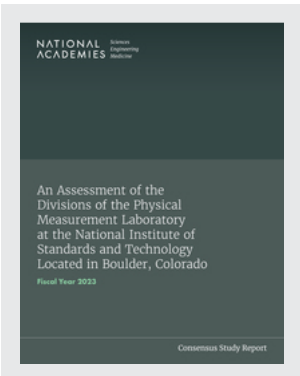

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CONTRIBUTORS

Panel on the Assessment of the National Institute of Standards and Technology (NIST) Physical Measurement Laboratory; Laboratory Assessments Board; Division on Engineering and Physical Sciences; National Academies of Sciences, Engineering, and Medicine

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Fiscal Year 2023

Panel on the Assessment of the National Institute of Standards and Technology (NIST) Physical Measurement Laboratory

Laboratory Assessments Board

Division on Engineering and Physical Sciences

Consensus Study Report

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ROBERT H. AUSTIN (NAS), Princeton University, *Chair*
RYAN E. BAUMBACH, National High Magnetic Field Laboratory, Florida State University
HARISH B. BHANDARI, Radiation Monitoring Devices, Inc.
RAINER BLATT (NAS), University of Innsbruck, Austria
GILLES BUCHS, Oak Ridge National Laboratory
YOUNG-KAI CHEN, Coherent, Inc.
DAPHNA G. ENZER, Jet Propulsion Laboratory, California Institute of Technology
RACHEL M. GODUN, National Physical Laboratory, United Kingdom
RICHARD A. GOTTSCHO (NAE), Lam Research
RICHARD A. HAIGHT, IBM Thomas J. Watson Research Center
LINDA KATEHI (NAE), Texas A&M University, College Station
KATE KIRBY, American Physical Society
KEVIN O. KNABE, Vescent Photonics
SHIMON J. KOLKOWITZ, University of California, Berkeley
JOHN R. LOWELL, The Boeing Company
LUTE MALEKI, OEwaves, Inc.
PIERRE MEYSTRE, University of Arizona (retired)
JULIO A. NAVARRO, The Boeing Company
KAREN F. O'DONOGHUE, Internet Society
C. KUMAR N. PATEL (NAS/NAE), Pranalytica, Inc.
MATTHEW J. REAGOR, Rigetti Computing
KATHY-ANNE BRICKMAN SODERBERG, Air Force Research Laboratory
JAMES (JIM) C. STEVENS (NAE), The Dow Chemical Company
RUDOLF MARIA TROMP (NAE), IBM Thomas J. Watson Research Center

Study Staff

KATIE BRATLIE, Director, Laboratory Assessments Board
JAMES MYSKA, Senior Program Officer and Study Director
AZEB GETACHEW, Administrative Assistant
JAYDA WADE, Research Associate (until August 4, 2023)

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Staff

KATIE BRATLIE, Director, Laboratory Assessments Board
AZEB GETACHEW, Administrative Assistant
LIZA RENEE HAMILTON, Senior Program Officer
JAMES MYSKA, Senior Program Officer
JAYDA WADE, Research Associate (until August 4, 2023)

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:

MEI CAI, General Motors
HUI CAO (NAS), Yale University
MICHAEL ETTENBERG (NAE), Dolce Technologies (retired)
MARINA GERTSVOLF, National Research Council Canada
GABRIELA GONZALEZ (NAS), Louisiana State University
KELIN JO KUHN (NAE), Cornell University
BONNIE MARLOW, MITRE Corporation
JUDITH BERGET OLSON, Infleqtion

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 **DAVID W. JOHNSON,** University of Minnesota, Twin Cities, and **JENNIE S. HWANG (NAE),** H-Technologies Group, Inc. They were 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.

Contents

Summary

BACKGROUND AND TASK

Since 1959, the National Institute of Standards and Technology (NIST) has annually commissioned the National Academies of Sciences, Engineering, and Medicine to assess its various measurements and standards laboratories. Presently, there are six such laboratories in operation. In the fiscal year 2023, NIST enlisted the Laboratory Assessments Board of the National Academies to appraise the Physical Measurement Laboratory (PML). This document encompasses the assessment provided by the Panel on Assessment of the National Institute of Standards and Technology (NIST) Physical Measurement Laboratory for four divisions of PML situated at the NIST Boulder campus—namely, the Applied Physics Division, the Time and Frequency Division, the Quantum Electromagnetics Division, and the Quantum Physics Division. Complementary assessments are available for the Material Measurement Laboratory and the NIST Center for Neutron Research, each in their respective companion reports (NASEM 2023, 2024). This assessment encompassed an onsite visit by the panel, featuring comprehensive laboratory tours, one-on-one interactions with PML researchers, and subsequent inquiries post-visit. After this, the panel used its combined experience and expertise to appraise PML in alignment with the statement of task (presented in Chapter 1) and to formulate recommendations accordingly. The divisions assessed in this report were last evaluated in 2018 (NASEM 2018).

The statement of task encompasses four primary components. The panel's foremost objective is to assess PML's technical programs, comparing the caliber of research at PML with similar international programs, and determining whether PML's programs adequately align with its objectives. Secondly, the panel is tasked with assessing the range of scientific and technical expertise available within PML, gauging its global standing, and evaluating its effectiveness in supporting both PML's technical initiatives and its overall objective attainment. Thirdly, a scrutiny of PML's budget, facilities, equipment, and Human Resources is required, including an examination of how effectively these components bolster PML's technical endeavors and contribute to the fulfillment of its goals. Lastly, the panel is to assess the efficacy of PML's methods for disseminating the products of its work. This encompasses an assessment of the extent to which PML's work is driven by the needs of stakeholders, the comprehensiveness and effectiveness of dissemination and technology transfer mechanisms, and the adequacy of PML's monitoring of stakeholder utilization and the impact derived from PML's outputs.

Physical Measurement Laboratory

PML comprises nine separate divisions, each devoted to a particular aspect of measurement science and technology. This report is focused on the four PML divisions located in Boulder: Applied Physics, Quantum Physics, Quantum Electromagnetics, and Time and Frequency. These divisions engage in research and development of almost every type of measurement science used industrially and for research. They also provide NIST-traceable calibrations and develop standards and best practices. These divisions have strong ties to industry, universities, professional and standards setting organizations, and other agencies of government (NIST 2022).

OVERARCHING THEMES AND KEY RECOMMENDATIONS

The panel organized itself into four largely independent sub-panels to assess the divisions included in this report in parallel, one sub-panel aligned with each division being assessed. In the course of their work, three overarching themes emerged that apply to all of PML. These are the adequacy of facilities and equipment, adequacy of staffing, and safety posture. For each of these themes, the panel offered a key recommendation that applies to most of the divisions.

Adequacy of Facilities and Equipment

Each of the four sub-panels identified facilities and infrastructure as a crucial area to address. The 2018 report that assessed the PML division and Boulder, and the more recent 2023 National Academies' report *Technical Assessment of the Capital Facility Needs of the National Institute of Standards and Technology* (NASEM 2023b; the "*Capital Facility Needs* report") both highlight the aging facilities and infrastructure that present severe impediments to PML research staff continuing to produce the high quality of work that they are known for. Of particular note, the 2023 report found that NIST research staff are devoting 10 to 40 percent of their time on workarounds and do-it-yourself repairs. This comes at the cost of research time and may impact PML's status as a world-leading institution, along with its ability to attract high-quality talent.

For the Applied Physics Division, the sub-panel identified the electrical supply and the water system as particular areas in need of upgrades. The Quantum Physics Division sub-panel pointed to serious space and infrastructure problems at JILA. The Quantum Electromagnetics Division sub-panel identified renovations and improvements to the division's device fabrication facility as a priority. The Time and Frequency Division sub-panel called out improvements in Building 01 and the mitigation of power outages in multiple buildings as hindering progress.

Key Recommendation 1: The Physical Measurement Laboratory (PML) should work with the National Institute of Standards and Technology's Office of Facilities and Property Management to identify facilities and infrastructure with critical infrastructure issues. Infrastructure and facilities that are critical in supporting the scientific mission of PML should be considered in assessing remodeling and upgrading needs.

Adequacy of Staffing

Attention needs to be paid to staffing, both now and in the future. Several programs currently have insufficient staffing levels, and retirements could lead to a loss of knowledge and expertise unless effective succession plans are put in place. The sub-panel that reviewed the Quantum Electromagnetics Division identified the Spin Electronics Group as needing additional personnel and resources. It also recommended that this group consider succession plans to close experience gaps. Similarly, the sub-panel evaluating the Time and Frequency Division recommended the development of succession plans and furthermore called for knowledge and responsibilities to be shared and distributed among members and teams to guarantee that knowledge was preserved if key members left. That sub-panel was also concerned about inadequate staffing, in particular for the division's time distribution service. The Applied Physics Division sub-panel emphasized the importance of addressing personnel issues in a timely fashion and, to that end, recommended that PML ensure that the division has one or more excellent Human Resources professionals onsite.

