff, demonstrations of NIST projects, tours of NIST facilities, and discussions with NIST staff. The panel will deliberate findings in a closed session panel meeting and will prepare a report summarizing its assessment findings.

The Director of NIST also suggested that the panel consider during its assessment the following factors:

1. Assess the organization's technical programs.
   - How does the quality of the research compare to similar world class research in the technical program areas?
   - Is the quality of the technical programs adequate for the organization to reach its stated technical objectives? How could it be improved?
2. Assess the portfolio of scientific expertise within the organization.
   - Does the organization have world class scientific expertise in the areas of the organization's mission and program objectives? If not, what areas should it be improved?
   - How well does the organization's scientific expertise support the organization's technical programs and the organization's ability to achieve its stated objectives?
3. Assess the adequacy of the organization's facilities, equipment, and human resources.

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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.

- How well do the facilities, equipment, and human resources support the organization's technical programs and its ability to achieve its state objectives? How could they be improved?

4. Assess the effectiveness by which the organization disseminates its program outputs.
   - How well are the organization's research programs driven by stakeholder needs?
   - How effective are the technology transfer mechanisms used by the organization? Are these mechanisms sufficiently comprehensive?
   - How well is the organization monitoring stakeholder use and impact of program outputs? How could this be improved?

The expertise of the panel of 22 volunteers matched that of the work performed by the Physical Measurement Laboratory (PML) staff.[2]

On May 1-3, 2018, the panel assembled at the NIST facilities in Boulder, Colorado, for a two-and-a-half-day assessment, during which it received welcoming remarks from the Director of NIST and from the PML director, heard overview presentations by PML management and presentations by researchers at the PML, toured portions of the PML facilities, and attended an interactive session with PML management. The panel also met in a closed session to deliberate on its findings and to define the contents of this assessment report.[3]

The panel's approach to the assessment relied on the experience, technical knowledge, and expertise of its members. The panel did not attempt to report an exhaustive assessment of every project reviewed. Rather, the panel's goal was to identify and report accomplishments and opportunities for further improvement with respect to the following: the quality of the technical programs at the PML; the portfolio of scientific expertise within the laboratory; the adequacy of the laboratory's facilities, equipment, and human resources; and the effectiveness by which the organization disseminates its program outputs. The panel illustrated its conclusions with salient examples of programs and projects that are intended collectively to portray an overall impression of the laboratory, while preserving useful suggestions specific to projects and programs.

To accomplish its mission, the panel reviewed the material provided by the PML prior to and during the review meeting. The choice of projects to be reviewed was made by the PML. The panel applied a largely qualitative approach to the assessment. Given the nonexhaustive nature of the review, the omission in this report of any particular PML project should not be interpreted as a negative reflection on the omitted project. For all the projects reviewed, at least two panel members had direct expertise.

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[2] See the NIST Physical Measurement Laboratory website at https://www.nist.gov/pml for information on Physical Measurement Laboratory organization and programs (accessed July 10, 2018).

[3] The agenda for the May 1-3, 2018, assessment meeting is at the National Academies of Sciences, Engineering, and Medicine website, http://www8.nationalacademies.org/cp/meetingview.aspx?MeetingID=9904&MeetingNo=1.

2

Organization and Mission of the Physical Measurement Laboratory

The nine divisions that comprise the NIST Physical Measurement Laboratory (PML) are in either Boulder, Colorado, or Gaithersburg, Maryland. The Boulder campus of NIST includes four divisions—Applied Physics, Quantum Electromagnetics, Time and Frequency, and Sensor Sciences.[1] A fifth division, Quantum Physics, is located on the campus of the University of Colorado, Boulder. The balance of the nine divisions are located in Gaithersburg, Maryland, and include Engineering Physics, Quantum Measurement, Radiation Physics, and Weights and Measures. The divisions themselves are further made up of groups; this report discusses the science in four of the groups located in Boulder that were specifically the subject of the present review.

APPLIED PHYSICS DIVISION

One of the four divisions in Boulder, the Applied Physics Division has the mission to advance measurement science and technology throughout the electromagnetic spectrum in areas of critical importance to national priority needs. These areas include advanced manufacturing, national security, biological innovations, climate change science, and clean energy. The division provides industry, and its suppliers and customers, with comprehensive measurement capabilities and standards, as well as traceability to those standards.[2] Its groups are as follows:

- Advanced Microwave Photonics,
- Faint Photonics,
- Fiber Sources and Applications,
- Magnetic Imaging,
- Molecular and BioPhotonics,[3]
- Quantitative Nanostructure Characterization,
- Quantum Nanophotonics, and
- Sources and Detectors.

QUANTUM ELECTROMAGNETICS DIVISION

The Quantum Electromagnetics Division (Boulder) has the mission to provide the metrological foundation for strategic, emerging electronic, magnetic, and photonic technologies by developing high-precision measurement devices, systems, standards, and methodologies and disseminating them to address national needs. The group interacts and collaborates with stakeholders in industry, academia, and other government agencies to ensure that responsiveness to their measurement needs in quantum electrical standards; advanced materials analysis using X-ray sensor arrays; superconducting electronics

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[1] The Sensor Science Division, although located in Boulder, Colorado, was not reviewed. It includes the following groups: Fluid Metrology Group, Optical Radiation Group, Remote Sensing Group, Thermodynamic Metrology Group, and Ultraviolet Radiation Group.

[2] Adapted from National Institute of Standards and Technology (NIST), "Physical Measurement Laboratory Divisions," available at https://www.nist.gov/pml/divisions, accessed September 27, 2018.

[3] Was located within the Quantum Electromagnetics Division at the time of the panel's review.

and nanomagnetics for high-speed, energy-efficient, future-generation computing; and quantitative medical diagnostic imaging.[4] Its groups include the following:

- Microfabrication,
- Nanoscale Spin Dynamics,
- Quantum Processing,
- Quantum Sensors,
- Spin Electronics, and
- Superconductive Electronics.

TIME AND FREQUENCY DIVISION

The Time and Frequency Division (Boulder) maintains the standard for frequency and time interval for the United States, provides official time to the United States, and carries out a broad program of research and service activities in time and frequency metrology.[5] The division's research and metrology have three major thrusts: (1) accurate and precise realization of UTC (Coordinated Universal Time), (2) a range of measures to disseminate this time, and (3) research and technology development.[6] Its groups are as follows:

- Atomic Devices and Instrumentation Group,
- Atomic Standards Group,
- Ion Storage Group,
- Optical Frequency Measurements Group,
- Time and Frequency Metrology, and
- Time and Frequency Services.

QUANTUM PHYSICS DIVISION

The Quantum Physics Division, located on the campus of the University of Colorado, Boulder, at a joint institute, JILA, performs experimental and theoretical research and innovation advancing fundamental measurement science through quantum optics, quantum degenerate gases of atoms and molecules, quantum many-body physics, chemical physics, biophysics, and nanoscale quantum science.[7] Its functional research and training focus areas are as follows:

- Quantum Information Science and Technology,
- Precision Measurement,
- Nanoscience,
- Laser Physics,
- Chemical Physics,
- Biophysics,
- Atomic and Molecular Physics, and
- Astrophysics.

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[4] Adapted from NIST, "Physical Measurement Laboratory Divisions," available at https://www.nist.gov/pml/divisions, accessed September 27, 2018.

[5] Adapted from NIST, "Time and Frequency Division," available at https://www.nist.gov/pml/time-and-frequency-division, accessed September 27, 2018.

[6] Adapted from C. Oates, 2018, *Time and Frequency (688) Report 2018*, NIST, Boulder, Colo.

[7] Adapted from NIST, "Quantum Physics Division," https://www.nist.gov/pml/quantum-physics, accessed September 27, 2018.

SCIENTIFIC AND TECHNICAL RELEVANCE

Adding together the contributions of both the Gaithersburg and Boulder branches, PML develops and disseminates the national standards of length, mass, force and shock; acceleration; time and frequency; electricity; temperature; humidity; pressure and vacuum; liquid and gas flow; and electromagnetic, optical, microwave, acoustic, ultrasonic, and ionizing radiation. Activities range from fundamental measurement research through provision of measurement services, standards, and data. PML applies its measurement capabilities to problems of national significance through collaborations with industry, universities, professional and standards setting organizations, and other agencies of government. PML supports the research community in such areas as communication, defense, electronics, energy, environment, health, lighting, manufacturing, microelectronics, radiation, remote sensing, space, and transportation.

PML establishes spectroscopic methods and standards for infrared, visible, ultraviolet, x-ray, and gamma-ray radiation; investigates the structure and dynamics of atoms, molecules, and biomolecules; develops the electrical, thermal, dimensional, mechanical, and physical metrology for measuring the properties of precision measurement devices and exploratory semiconductor, quantum electronic, nanoelectronic, bioelectronic, biooptical, optoelectronic, and quantum information devices and systems; and examines the thermophysical and interfacial properties of streams of flowing fluids, fluid mixtures, and solids.

It develops and disseminates national standards by means of calibrations, measurement quality assurance, standard reference materials, technology transfer, education and training, and a comprehensive weights and measurement program to promote uniformity and accuracy at the international, federal, state, and local levels.

It generates, evaluates, and compiles atomic, molecular, optical, ionizing radiation, electronic, and electromagnetic data in response to national needs, measures and improves accuracy of the fundamental physical constants, and develops and operates major radiation sources for measurement science and metrology.

3

Applied Physics Division

INTRODUCTION

The Applied Physics Division (APD) has seven groups with a complement of 140 personnel, many of whom work on projects in multiple groups. These groups are Advanced Microwave Photonics, Faint Photonics, Quantum Nanophotonics, Fiber Sources and Applications, Magnetic Imaging, Sources and Detectors, and Quantitative Nanostructure Characterization. There appears to be an extensive cross interaction of personnel and resources between groups and excellent communications within the division.

Total annual funding is $22 million of which NIST base funding is 53 percent, decided centrally. Budgets allocated to groups range between $2 million and $ 4 million per year. The other sources are from NIST initiatives, including targeted funding such as laser welding, integrated photonics, and LIDAR; calibration services; and external funding sources, such as the Department of Defense (DoD), the Defense Advanced Research Projects Agency, the Advanced Research Projects Agency-Energy (ARPA-E), and Cooperative Research and Development Agreements (CRADAs) with universities and industry.

ASSESSMENT OF TECHNICAL PROGRAMS

Advanced Microwave Photonics

The activities of the program are summarized by the division as follows: “We research and develop technical approaches that address near- and medium-term resource bottlenecks in quantum information and quantum computing, specifically in the microwave frequency domain using superconducting circuits.”[1]

The Advanced Microwave Photonics Group (AMPG) consists of three NIST principal investigators, any one of whom could be a professor at a top-25 physics department. Also in the group are six associate scientists. Although relatively small in size, the AMPG investigates broad areas of superconducting quantum systems, perhaps indicating that “quantum microwave photonics” is a more natural designator. Given the impressive technical impact to date (e.g., pioneering optomechanical systems in the microwave regime and making seminal contributions to superconducting amplifiers), NIST may consider further augmenting the group with more staff scientists and/or technicians. In particular, there may be opportunities for this group to participate technically at a leadership level in helping develop and maintain standards of components for the emerging quantum information technology area.

Similar to other groups in the APD, the AMPG relies on NIST funding as well as external support, the latter predominantly from DoD. Notably, one research group is currently being partially supported by a Presidential Early Career Award, a testament to the group’s ability to attract top talent. In the long run, an additional outside funding source would give the group’s varied research interests more

[1] National Institute of Standards and Technology (NIST), “Applied Physics Division NRC Review,” presentation to the committee, May 1, 2018.

stability.

The AMPG uses state-of-the-art equipment to conduct its research, mostly purchased from companies (e.g., dilution refrigerators), although custom amplifiers and devices are designed and fabricated in-house.

Quantum Computing

The AMPG has extensive expertise in superconducting devices and systems—of direct relevance to superconducting quantum computing. Quantum computation relies on fast and high-fidelity coupling between quantum information-holding systems, that is, qubits. The most successful two-qubit gates today rely on direct, resonant, or dispersive coupling between two qubits; the nature of this coupling is such that only two qubits can be coupled at a time, and it is very difficult to turn off coupling in the qubit's idle state.

Accomplishments

AMPG scientists have been leaders in developing parametric-based gates. Parametric-based strategies for qubit gates have percolated through the superconducting qubit community over the past few years; they offer opportunities to improve scaling of many-qubit systems, such as reducing wire count and reducing the need for microwave passives (hardware volume in the cryostat), while increasing connectivity and gate speed. The AMPG has developed a parametric-based architecture that dramatically increases the connectivity between qubits in a superconducting qubit system and reduces wire counts by almost a factor of four.

Opportunities and Challenges

AMPG scientists are well connected with the quantum computing community, so dissemination of their ideas is not difficult. There has been a lack of publications in this area over the past couple years. Validation of the group's concepts experimentally, or even the dissemination of theoretical manuscripts describing their proposals, would benefit the community and the group.

Optomechanics

AMPG scientists are pioneers of the relatively new field of optomechanics in the microwave regime. They are the inventors of a novel "drum-based" approach to mechanical motion-microwave photon coupling, with dramatically increased coupling strengths beyond the state of the art. Utilizing mechanical motion strongly coupled to photons offers the ability to both demonstrate fundamental quantum measurement concepts in well-controlled systems and provides opportunities for new devices. In particular, mechanical systems offer an excellent means to transduce information between energy regimes of relevance to many fields.

Accomplishments

The AMPG has demonstrated efficient nonreciprocity in a microwave optomechanical circuit. The group has also performed significant work on mechanically mediated microwave frequency conversion in the quantum regime.

Opportunities and Challenges

The optomechanics activities of the AMPG are well integrated within the group and with JILA; this synergy could reveal further opportunities for progress in work on optomechanics.

Amplification and Measurement

The AMPG uses coupled-mode theory to understand nonreciprocity and to synthesize directional parametric amplification. Parametric multimode theory promises a new class of directional parametric amplifiers, signal routers, programmable filters, and even creation of synthetic gauge fields—of interest for exploration of new quantum systems.

Accomplishments

The AMPG has created novel and useful superconducting amplifiers and nonreciprocal systems. The group has developed a novel graph-theoretic approach to designing and understanding driven amplifier (and related) systems, which they applied to develop new and useful microwave components, which is relevant to quantum computing and measurement science. In a sense, these amplification and measurement efforts attempt to unify the disparate quantum technologies across AMPG under a single conceptual umbrella. The AMPG investigators are leaders in superconducting amplifier development.

Opportunities and Challenges

AMPG's scientists have taken steps to apply their technology to standards—both for traditional research thrusts and for the nascent quantum information science and technology industry. The field could use an expert body to qualify and develop standards for cryogenic, superconducting, and microwave components. These standards are generally and widely needed across the community. The AMPG could take a leading role in this space, but it would require resources for the needed staff technicians, along with relevant equipment.

Faint Photonics Group and Quantum Nanophotonics Group

The activities the Faint Photonics Group (FPG) and Quantum Nanophotonics Group (QNG) are summarized as follows: "We are developing the best metrology at faint light levels. We provide and use optical single-photon sources, detectors to solve challenging research, industrial, and governmental problems when applicable."[2]

Superconducting Detectors

The FPG develops two types of single-photon detectors; both are based on the fragility of the superconducting state close to its transition.

The high-efficiency (70 to 95 percent) superconducting nanowire single-photon detectors (SNSPDs) from ultraviolet to mid-infrared are currently the fastest single-photon detectors for counting photons. Unlike most groups, who use niobium-nitride superconducting meander structures,[3] the FPG is

[2] NIST, "Applied Physics Division NRC Review," presentation to the committee, May 1, 2018.

[3] The meander structure is a geometrical configuration of the detector in which the conductors are folded back and forth to make the overall length of detector shorter than the original length of straight wire.

using amorphous tungsten silicide (WSi), which offers better homogeneity and therefore less possibility for weak spots.

The high-efficiency (~98 percent) transition edge sensors (TESs) for 1550 nm are made of superconducting tungsten. The current version of these detectors was initially developed at NIST and is a widely used method for cryogenic particle detectors. It is evident that the FPG is a world leader in the development and use of both detectors.

Accomplishments

Noteworthy FPG accomplishments in superconducting detectors include the following:

- Increasing the efficiency of the SNSPD by using amorphous WSi.
- Developing the fastest detector for single photon counting (< 100 picoseconds) while working at approximately 5 K, which is easily obtained with, for example, closed-cycle refrigeration.
- Using its SNSPD in the first (one of three) Loophole-free Bell inequality experiments with photons.
- Providing its TES detectors to the Zeilinger group for their Loophole-free Bell inequality experiments with photons.
- Demonstrating a high-efficiency SNSPD at a wavelength of 315 nm and an operating temperature of 3.2 K, with a background count rate below 1 count per second at saturated detection efficiency.[4]

Opportunities and Challenges

FPG's opportunities are primarily in the use of its detector capabilities in exploratory projects (with the QNG), such as three-dimensional (3D) fluorescence imaging with entangled photons, in the area of quantum biometrology, and use of Bell inequality experiment as a random-number generator.

Nanophotonic Devices to Enable Optoelectronic Measurements

The QNG uses one chamber of a double-molecular-beam epitaxy (MBE) system for growth of gallium-arsenide (GaAs)-based MBE structures (the second chamber is used by the Quantitative Nanostructure Characterization Group for gallium-nitride (GaN)-based structures). The following projects associated with this facility:

- Semiconductor saturable absorber mirrors (SESAMs),
- GaAs:Er for ultrafast carrier recombination (terahertz generation, photoconductive switches),
- InAs quantum dots for single-photon sources and transduction,
- Vertical (external) cavity surface-emitting lasers (NIST-on-a-Chip), and
- GaAs/AlGaAs heterostructures for chip-scale nonlinear optics.

Accomplishments

Obviously, the QNG group is not an MBE-centered group, but rather uses the MBE to fabricate structures that are needed for its projects. It seems to be achieving high-quality growth, which will allow it to integrate the semiconductor-based sources with its experiments. It develops and produces novel devices such as sources and saturable absorber mirrors. An example is the ultra-low-noise, monolithic,

[4] D.H. Slichter, V.B. Verma, D. Leibfried, R.P. Mirin, S.W. Nam, and D.J. Wineland, 2017, UV-sensitive superconducting nanowire single photon detectors for integration in an ion trap, *Opt. Express* 25:8705-8720.

mode-locked solid-state laser. The group has a fabrication facility that enables development of state-of-the-art structures.

Opportunities and Challenges

The MBE facility and its projects are well integrated into the research of the APD, and so this synergistic collaboration may yield future applications of the group's device development efforts.

Integrated Optics, Quantum Optics, and Quantum Biometrology

The QNG develops nanophotonic devices to enable optoelectronic measurements in a wide range of wavelengths. Guided by fundamental physics measurements, or by technological challenges, the group works on a wide range of projects.

Accomplishments

A notable integrated optics experiment, which utilized the single-photon detectors produced by FPG and single-photon sources produced by QNG, is the Loophole-free Bell Inequality experiment.

Supporting another thrust on neuromorphic computing, the group developed multiplanar amorphous-Si waveguides exhibiting low-loss crossings, low crosstalk, and efficient interplanar coupling.

A new direction is in microscopy, involving entangled photons. Entangled photons significantly improve ordinary optical techniques, particularly in enhanced microscopy. PML and the NIST Materials Measurement Laboratory (MML) joined efforts to develop entangled photon microscopy capabilities, directed toward biomedical applications. The main advantage of the technique is the ability to use low power, which will minimize biologic cell damage.

Opportunities and Challenges

The present project concentrates on 3D fluorescence imaging with entangled photons. Other biomedical applications will be enabled with the successful demonstration of this capability.

Non-Conventional Superconducting Electronics

The FPG integrates the single-photon detectors into superconducting structures for a variety of applications. In collaboration with JILA, it also develops optical/microwave hybrid quantum systems.

Accomplishments

The group has integrated silicon nitride waveguides with evanescently coupled ring resonator filters of SNSPDs to couple specific colors to the SNSPDs.

Fiber Sources and Applications

The Fiber Sources and Applications Group currently performs four projects: fiber-optic based combs, dual-comb spectroscopy, time-frequency transfer, and laser ranging. Personnel include approximately eight full-time equivalent staff (FTEs) with nine associates. The group leader is also presently serving as interim division director. More than half of this group's $4 million budget is external in the form of significant DoD funding, along with CRADAs and support from the U.S. Department of Energy.

Accomplishments

The work of the Fiber Sources and Applications Group is primarily based on the scientific understanding, development, and application of fiber-based frequency combs; in this field, the group is world-renowned for its contributions and leadership. One notable and important application is dual-comb spectroscopy that is broadband and requires no moving parts. The technology is based on telecommunications wavelengths and components. Initial demonstrations show that these combs can be used for remote optical sensing of greenhouse gases or hazardous gases with highly accurate spatial resolution and ranging information.

The group has developed a free-space, open-path testbed on the NIST campus and a longer-range path over the city of Boulder, Colorado. These systems have been operated for periods of multiple weeks with accuracies for quantification of CO_2 and CH_4 concentrations that are 10 to 100 times better than other open-path systems. A demonstration of an open-path measurement using a drone as an airborne reflector showed collection of greenhouse gas data at arbitrary distances and altitudes. Further trials at longer distances and remote sites are under way.

Another important application of these fiber-based frequency combs is for time and frequency transfer (i.e., dissemination) for multiple potential applications, including highly accurate position, navigation, and timing. In particular, coarse and fine two-way timing can be obtained by employing a redefinition of the "second" as precisely placed optical pulses in a comb-based synchronization system. A pair of clocks has been synchronized in this manner via the flight path of an airborne retroreflector on a quadcopter.

The level of external interest in this work is impressive, as evidenced by the significant level of external financial support. In addition, the breadth of the work—from concept to field-test—is also impressive.

Challenges and Opportunities

There are major challenges inherent in the mission of this group, but these are primarily of a technical nature that the group is well-equipped to attack, including enhancing the amplitude uniformity and output power of the comb lines and increasing the coherency and reducing the noise. The group is successful at choosing, addressing, and solving problems that are of interest to others in the commercial and governmental world. Laudably, the group intends to continually push the state of the art of their technology and applications.

The group has used drones with retroreflective mirrors for signal return in order to do vertical sampling of the air. While the concept is an opportunity for environmental monitoring, the use of drones entails potentially undesirable consequences. Consideration might be given to helium-filled balloons equipped with global positioning system (GPS) and gas jets for positioning and station keeping.

Magnetic Imaging

The Magnetic Imaging Group, a research and service group, serves the global need for calibration standards—ensuring that imaging instruments perform to specifications, making commercially available calibration standards (phantoms) for human magnetic resonance imaging systems, and calibrating or measuring the relaxation parameters of proposed magnetic resonance imaging (MRI) contrast agents. The group also has embarked on micro-fabricated contrast agents for MRI, ultralow-field MRI, and neuromorphic computing.

The principal scientific personnel consist of three career scientists, four term scientists, and two affiliates. The annual budget is $2.51 million, with 81 percent NIST-base funding and 19 percent split between non-base NIST and external contracts.

NIST has an in-house variable field nonclinical scanner and access to other clinical scanners in the Boulder and Denver area, including clinical commercial MRI systems and a small-bore 14 Tesla nuclear magnetic resonance (NMR) system at the University of Colorado. The group is installing a very-low-field, portable MRI system with 100 milliTesla capability to enable agricultural optimization studies of feed grasses.

Major improvements in space available to this group have occurred in the past 3 years with the opening of a new building and renovations of laboratory spaces needed for the specific goals of this and other groups (e.g., clean rooms).

Accomplishments

Physical Phantoms

Phantoms for breast imaging, conventional, and diffusion-weighted brain-imaging MRI have been fabricated and to some extent commercialized. These were developed in collaboration with the major MRI society, the Radiological Society of North America (RSNA), and the National Cancer Institute and the University of California, San Francisco, Medical Center.

The MRI Standards project develops "phantoms" (i.e., calibration structures) and validates quantitative imaging protocols. Its area of emphasis is on standards for cancer, brain, and multimodal imaging.

This work of the Magnetic Imaging Group is of global importance because the phantoms allow calibration and standardization work, which is vital to population studies and multicenter trials of proposed medical therapies where imaging endpoints are needed.

New work is under way on a phantom that would provide evaluation of diffusion-weighted imaging and nerve bundle tractography, where algorithm optimization is a major issue in neuroimaging of brain circuit connectivity.

The group envisages that future directions may focus on multimodal imaging, such as combine information from two or more imaging modalities—MRI, computed tomography (CT), positron emission tomography (PET), or ultrasound (US). These combined techniques, such as PET-Magnetic Resonance (PET-MR) or MR-US, necessitate the development of quantitative imaging protocols. These projects develop the calibration structures and quantitative imaging protocols with collaborators from academic institutions, professional societies (International Society of Magnetic Resonance in Medicine [ISMRM], RSNA), and where applicable, other federal agencies.

Biomarker Calibration Service

An excellent example of the sophistication and elegance of the NIST culture in calibration and standards is the service for calibration of contrast-agent proton-spin relaxation times,[5] which describes the calibration service as providing T1 and T2 relaxation times of materials used in phantoms in order to verify the accuracy of quantitative MRI measurements. The measurements are made at fields of 1.5, 3.0, and 7 Tesla and temperatures between 0 and 50°C, as specified by the customer. A unique aspect of NIST calibration is the careful attention to precise temperature control, because the community has not yet recognized that there is a 2 percent change per degree C in both T1 and T2 relaxation times.