Key Recommendation 2: The Physical Measurement Laboratory should act to ensure adequate staffing at the four divisions now and for the future and, as part of that, should work to improve the ways it addresses personnel issues. This would include having an excellent Human

Resources professional(s) onsite who can address an array of personnel issues in a timely fashion within the context of the PML culture.

Key Recommendation 3: The Physical Measurement Laboratory should establish clear and open policies and practices across the organization on recruiting permanent government employee positions and promoting interactions and collaborations. In particular, the open positions should be made available to staff and guest researchers across the organization. National Institute of Standards and Technology–wide seminars and activities should be established to promote inter-group interactions and collaborations.

Safety Posture

The safety posture of PML does not adequately ensure the safety of PML staff and visitors. Initial steps to improve safety have been taken by PML staff, but improvements need to accelerate. Safety inspections and standards need to be reevaluated with the goal of bringing safety across the divisions to a level that is comparable with major industrial companies. The sub-panel that reviewed the Applied Physics Division recommended that the frequency of safety inspections be increased and that the PML leadership should reach out to major industrial companies for advice on improving laboratory safety. The Quantum Physics Division sub-panel identified laser safety as a particular concern and recommended that NIST and the University of Colorado Boulder jointly establish a clear and aggressive timeline for meeting American National Standards Institute laser safety standards.

Key Recommendation 4: The Physical Measurement Laboratory should address persistent safety concerns related to safety inspections and standards, particularly within the Applied Physics Division and the Quantum Physics Division.

REFERENCES

NASEM (National Academies of Sciences, Engineering, and Medicine). 2018. *An Assessment of Four Divisions of the Physical Measurement Laboratory at the National Institute of Standards and Technology: Fiscal Year 2018*. Washington, DC: The National Academies Press. https://doi.org/10.17226/25281.

NASEM. 2023a. *An Assessment of the Materials Measurement Laboratory at the National Institute of Standards and Technology: Fiscal Year 2023*. Washington, DC: The National Academies Press. https://doi.org/10.17226/26048.

NASEM. 2023b. *Technical Assessment of the Capital Facility Needs of the National Institute of Standards and Technology*. Washington, DC: The National Academies Press. https://doi.org/10.17226/26684.

NASEM. 2024. *An Assessment of the National Institute of Standards and Technology Center for Neutron Research: Fiscal Year 2023*. Washington, DC: The National Academies Press.

NIST (National Institute of Standards and Technology). 2022. "Physical Measurement Laboratory: Gauging Nature on All Scales." https://www.nist.gov/system/files/documents/2022/01/21/pml-brochure.pdf.

1
Introduction

Each year since 1959, the National Institute of Standards and Technology (NIST) has asked the National Academies of Sciences, Engineering, and Medicine to conduct an assessment of one or more of its measurements and standards laboratories, of which there are currently six. For fiscal year 2023, NIST asked the National Academies' Laboratory Assessments Board to review the Material Measurement Laboratory (MML), the NIST Center for Neutron Research (NCNR), and segments of the Physical Measurement Laboratory (PML). This report contains an assessment of the four PML divisions located on the NIST Boulder campus: the Applied Physics Division, the Time and Frequency Division, the Quantum Electromagnetics Division, and the Quantum Physics Division, conducted by the Panel on Assessment of the National Institute of Standards and Technology (NIST) Physical Measurement Laboratory. Companion reports review the MML and NCNR (NASEM 2023a, 2024, respectively).

The PML divisions covered in this review were last reviewed in 2018, 5 years ago (NASEM 2018). The rapid evolution of technology over the past 5 years, particularly in quantum physics, makes it very appropriate that the PML Boulder divisions be reviewed to ascertain how they have responded to the challenges that have emerged over the past 5 years in a critical technology sector and whether they have appropriate support for their challenging tasks.

The stakeholders of PML are extremely diverse. PML sets the definitive U.S. standards for nearly every kind of measurement in modern life, sometimes across more than 20 orders of magnitude in value. Exact and repeatable measurements are essential to industry, medicine, the research community, and government. These sectors depend on PML to develop, maintain, and disseminate the official standards for a wide range of quantities. The PML divisions at the NIST Boulder campus are at the technological cutting edge of modern quantitative physical science and are absolute world leaders in their fields. It is vital to the PML stakeholders and to the nation's security that they remain so.

STATEMENT OF TASK

The panel closely followed the statement of task, reprinted below, although it did find some issues of safety concerns that it felt were necessary to bring to the attention of NIST leadership. Also, as is explained below, issues of facility decay were of enough urgency that they merited special attention.

> The National Academies shall appoint a panel to assess independently 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 Physical Measurement Laboratory. Visits will include technical presentations by NIST staff, demonstrations of NIST projects, tours of NIST facilities, and discussions with NIST staff. The panel will deliberate findings in closed sessions and will prepare a report summarizing its assessment findings and recommendations.
>
> NIST has requested that the laboratories be assessed against the following broad criteria:
>
> 1. Assess the organization's technical programs.
>   a. How does the quality of the research compare to similar world-class research in the technical program areas?

   - b. 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.
   - a. Does the organization have world-class scientific expertise in the areas of the organization's mission and program objectives? If not, in what areas should it be improved?
   - b. 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 budget, facilities, equipment, and human resources.
   - a. How well do the facilities, equipment, and human resources support the organization's technical programs and its ability to achieve its stated objectives? How could they be improved?
4. Assess the effectiveness by which the organization disseminates its program outputs.
   - a. How well are the organization's research programs driven by stakeholder needs?
   - b. How effective are the dissemination methods and technology transfer mechanisms used by the organization? Are these mechanisms sufficiently comprehensive?
   - c. How well is this organization monitoring stakeholder use and impact of program outputs? How could this be improved?

CONDUCT OF THE ASSESSMENT

The panel conducted its review in person in Boulder, Colorado, for 3 days, May 23–25, 2023. This assessment covers the four PML division located at Boulder, Colorado, and considers developments since the previous assessment of these divisions in 2018. PML staff and NIST directorate staff provided substantive and informative presentations. The presentations were augmented with tours of PML facilities and discussions between NIST staff and the panel. NIST staff provided written responses to queries generated by the panel. The panel was divided into 4 sub-panels. After an opening plenary session with general presentations and discussions, the panel broke out into its sub-panels to work independently, receiving briefings, engaging in discussions, and going on tours. By design, each sub-panel was focused on the division or office that it assessed. There was a final working plenary where the panel deliberated as a whole and then a session for it to confirm its understandings with PML leadership.

The panel relied on the experience, technical knowledge, and expertise of its members. The panel focused on the research and materials that the leadership of PML chose to present and used a largely qualitative approach to conducting the assessment. Omission of any particular PML project from this report should not be viewed negatively. The report is focused on the work that PML is currently undertaking, and any opportunities and challenges related to that work. NIST has a separate review body, the Visiting Committee on Advanced Technology, that addresses the question of what PML or any other laboratory at NIST should be doing. As such, discussions on whether PML is pursuing the right kinds of research is outside of the purview of this review.

USE OF THE 2023 NIST CAPITAL FACILITY NEEDS REPORT IN THE PANEL'S WORK

The assessment panel found issues regarding the facilities similar to the report *An Assessment of the Material Measurement Laboratory at the National Institute of Standards and Technology: Fiscal Year 2023* (NASEM 2023a), which is operating in parallel to this panel. This report is also adopting the full description of the problems identified in *Technical Assessment of the Capital Facility Needs of the National Institute of Standards and Technology* (NASEM 2023b). Box 1-1 summarizes that report and its findings and recommendations.

BOX 1-1

Technical Assessment of the Capital Facility Needs of the National Institute of Standards and Technology

In February 2023, the National Academies of Sciences, Engineering, and Medicine released the report *Technical Assessment of the Capital Facility Needs of the National Institute of Standards and Technology* (NASEM 2023b, the "*Capital Facility Needs* report"). The committee that authored this report was tasked to assess National Institute of Standards and Technology's (NIST's) facilities and utility infrastructure, review and assess plans and projects to reinvigorate NIST's facilities and utility infrastructure, the cost estimates for doing so, and the factors that NIST should consider in developing a comprehensive capital strategy for the facilities and utility infrastructure at NIST's campuses in Boulder, Colorado, and Gaithersburg, Maryland. The committee engaged with the Department of the Interior, the National Institutes of Health (NIH), the U.S. Army Engineer Research and Development Center, and the Johns Hopkins University Applied Physics Laboratory to learn about their methods and metrics for assessing facility conditions and maintaining their facilities.

The condition of NIST's facilities and utility infrastructure has been a concern since 2002 when the Visiting Committee on Advanced Technology (VCAT) issued a report calling NIST's facilities condition and the related funding situation "alarming" and "critical." Over the following 20 years, VCAT returned consistently to this theme with increasingly dire language. Eventually, the conference report accompanying the Consolidated Appropriations Act of 2021 (P.L. 116-260) requested that NIST "contract with an independent entity to develop a report that assesses the comprehensive capital needs of NIST's campuses." In response, NIST's Office of Facilities and Property Management approached the National Academies to conduct a study based on a successful study and report completed for NIH in 2019 (NASEM 2019). The result was the *Capital Facility Needs* report (NASEM 2023b).