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[5] M.A. Boss, A.M. Dienstfrey et al., 2018, *Magnetic Resonance Imaging Biomarker Calibration Service: Proton Spin Relaxation Times*, NIST Special Publication 250-97, U.S. Department of Commerce. Gaithersburg, Md., May.

Neuromorphic Computational and Simulation Systems

Three groups in the APD are engaged in development of systems that measure attributes of the human central nervous system. To understand how the human brain works, experiments investigate brain function and dysfunction. Neural systems that can operate 10 billion times faster than biological systems are intended to measure spatial and temporal correlations in high-density networks to understand memory and data processing.

This project utilizes superconducting single flux quantum (SFQ) and spintronics devices. The Magnetic Imaging Group has developed a stochastic model of magnetic Josephson junctions suitable for high-density neural simulations. The circuits allow most, if not all, known neurophysiology functions, including inhibition.

Ultra-Low Magnetic Field Instrumentation

Ultra-low field (0.1 milliTesla) scanners can serve major biomedical applications as well as for materials characterization. New magnetic imaging modalities are being developed, including magnetic particle imaging (MPI), electron paramagnetic resonance (EPR)-enhanced MRI, and micro-fabricated sensors and contrast agents visible in an MRI.[6] For example, the Magnetic Imaging Group is developing a plant root/soil imaging system that is expected to allow studies of the effect of climate, irrigation, fertilizer, and so on, on plant growth. The goal is to provide an image of roots in an intact soil column, using MRI with a very low magnetic field in order to avoid the magnetic susceptibility heterogeneity between plant tissues and various components of soils. These susceptibility differences lead to magnetic resonance signal-phase differences with the creation of large artifacts. The project is run by Texas Agricultural and Mechanical University (TAMU), and the instrumentation is led by a researcher at Harvard University. NIST is developing appropriate phantoms for the project, as well as doing some in-lab studies to advise some of the in-field work. The funding proposal to ARPA-E was $10 million; $4 million was made available. The goal now is to produce 15 MRI systems that can be implanted in the soil. The current instrument is copied after the Boston system and serves as a testbed to show any influences of the instrument on normal plant growth. The prototype is nearly ready for experiments.

The project is supported by ARPA-E and a collaboration with TAMU, with partners at the Athinoula A. Martinos Center for Biomedical Imaging in Charlestown, Massachusetts, and ABQMR, Inc., in Albuquerque, New Mexico.

Innovations in MRI In Vivo Sensors of Tissue Physiology

Work on MRI injectable "smart" agents is aimed at developing new micro- and nanoparticle-based contrast agents for magnetic resonance imaging and sensing schemes. The major benefit is that these sensors, plus MRI detection, do not suffer from attenuation of light photons and limitations of ionizing radiation; however, they do have the limitations of sensitivity inherent in magnetic resonance imaging and spectroscopy. The new agents include synthetic antiferromagnet nanoparticles. The high-moment iron microparticles provide enhanced T2* contrast for in vivo cell tracking. The radio-frequency-addressable sensor assemblies comprise pairs of magnetic disks with interstitial, swellable hydrogel material; these are able to reversibly reconfigure in rapid response to select stimuli and provide dynamic NMR spectral signatures that are geometry dependent. The sensors can be fabricated from biocompatible materials and are themselves detectable at low concentrations.[7] Applications include remote sensing of biological tissue mechanical stresses in human physiology research.

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[6] Adapted from NIST, "Advanced Magnetic Imaging Methods," https://www.nist.gov/programs-projects/advanced-magnetic-imaging-methods, accessed October 1, 2018.

[7] G. Zabow, S.J. Dodd, and A.P. Koretsky, 2015, Shape-changing magnetic assemblies as high-sensitivity NMR-readable nanoprobes, *Nature* 520:73-77.

Challenges and Opportunities

The Magnetic Resonance Group provides a vital service to the magnetic resonance clinical and research communities. Not only does this work on standards address the wide variations in MRI equipment performance from manufacturer to manufacturer, but from clinic to clinic and even day to day for the same manufacturer. The phantom systems allow not only physical system calibration but also allow evaluation of slight differences in pulse sequences, including radio frequency and gradient protocols so that algorithms may be optimized.

In addition to service, the group has launched projects where a national need is perceived and has taken on the challenge of investigating how its talents can provide solutions. Collaborations both within the division and outside NIST exist for every one of the seven groups (e.g. neuromorphic systems, imaging plant growth).

While instrumentation and space resources are excellent for most of the groups, the Magnetic Resonance Group is badly in need of a clinical-class MRI so that appropriate phantom design, as well as initial testing, can be readily accomplished without going to other sites. NIST has access to nearby clinical commercial MRI systems, but nonetheless might evaluate whether a clinical system of its own would improve productivity by eliminating wait times, provide opportunities for CRADAs and other partnerships that offset costs, and decrease costs that would otherwise occur using other clinical scanners in the area.

Productivity of the investigators is great in spite of sparse evidence of administrative support (e.g., no human resources staff in Boulder).

Sources and Detectors

The Sources and Detectors Group is an excellent example of the value that NIST brings to the scientific and industrial communities. The group uses its expertise to significantly advance the science of measuring light; it makes prototypes, such as detectors, for measuring light pressure from laser sources. In doing so, NIST reduces fundamental advances to practical instruments, and it provides essential service to outside entities in calibrating optical technologies that cannot be calibrated elsewhere with the required accuracy. From a technical standpoint, the group has made excellent advances, identified key challenges, and is planning for future approaches. The funding for this group is $4.11 million, with 11 percent from calibration for outside entities on a cost-neutral basis, making it highly valuable to external stakeholders in the true spirit of NIST. The group's expertise and personnel are highly qualified and productive.

Accomplishments

Examples of Sources and Detectors Group accomplishments include the following:

- The group's goal of advancing the science of accurately measuring optical power from very high to very low powers over wide wavelength ranges is laudable. This vision makes their current excellent advances applicable to an extremely wide variety of commercially significant applications. Their scope includes all properties of light, including phase, polarization, and spatial distribution.
- Measurements of mass tend to have errors that compound as the mass size is reduced. The group's approach is to break this condition when measuring optical power, such that measuring extremely low power will be accomplished by comparisons to single photons rather than by tracing back to the larger powers. This new approach makes the measurement errors more independent of power level. The science and impact of this work are highly significant.

- The group's advances in miniaturization of radiometry equipment are innovative. It has reduced the size and weight of many types of optical measurement equipment, with an increase in robustness and reduction in cost. This opens up many new avenues of deployment for optical metrology in the field, where it is most needed. One example is to place radiometry devices on small satellites. It has taken seriously the vision of NIST-on-a-Chip.
- Metrology science could benefit greatly by their work in tracing optical power back to the kilowatt. This can holistically tie together multiple different metrology subfields under a single paradigm.

Challenges and Opportunities

The group's equipment and facilities are outstanding, provide capabilities that are among the best in the world, and merit support at a high level so that it can remain a world leader.

It has hosted various impressive workshops in order to disseminate ideas, facilitate collaborations, and make available its capabilities and expertise.

Quantitative Nanostructure Characterization

The Quantitative Nanostructure Characterization Group currently performs four projects: atomic scale characterization, quantitative precision imaging facility (PIF), nanoelectromagnetics, and nanostructure synthesis. Personnel include seven FTEs, two post-doctoral researchers, and one graduate student. The annual budget is \$3.15 million, with 71 percent NIST base and 12 percent from service. A significant infrastructure for the group includes a cluster of four ion- and electron-beam imaging tools, near-field scanning microwave microscopy, and GaN MBE growth capability. The group is developing new atom probe tomography tools.

Accomplishments

The Quantitative Nanostructure Characterization Group has modified commercial instrumentation to obtain broadband microwave reflection and transmission measurements in the frequency range 1 to 17 GHz. This instrumentation has been used for sensitive defect localization in two-dimensional (2D) materials. In addition, the group has investigated carrier dynamics in 2D tellurene under electrically biased operation.

The group has assembled a sophisticated tool set cluster for ion- and electron-beam analysis of materials and structures. These tools are usually commercial instruments that have been modified by NIST investigators to make them at or ahead of the state of the art. NIST investigators have also used the cluster tools for projects that serve the twin purposes of proving the limits of the tools and of making original contributions to the art. Two excellent examples include transmission electron microscopy-based analysis of crystal phases at interfaces in rhenium– gold (Re+Au) superconducting films, and selective-area growth of GaN nanowires by MBE. Studies of the regrowth interface of these nanowires, grown in the NIST MBE chamber, yielded information on polarity differences in hexagonal GaN. The NIST LED nanowire device results have shown the need to consider these post-processing regrowth interfaces.

The group is extending atom probe tomography to include laser-assisted tomography and extreme atom probe tomography. Laser assistance has been used to trigger field evaporation and has been used in collaboration with the University of California, San Diego, to reveal Si incorporation in Hf-doped ZnO multilayers. The group is developing extreme atom probe tomography to eliminate the conventional laser and move to the extreme ultraviolet (EUV) regime, adding in situ transmission electron microscope analysis. This work has the potential to significantly advance the practical utility of atom probe tomography.

The technical programs in this group are strong and reflect development of sophisticated characterization tools that are among the best in the world. Although its mission is primarily development of these tools, its research contributions using these tools are strong and include a mix of collaborative research and unique NIST-based research.

The expertise within the group is diverse. The group's personnel have strong interactions with other scientists in the division and some effective collaborations outside NIST. The group's facilities, equipment, and human resources are adequate and balanced with respect to instrumentation development. Its research programs seem to be well coupled to stakeholder needs.

Challenges and Opportunities

There are two major challenges inherent in the mission of this group. The first is to continually push the state of the art of their unique characterization tools and processes in order to remain a world leader. At the same time, it is important to make the most of these capabilities while at the leading edge. There is, of course, tension between these challenges, because upgrading equipment often takes it out of service. Additionally, while there is significant collaboration, it could be increased. The group may benefit from broader collaborations on different materials systems, particularly with the atom probe tomography development. Validation and then commercial transfer of atom probe tomography could be accelerated.

As a potential provider of unique characterization, it is incumbent on the group to broadly articulate its expertise. The group participates in the normal avenues for dissemination—papers, patents, and presentations—and has a significant investment in workshops held locally.

PORTFOLIO OF SCIENTIFIC EXPERTISE

Overall, the review panel found APD's accomplishments and current leadership outstanding, as evidenced by the groups' activities and contributions. This progress is particularly noteworthy in view of the major changes in leadership and administrative posts since September 2017.

The visit left the panel with the clear impression that APD's principal investigators are competent scientists engaged strongly with external partners and with one another working at the forefront of their fields. The division has an impressive list of former alumni, some of whom are now leading principal investigators.

ADEQUACY OF FACILITIES, EQUIPMENT, AND HUMAN RESOURCES

APD's personnel resources have experienced major changes occasioned by the loss of 7 persons (of a total of 17) from leadership and administrative personnel since September 2017, including the division leader and one of the group leaders. Replacements in four areas have occurred with acting appointments, including the division leader, who has kept the division on a steady and progressive path of continuing high performance. An overall administrative concern in Boulder is the apparent absence of an onsite human resource support office and personnel.

DISSEMINATION OF OUTPUTS

Dissemination of APD outputs is through publications, conference presentations, interactions with other federal agencies (e.g., DARPA, DoD, Intelligence Advanced Research Projects Activity, and

ARPA-E), contracts with industry and university, and provision of measurement services (e.g., calibrations and standard reference data and materials).

Collaboration with universities and industry, as well as CRADAs and patents, are additional modes of dissemination. Other forms of dissemination are workshops, symposia, visiting science and engineering personnel, and the fact that many postdoctoral researchers and affiliates leave NIST to join industry and universities, as well as other government research organizations.

Information on involvement in the scientific community through leadership roles, recognition through awards, invited presentations, and international activities was not completely available at the time of this assessment, but members of this division had received national recognition for innovations. As part of the dissemination portfolio, an enhanced division-wide culture that values increased involvement in external professional activities, such as conference organization, journal editorships, and professional society governance, would lead to greater visibility for the investigators and NIST in general. These also lead to society fellowships, research awards, and other forms of recognition.

Accomplishments

The scientists in APD have placed highly cited publications in refereed journals, including two with over 400 citations in 2015;[8,9] one with over 300 in 2014;[10] and one with over 700 in 2013,[11] to pick just a few examples. More recent publications will likely accumulate comparable numbers of citations.

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[9] M. Giustina, M.A.M. Versteegh, S. Wengerowsky, J. Handsteiner, A. Hochrainer, K. Phelan, F. Steinlechner, et al., 2015, Significant-loophole-free test of Bell's Theorem with entangled photons, *Phys. Rev. Lett.* 115:250401.

[10] R.W. Andrews, R.W. Peterson, T.P. Purdy, K. Cicak, R.W. Simmonds, C.A. Regal, and K.W. Lehnert, 2014, Bidirectional and efficient conversion between microwave and optical light, *Nature Physics* 10:321.

[11] F. Marsili, V.B. Verma, J. A. Stern, S. Harrington, A. E. Lita, T. Gerrits, I. Vayshenker, B. Baek, M. D. Shaw, R. P. Mirin, and S.W. Nam, 2013, Detecting single infrared photons with 93% system efficiency, *Nature Photonics* 7:210.

4

Quantum Electromagnetics Division

ASSESSMENT OF TECHNICAL PROGRAMS

High-Performance Computing

The Quantum Electromagnetics Division (QED) has an active and externally visible program in quantum computing based on superconducting qubits. This activity leverages NIST's world leading expertise in superconducting electronics and the laboratory's many advances in the materials science of Josephson junctions. NIST plays an important role in materials development and analysis, working as a trusted partner to large corporate players in quantum computing, such as IBM. Recent device development at NIST benefits greatly from the well-equipped and well-utilized microfabrication facility. Fabrication capabilities are remarkable. Superconducting device fabrication capabilities are state of the art, and the basis for a broad range of activities across the laboratory. Responsibility for this capability rests within the QED. This is an important service to the entire Physical Measurements Laboratory. Development of quantum accurate arbitrary waveform synthesis in the gigahertz range is under way within the QED. If successful, this exciting project may find applications in qubit control. This project naturally combines NIST's expertise in quantum voltage standards and single flux quantum logic (SFQ). Through ongoing work in the QED, NIST is positioned to make important contributions to quantum computing for years to come.

Accomplishments

At the well-equipped, well-utilized microfabrication facility, superconducting device fabrication capabilities are state of the art and the basis for a broad range of activities across the laboratory.

Challenges and Opportunities

Development of quantum accurate arbitrary waveform synthesis in the gigahertz range, if successful, may find applications in qubit control.

Quantum Computing

Accomplishments

This group is developing capabilities to verify novel developments from researchers in this field. In addition, the new microfabrication facility is enabling creation of novel devices that optimize performance.

Opportunities and Challenges

In view of the significant efforts from sizeable groups working at IBM and Google, as well as at academic institutions, NIST recognized that it should not be aiming to develop large-scale efforts that would compete with these other sectors. Instead, the group is developing capabilities to confirm performance of devices from these other groups, as is appropriate for a standards group.

Superconductive Electronics

The Superconductive Electronics Group maintains direct current (DC) and alternating current (AC) voltage standards based on the Josephson effect. The Josephson junction's quantization of magnetic flux make it an ideal frequency-to-voltage converter. Frequency is among the most precisely defined of quantities, an attribute that enables a very precise voltage standard.[1]

To realize a voltage standard requires synchronous operation of a large number of junctions in series. This is accomplished in part using the resources of the excellent microfabrication facilities that are managed by the QED. Recent advances in voltage standards have been enabled by the development of new material systems that produce better Josephson tunnel junctions. The enablers of these developments included the modernized clean room facilities at NIST.

NIST has used its apparatus developed for electronic measurements of Boltzmann's constant in the development of a fundamental method to measure temperature without using fixed points and extrapolation. This work will harness the Josephson quantum AC voltage generator that has recently been developed by the same group.

Using the advanced thin-film facilities of the new clean room, the group has developed an improved material, niobium-doped silicon, for the Josephson tunnel barrier. This allows more reliable production and more reproducible and precise operation of the voltage standard. Moreover, work in the Spin Electronics group has further modified the manganese-doped silicon barrier material with magnetic inclusions to allow incorporation into novel magnetic random-access memory (MRAM) nanodevices. This synergy of the materials development was a benefit of both the new facilities, and also of the cross-fertilization within the division.

Accomplishments

The group has realized a programmable DC voltage standard that has demonstrated accuracy to nine parts in 10^{12}, has been disseminated to national metrology institutes (NMIs) around the world, as well as to U.S. military primary standards laboratories, 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. Its synthesizers can perform this function from audio to microwave frequencies with the exceedingly small harmonic distortion implicit in a frequency standard.

The group has also played a key role in the electronic measurement of Boltzmann's constant, in anticipation of its conversion from a measured to a defined quantity.

Additionally, the group has developed niobium-doped silicon for the Josephson tunnel barrier, enabling more precise operation of the voltage standard.

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[1] Adapted from National Research Council (NRC), 2016, *An Assessment of the National Institute of Standards and Technology Physical Measurement Laboratory—Fiscal Year 2015*, The National Academies Press, Washington, D.C.

Opportunities and Challenges

The apparatus that NIST has devised for electronic measurement of Boltzmann's constant will have immediate application in advancement of the measurement of static temperature, which will concomitantly be unhooked from its current definition utilizing specific physical conditions, such as the triple point of water.

Quantum Sensors

The Quantum Sensors Group develops detectors and readouts used in millimeter-wavelength astronomy, and for x-ray spectroscopy. The latter NIST-produced devices are used in various x-ray beam lines, with x rays generated from circulating electrons that produce intense synchrotron radiation. The group is the leading supplier in the United States of both of these and is the dominant supplier of the complex Semiconducting Quantum Interference Device (SQUID) readouts used to read out the detector signals, usually with time-domain multiplexing.

The future needs in millimeter-wavelength astronomy will be for even larger detector arrays in the instrument focal plane, moving from the present ≈10,000 or so elements to an order-of-magnitude or more detector elements. This will likely require a more highly multiplexed readout. This can be most efficiently accomplished with a newer kind of millimeter-wavelength detector, the Microwave Kinetic Inductance Detector (MKID)—a detector with which the Quantum Sensors Group has experience. A very large number of detector elements can be read out with one on-chip microwave line, using a microwave frequency comb generated and de-multiplexed by room-temperature electronics. This allows a small and practical number of microwave lines between room temperature and the cryogenic environment.

Accomplishments

The group's detectors and readouts are used in millimeter-wavelength astronomy and in detection of individual soft x rays. The users in the astronomy community of the millimeter-wavelength range, and in the materials analysis, communities using soft x rays, are very well served by these detectors.

Opportunities and Challenges

The future needs for detectors in millimeter-wavelength astronomy applications can be most efficiently accomplished with the Microwave Kinetic Inductance Detector (MKID). Development of the latter is in its beginning stages at NIST, and the development and integration of such superconducting detectors is a significant skill of the NIST group.

Spin Electronics

The Spin Electronics Group is concerned with the frontiers of measurement of magnetic devices and phenomena essential to small-scale and high-frequency spintronic devices. MRAM is an example of such devices. (As discussed above, in the section, Superconductive Electronics, the Group has further modified the manganese-doped silicon barrier material with magnetic inclusions to allow incorporation into novel MRAM nanodevices.) MRAM has been an also-ran contender for computer memories for decades, even though it is superior to the semiconductor dynamic random-access memory (DRAM) by being nonvolatile and by being faster and superior to flash memory because it's fatigue-proof. It also attracts interest due to its being radiation resistant. A perennial problem with such devices has been scaling with respect to write current—current density did not scale downward properly as device size was decreased. This dilemma has now changed with the invention of spin-torque writing, which improves as devices get smaller. MRAM is now a hot topic for future high-performance, low-power computers.

The projects in this group span the gamut from basic physics to the understanding of (external-partner-produced) devices' defects and error performance. The group's expertise in high-frequency and nanoscale measurements and its partnerships with industry and universities afford it a unique advantage for advancing the art in this rapidly growing field. The staff have a fine mix of laboratory skills and physical understanding. The creativity found on the laboratory tours was noteworthy.

Accomplishments

The new e-beam tool in the clean room makes it possible to produce test samples in the 10 nm range, which, while below the range of interest for Josephson devices, are perfectly relevant for memory chips.

Opportunities and Challenges

The invention of spin-torque writing, which improves as devices get smaller (i.e., as they scale), makes MRAM a promising topic in the development of future high-performance, low-power computers.

Spintronics

The QED supports a successful program focused on non-Boolean spintronic computing; spectroscopic measurement of spin-charge transduction; and magneto-optical measurements of spintronic materials. (These activities are carried-out in the Spin Electronics Group and the Nano-scale Spin Dynamics Group.) In this area, the division impressively balances core activities in measurement development with simultaneous production of exciting new results in the fundamental science of magnetism. For example, experiments employing the ferromagnetic resonance (FMR) world-record sensitivity, developed within the group, have identified ultra-low damping in binary compounds of cobalt and iron. The Nano-scale Spin Dynamics Group has also used inelastic photon-magnon scattering (Brillouin light scattering) to study the relationship between interfacial Dzyaloshinskii-Moriya interaction (DMI) and Heisenberg exchange interactions in thin metal films, demonstrating for the first time their proportionality. The development of heterodyne magneto-optic microwave microscopy within the group holds promise to interrogate magnetic properties of individual nano-magnets as small as 10 nm. The group is also collaborating with faculty at University of Colorado to build a system for time-resolved extreme-ultraviolet magneto-optics for time-resolved studies of spin dynamics in magnetic multilayers. This is a wise combination of local expertise to develop a new probe of magnetic systems that will surely yield new information.

The aforementioned development of measurement techniques are great examples of how NIST's core mission also generates understanding of key physical mechanisms underpinning the operation of technologically important materials.

Accomplishments

The Nano-scale Spin Dynamics group has utilized FMR with world-record sensitivity to identify ultra-low damping in binary compounds of cobalt and iron. The group demonstrated the proportionality of the relationship between interfacial Dzyaloshinskii-Moriya interaction (DMI) and Heisenberg exchange interactions in thin metal films, using inelastic photon-magnon scattering (Brillouin light scattering). While the research thrust in quantum computing is visible both within NIST and externally, the quality of the work in the area of spintronics also deserves recognition and strong support from NIST.

Opportunities and Challenges

The group's development of heterodyne magneto-optic microwave microscopy will, if successful, facilitate experiments that interrogate magnetic properties of individual nano-magnets as small as 10 nm. A further area of promise is the development, with University of Colorado, of a system for time-resolved extreme ultraviolet magneto-optics for time-resolved studies of spin dynamics in magnetic multilayers.

Optical Medical Imaging

The Optical Medical Imaging Group is providing standardized benchmarks, known as phantoms, for state-of-the-art biomedical optical imaging techniques. The group has developed a layered phantom for optical coherence tomography (OCT), a widely used tomographic technique for imaging the layers of the retina to find disease. There is a significant lack of imaging standards by which these instruments are calibrated. The group has demonstrated fabrication using techniques developed in-house and is preparing to disseminate the phantoms by offering them for sale. Another phantom is under development for photoacoustic tomography (PAT), a recently developed technique that enables depth-resolved imaging of hemoglobin through thick tissues by combining the biochemical specificity of light absorption with the deep penetration of ultrasound. The phantom is based on creating precision distributions of carbon nanotubes, which offer uniform absorption across the visible spectrum. This phantom is in a developmental stage and will likewise provide a much-needed standard for researchers developing PAT instrumentation. A third area of emphasis is to develop a phantom that can be used to calibrate measurements of hemoglobin oxygen saturation. The group possesses a state-of-the-art hyperspectral imaging system, which will enable its development. This is a much-needed resource across the field, as it can be quite difficult to create accurate oxygen saturation distributions.

Accomplishments

Responding to a national need for standardized imaging benchmarks, the group has developed a layered phantom for OCT and begun dissemination.

Opportunities and Challenges

The group is developing a phantom to serve as an imaging standard for PAT. It is likewise developing a phantom that can be used to calibrate measurements of hemoglobin oxygen saturation. Both these endeavors respond to the need for instrument calibration to be standardized across research groups nationwide.

Remote Sensing Laboratory

The Remote Sensing Laboratory Group is conducting measurements of atmospheric gasses, such as carbon dioxide and methane, using differential absorption LIDAR. This is an important area of research, but there seems to be a disconnect with its application to environmental monitoring between the monitoring and sensing tasks, on the one hand, and the environmental impact, on the other. The group employs unique sensing capabilities such as the use of high power, multi-frequency tunable laser lines to monitor atmospheric gases with high sensitivity and specificity. They have implemented an impressive gantry on the fifth floor that enables them to conduct these measurements. This new facility is still under renovation but will provide a suitable site with rooftop access for continued research.

Accomplishments

The group is using the technique of frequency combs to develop unique sensing capabilities and has implemented an impressive gantry as platform for these unique measurements.

Opportunities and Challenges

The environmental monitoring researchers need to establish clearer linkages between the sensing and monitoring tasks that detect atmospheric constituents and the imputed environmental impacts.

Boulder Microfabrication Facility

As noted in the 2015 review,[2] 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.[3] The recently added e-beam lithography tool has allowed greatly enhanced resolution (below 10 nm), which is essential for magnetic sensors and devices.