The committee that authored the *Capital Facility Needs* report visited both the Boulder, Colorado, and Gaithersburg, Maryland, campuses. It discovered that many NIST facilities are inadequate to support the world-leading research that is NIST's mission. Both the quality and the reliability of power can be problematic, resulting in slowed work, lost work, and unnecessary time spent recalibrating sensitive instruments. Inadequacies in basic environmental controls can result in laboratories that are too hot or cold, too humid, or not humid enough, and lack proper vibration insulation. In one 1950s-era Boulder laboratory, the gaps between the windows and frames allow dust to blow straight into the laboratory. Roof leaks have destroyed multi-million-dollar pieces of equipment, such as tunneling electron microscopes in both Boulder and Gaithersburg. A water leak in Gaithersburg resulted in permanent damage to the world-leading Kibble balance that tied the standard kilogram to the speed of light. There are many more instances and stories. In all, the committee found that the NIST research staff loses between 10 to 40 percent of its working time fighting against facility inadequacies, also consuming research money to do so. Things have reached the point where NIST researchers will not be able to continue their world-class research no matter their efforts. This is already impacting the ability to recruit and retain staff and the willingness of foreign researchers to do work at NIST. At risk is also NIST's international credibility and influence and its ability to support national security, U.S. international competitiveness, medical therapeutics, and a wide range of other activities upon which users in the U.S. government, industry, and academia rely.

In the course of its work, the committee found that NIST's internal facility and property management policies are not responsible for this situation. Rather, the cause is more than two decades of erratic, unpredictable, and inadequate funding for NIST's construction of research facilities budget, which includes facility sustainment, restoration, modernization, and expansion. Exacerbating this problem is congressionally directed pass-through funding for things like building laboratories on university campuses that are not used by NIST. This pass-through funding is not revenue neutral to NIST, costing staff time and money to administer, draining even more much needed money from NIST's facilities coffers.

In short, the committee found that the situation requires serious and sustained attention, particularly from leadership levels above NIST. The committee also endorsed the coordinated recovery plan drafted by NIST's Office of Facilities and Property Management and recommended its continued refinement and shortening it to complete it in 12 years. Critically, the committee identified the need for significant and sustained funding to address NIST's facilities and utility shortcomings and bring them to the standard necessary for modern metrology. This funding is the critical piece of the recovery plan. The committee recommends $420 million to $550 million per year in funding for NIST's construction of research facilities budget over at least 12 years. As shown in Table 1-1-1, this includes $120 million to $150 million per year for safety, capacity, maintenance, and major repairs funding to address the more than $800 million deferred maintenance backlog and bring existing facilities to an acceptable condition and keep them there. It also includes $300 million to $400 million per year over at least 12 years for the construction and major renovations budget to upgrade, renovate, and build the new laboratories with the new capabilities needed to conduct modern metrology research.

TABLE 1-1-1 Overview of NIST Facility and Infrastructure Funding Needs

Funding Component	Amount Needed Annually
Construction and major renovations (CMR)	$300 million to $400 million
Safety, capacity, maintenance, and major repairs (SCMMR)	$120 million to $150 million
Total needed for construction of research facilities (CRF)	$420 million to $550 million

NOTE: CRF funding is the sum of CMR and SCMMR funding.
SOURCE: NIST (2022).

The picture is not unremittingly bleak. NIST has already begun to modernize laboratories as its current budget allows. These new laboratories are state of the art and enable the cutting-edge world-leading research that is NIST's mission. As an example, one NIST research group—after waiting 18 months to be relocated into a new, modern laboratory—won the 2021 Physics World Breakthrough of the Year award for a previously unprecedented demonstration of the quantum entanglement of microresonators. NIST's staff is world-class and capable of producing amazing results, results that will serve the nation and inspire the next generations of researchers, provided they are given the facilities and tools needed to do their work.

SOURCE: NASEM (2023b).

STRUCTURE OF THIS REPORT

The report consists of eight chapters. Within the common structure of each chapter, each sub-panel had the flexibility to implement a substructure that it believed made the most sense for the information that it wanted to convey. This results in different substructures among the chapters. Any issue that the panel believed applies to PML as a whole, or is of particular import, is addressed with a key recommendation. These are presented in the Summary, in the chapters in which they appear, and in the final recommendation summary chapter.

After this introductory chapter, which presents an overview of the importance of PML to the nation's stakeholders, the charge to panel as delivered by the National Academies, and the process by which the assessment was carried out, the next chapter (Chapter 2) provides background on and an overview of the four PML divisions reviewed in this report. This is followed by four chapters that are each devoted to a sub-panel review of one of the four divisions assessed in this review (Chapters 3–6). After the assessment chapters is a chapter that presents the recommendations from the fiscal year 2018 PML assessment report, PML's responses to those recommendations, and an assessment of those responses. The final chapter (Chapter 8) gives a more detailed analysis of the key recommendations drawn from the divisional reviews.

Special Considerations

There are two items that need to be addressed to fully understand this report.

Comparison to International Research Efforts

One of the questions in the statement of task (item 1.a) is "How does the quality of the research compare to similar world-class research in the technical program areas?" The panel was impressed with the quality of research conducted at PML and found it to be generally world-class or world-leading. As with all other assessment topics, this is based on the panelists' individual and cumulative expertise and experience. However, within the time constraints of this project, there was not time to engage in extensive additional research. Therefore, the report might have fewer concrete examples in regard to this item of the statement of task than the others. Any lack of examples should not be taken as a lack of quality.

Safety

Also, the panel makes observations and a recommendation on safety. It was very careful in doing so. Safety is not part of the formal charge to the panel, and so the panel was not composed to conduct a rigorous safety review. Accordingly, the report notes some things that the panel observed that are of concern to it and makes a high-level safety Key Recommendation 4 to draw attention to the panel's concerns and suggest a path forward within the limits of the scope, information available to the committee, and the panel's collective expertise. Due to these limitations, the panel took a relatively light touch on this matter.

REFERENCES

NASEM (National Academies of Sciences, Engineering, and Medicine). 2018. *An Assessment of Four Divisions of the Physical Measurement Laboratory at the National Institute of Standards and Technology: Fiscal Year 2018*. Washington, DC: The National Academies Press. https://doi.org/10.17226/25281.

NASEM. 2019. *Managing the NIH Bethesda Campus Capital Assets for Success in a Highly Competitive Global Biomedical Research Environment*. Washington, DC: The National Academies Press. https://doi.org/10.17226/25483.

NASEM. 2023a. *An Assessment of the Materials Measurement Laboratory at the National Institute of Standards and Technology: Fiscal Year 2023*. Washington, DC: The National Academies Press. https://doi.org/10.17226/26048.

NASEM. 2023b. *Technical Assessment of the Capital Facility Needs of the National Institute of Standards and Technology*. Washington, DC: The National Academies Press. https://doi.org/10.17226/26684.

NASEM. 2024. *An Assessment of the National Institute of Standards and Technology Center for Neutron Research: Fiscal Year 2023*. Washington, DC: The National Academies Press.

NIST (National Institute of Standards and Technology). 2022. "NIST Facilities Summary for Representative Trone." Point Paper. Office of Facilities and Property Management. June.

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Overview of the Physical Measurement Laboratory

The Physical Measurement Laboratory (PML) of the National Institute of Standards and Technology (NIST) is the U.S. agency responsible for setting the measurement standards for time, length, mass, and many other physical qualities. These standards are crucial to industry, academic research, medicine, government agencies, and to many other parts of society. Thus, one major responsibility of PML is to develop, maintain, and disseminate the official standards for such things as length, mass, force and shock, acceleration, time and frequency, electrical units, temperature, humidity, pressure and vacuum, liquid and gas flow, optical quantities, acoustic quantities, and ionizing radiation (NIST 2022).

In support of its work in setting measurement standards, the laboratory carries out a wide range of research related to measurement and to the development of measurement technologies. For example, it establishes spectroscopic methods and standards for infrared, visible, ultraviolet, X ray, and gamma-ray radiation. It also carries out research into the structure and dynamics of atoms, molecules, and biomolecules; it develops and improves the electrical, thermal, dimensional, mechanical, and physical metrology used to measure the properties of precision measurement devices and exploratory semiconductor, quantum electronic, nano-electronic, bioelectronic, bio-optical, optoelectronic, and quantum information devices and systems; and it studies the thermophysical and interfacial properties of streams of flowing fluids, fluid mixtures, and solids. In addition to those fundamental research efforts, PML also generates, evaluates, and compiles atomic, molecular, optical, ionizing radiation, electronic, and electromagnetic data; it measures and improves the accuracy of the fundamental physical constants; and it develops and operates major radiation sources used in measurement science and metrology (NIST 2023a).

In its role as the developer, repository, and disseminator of national measurement standards, PML works to promote uniformity and accuracy at the international, federal, state, and local levels through the development and sharing of calibrations, measurement quality assurance, and standard reference materials as well as through technology transfer, education and training, and a comprehensive weights and measurement program.