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

An innovation at the BMF, is its unique and successful scheme for handling fabrication requests. Instead of allowing numerous amateurs in the clean room, which would degrade it, or going to a full-service system, which would swamp it with sample requests and billing nightmares, the group instituted a system whereby a small, dedicated staff works with super-users from the requesting groups who help maintain the tools essential to their own projects. Among other things, this has kept the facility working at near-optimal capacity while turning out thousands of extremely useful sensors, programmable Josephson arrays, and test samples. One measure of that operational success is that they are making magnetic-atom-doped spin-torque oscillators in the same facility as yield-critical Josephson arrays, without mishaps and with collegiality between groups.

The new clean room has been key in allowing production of the large (150 mm) wafers that are essential in current and future astronomy projects. The cross-fertilization of the thin-film materials ideas has been notable, and likely is facilitated by the flexibility of the clean room equipment and the non-rigid arrangement of user/maintainer people.

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[2] National Research Council, 2016, *An Assessment of the National Institute of Standards and Technology Physical Measurement Laboratory—Fiscal Year 2015*, The National Academies Press, Washington, D.C.

[3] NRC, 2016, *An Assessment of the National Institute of Standards and Technology Physical Measurement Laboratory—Fiscal Year 2015*.

Accomplishments

The group has maintained the microfabrication facility's impressive capabilities, adding e-beam lithography tool has allowed greatly enhanced resolution (below 10 nm), essential for magnetic sensors and devices. They have kept the facility working at near-optimal capacity while turning out thousands of extremely useful sensors, programmable Josephson arrays, and test samples.

Opportunities and Challenges

Continuing the cross-fertilization of the thin-film materials ideas represents an opportunity, and likely is facilitated by the flexibility of both the clean room equipment and the users and maintainers.

General Comment

This division has commendably maintained continued focus on standards and calibration devices, in spite of the siren song of doing basic science and technology research. The numerous projects that reflect this core responsibility of NIST are very well served in the projects that were reviewed. Who would do them properly if NIST didn't?

PORTFOLIO OF SCIENTIFIC EXPERTISE

The QED is best in the world with respect to Josephson standards and also millimeter-wavelength astronomy detector arrays. The large testing capabilities at NIST are fully appropriate for almost all near- and medium-term astronomy applications in ground-based observatories. These observatories employ the same kind of large cryogenic systems that are at NIST.

The technical programs reviewed are at the leading edge of measurement and are adequate to meeting their stated goals. While the program in quantum computing is visible both within NIST and externally, the quality of the work in the area of spintronics deserves similar recognition and strong support from NIST.

The quantum computing effort is a partnership with large industrial teams and is also externally visible in its own right through its publications and conference presentations. The QED works to understand the material science needed for highly coherent qubits. This is a valuable service to the community. It appears well-coupled to stakeholders. The Spintronics Group also performs within several large-scale collaborations with industrial partners, providing valuable service to the community. It also has an impressive record of high-profile publications originating at NIST, which further amplify the group's impact. The Spintronics Group deserves recognition as it seems to couple to stakeholders needs and generate high-quality science in equal measure.

The Quantum Computing and the Spintronics groups have strong technical expertise within their ranks. The Spintronics Group appears to have a broad range of measurement expertise. The Quantum Computing Group's core expertise is in material science of materials used for quantum computing. It is also involved in device design and circuit testing. As currently configured, the group is well positioned to perform as a collaborator on large-scale quantum computing programs of the sort typically led by larger players in industry and academia. This is a strong position for NIST.

The QED has a good mix of experts, both senior and more junior. Recent retirements have been manageable, and the more junior researchers are also impressive. Being located in Boulder appears to be an advantage in attracting new staff.

FACILITIES AND EQUIPMENT

The QED facilities at NIST are among the best in the world, with the exception of the physical state of the older buildings. The clean room facility is state of the art and well run. It is the cornerstone of much of the division's success in quantum computing voltage standards, and spintronics. The measurement laboratories appear to be well-equipped with the latest technology. The laboratory space is adequate in size, but improvements need to be made in environmental control. A bucket in a hallway catching rainwater, observed during the laboratory tour, was a reminder that the older buildings were built a half-century ago.

The new clean room has been key in allowing production of the large (150 mm) wafers that are essential in current and future astronomy projects. The cross-fertilization of the thin-film materials ideas has been notable and likely is facilitated by the flexibility of the clean room equipment and the non-rigid arrangement of user/maintainer people.

Accomplishments

The QED has maintained the microfabrication facility's impressive capabilities, and adding the e-beam lithography tool has allowed greatly enhanced resolution (below 10 nm), essential for magnetic sensors and devices. The facility has been working at near-optimal capacity while turning out thousands of extremely useful sensors, programmable Josephson arrays, and test samples.

Opportunities and Challenges

The environmental controls in the laboratory space need to be improved. The aging facilities have problems with the building envelope, such as the observed roof leaks.

DISSEMINATION

Dissemination of outputs varies (appropriately) by project. Standards projects are expected to have infrequent publications aimed at a small and focused audience. Device and physical phenomena projects are of much wider interest and require conference and journal publication. Patent applications and patent-protective publications have been inadequate and seem to require a more pro-active policy by management. However, unlike journal publication, which is subject to peer review and subsequent citation count, patent activity and its resulting impact are difficult to evaluate in the short term. It is easy to stimulate an increased number of worthless patent applications. Therefore, the QED would benefit from increased guidance in this area.

The division has demonstrated laudable use of guest scientists, students, postdoctoral researchers, and visiting researchers as a way of increasing technical vitality and spreading NIST expertise and knowledge to the outside world. It broadens the impact of their device and technique advances, especially in astronomy, where there is a large U.S. community that will benefit by learning more, in a hands-on fashion, than is accomplished from reading publications about microfabrication. The posting of a Stanford University graduate student to the device fabrication group is a good example of how such technology transfer can be done to benefit both sides.

Accomplishments

The division's use of guest scientists, students, postdoctoral researchers, and visiting researchers increases both its technical vitality and the spread of NIST expertise and knowledge to the outside world.

Opportunities and Challenges

The division would benefit from increased guidance on the value to NIST of its patent activity vis-à-vis journal publications and other metrics.

5

Time and Frequency Division

INTRODUCTION

The Time and Frequency Division (TFD) is located in Boulder, Colorado. The division has 121 staff, including 8 administrative support; 40 NIST scientists; 70 associates (postdoctoral researchers, graduate and undergraduate students, and visiting scientists); and 3 emeritus scientists.[1] The annual budget is $22 million, 23 percent of which is sourced from other agencies.

Disseminating accurate and reliable time and frequency information is a core responsibility of NIST and the core responsibility of the TFD. Accurate time and frequency services are critical to areas of the U.S. economy, such as coordination of the phase of electrical power generation for the smart grid, the Global Positioning System (GPS), synchronization of computer networks, time stamping of financial transactions, and national security and research. The TFD, in coordination with the U.S. Naval Observatory, is responsible by law for disseminating time throughout the United States to all stakeholders.

ASSESSMENT OF TECHNICAL PROGRAMS

Time and Frequency Services

NIST disseminates time signals based on the coordinated universal time (UTC) time scale, the internationally generated scale that is coordinated by the International Bureau of Weights and Measures in France. UTC is not available for dissemination, and therefore NIST employs UTC1, a version of UTC that is controlled by two atomic frequency standards, NIST-F1 and NIST-F2. These employ fountains of laser-cooled cesium atoms that are interrogated by microwaves and have fractional uncertainty in their generation of the SI second of 1 part in 10^{16}. NIST-F1 and NIST-F2 (along with the NIST-F2 copy housed at Italy's National Metrology Bureau) are the world's most accurate frequency standards.

The time scale UTC1 is generated by an ensemble of about 10 commercial atomic clocks (mostly hydrogen masers). The "tick rate" of this ensemble is calibrated against NIST-F1 and NIST-F2 every few months, permitting UTC1 to be steered to UTC. This system operates effectively, efficiently, and reliably.

Time must be disseminated continuously and in a variety of forms depending on the need. A measure of the value of the service NIST provides in dissemination is the 40 billion synchronization requests it serves each day. The primary methods for disseminating time and frequency are the following:

- For the most stringent requirements, NIST provides frequency uncertainty of 1 part in 10^{13} and time uncertainty of 1 nanosecond, using specialized black-box devices that NIST makes available to the user. NIST uses telecommunications and GPS satellites to broadcast time and frequency to such devices. These are the only such remote time and frequency measurement

[1] Chris Oates, National Institute of Standards and Technology, Physical Measurement Laboratory, "Division 688: Time and Frequency," presentation to the committee, May 1, 2018.

services in the world at this level of precision and accuracy and are used by about 50 high-tech companies.

- For broad public use, NIST broadcasts time and frequency information by radio on station WWVB, with a frequency stability of 1 part in 10^{11} and time uncertainty of 1 microsecond. Signals are broadcast at different frequencies for purposes ranging from synchronizing wall clocks and wristwatches to high-precision scientific experiments.
- The Internet Time Service (ITS) synchronizes computers and network devices to NIST time with an accuracy of about 1 millisecond and is used billions of times per day. ITS is the most heavily used network time service in the world and is built into all major computing operating systems (e.g., Windows, Apple, and Linux).

For their respective applications, these three primary methods of time distribution are widely regarded as among the best in the world.

Optical Frequency Metrology and Ion Storage

A New Generation of Frequency Standards

A revolution in metrology is under way, enabled by the invention of the optical frequency comb and the development of trapped ion and atom lattice optical clocks.

NIST's TFD is a leader in all of these developments. The optical frequency comb was created by John Hall in the Quantum Physics Division (JILA) and Theodor Hänsch in Garching, for which they received the Nobel Prize in 2005. David Wineland of the Ion Storage Group received the Nobel Prize in 2012 for developing the trapped ion technique. There has been major progress in time and frequency metrology since those prizes were awarded.

The optical comb makes it possible to read out optical signals with the same facility that microwave, and lower, frequencies can be manipulated. Its creation opened the road to the development of frequency standards that operate at optical frequencies. The advantage of optical frequencies is that they are 100- to 1,000-times higher than the microwave frequencies of current frequency standards, permitting a corresponding decrease in uncertainty. The advances in high-precision time metrology at the TFD have been rapid.

One of the new generation of optical frequency standards employs ytterbium atoms trapped and cooled in an optical lattice. The ytterbium optical standard has achieved a world-record uncertainty of a few parts in 10^{19} after several hours of observation. Two independent ytterbium lattice frequency standards were constructed within the TFD and compared, confirming that they agree to better than 1 part in 10^{18}. A second type of standard is based on a single-trapped and cooled aluminum ion. The ion is interrogated by entanglement with a co-trapped beryllium ion using quantum logic protocols pioneered at NIST. A third type of optical standard with comparable uncertainty, based on strontium atoms trapped and cooled in an optical lattice, was created at JILA. These three standards have the lowest uncertainty in the world, and the fact that all three co-exist within the same institution enables unique studies. For example, direct comparison between these frequency standards constitutes one of the most sensitive tests of the invariance of fundamental constants.

The problem of transmitting time signals and comparing frequency standards in this new regime of precision poses a serious challenge. Comparisons in the same laboratory are relatively straightforward, but the problem of comparisons at large distances remains to be solved.

Compact Frequency Combs

Frequency combs are a crucial component of optical clocks, making it possible to compare clocks and to generate outputs at chosen frequencies. They also enable a host of additional applications in precision signal generation and measurement. For example, TFD researchers have applied combs to generate 10 GHz microwave signals with the smallest low-frequency phase noise ever reported. Because sensing slow motion requires low phase noise, this advance is important for radar detection of slowly moving objects. The original combs involved mode-locked lasers. These are bulky and power-hungry laboratory devices that are unsuited for many commercial and military applications. Also, the frequency spacing of their comb lines is too small for some important needs.

TFD researchers have investigated alternative approaches that overcome both problems. One frequency comb alternative uses micro-resonators that are small, require little power, and are well suited to portable operation; some realizations are compatible with integrated silicon photonics. The TFD is among the most active laboratories, both in elucidating the science of micro-resonator frequency combs and in developing them for applications, with an emphasis on those central to time and frequency—for example, chip-scale atomic clocks (CSAC), low-phase noise microwave generation, and precision optical frequency synthesis. In another alternative approach, TFD researchers have developed electro-optic combs (combs generated via strong-phase modulation of a single-frequency input laser) for broad optical bandwidth while maintaining low-phase noise. Recently, they have installed a portable version of their electro-optic comb at the 10-meter Hobby-Eberly telescope in the McDonald Observatory in Texas, where it provides precise astronomical spectrograph calibration with application to the search for exoplanets.