PML comprises nine separate divisions, each devoted to a particular aspect of measurement science and technology. Five of those divisions are in Gaithersburg, Maryland: Microsystems and Nanotechnology, Nanoscale Device Characterization, Quantum Measurement, Radiation Physics, and Sensor Science. The office of Weights and Measures is also located in Gaithersburg. The remaining four are in Boulder, Colorado. One division, Quantum Physics, is found on the University of Colorado Boulder campus. The other three—Applied Physics, Quantum Electromagnetics, and Time and Frequency—are on the NIST Boulder campus.

This report is concerned with the four divisions located in Boulder: Applied Physics, Quantum Physics, Quantum Electromagnetics, and Time and Frequency. A brief description of each of those four divisions follows.

APPLIED PHYSICS DIVISION

The laboratory's Applied Physics Division is focused mainly on measurements involving electromagnetic radiation across its entire spectrum, working to advance measurement science and technology in many critically important areas, including national security, advanced manufacturing, quantitative imaging, strategic computing, and quantum communications (NIST 2023b). To that end, the division operates a cutting-edge precision imaging facility that characterizes devices used for measurements and standard setting. The division's metrological expertise is vital to the development of many transformative technologies, including photonics, magnetics, and imaging. Its staff include world-class experts in laser and quantum metrology, quantitative imaging, spectroscopy, advanced communications, sensing, laser safety, and photonic and magnetic applications. The beneficiaries of its research and expertise are found throughout industry, academia, and government.

The division includes the following seven individual research groups:

- Advanced Microwave Photonics Group
- Faint Photonics Group
- Magnetic Imaging Group
- Molecular and Biophotonics Group
- Quantitative Nanostructure Characterization Group
- Quantum Nanophotonics Group
- Sources and Detectors Group

Specific areas of focus in the seven research groups include optical power measurements, quantum information, magnetic imaging, terahertz imaging research, research in optical frequency combs (used for precision time and frequency measurements) and quantum nanostructure characterization.

QUANTUM PHYSICS DIVISION

The Quantum Physics Division is the NIST component of JILA, a physical science research institute which is a collaboration between NIST and the University of Colorado Boulder, where JILA has its physical presence. At JILA, which was previously known as the Joint Institute for Laboratory Astrophysics, scientists carry out both theoretical and experimental research aimed at advancing fundamental measurement science. Studies focus on such topics as the quantum physics underlying interactions between light and matter and the ultimate limits of quantum measurements (NIST 2022), with specific areas of interest including quantum information science, quantum-enhanced precision measurement, ultracold atoms and molecules, quantum many-body physics, chemical physics, biophysics, and nanoscale quantum science (NIST 2023c). In addition to research, the division also emphasizes the training of scientific leaders and innovators for jobs in academia, industry, and national laboratories.

The division's primary research and training focus areas are as follows:

- Quantum information science and technology
- Precision measurement
- Atomic and molecular physics
- Laser physics
- Chemical physics
- Biophysics

QUANTUM ELECTROMAGNETICS DIVISION

The mission of the Quantum Electromagnetics Division is 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" (NIST 2023c). Taking advantage of the electronic, magnetic, quantum-mechanical, and photonic properties of materials and the interactions of those materials with electromagnetic waves, the researchers in the division develop high-precision measurement tools that can be used for quantum-based electrical standards, high-resolution photon sensors for imaging and spectroscopy, and energy-efficient spintronic devices (NIST 2022). The division's capabilities are valuable in a wide variety of fields, including advanced computing, new analytical tools and reference data, instrumentation for astrophysics and cosmology, and quantum information science, artificial intelligence, superconducting quantum information, and hyper-dimensional imaging as well as in fundamental physics. As is the case in the other divisions, the staff of the Quantum Electromagnetics Division collaborate and communicate with interested parties in academia, industry, and government to understand and address their measurement needs.

This division has the following five groups:

- Device Microfabrication Group
- Quantum Calorimeters Group
- Long Wavelength Sensors and Applications Group
- Quantum Electronics Group
- Spin Electronics Group.

Among its many activities, the division

- Operates a state-of-the-art Boulder microfabrication facility.
- Develops and disseminates instruments based on quantum sensors for the analysis of nuclear materials. These instruments provide new capabilities for precise, nondestructive composition measurements, and are in use at several nuclear facilities.
- Develops and disseminates large arrays of microwave polarimeters that are essential tools for modern cosmology.
- Develops new superconducting circuits for neuromorphic computing.
- Innovates in spin electronics and nanoscale spin dynamics research.
- Fabricates best-in-class, ultra-sensitive superconducting detector arrays (NIST 2022).

TIME AND FREQUENCY DIVISION

The missions of the Time and Frequency Division include maintaining the U.S. standards for frequency and time intervals, providing official time to the United States, and carrying out a broad program of research and service activities in time and frequency metrology (NIST 2023e). Thus, a major research thrust is dedicated to achieving an accurate and precise realization of Coordinated Universal Time (NASEM 2018), which is achieved with a cesium fountain atomic clock. The division also develops and maintains other technologies related to the measurement of time and frequency, including a ytterbium optical lattice clock, an aluminum ion quantum logic clock, optical frequency combs, the quantum control of single molecular ions, quantum information processing with trapped ions, quantum simulation and sensing with large trapped-ion crystals, chip-scale wavelength references and clocks, and microresonator devices. (NIST 2022).

The division currently has the following seven individual research groups:

- Atomic Devices and Instrumentation Group
- Ion Storage Group
- Neutral Atom Optical Clocks Group
- Phase Noise Metrology Group
- Precision Photonic Synthesis Group
- Quantum and Nonlinear Nanophotonics Group
- Time Realization and Distribution Group

REFERENCES

NASEM (National Academies of Sciences, Engineering, and Medicine). 2018. *An Assessment of Four Divisions of the Physical Measurement Laboratory at the National Institute of Standards and Technology: Fiscal Year 2018*. Washington, DC: The National Academies Press. https://doi.org/10.17226/25281.

NIST (National Institute of Standards and Technology). 2022. "Physical Measurement Laboratory: Gauging Nature on All Scales." https://www.nist.gov/system/files/documents/2022/01/21/pml-brochure.pdf.

NIST. 2023a. "About PML." https://www.nist.gov/pml/about-pml.

NIST. 2023b. "Applied Physics Division." https://www.nist.gov/pml/applied-physics-division.

NIST. 2023c. "Quantum Physics Division." https://www.nist.gov/pml/quantum-physics.

NIST. 2023d. "Quantum Electromagnetics Division." https://www.nist.gov/pml/quantum-electromagnetics.

NIST. 2023e. "Time and Frequency Division." https://www.nist.gov/pml/time-and-frequency-division.

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Applied Physics Division

The mission of the Applied Physics Division is to carry out research and develop technologies that will enhance measurement capabilities in such vital areas as national security, advanced manufacturing, strategic computing, quantitative imaging, and quantum communications. Among the strategically important technologies that rely on the laboratory's state-of-the-art measurement capabilities are photonics, magnetics, and imaging. To fulfill its mission, the division has developed world-class expertise in radiometry, spectroscopy, sensing, quantitative imaging, quantum measurements, and advanced communications, among other areas, with a specific focus on such capabilities as optical power measurements, quantum information, magnetic imaging, terahertz imaging research, optical frequency combs research, and quantum nanostructure characterization. The division also operates a state-of-the-art precision imaging facility used to characterize devices that are important to advancing measurement science, standards, and services.

The division includes seven individual research groups and more than 105 staff and associates from the United States and around the world, many of whom work on projects in more than one group. The groups are Advanced Microwave Photonics, Faint Photonics, Molecular and BioPhotonics, Quantum Nanophotonics, Magnetic Imaging, Sources and Detectors, and Quantitative Nanostructure Characterization. In addition to the work within and across groups in the division, the workers in the division share their expertise and innovations with colleagues in academia, industry, and other government agencies in order to maximize the value of their research.

ASSESSMENT OF TECHNICAL PROGRAMS

The Applied Physics Division has seven group leaders and spans a variety of disciplines including optical power measurements, quantum information, magnetic imaging, terahertz imaging, and quantitative nanostructure characterization. The division also provides a variety of calibration services including laser power and energy instrument metrology, magnetic resonance imaging (MRI), optical medical imaging, and precision semiconductor nanostructures. Many of these laboratories are sited in newly renovated space, which enables their activities. All of these efforts are remarkably well integrated with each other, and there is synergy between seemingly different projects. This is also true regarding interactions between calibration services and basic science, which superficially would appear to have different objectives. Furthermore, there is substantial enthusiasm for all activities. The success of these programs is evident in metrics such as publications per year, citations per year, external collaborations, press coverage, and awards (discussed in more detail in the Assessment of Scientific Expertise and the Effectiveness of Dissemination Efforts sections, below). The technical programs are clearly highly successful. However, there are opportunities for further development that would build on these successes in the areas of artificial intelligence (AI) expertise, materials characterization capabilities, and broader outreach to major industries. In addition, there are also opportunities to make improvements in the facilities infrastructure, laboratory safety, and onsite human resources support. These items are described in more detail throughout the report. Several examples of the exciting, innovative programs in this division are described below.