Accomplishments

The advances in high-precision time metrology at the TFD have been rapid. Two independent ytterbium lattice frequency standards were constructed within the TFD and compared to confirm that they agree to better than one part in 10^{18}.

Opportunities and Challenges

The definition of the SI second is exactly 9,192,631,770 cycles of the unperturbed ground-state hyperfine transition in the cesium-133 atom. The second can be realized in practice only to the limit of the accuracy of the cesium atomic clocks, currently 1 part in 10^{16}. This is widely regarded as the limit for cesium-based frequency standards, but it is far below the stability and accuracy already demonstrated for optical clocks. To take advantage of the hundred-fold improvement in determination of time and frequency that has been enabled by optical clocks, the SI second must be redefined. There are plans to do this in about a decade, but several significant challenges must first be overcome.

The first challenge is to create and select the best practical optical frequency standard. Several types have already been demonstrated, and others may yet be created. The task of turning these laboratory devices into practical frequency standards is enormous, but work is under way. For instance, the TFD is constructing a portable ytterbium optical lattice clock that can be physically moved to other locations for local clock comparisons with laboratories throughout the world. One can reasonably look forward to advances in making ion and atom-lattice clocks practical.

The problem of transmitting time signals and comparing frequency standards separated by long distances remains a challenge. The second challenge is to develop methods for distributing time over long distances at the new levels of accuracy. Presently, NIST employs the GPS system and two-way microwave satellite time and frequency transfer to synchronize NIST time with UTC. These techniques are suitable for time coordination at the level of 1 part in 10^{16}, but they are not adequate for the future.

The TFD is seriously engaged with the problem. In collaboration with the Applied Physics Division, it has carried out studies using optical fibers to transfer frequency and has demonstrated stability and accuracy at a few parts in 10^{19} over distances of a few hundred kilometers. (Time transfer has been demonstrated over distances of up to about 10 km with a similar level of degradation.) This accuracy would be sufficient to coordinate UTC at the 1 part in 10^{18} level that will be required in the future. They have demonstrated similar stability and accuracy of time and frequency transfer using laser beams propagating through free space over distances of a few kilometers. The challenge for extending either fiber- or free-space techniques to intercontinental transfer is formidable. Future experiments with longer distance fiber networks and free space time/frequency transfer are essential for taking advantage of the levels of precision being provided by the new generation of optical frequency standards.

A final challenge to the redefinition of the second is gravity, which is a nuisance, an opportunity, and a dilemma. Near Earth, gravity causes time to change by about 1 part in 10^{18} per centimeter of altitude, as predicted by General Relativity. The effect is already significant for metrology: corrections for it had to be made in high-precision comparisons of frequency standards in NIST's own laboratories, some of which are separated by 4 km. For large distances, the problem is severe. Altitude is essentially the distance above the geoid, a hypothetical surface of constant gravitational potential. Because of fluctuations in Earth's mass distribution, the geoid fluctuates by millimeters or more over periods of a day or less, and by centimeters over periods of longer than a month. The new generation of frequency standards and clocks will be sensitive to these fluctuations.

In preparation for clock comparisons at large distances, NIST carried out a geodetic survey of its campus and its laboratories at JILA (separated by about 4 km) to facilitate comparisons of clocks in those locations.[2] The survey achieved a precision that corresponds to a frequency uncertainty at the level of approximately 5 parts in 10^{18}, somewhat larger than the estimated uncertainty of the test clocks. At very large distances, one would expect the geodetic precision to be even lower. Furthermore, as noted above the geoid is known to fluctuate at this level. This implies that ultimately it will not be possible to transfer terrestrial time and frequency information with the accuracy of forthcoming frequency standards. The underlying problem is that at such a level of precision, time is inextricably coupled to the gravitational field. It would be natural to reverse the logic and use frequency standards as a tool for geodesy, a step that is being mentioned increasingly. This offers the possibility of opening new pathways for geodesy. This could have important applications, but it does not solve the problem of time transfer.

The ultimate significance of the new regime of frequency accuracy is that it forces a confrontation between the concepts of space, time, and mass. Clocks cannot be compared without knowing the distribution of nearby mass. The problem could be avoided by requiring that clocks be compared close to the same location. This procedure would necessarily introduce some imprecision. More seriously, it requires giving up the fundamental concept of space, time, and mass as independent physical quantities.

Such a situation has occurred once before. Space and time are now joined by the definition of the speed of light, c. The meter is the distance traveled by light in the time $1/c$. Formally, we refer not to space and time but to space-time. With gravity entering the picture, space-time and mass are joined by General Relativity. There is, however, a dramatic difference between the issues of space-time and space-time-gravity: the speed of light, which connects space and time, is the most precisely measured fundamental constant, whereas the gravitational constant, G, which connects mass to space-time, is the least precisely known constant. Consequently, it is difficult to visualize a metrological procedure that involves G. This problem must be resolved in the process of redefining the SI second.

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[2] N.K. Pavlis and M.A. Weiss, 2017, A re-evaluation of the relativistic redshift on frequency standards at NIST, Boulder, Colorado, USA, *Metrologia* 54:535.

Atomic Devices and Instrumentation Group

Chip-Scale Atomic Sensors: NIST-on-a-Chip

The Atomic Devices and Instrumentation Group (ADIG) was founded in 2008, with its precursor elements having had a role in developing the chip-scale atomic clock (CSAC) under Defense Advanced Research Projects Agency (DARPA) funding. This stimulated the military and telecommunications industry to develop a new class of small and relatively inexpensive metrological instruments that are described under the rubric of NIST-on-a-chip, a NIST-wide initiative to which the ADIG is a contributor and PML the lead. One class of the proposed chip instruments involves metrological tools based on accurate representations of SI base units such as length, electric current, temperature, luminous intensity, and, of course, time. Common to these applications is a vapor cell under development at ADIG that may be able to provide length (meter), electric current (ampere), temperature (Kelvin), luminous intensity (candela), and time (second). Another innovation within the group involves chip-scale inertial sensors that would take over when GPS becomes unavailable. Such devices have the potential to make high precision widely available without the user needing to turn to NIST to assure calibration. Design goals emphasize miniaturization and portability. Manufacturing would employ micro-fabrication techniques to achieve high-volume production that would decrease costs. The chip-scale magnetometers developed by the ADIG are now widely used in industry.

Accomplishments

The ADIG has made important contributions to the vapor cell metrological tool—which provides numerous measurements such as that of length, electric current, and so forth—resident in NIST-on-a-chip.[3] The group is also developing a novel chip-scale inertial sensor.

PORTFOLIO OF SCIENTIFIC EXPERTISE

NIST is widely regarded as the world's leading time standards laboratory. Reasons for this include its long history of atomic clocks—the atomic clock was invented at NIST—and the tradition of carrying out time-keeping activities in an atmosphere of frontier research, a tradition of excellent management that permits the TFD to attract and retain outstanding talent, excellent facilities, and adequate resources. NIST's TFD has a culture in which routine operations are constantly analyzed and improved. For example, research on the effect of blackbody radiation on the primary frequency standards resulted in a significant reduction in their fluctuations. Furthermore, NIST has a culture of collegiality that encourages a free flow of ideas between the various groups within the TFD, with other divisions throughout the PML, and with the many visiting researchers and students. Ultimately, these visiting researchers and students are NIST's most effective envoys for spreading the new knowledge and technology to the broad community.

FACILITIES, EQUIPMENT, AND HUMAN RESOURCES

The TFD is primarily located in the new Katharine Blodgett Gebbie Laboratory Building in Boulder. This building has superb facilities. The equipment is judged by the staff to be adequate for the TFD's needs. Some of the work is located in Wing 5, which is slated for renovation in the coming year

[3] For a discussion of atomic vapor cells, see National Institute of Standards and Technology (NIST), "NIST-on-a-Chip: Atomic Vapor," https://www.nist.gov/pml/nist-chip-atomic-vapor, accessed July 10, 2018.

with a predicted completion date of 2021. Once Wing 5 is renovated, all the facilities will be adequate. PML envisages the renovation as closing the gap between its "world-class lab space" and its 1960s-era space.[4]

Judged by the presentations, the quality of conversations with staff members, and the scientific output of the TFD, the quality of the staff is outstanding. Further evidence for the quality of scientific expertise is provided by their honors. These include numerous awards from the Institute of Electrical and Electronics Engineers, NIST's Condon and Astin awards, fellowship in the American Physical Society, and others. Their publications appear in the most prestigious scientific journals and are more numerous and impactful than publications from similar national time and frequency metrology laboratories around the world. The scientific atmosphere, facilities, and staff at NIST attract luminaries, visiting scholars, postdoctoral researchers, and students, who contribute significantly to NIST's programs.

The human resources appear to be well matched to TFD's needs.

DISSEMINATION AND TECHNOLOGY TRANSFER

At the top of TFD's agenda is the dissemination of time and frequency, an enormous responsibility that it meets at the highest level. However, the TFD provides many other services to the community: it performs 500 to 600 calibrations per year—for example, precision phase-noise calibrations at a level unique in the world; it provides calibration equipment and specialized services directly to about 50 industrial firms, which greatly reduces calibration time for industry and reduces the calibration burden on the TFD; and it helps industry to develop new products such as the chip-scale atomic clocks, magnetometers, and phase noise test equipment.

Accomplishments

The TFD has an outstanding record of sharing its scientific and technical advances and stimulating new industries for commercial, military, and scientific use. For example, today CSACS are in use for important military applications, and about 100,000 CSACS are used commercially with sales of about $100 million in telecommunications systems, seismic exploration activities, and other areas. In a closely related technical development, chip-scale magnetometers are now widely used by the oil industry. The magnetometers are also being applied in medicine, making magneto-encephalography a practical diagnostic tool that has been commercialized by a number of companies.

In another application, the TFD, working with external collaborators, has developed a compact and portable version of a laser-cooled microwave frequency standard. This was created through partnership with a nearby small company, Spectradynamics. The device was funded in part through a DARPA Small Business Innovation Research grant and is near commercialization.

Opportunities and Challenges

Notwithstanding these remarkable successes, there are some issues related to the commercialization of NIST-on-a-chip. Given that people from NIST, especially in the TFD, are the strongest evangelists for the NIST-on-a-chip concept, and given the success of their vapor-cell-based CSAC and miniature atomic magnetometer efforts, both of which have been commercialized, NIST is arguably in the best position to develop the concept to a level to where industry would take over. While NIST is adept at working the science of this initiative, there are questions regarding how far they are

[4] Chris Oates, NIST, Physical Measurement Laboratory, "Division 688Time and Frequency," presentation to the committee, May 1, 2018.

prepared to do the engineering needed to make the product viable for development. Perhaps more important than solving the scientific problems is the need to realize the control mechanisms and packaging around the science that assure low power consumption and low cost. Much of the work needed might be most appropriate for engineers, particularly those skilled in microelectromechanical systems (MEMS).

NIST-on-a-chip is somewhat new territory for NIST; its success requires a much higher volume product output than previous NIST outputs. NIST will probably need to court companies unlike the low-volume, timing- and frequency-control companies that speckle their past. Companies familiar with MEMS technology will likely be most appropriate for NIST-on-a-chip, and these companies will require some amount of convincing to jump on the NIST-on-a-chip bandwagon. If this requires that NIST take NIST-on-a-chip closer to a product than previously needed, using more MEMS and integrated circuit technology, then they may need to invest in engineering talent. In particular, although the current NIST staff seems happy to do the needed science, they perhaps are not as interested in undertaking the needed engineering. With a new cleanroom fitted with nanofabrication technology, NIST has equipment appropriate to do the engineering itself.

Another approach might be to (continue to) rely on companies or academic institutions proficient in MEMS technology and integrated circuit design to do the necessary engineering. This approach, however, would likely require more support from NIST, not only on technical fronts, but political and financial, as well. Specifically, NIST might need additional funds to direct to technology transfer sites. Alternatively, the local NIST-on-a-chip evangelists might need to focus their convincing arguments on funding agencies that can direct funding to companies interested in commercializing NIST-on-a-chip. This issue is important to consider.

A major emphasis of the TFD is transfer of scientific and technical knowledge through training its many students, postdoctoral researchers, and visiting workers, as well as through publications, talks, seminars, and direct work with collaborators and colleagues. They do this very well. Technology transfer via product development is somewhat secondary to TFD’s main line of activities, despite a number of successes, as narrated above. The review did not include presentations of policies regarding mechanisms for fostering product development through spinning off companies, sponsoring Small Business Innovation Research grants, or policies such as employee leaves to pursue commercialization activities. It is worth making sure that clear policies governing such activities related to technology transfer are in place and communicated to staff.