Qubits

The Faint Photonics and Quantum Nanophotonics Group carries out a number of synergistic experiments that couple and build on technologies developed in house, including superconducting nanowire single-photon detectors. The nanowire single-photon detectors provide the basis for many of the measurements in associated experiments. As transmon qubits operate in approximately the 5 GHz regime, expertise in microwave quantum optics is critical, and the group within the Applied Physics Division does a superb job in producing high-quality research, publishing in well-respected international journals, and creating overall work that competes with the best in the world. The entangled mechanical resonators are but one example of this exciting work.

The entangled-photon experiment used to achieve loophole-free Bell tests is an example of a core application within the National Institute of Standards and Technology (NIST) charter, where entangled photons are separated by polarization and transmitted through optical fibers to demonstrate the usefulness of such photons in "tamper-resistant" communications. While the periodically poled nonlinear crystals used to down-convert 775 nm photons to two entangled and cross-polarized 1,550 nm photons are also being used in this way in several other laboratories world-wide, the high level of engineering of this experiment at NIST produces a high detection success rate that brings entangled communication closer to actual utility.

Another example of important work being carried out here is the transduction work incorporating a quantum dot interacting with a surface acoustic wave to encode a radio-frequency photon (e.g., produced by a transmon qubit) onto an optical photon appropriate for transmission in an optical fiber. At this stage of development, this somewhat complicated process involving synchronization of signals is challenging. Of great importance will be the demonstration of high conversion rates which will be critical to successful wavefunction transmission between, for example, one dilution refrigerator and another for scaling.

Overall, mastering the interactions among microwave photons and resonators, nanomechanical systems, transduction, and more, all operating at 10 mK to 1 K is critically important in measurement science, and NIST's contributions are a key component of that research.

MRI (Phantoms and Low Field)

Several activities related to magnetic resonance imaging were discussed, with the highlights including quantitative MRI for medicine, contrast agents, and low-field MRI. Quantitative MRI focuses on the development of phantoms; that is, calibration structures that mimic biological structures of interest. The dissemination of these resources is accomplished through engagement with various institutes and international societies as well as through a lending library. Work on contrast agents focuses on testing existing contrast agents and developing new materials with enhanced functions. Both of these activities are well justified, organized, impactful, and likely to continue to be in demand by medical professionals. Low-field MRI presents a developing opportunity with the potential for rapid growth because of the portability and reduced cost of these instruments. Current areas of activity include developing a low-field system for monitoring of plant root systems and acquisition of a Food and Drug Administration–approved Hyperfine Swoop MRI scanner. If successfully developed, these technologies will present opportunities for commercialization. However, the disadvantage to low-field MRI is that it produces low-resolution images. In order to overcome this, AI is being trained to improve image quality. This is primarily being done through a collaboration with NIST's Information Technology Laboratory. As described below, the panel is unsure whether this is a sufficiently robust investment of resources in this important problem. AI technologies are advancing at an unprecedented pace, and it may be beneficial to embed AI experts directly in this project or to develop a group in Boulder that is focused on AI which can provide expertise to other projects.

Differential Absorption LIDAR

NIST has undeniably demonstrated an exceptional prowess in remote sensing technology through its groundbreaking work in differential absorption light detection and ranging (LIDAR and Differential absorption LIDAR [DIAL]). NIST's expertise in this field is evident in its ability to perform standoff measurements of atmospheric trace gases, showcasing its advanced and precise measurement techniques using LIDAR. With such remarkable achievements, NIST's proficiency in developing and refining DIAL technology is truly commendable.

As the demand for reliable and safe semi-autonomous cars continues to grow, the significance of LIDAR technology as a critical component for environmental perception and hazard detection during driving cannot be overstated. Given NIST's expertise in DIAL, it is ideally positioned to leverage its knowledge and translate its cutting-edge technology to the development of LIDAR systems for semi-autonomous vehicles.

This translation holds immense promise for enhancing the safety of semi-autonomous vehicles, aiding in the establishment of government regulations, and fostering advances in autonomous driving technology. By applying its DIAL expertise to LIDAR for cars, NIST would contribute to the broader landscape of the automotive industry, fueling innovation and paving the way for the widespread adoption of reliable and efficient semi-autonomous driving systems.

Optoelectronic Hardware for Artificial Intelligence

The Hardware for Artificial Intelligence project (also known as Superconducting Optoelectronic Networks) is a project that combines novel, enabling technologies in single-photon detection with an optical fan-in and fan-out architecture that closely mimics the human brain. The promise is a computing speed greater than that exhibited by cloud super-computers but with only one-fifth the power dissipation. The project is an illustration of how the Applied Physics Division collaborates effectively across boundaries (e.g., the additional application of superconducting nanowire single-photon detectors) and how innovation is encouraged from the bottom up: the project is a recipient of an Innovations in Measurement Science award. Not only is this work likely to garner recognition in the scientific community, but it may also contribute to important commercial applications. The Applied Physics Division has an opportunity to capitalize on this opportunity and accelerate the project from the current "aspirational" objective of 15 years. The team inspired confidence by communicating with passion their logic, plan, and objectives.

ASSESSMENT OF SCIENTIFIC EXPERTISE

In general, the Applied Physics Division staff appear to have excellent scientific knowledge, skills, and innovative talent. They excel in many areas, including optical physics, spectroscopy, superconducting device physics, quantum physics, cryogenics, and fabrication of devices. They are uniformly passionate about the science they are doing and committed to the mission of NIST. They display good teamwork as well as the ability to work across boundaries. There is considerable synergy among a broad array of programs. Division scientists have been the recipients of notable awards and recognitions, highlighting the exceptional quality and impact of their scientific contributions. These awards include Gold, Silver, and Bronze Awards internal to NIST, as well as fellowships from membership organizations such as the Institute of Electrical and Electronics Engineers, the American Physical Society, and Optica, and several Presidential Early Career Awards for Scientists and Engineers (PECASE). These accolades serve as a testament to the expertise of division's staff and the value they bring to their field.

A very fruitful meeting with early career scientists was held. At least one scientist expressed frustration that there seemed to be no opportunities for career positions or advancement, a comment which suggests that NIST is not viewed as a desirable place to work. There were, however, two scientists among the group of seven who had recently advanced to permanent positions. Among this group every one of them seemed to be very pleased with the mentoring they were receiving from their advisors and supervisors. Mentoring is critically important for the scientific and career growth of young scientists, and it appears that mentoring in the Applied Physics Division is of high quality.

Applications of Artificial Intelligence

There appear to be several projects that would benefit from more robust support by experts in AI within the Applied Physics Division, in order to develop an organized AI strategy. Prominent examples of work that could use such support are activities that produce low-resolution images (and possibly even higher-resolution images). This includes low-field MRI, terahertz imaging, and hyperspectral imaging for tumor margin analysis, although there are probably other areas in addition that are well suited. An interesting example is seen for terahertz spectroscopy when it is implemented to nondestructively image the internal structure of bridge decks. This is accomplished by locally heating steel-reinforced concrete and then observing the magnetic phase transition of hematite, which is produced as steel ages. This is a novel application that relies on low-resolution terahertz images that are subsequently improved by AI. If this technology could be deployed, it would have great value for assessing aging infrastructure throughout the nation and would be likely to find other applications in industry. Current AI support for this type of work appears to come from the NIST Information Technology Laboratory, but it is unclear whether this is sufficient.

Recommendation 3-1: The Applied Physics Division should consider incorporating artificial intelligence (AI) expertise within the division, rather than just relying on the National Institute of Standards and Technology's Information Technology Laboratory. Such expertise would allow for the development of a strategic plan for AI capabilities to be organically rolled into the Physical Measurement Laboratory's work where appropriate.

Developing a Diverse Workforce

Like many organizations that rely on a workforce with expertise in physics and engineering, there is limited diversity in the Applied Physics Division. To address this, NIST has developed a diversity, equity, inclusion, and accessibility (DEIA) plan with specific goals (NIST 2022). PML has ongoing activities that align with the NIST plan. This is laudable, but many of the plan's goals are inward looking or address DEIA issues at the NIST employment stage. It is desirable to have a more proactive approach to developing the pipeline of future applicants. To an extent, this is being done through engagement with institutions that serve underrepresented minorities (e.g., travel to conferences and to universities)—but even more engagement would be beneficial. The APS Bridge Program could serve as a resource to help NIST seek a more diverse talent pool. The Bridge Program is a post-baccalaureate program lasting 1 to 2 years that provides underrepresented minority students with research experience, advanced coursework, and coaching to prepare them for graduate school admission. Because this program has been in operation for more than 8 years, many graduate students who have participated in this program have started receiving their PhDs and are looking for postdoctoral positions. By approaching key staff at APS, NIST leaders could obtain valuable advice and help in letting students in the program know of NIST's exciting work in measurement science and NIST's interest in attracting postdocs from diverse backgrounds.