6

Quantum Physics Division

INTRODUCTION

The Quantum Physics Division (QPD) and JILA—the latter established in 1962 and located on the campus of the University of Colorado, Boulder (CU)—together comprise a very unusual but extremely successful collaboration involving the NIST Physical Measurement Laboratory and CU. In fiscal year 2017, JILA received 31 percent of its funding for research and training from CU, 32 percent from NIST, and 38 percent from other federal agencies.[1] An important aspect of JILA funding is the JILA Physics Frontier Center (JILA PFC). The first National Science Foundation (NSF) PFC grant to JILA covered the 5-year period from mid-2006 through mid-2011. The award was $3.2 million per year. The NSF PFC 5-year renewals since that time have remained at $3.2 million per year, including the most recent renewal to begin in mid-2018 through mid-2023. There has never been a lapse in group grant or PFC funding since that funding began.

JILA has 10 NIST-supported fellows, the chair of JILA among them, out of a total of 28 JILA fellows. The JILA fellows act effectively as a faculty department at NIST/CU. They collectively and remarkably coherently make hiring decisions and try to guide JILA toward new frontiers in quantum physics and biological physics, among other areas. The presence of biological physics NIST JILA fellows is another example of how JILA marches somewhat to its own drumbeat as to the future of quantum physics very broadly defined.

ASSESSMENT OF TECHNICAL PROGRAMS

The NIST QPD/JILA effort is clearly among the best in the world. Two of the fellows have been among the Reuter's top 100 most-cited physicists[2] for the past 5 years. The Cornell group is both overseeing the first Bose-Einstein Condensate (BEC) experiment in microgravity at the International Space Station (ISS) and testing fundamental high-energy physics with work to set limits on the electron electric dipole moment. The Rey Theory Group is driving a spectacular theoretical effort to understand quantum many-body effects in cold atom three-dimensional (3D) lattices, central to the remarkable10^{-19} stability limits in the Ye Group's lattice clocks.

The death of Deborah Jin in September 2016 was a tragic loss. Her work on fermion cold atom lattices was central to the Ye Group's work. Because her group was extremely well embedded in many JILA projects and central to them, her group was seamlessly absorbed into other groups and what could have been a really major technology blow was averted.

QPD/JILA has strong overlapping interests with other PML divisions, in particular the Time and Frequency Division (TFD). Because QPD/JILA is housed in a CU facility and not at NIST Boulder, there is little trickle down of improvements in the TFD to QPD/JILA.

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[1] Tom O'Brian, "JILA: NIST/CU Partnership for Research, Innovation and Training," presentation to the committee, May 1, 2018.

[2] Further information, see Clarivate Analytics, "2017 Highly Cited Researchers," https://clarivate.com/hcr/2017-researchers-list/#categories%3Dphysics, accessed September 27, 2018.

It would be worth exploring the possibility of stronger technical coordination between the TFD and QPD/JILA to avoid barriers to cooperation (e.g., "not invented here") within the divisions, given the overlapping agendas. CU, the partner with NIST in JILA, funds only a small portion of its total budget from state appropriations and depends ever more heavily on increases in tuition charges. Maintaining JILA facilities and paying the salaries needed to attract the best people could become extremely difficult as costs rise and federal budgets are less assured. With respect to the latter, the group relies on NSF to fund its PFC and must apply for renewed funding every 5 years.

Quantum Physics

Much of the current research carried out by the Ye Group, the Rey Theory Group, and the Bohn Group exploits the remarkable control achieved in the preparation and observation of ultra-cold atoms trapped in optical lattices to produce revolutionary advances in metrology, in many-body physics, and fundamental physics.

A substantial part of this work finds its original motivation in the desire to build atomic clocks of increasing precision, with a current state of the art of about 1 part in 10^{19}. Understanding what limits this precision and degrades the performance of such atomic clocks relies on a detailed study of many-body effects in atomic and molecular systems. This, in turn, has led to the realization that these many-body effects, which can be under exquisite experimental control in clock development, permit the investigator to simulate experimentally, and study theoretically, a number of challenging problems at the interface between atomic, molecular, and optical (AMO) physics and condensed matter physics. As a result, in addition to their metrological applications, lattice clocks can now be used as quantum simulators of complex interacting, open driven quantum systems whose understanding remains a considerable challenge. In a sense, the research in the Quantum Physics Group can be understood as exploring quantum physics with highly accurate clocks.

Examples of such problems tackled by the Rey Theory Group and its collaborators include, but are not limited to, quantum magnetism, the study of AMO analogs of systems where localized magnetic moments interact with one another or with mobile fermions, such as AMO analogs of the SU(N) lattice models;[3] quantum systems and quantum engineering, the investigation of the behavior of open driven and interacting many-body systems, one of the frontiers of modern quantum physics; and cold molecule physics, a topic driven by and feeding into the experimental capability developed in the Ye Group to control experimentally the initial state of molecules, monitor how they approach each other and their intermediate states, and analyze the end products in a situation where the molecular reaction processes are essentially limited only by the laws of quantum mechanics.

The experimental side, led by the Ye Group as well, implements this broad vision, together with the fusion of quantum many-body physics and metrology, which results in world-leading research of the highest quality and interest. Noteworthy here is the work on the optical lattice clock, currently having a precision of approximately 10^{-19}, with the further promise to reach 10^{-21} in the coming years, owing to developments of a fermionic atomic lattice clock. There seems to be no apparent fundamental limit to how good this system can become, and at this point, the fusion of metrology and many-body physics should be expected to be further enlarged, opening up fascinating new directions of research in both applied and fundamental physics. The latter might include use of such clocks for gravitational wave detection, searches for dark matter, long baseline interferometry, geodesy, searches for physics beyond the Standard Model, and more. Much as the development of clocks has historically been at the center of discovery and scientific breakthroughs, and so too the quest for ever-increasing precision will continue to open up unexpected avenues of inquiry.

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[3] See, for example, M.E. Beverland, G. Alagic, A.P. Koller, A.M. Rey, and A.V. Gorshkov, 2016, "Realizing exactly solvable SU(N) magnets with thermal atoms, *Phys. Rev. A* 93(5):051601(R).

The Thompson Laboratory has extended the discussion of precision measurements with single quantum objects to new possibilities with many quantum objects. One important application is reducing quantum noise by entangling, for example, spin states. This has already enabled surpassing the standard quantum limit by 17.7 decibels (dB). The group also described realizing an idea of the noted physicist Robert H. Dicke—a superradiant laser that is insensitive to fluctuations in the cavity length because the bandwidth of the emission is much smaller than that of the cavity resonance frequency.[4] This results in a laser 500,000-times less sensitive to cavity length than conventional stable lasers.

The exceedingly narrow linewidth of the superradiant laser can be further improved by utilizing forbidden transitions with even longer lifetimes (i.e., with narrower linewidths). The potential exists for orders of magnitude improvement, which can lead to improved clocks and applications in fundamental science, such as general relativity. The approximately 60-fold improvement over the standard quantum limit obtained by squeezing via entanglement can be further improved, opening up applications to optical lattice clocks and matter wave interferometers.

The research plan of the Kaufman Group is to marry the tools of quantum gas microscopy, optical tweezer technology, and high-precision spectroscopy in order to gain single-particle control at fundamental length scales and very small energy scales. The work of this group is expected to continue to impress.

The work of the Cornell Group has carved out a unique space in the world of BEC, and their work with the electron electric dipole moment (EDM)—work that is already challenging some of the more conventional improvements to the Standard Model—is among the best in the world. The purpose of this experiment is to make a precision measurement of the EDM of the electron. Because a finite electron EDM violates time symmetry, and thus by the CPT[5] theorem violates CP symmetry as well, a precision upper bound on an electron EDM constrains the Standard Model. Cornell also works in collaboration with the Ye Group[6] using an ultracold gas of Rubidium-85 to create a strongly interacting BEC, which will provide an ideal platform to study few- and many-body physics.

The Lehnert Laboratory works on a number of different topics, including the transduction of mechanical motion into electrical signals; development of Josephson parametric amplifiers from an arcane and poorly understood device to what is now a heavily used, quantum-limited amplifier central to superconducting qubit development; and, more recently, development of an optomechanical transducer connecting microwave and optical signals. Prior to starting this last effort, the group had led the first effort to successfully use light to cool a mechanical resonator to its quantum ground state, adapting the AMO technique of sideband cooling and applying it to a microwave system to achieve this result.[7] The group's parametric amplifiers are being used in a collaborative effort involving Yale University, the University of California, Berkeley, and Lawrence Livermore National Laboratory to search for axions,[8] which, if detected, would have very important implications for fundamental physics and searches for dark matter.

The optomechanical transduction effort is in a highly competitive area, with perhaps a dozen quite different but similarly targeted efforts worldwide. This effort is being pursued, in what seems a signature of JILA, as a close collaboration with the Regal Laboratory of JILA. This JILA collaboration has achieved more benchmark advances than any of the competing efforts. The most recent demonstration includes the highest-efficiency (by a couple of orders of magnitude) bi-directional transduction of coherent signals between the optical and microwave frequency domains. While not yet operating in the

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[4] James Thompson, JILA, "Quantum many-body states for precision measurement," presentation to the committee, May 1, 2018.

[5] CPT = charge conjugation (C), parity transformation (P), and time reversal (T).

[6] Further information available at JILA, "About the Ye Group," http://jilawww.colorado.edu/ye/, accessed September 27, 2018.

[7] Konrad Lehnert, JILA, "Quantum transduction between the microwave and optical domains," presentation to the committee, May 2, 2018.

[8] The axion was postulated to account for strong charge-parity symmetry in the Standard Model.

quantum limit, this experiment is close to doing so, with no obvious roadblocks other than improving the performance of each element involved in the transduction.

This technology could prove central to building practical quantum communication networks and comprises a very remarkable advance. Note that the devices involved in this are highly sophisticated combinations of a superconducting, extremely low-loss, microwave resonator; a very high finesse optical cavity; and a carefully designed, high-quality-factor silicon nitride membrane with superconducting metal patterned on its surface, through which the optical and microwave signals are coupled to one another. The successful fabrication of these devices uses the PML cleanroom[9] quite heavily, and the use of these devices employs very sophisticated microwave techniques (relying on the Lehnert Laboratory's expertise) combined with optical techniques (relying on the Regal Group expertise) in a way that would be hard to reproduce anywhere but at JILA.

The Nesbitt Laboratory performs experiments in the areas of biophysics, nanoscience, chemical physics, and molecular spectroscopy. One nanoscience project focuses on the fundamental nature of the quantum confined exciton state, and luminescence blinking, in single core/shell chemical quantum dots via their response to very high electric fields. This is a central problem in semiconductor quantum dots, and despite intensive worldwide effort remains poorly understood. A second project explores femtosecond (fs) hot electron relaxation dynamics and photoemission in single plasmonic gold (Au) nanostructures of various shapes. Here the laboratory has made the remarkable discovery that the direction of photo-emitted electrons is often at right angles to the optically excited plasmon axis. This points to unexpectedly complex relaxation kinetics during the 30-fs relaxation process. This discovery is an important step in helping to understand the recently discovered ability of hot electrons in optically excited Au nanostructures to catalyze surface chemical reactions.

Accomplishments

The division's optical lattice clocks have a precision of approximately 10^{-19}, with the further promise to reach 10^{-21}, owing to development of a fermionic atomic lattice clock. A further novelty is the realization of Robert H. Dicke's idea of a superradiant laser that is insensitive to fluctuations in the cavity length owing to its emissions bandwidth being much smaller than that of the cavity resonance frequency. The result is a laser 500,000 times less sensitive to cavity length than conventional stable lasers.

Opportunities and Challenges

QPD/JILA has strong overlapping interests with other PML divisions, in particular the Time and Frequency Division. Because QPD/JILA is housed in a University of Colorado, Boulder (CU) facility and not at NIST Boulder, there is little trickle down of improvements in the Time and Frequency Division to QPD/JILA.

Biological Physics

In biophysics, the Nesbitt Laboratory studies the effects of molecular crowding such as occur in live cells on the kinetics and thermodynamics of biochemical processes, including ribonucleic acid (RNA) folding. Under crowded conditions, single-RNA molecules folded 35-times faster than in the dilute solution. Crowding also led to a modest decrease in the unfolding rate. In related work, the folding–unfolding kinetics of a ubiquitous tertiary interaction motif, the GAAA[10] tetraloop–tetraloop receptor

[9] The clean room is part of the Quantum Electromagnetics Division of the Physical Measurement Laboratory.
[10] G = guanine; A = adenine.

(TL–TLR), was investigated by single-molecule fluorescence resonance energy transfer spectroscopy in the presence of natural amino acids both with (e.g., lysine, arginine) and without (e.g., glycine).[11] This is a productive line of research relevant to cellular chemical biology.

Impressive advances were made in the time resolution and noise characteristics of biological atomic force microscopy (AFM) for membrane protein studies at the Perkin's Laboratory.[12] By shaping the cantilever, by focused ionic beam (FIB) machining, and by optical stabilization of both sample and tip, remarkable combinations of time resolution (~ 1 microsecond) and low noise were achieved. This very substantial advancement was applied to the unfolding dynamics of bacteriorhodopsin in near native purple membranes. The experiments are now sensitive enough to reveal multiple unfolding intermediates and reveal the stabilizing effect of binding retinal and of individual amino acids.