A longer-term goal is to establish diverse mentors at the upper career levels who can act as attractors for the next generation of diverse scientists. In practice, the PML leadership might partner with the University of Colorado or other host institutions. Beyond this, it is also important to recognize that future participation of individuals from underrepresented minorities depends on addressing needs below the university level. To do this, it is useful to develop laboratory experience opportunities for K–12 teachers, who are trusted mentors who can broaden the perspectives of students who might otherwise be unaware of the existence of organizations like NIST. This can also be accomplished through outreach of individual scientists into local K–12 schools. Many organizations undertake such activities on an ad hoc basis, leaving staff to self-organize.

BUDGET, FACILITIES, EQUIPMENT, AND HUMAN RESOURCES

The budget is essentially flat funded, but with inflation and rising salaries there is little room for growth. Thus, there are few opportunities for hiring new staff. There was some frustration expressed about this during the panel's meeting with early career scientists, most of whom were in term positions. There are also few opportunities for obtaining additional expensive equipment. Thus, while funding for current activities is adequate, without additional funding the Applied Physics Division could not act on Recommendations 3-1 and 3-3. In making this assessment it is assumed that the costs for upgrading the laboratory infrastructure (e.g., improving the water supply and protecting against power glitches; see Recommendation 3-2) would not be borne by the division alone.

Facilities

Laboratory facilities in the Applied Physics Division, on the whole, are impressive and adequate for the needs of the scientists; however, there were several challenging situations that directly affect the science. There has been significant improvement in many of the laboratory spaces since the past review, which is a positive development, but more upgrading of the facilities and infrastructure is required. In particular, some of the utilities have issues that are limiting the productivity of the division. The electricity supply is frequently interrupted. These interruptions, even very brief ones, have an impact on many of the experiments and operations within the division. The panel heard that electrical interruptions can ruin experiments in the fabrication laboratories and cleanroom, which result in a setback of several weeks. The technical programs of the organization depend on timely high-quality microfabrication of advanced devices.

Power glitches caused setbacks in many of the other research programs throughout the division. In the Superconducting Circuits for Quantum Information Laboratory, power interruptions would ruin long-term experiments, requiring an automatic alert system to be installed to notify the staff so they could quickly rush to the laboratory at all times, day or night, and reset the equipment. The laboratory was forced to install an uninterruptible power supply to improve their operations. The electrical supply issue needs to be addressed site-wide, with backup power or uninterruptible power devices as needed; otherwise, the facility cannot be considered best-in-class.

There has been a degradation in the quality of the water supply which is causing corrosion in the existing pipes. This has caused the water supply to be contaminated with magnetic particles which affects many of the experiments within the division. An incident was reported in which the poor-quality water and cold weather caused corrosion and a pipe break which flooded a laboratory, ruining expensive equipment. The laboratory required almost a year to recover from this incident. The panel recommends that the quality of the water supply be addressed in order to prevent further incidents.

> **Recommendation 3-2: The Physical Measurement Laboratory should invest in additional upgrading of the division's facilities and infrastructure. In particular, the electrical supply needs to be upgraded to avoid the frequent interruptions that have been setting back and ruining experiments, and the water system needs to be improved to avoid pipe breaks.**

Equipment: Materials Characterization Tools

There exist a number of materials characterization tools presently within and available to the Applied Physics Division, along with the expected delivery of additional tools in fiscal year (FY) 2024 and FY

2025. While the focus of the division is not primarily on materials science and development, the wide array of devices and experiments under study within the division critically depends on the growth and processing of unique material structures. A concern is that a lack of key characterization tools might slow or inhibit the future development of materials and processes in the critical path to realizing new cutting-edge material structures and devices.

The division's analytical tools, while extensive in number, are focused primarily on structural characterization; for example, electron and optical microscopes such as scanning electron microscope (SEM), tunneling electron microscope, profilometers, ion beam/SEM, X-ray diffraction, atomic force microscope, secondary ion mass spectroscopy, and energy-dispersive X-ray spectroscopy. The atom probe tomography instrument is extremely valuable, but it is a research instrument, as opposed to a characterization tool.

What is lacking are any tools that interrogate the surface composition of materials used in the fabrication of devices, such as high-resolution X-ray photoelectron spectroscopy and ultraviolet photoelectron spectroscopy. These tools are invaluable in determining the surface and near-surface elemental compositions as well as the presence of contaminants. They can also determine whether the material is metal or semiconducting. Modern XPS systems have high spatial resolution necessary for both blanket films and device structures and software packages typically sold with these advanced systems identify the elemental, chemical, and stoichiometric properties of the materials. These instruments would greatly benefit the materials efforts within the Applied Physics Division. Given that molecular-beam epitaxy is an important growth modality, the suggested characterization tools would optimize and accelerate such process development, including searching for deleterious impurities. These tools can quickly assess the elemental composition of a material surface and the chemical state of the system with small spot capabilities down to and below 1 micron; that is, at spatial scales that are relevant to many of the devices being fabricated and studied in the division, including transmons, transduction devices, and more. There are multiple ways to acquire access to these tools. They can be purchased by the division or through collaboration with other organizations that have these capabilities. Purchasing them would ensure that the division has whatever access to them that it needs to conduct its work, while collaboration could result in work delays while others use the tools.

Recommendation 3-3: The Applied Physics Division should further expand its materials characterization capabilities, as these are critical in constructing some of the devices used in the division's experiments. New capabilities could include tools that interrogate the surface composition of materials used in the fabrication of devices, such as high-resolution X-ray photoelectron spectroscopy, ultraviolet photoelectron spectroscopy, and molecular-beam epitaxy. The Applied Physics Division should purchase these capabilities to support their work rather than relying on coordinating with others to have access.

Human Resources

Almost 2 years ago the response from the Human Resources (HR) Department (NIST Gaithersburg) regarding personnel actions in hiring and promotions was essentially nonexistent. This lasted for more than a year and was extremely frustrating for the division chief and group leaders. Lack of support from HR affects the division's ability to hire, promote, and retain good people in a timely way and therefore affects the progress of science. This appeared finally to get fixed, but concerns exist that this could happen again in the future if HR is not prepared to address a higher rate of hiring, such as might be anticipated with the advent of the CHIPS and Science Act of 2022.

There is no HR representative onsite to field complaints about harassment, bullying, ethics issues, etc. There is apparently a well-respected ombudsperson to whom one can go with such concerns. That individual, however, has no authority to launch investigations, and apparently the division chief has had to perform an initial inquiry herself. This presents a serious conflict of interest. There is a need for an excellent HR person onsite who can take on such issues and launch outside investigations as needed in a timely fashion. Often, with sensitive personnel issues, an in-person presence by an HR professional is particularly helpful and more effective than a remote presence.

Recommendation 3-4: The Physical Measurement Laboratory (PML) should have excellent Human Resources professionals onsite who can address an array of personnel issues in a timely fashion within the context of the PML culture.

Technical Support

Much of the laboratory space that is in use by the PML group is newly refurbished and has been equipped with high-quality instrumentation. The expert installation of equipment and the general setup of the laboratories are impressive, but apparently this has been done by the scientists themselves without the assistance of technicians. Importantly, this also included some rudimentary items such as installing noise damping panels in a cryogenics laboratory. It is impressive that the staff are motivated and capable of doing all of these activities, but it is unclear whether this is the most effective use of research staff hours. The addition of technicians to the staff could free up researcher time to do the work that only the researchers can do.

Laboratory Safety

The safety practices within the division raised some concerns. There have been several serious safety incidents at NIST recently, including a problem with a research nuclear reactor because of an improperly latched fuel rod and a fatality during the demolition of a test structure. According to staff, the Applied Physics Division has periodic safety walk-throughs about every 6 months, which seemed to be less frequent than necessary and not best practices for a research organization with such risks as high-power lasers, power supplies with dangerous voltages, and chemical hazards. During laboratory walk-throughs, the panel noticed that many experimental samples were not labeled with chemical or physical hazards.

Purchasing requirements imposed by the government have caused difficulty in the procurement of personal protective equipment (PPE) for some employees. Proper PPE is an absolute requirement for conducting safe work in PML, especially given the widespread use of powerful lasers, potentially hazardous electronics, cryogenics, and hazardous chemicals.

Recommendation 3-5: The frequency of safety inspections by the Physical Measurement Laboratory (PML) should be increased and PML leadership should reach out to major industrial companies for advice on improving laboratory safety. In particular, the leadership should look to those companies that are recognized as having among the best safety programs in the world. Large chemical and petrochemical companies, for instance, are widely recognized as having very high-quality safety programs and may be willing to share key aspects of their safety practices.

EFFECTIVENESS OF DISSEMINATION EFFORTS

The Applied Physics Division team has a stellar publication record, consistently contributing to high-quality scientific journals renowned in their field. These journals boast an impressive impact factor, reflecting the significance and influence of the published research. The division's work has consistently appeared in prestigious journals, underscoring its ability to meet rigorous standards of scientific excellence and peer review.

The Applied Physics Division at NIST has garnered exceptional press coverage, reflecting its groundbreaking work and advancements. For instance, *Smithsonian Magazine* published "New Atomic

Clocks May Someday Redefine the Length of a Second" (Fox 2021). Other articles[1] appearing in a variety of publications have effectively highlighted the division's significant contributions to scientific research and technological innovation, bringing deserved attention to its accomplishments. By showcasing its achievements to the public and stakeholders, NIST can demonstrate the value and impact of its research, garner support, and attract collaborations. Furthermore, press coverage facilitates knowledge dissemination, allowing NIST's scientific breakthroughs to reach a wider audience and inspire future generations of scientists and researchers. It also helps foster transparency and accountability, ensuring that tax-payer investments in NIST are recognized as yielding tangible benefits and advancements that positively impact society.

Further Industrial Engagement

For more than three decades the United States has been experiencing the slow but steady loss of fundamental research within industrial laboratories. The decline of Bell Labs is a classic example. Many smaller technology companies do not have the resources or bandwidth to carry out more basic research critical to their needs in areas such as optics, communications, and materials. NIST is known informally by many as "the national laboratory for industry" and the research at NIST is critical to the overall support of U.S. technology industries. Wider engagement is warranted.

The Applied Physics Division does a great job serving industry requests. The following Key Recommendation is not in response to a shortcoming. Rather, it would address some challenges that industries face, which could benefit from an improvement in measurement science that the division does not currently perform. This would be an opportunity for Applied Physics Division to broaden its impact in measurement science.

Key Recommendation 4: The Applied Physics Division should create opportunities to take part in more collaborations that address critical industry needs in measurement science and to generate support for such work.

The Applied Physics Division staff include best-in-the-world technologists pushing the boundaries in multiple disciplines. Its members constitute a high-performing team and, as such, should offer more value to the American industrial ecosystem. The team has an impressive stakeholder community consisting of federal agencies, foreign counterparts, and industrial enterprises. Nonetheless, broader industrial engagement would enable the division to learn more about industry needs and challenges that can be addressed by advances in measurement science and technology. For example, in the semiconductor industry it is necessary to match the critical device dimensions produced in one process chamber with another to within less than 0.5 nm. Typically, such dimensional control is obtained by controlling wafer temperature to less than 0.2 K accuracy and precision for absolute temperatures less than 600 K. Yet, low-temperature pyrometry and similar techniques for measuring the temperature of thin films on Si wafers lack standards to this degree of accuracy, and industry is thus forced to rely on expensive, iterative, and convoluted methods to achieve the desired result. A direct, accurate, and precise temperature measurement would have large value. This is but one example. Similar challenges exist in radio frequency power and fluid flow measurement and control.

There is an opportunity, therefore, for the Applied Physics Division to engage more broadly with industry to understand such challenges and the funding the division would require from the industrial sector to address those challenges. By working to deliver solutions to industrial needs, NIST would be

[1] See, for example, "Quantum Entanglement Has Now Been Directly Observed at a Larger Macroscopic Scale" in *Science Alert* (Nield 2021), "Scientists Come Closer to Building Quantum Computer Capable of Solving Virtually Any Equation" in *The Academic Times* (Gallagher 2021), and "You May Have Missed… Roman Coins Authenticated; Using Sugar to Print Microchips; Aussie Summer Injuries; and the Glow Between Galaxies" in *Cosmos* (Perfetto 2022).

directly helping industry to create products which could be manufactured with greater precision, more rapidly and cheaply. This would be a great benefit to the nation's economy and the American public.

REFERENCES

Fox, A. 2021. "New Atomic Clocks May Someday Redefine the Length of a Second." *Smithsonian Magazine*, April 1. https://www.smithsonianmag.com/smart-news/new-atomic-clocks-hone-length-second-180977387.

Gallagher, N. 2021. "Scientists Come Closer to Building Quantum Computer Capable of Solving Virtually Any Equation." *The Academic Times*, March 24. https://academictimes.org/scientists-come-closer-to-building-quantum-computer-capable-of-solving-virtually-any-equation.

Nield, D. 2021. "Quantum Entanglement Has Now Been Directly Observed at a Larger Macroscopic Scale." *Science Alert*, May 7. https://www.sciencealert.com/quantum-entanglement-has-now-been-directly-observed-at-a-larger-macroscopic-scale.

NIST (National Institute of Standards and Technology). 2022. "Diversity, Equity, Inclusion, and Accessibility Strategic Plan: FY22–FY24." https://www.nist.gov/system/files/documents/2022/10/31/nist-deia-strategic-plan-final-2022.pdf.

Perfetto, I. 2022. "You May Have Missed… Roman Coins Authenticated; Using Sugar to Print Microchips; Aussie Summer Injuries; and the Glow Between Galaxies." *Cosmos*, November 28. https://cosmosmagazine.com/technology/roman-coins-sugar-print-microchip.

4
Quantum Physics Division

The Quantum Physics Division is the National Institute of Standards and Technology (NIST) component of JILA—the latter established in 1962 and located on the campus of the University of Colorado Boulder (CU). These two conjoined organizations together constitute a very unusual but extremely successful collaboration. In fiscal year 2022, the Quantum Physics Division funding was approximately $24.4 million, with about half of that funding from NIST and half from external sources. Important aspects of JILA funding include the JILA Physics Frontier Center, which has been continuously funded by the National Science Foundation (NSF) since 2006, as well as the q-SEnSE Institute (Quantum Systems through Entangled Science and Engineering), an NSF Quantum Leap Challenge Institute partnership of 12 research organizations launched in 2020 and directed by NIST and JILA Fellow Jun Ye.

JILA employs nine NIST-supported fellows, including the current JILA chair, out of a total of 29 JILA fellows. The JILA fellows act effectively as a faculty department at NIST and CU, collectively making decisions regarding research activities and faculty hiring to maintain the highly collaborative environment that has helped make it successful to date. The fellows try to guide JILA toward new frontiers in precision measurement and quantum, molecular, and biological physics, among other areas.

ASSESSMENT OF TECHNICAL PROGRAMS

JILA is clearly one of the crown jewels of NIST. It is a special place, absolutely world class, and needs to continue being a special place in the future. As one JILA fellow stated: “We are not here to come second.” Most, if not all, fellows are world-renowned scientists who work at the forefront of their respective research areas. The general technical program of JILA research is the development of fundamental measurement science, pioneering new technologies in the field of quantum physics and the training of early career researchers.

The central work of the Quantum Physics Division at JILA is in fundamental precision measurements in various areas of chemistry, physics, and biological physics. The measurements range from ultra-precise frequency measurements for time and frequency standards using quantum-enhanced techniques to fundamental measurements, such as of the electric dipole moment of the electron, and from the search for dark matter with high-Q resonators to precision measurements for biological and chemical processes.

The scientific expertise of the Quantum Physics Division ranges from quantum information science and exploring applications of quantum-enhanced sensing to quantum information processing and quantum simulations. In addition, there is expertise in the micro-fabrication of materials and electromechanical devices. Special knowledge and skills are available in atomic and molecular physics, especially on quantum many-body physics and controlling molecule formation and chemical reactions.

In the area of quantum information processing, the Quantum Physics Division has developed and demonstrated trapped alkaline-earth atoms in tweezer arrays, demonstrated record-breaking long coherence times, realized tweezer-programmable two-dimensional quantum walks, and demonstrated long-lived Bell states. There is theoretical expertise with quantum many-body physics (the group of Ana Maria Rey), which in collaboration with the Time and Frequency Division (Time and Frequency Division Group of John Bollinger) resulted in the demonstration of methods to harness and manipulate spin-interactions mediated by phonons in Penning traps. The collaboration of the Ana Maria Rey and Jun Ye teams demonstrated Hamiltonian engineering of spin-orbit coupled fermions in an optical lattice clock and showed that such clocks provide superior quantum coherence with interactions that can be manipulated to realize quantum simulations of spin models.

Precision measurements are central to the joint work of many teams of the division. The close collaboration of the teams of Jun Ye (JILA), Andrew Ludlow (NIST), and David Hume (NIST) has resulted in groundbreaking achievements over the past 5 years. This resulted in frequency ratio measurements with an 18-digit accuracy using an optical clock network, the amazing resolution of the gravitational redshift across a millimeter-scale atomic sample, the demonstration of a tweezer-array-based atomic clock, and the setting of a new bound of the electron's electric dipole moment. Precision measurements by Konrad Lehnert's group with high-Q microwave resonators enabled the search for wave-like dark matter with detection at the quantum limit.

Atomic, molecular, and optical physics has always been at the heart of the Quantum Physics Division work at JILA, especially research concerned with cold atoms and molecules. The manipulation of atomic and molecular samples and the control of their interactions enable new studies of quantum many-body physics and the respective quantum control. Special highlights during the period of this assessment included the demonstration of methods to use long-range exchange interactions in an optical cavity to generate new phases of matter, which is useful for optical clocks; the demonstration of cavity quantum electrodynamics measurements of the strontium milli-Hertz clock transition; theoretical work on the dynamical generation of spin-squeezing in ultra-cold molecules; and the demonstration of Pauli-blocking in atom light scattering.