The work of the Jimenez Laboratory combines ultrafast laser spectroscopy with microfluidic development in biological physics. The group is working on developing microfluidics-based single-cell spectroscopy techniques to characterize photophysics in vivo on 10^5-member libraries of fluorescent proteins. This laboratory uses microfluidics to isolate fluorescent protein clones with new properties and discover structure-dynamics relationships that would not be apparent from conventional biophysical studies focusing on a small number of variants.[13]

The Jimenez Laboratory also is conducting a new effort exploring the unique properties of entangled photons interacting with fluorescent proteins and other fluorophores used in cellular imaging. Time-energy entanglement can significantly enhance nonlinear light-matter interactions. Entangled two-photon absorption follows linear rather than the classical quadratic intensity dependence and can be observed at much lower photon fluxes than two-photon absorption in conventional multiphoton microscope.

Accomplishments

The use of single-molecule fluorescence resonance energy transfer spectroscopy in the presence of natural amino acids, both with (e.g., lysine, arginine) and without (e.g., glycine), is a productive line of research relevant to cellular chemical biology. The use of biological atomic force microscopy (AFM) for membrane protein studies achieved time resolution (~ 1 microsecond) and low noise.

Opportunities and Challenges

The efforts in biological physics are strong, but at a subcritical mass, with the compounding circumstance that the two biophysicists are somewhat isolated, making it a challenge to ensure their work is relevant. The Biology Frontier Center on the CU campus may be an important resource. PML could provide an environment in which JILA scientists working in biophysics continue to work on problems of priority to both biologists and biophysicists. This could include fostering collaborations and other mechanisms that bring them closer to the Biology Frontier Center as well as other options.

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[11] A. Sengupta, H.-L. Sung, and D.J. Nesbitt, 2016, Amino acid specific effects on RNA tertiary interactions: Single-molecule kinetic and thermodynamic studies, *J. Phys. Chem. B.* 120(41):10615-10627.

[12] Thomas Perkins, JILA, "Improved bioAFM for probing diverse molecular systems," presentation to the committee, May 1, 2018.

[13] Adapted from JILA, "The Jimenez Lab: About Ralph Jimenez," http://jila.colorado.edu/jimenez/node?page=2, accessed October 1, 2018.

PORTFOLIO OF SCIENTIFIC EXPERTISE

The program's scientific expertise is closely matched to the technical programs and strongly enables QPD/JILA's ability to be a world leader in quantum physics.

ADEQUACY OF FACILITIES, EQUIPMENT, AND HUMAN RESOURCES

The facilities at QPD/JILA are unique and the envy of many physics departments around the world, who have seen the steady erosion of facilities, in particular in human resources, in the short-sighted interests of local budget issues. QPD/JILA maintains a strong electronics shop where students work with staff to build things, an excellent machine shop both at the professional level and for students, and a fantastic glass shop. It is extremely important that this range of facilities and support staff remain.

Challenges and Opportunities: Facilities

However, there are some black clouds on the horizon. The JILA Laboratory is a mix of old and new construction, with the oldest part of the laboratories being simply incompatible with the extraordinary experiments being pursued there, and the newer parts of the laboratories not having been built to the highest level of temperature and humidity control. In spite of this, the control of vibration in the basement is at world-class level.

A complete renovation of the oldest wing of the laboratory, at the least, needs to be funded jointly by NIST and CU and completed in a timely fashion, in order that the world-class researchers have the best vibrational-, temperature-, and humidity-controlled laboratory space.

DISSEMINATION OF OUTPUTS

Outreach

JILA participates in the CU Wizards program, which explores the exciting worlds of physics, chemistry, biology, geology, mathematics, psychology, astronomy, and more. It is free to the public and geared toward children in grades K-12 and their families.

The CU Physics Department offers several 1-hour talks on Saturday afternoons. These afford adults and high school students the opportunity to interact with a CU professor, including JILA fellows. A further program, called *Alice's Adventures in Quantumland* incorporates JILA research on the novelties of quantum physics. It is in a whimsical narrative form, aimed at introducing a younger audience to the concepts of quantum physics.

JILA embraces the goal of providing "a supportive and welcoming environment for women scientists of all ages."[14] However, while JILA has some high-profile women and minority researchers, as well as a number of female postdoctoral researchers and graduate students, efforts to further recruit and advance both groups need to be continued.

[14] University of Colorado, Boulder, "Outreach," http://amalfi.colorado.edu/resources/outreach, accessed October 1, 2018.

Stakeholder Needs

It is difficult to assess to what degree the work of the division is driven by stakeholder needs. By its very title, the QPD has a strong emphasis on fundamental quantum physics. Remarkably QPD/JILA has now moved into the realm of testing fundamental aspects of general relativity and physics beyond the Standard Model of high-energy physics. In that sense, the stakeholders of the QPD/JILA effort are the community of fundamental scientists.

Owing to the unique charter of JILA among NIST laboratories, consideration is given to the educational stakeholders of QPD/JILA by recruiting and training the next generation of top students and postdoctoral researchers. QPD/JILA does a remarkable job for the educational stakeholders, which is a beneficial arrangement for CU. It might be instructive to see an accounting of the numbers of students and postdoctoral researchers passing through JILA in the past 5 years, together with categorization of where these people are now (industry, national laboratory, academia, entrepreneurs, and so forth).

Another interesting area with respect to stakeholders is biological physics. Here the Jimenez Laboratory, Perkins Laboratory, and Nesbitt Laboratory perform valuable functions. The Jimenez Laboratory is deeply involved in doing directed evolution of fluorescent protein biomarkers using advanced laser technology and microfluidics, and it recently has a very challenging but exciting project to use entangled 2-photon excitation to dramatically increase 2-photon cross-sections for use in biomedical tissue imaging. The Perkins Laboratory has made dramatic improvements in AFM cantilever technology to achieve microsecond response times in AFM microscopes, which will have immediate and important use in the rapidly expanding AFM imaging world, both for materials sciences and biology. The Nesbitt Laboratory is expanding fluorescence resonance energy transfer (FRET) imaging microscope technology, which plays an important role in many aspects of protein dynamics, and the work on electron emission from nanoscale objects could have important implications for electron gun development used in many technology areas.

Opportunities and Challenges

Technology Transfer

The challenges are complex. While JILA is mostly engaged in basic scientific research not compatible with patent protection and licensing, protecting some of the work would allow it to be translated into the commercial sector. Without intellectual property (IP) protection, companies will not want to invest the time and money to complete translation to market. Incentives for JILA researchers could be constructed that reward IP development, compatible with government restrictions, in a manner that does not distort the basic scientific effort but promotes technology transfer. Currently, it appears that IP protection and technology transfer are not seen as priorities and are not part of the reward structure, and therefore there is minimal effort to seek patents and transfer valuable technology.

Funding Sources

One concern regarding sources of funding is the degree to which JILA relies financially on its Physics Frontier Center, recently renewed for another 5-year term. There is need for planning how to handle the possible funding downturn should this center not be renewed in the future.

JILA's plans to hire an embedded fund raiser whose mission will be to raise funds for JILA from philanthropists is sensible.

7

Key Recommendations

The weak infrastructure highlighted in the 2015 assessment report[1] persists in some areas. NIST responded to this challenge by bringing on board the new Katharine Blodgett Gebbie Laboratory Building, which is devoted to research. Some fortunate PML staff have excellent research space in that new building. At the same time, however, the laboratories of some of the staff are housed in a building that has not been upgraded since the 1960s. The environmental controls in the laboratory space need to be improved. While the ability of PML researchers to operate in less-than-optimal physical space was impressive, they are rapidly reaching the day when the decaying infrastructure will limit their ability to perform their necessary duties, extend the accuracy of the standards that PML researchers have developed, and show the applicability of their research to ever-advancing high-tech industry.

Recommendation 1. The PML should develop with NIST management a plan to remodel and upgrade, as soon as possible, the infrastructure utilized by the PML, and should perform an assessment to determine which PML infrastructure assets are weakest in supporting the scientific mission.

The 2015 assessment report noted that NIST procedures and policies relating to patents and intellectual property (IP) were not clearly defined for technical staff. The present panel revisited this issue and found, for example, that JILA—the host institution of the Quantum Physics Division—is mostly engaged in basic scientific research not compatible with patent protection and licensing. Protecting some of the work would allow its translation into the commercial sector. Without IP protection, companies will not want to invest the time and money to complete translation to market. Incentives for JILA researchers could be constructed that reward IP development, compatible with government restrictions, in a manner that does not distort the basic scientific effort but promotes technology transfer.

At the conclusion of the committee's site visit, the chair of the committee and staff met with the Director of NIST (Dr. Walter Copan), who explained that a priority for him was developing and regularizing workable procedures and policy positions on patents and IP for all parts of NIST. The NIST Director reported this year that he is addressing this matter throughout the Department of Commerce (DOC), so that all DOC staff, including those at NIST, will be afforded a clear understanding of IP procedures and policies. NIST researchers need to be part of the conversation. The prospect of changes in patent and IP procedures and policies, being developed by the NIST Director, is encouraging and represents an opportunity for PML to regularize these procedures.

Recommendation 2. The PML should, maintain awareness of changes in patent and intellectual property procedures to encourage and more efficiently enable the movement of PML's discoveries into commercial space

Instrumentation and space resources are excellent for most of the groups, but the Magnetic Resonance Imaging group is badly in need of a clinical-class magnetic resonance imaging (MRI) so that

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[1] National Research Council, 2016, *An Assessment of the National Institute of Standards and Technology Physical Measurement Laboratory—Fiscal Year 2015*, The National Academies Press, Washington, D.C.

appropriate phantom design as well as initial testing can be readily accomplished without going to other sites. NIST has access to nearby clinical commercial MRI systems, but nonetheless might evaluate whether a clinical system of its own might not improve productivity by eliminating wait times, providing opportunities for Cooperative Research and Development Agreements and other partnerships that might offset costs, and decreasing costs it would otherwise incur using other clinical scanners in the area. In its work on quantitative nanostructure characterization, the Applied Physics Division (APD) may benefit from broader collaborations on different materials systems, recognizing that the group is not primarily a user community resource. APD's work on advanced microwave photonics applied to quantum computing and its stakeholder community would benefit from experimental validation or the development of theoretical manuscripts describing the proposals.

Recommendation 3. PML should study the costs and benefits of acquiring a clinical-class magnetic resonance imaging (MRI) machine that would assist in phantom design and enable testing on-site.

The Quantum Electromagnetics Division would benefit from increased guidance on the value to NIST of patent activity vis-à-vis journal publications and other metrics. (See Recommendation 2 above.) The environmental controls in the laboratory space need to be improved. The aging facilities have problems with the building envelope, such as the observed roof leaks. (See Recommendation 1 above.)

The problem of transmitting time signals and comparing frequency standards in this new regime of precision poses a serious scientific and technical challenge. Comparisons in the same laboratory are relatively straightforward, but the problem of comparisons at large distances remains to be solved.

Recommendation 4. PML should continue its work to develop methods for distributing time over long distances at the newly attainable levels of precision.

Acronyms

AAAS	American Association for the Advancement of Science
AAPM	American Association of Physicists in Medicine
AC	alternating current
AFM	atomic force microscopy
AMO	atomic, molecular and optical
APD	Applied Physics Division
ARRA	American Recovery and Reinvestment Act
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
CODATA	Committee on Data for Science and Technology
CSAC	Chip Scale Atomic Clock
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
EUV	extreme ultraviolet
FDA	Food and Drug Administration
FRET	Fluorescence Resonance Energy Transfer
FTS	Fourier transform spectrometer
GaN	gallium nitride
GDP	gross domestic product
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
ISO	International Organization for Standardization
ISS	International Space Station
ITL	Information Technology Laboratory
IUPAP	International Union of Pure and Applied Physics
JILA	joint institute between NIST and the University of Colorado, Boulder
JHU	Johns Hopkins University
JQI	Joint Quantum Institute
KRb	ultracold potassium-rubidium
LBIR	low-background infrared
LED	light-emitting diode
LIDAR	differential absorption 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
MPD	measurement program description
MRI	magnetic resonance imaging
NCNR	NIST Center for Neutron Research
NCWM	National Conference on Weights and Measures
NCSLI	National Conference of Standards Laboratories International
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
SESAM	Semiconductor Saturable Absorber Mirror
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
SNM	Society of Nuclear Medicine
SNMMI	Society of Nuclear Medicine and Molecular Imaging
SNSPD	superconducting nanowire single-photon detector
SQUID	superconducting quantum interference devices
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
VIIRS	visible infrared imaging radiometer suite
VUV	vacuum ultraviolet