Nanoscience expertise in the Quantum Physics Division intersects quantum optics, superconducting quantum circuits, and nanomechanical devices in close collaboration with the scientists at NIST Boulder. Research highlights during the past 5 years include the conversion of photons from the microwave to the optical regime with the demonstration of superconducting qubit readout with an electro-optomechanical transducer, among others.

There are three groups doing biological physics in the Quantum Physics Division: those run by Tom Perkins, Ralph Jimenez, and David Nesbitt. Nesbitt has recently begun a collaboration with Jun Ye to do ultra-sensitive detection of biomarker aerosols using femto-second frequency combs.

Tom Perkins has systematically been developing single-molecule force-extension curves using atomic force microscopy (AFM). Perkins uses commercial AFMs (Asylum) but specializes in the improvement of the AFM's crucial cantilevers. The fundamental problem this project has addressed is optimizing the cantilevers for stable, accurate, and highly sensitive force measurements, while simultaneously decreasing the mechanical relaxation time from the standard 400 μsec to 2 μsec, allowing for much improved measurements of biomolecule conformational dynamics. This technology took extensive advantage of scanning electron microscopes and focused ion beam technologies on the CU campus.

A particularly exciting development has been including the optical excitation of bacteriorhodopsin molecules at the same time that the AFM is measuring the conformational rigidity of the bacteriorhodopsin at the μsec time scale. Because the light-activated dynamics of bacteriorhodopsin are critical to its function of charge-pumping across a membrane, this opens a new avenue of exploring functional protein dynamics.

Ralph Jimenez has engineered intrinsically fluorescent proteins to have enhanced photophysical properties, such as brightness, by using a combination of random and targeted mutagenesis, and the project has designed several novel microfluidic systems for screening libraries of mutants. A recent effort was to use entangled down-converted photons for two-photon excitation microscopy. The hope was that an entangled pair of photons would have enhanced two-photon excitation owing to the spatial correlations of the entangled pair. This has proved to be a challenging task.

David Nesbitt works in both the areas of photochemical dynamics and time-resolved biomolecule folding. The three-dimensional momentum distributions of photo-electrons (excited by the multi-photon plasmon excitation of complex metallic nanostructures) are measured using a technology called scanning photoelectron imaging microscopy. These photoelectrons can potentially be used for photo-driven chemistry of absorbed molecules on the nanostructures in a directed manner. This effort appears to be rather isolated and could benefit from a direct engagement with time- and space-resolved studies of surface electric fields and surface plasmon polaritons, using related forms of photo-electron emission microscopy in other institutions in both the United States and Europe.

The more direct biological physics work is on the time-resolved folding dynamics of RNA molecules. The basic technology uses fluorescent resonant energy transfer with picosecond visible laser sources to measure the structural dynamics of RNA molecules, with the use of a pulsed near-infrared laser to create a transient "bath-tub," which allows for the determination of the free energies of folding.

A very exciting recent collaboration, driven by the COVID-19 pandemic, is a collaboration between David Nesbitt and Jun Ye to analyze biomarkers in aerosols using a femtosecond frequency comb injected into a high-finesse optical cavity. The frequency comb consists of 25,000 discrete channels covering a range of 3–10 microns, with an effective path length of 10 km, providing enormous sensitivity. Preliminary results using breath samples from 173 CU people yielded an 83 percent "area under curve" true-positive versus false-positive rate, which is comparable to state-of-the-art polymerase chain reaction tests. Potentially this technology could be used for a large spectrum of human diseases.

Challenges and Opportunities in Biological Physics

Historically, the biological physics section has had sub-critical mass, but given the extraordinary strengths of the other groups in the division, there is no real room for biological physics to grow. There is a potential retirement coming up. The good news is the new collaborations growing between biological physics and the atomic, molecular, and optical parts of the division, which the panel strongly encourages. There is a growing interest in quantum aspects of biology; this may be an area for further collaborations.

ASSESSMENT OF SCIENTIFIC EXPERTISE

The JILA Quantum Physics Division group leaders are world class scientists. They carry out research at the frontiers of their fields and in many ways define those frontiers. Their achievements are evidenced by an extraordinary number of awards that they have received at the international, national, and NIST levels (4 of the 40 NIST fellows are members of the division). Particularly worth mentioning in the assessment period are Ana Maria Rey's 2023 election to the National Academy of Sciences, the award to Jun Ye of both the 2020 Micius and the 2022 Breakthrough prizes, and the recognition of Adam Kaufmann with the 2023 New Horizon Prize in Fundamental Physics.

Challenges and Opportunities

The emerging quantum information industry is aggressively recruiting freshly minted PhD physicists and engineers and offering them extremely attractive starting salaries and incentives. This situation is likely to be exacerbated if this industry continues its exponential growth. Because typical postdoctoral salaries are not competitive with such offers this can be expected to result in significant recruitment challenges. Although the top-notch research being performed at JILA will certainly remain a significant attraction, it is important not to underestimate this issue and to be proactive in addressing it. The future will be grim if JILA and NIST lose all our best young people to industry at such an early stage.

Some of the graduate students reported a laboratory and group culture or environment in which psychological safety is an issue. Indeed, they reported not feeling safe asking scientific or research questions that they think might be too basic or might make them feel less smart. This concerns the panel deeply and is clearly a problem that needs to be addressed between PML and CU.

BUDGET, FACILITIES, EQUIPMENT, AND HUMAN RESOURCES

Budget

The funding required to carry out the division's current tasks is provided in almost equal parts by NIST appropriations ($12.6 million, 52 percent) and third-party non-NIST funding ($11.8 million, 48 percent). Of the non-NIST finding, 88 percent is from government sources: NSF ($3.03 million), the Department of Defense ($4.25 million), the Department of Energy ($2.84 million), and the National Aeronautics and Space Administration ($105,000), and 6 percent each is from academic and industry sources. Thanks to the division's remarkable strength in attracting external support evidenced by these numbers, its total operational funding appears to be currently adequate.

However, the continuing excellence of JILA is seriously endangered by a combination of aging and lacking facilities and infrastructure. These problems are a critical issue, and there is an urgent need to improve and expand the laboratory facilities. The Quantum Physics Division leadership indicated that an additional $200 million in capital funds for facility upgrades—both new construction and renovation—would barely bring the facilities up to the standards of international peer institution.

Technical Support

Shop technicians are the secret weapon of JILA. Their technical support is highly appreciated by students and scholars alike. However, the panel heard during its visit that there are constant challenges to keep funding the technical support staff and facilities at a level that makes their use viable for the principal investigators (PIs)—if the base funding provided for the shops is not sufficient, then the user fees are too high to be affordable. This decision is one of choosing between funding additional research activities or maintaining the support capability given all available funding. Right now, JILA is at the threshold of a challenge in the matter of maintaining shops.

Laboratory Space and Conditions

Aside from the budgetary challenges to maintain the technical infrastructure, the panel has identified a major problem for the ongoing future work of JILA. In fact, visiting the site and talking to the PIs revealed that the continuing excellence of JILA is seriously endangered by a combination of aging and lacking infrastructure. The panel was left with the impression that the successful future of the Quantum Physics Division at JILA is at best extremely close to—or, more likely, already past—the tipping point where the facility issues are able to be deferred while the institution continues being successful, because the ongoing work hinges critically on the availability of up-to-date infrastructure combined with modern and sufficient laboratory space.

Laboratory space is indeed an existential problem: most JILA buildings are more than 50 years old, and deferred maintenance in the $20 million range is significantly affecting daily work and resulting in periodic damage to equipment. In addition, presentations by division leadership indicated to the panel that an additional $200 million in capital funds for facility upgrades would barely bring the facilities up to peer institution standards (this estimate considers both new construction and renovation of current facilities). Given the competitive environment at the highest level in the fields of research represented by the Quantum Physics Division, this limitation places severe constraints on the organization. It is the opinion of the panel that the ability of the institution to hire the most qualified candidates for faculty positions has already been affected by substandard facilities and that this impact will only get worse, severely limiting the ability of the group to hire in anticipation of growth and future retirements. As the panel learned, JILA facilities upgrades and expansions are not captured in the NIST master plan, but JILA is in the CU master plan. As a consequence, NIST cannot simply address JILA's problems on its own but must rely on CU to do so in cooperation. Since problems have obviously arisen that have not been addressed, this could seriously endanger JILA's capabilities in the future.

A lack of space, failing infrastructure (water leaking into the laboratories, failing air conditioners, etc.), and sub-standard safety conditions have already had a negative impact on research. This is a liability for the ongoing work and a serious danger for the future of the Quantum Physics Division and JILA. In particular, the recruitment of competitive PIs is being strongly hampered, especially because all space expansion ideas are unfunded plans, which are at present not even considered by CU nor by NIST. Therefore, in the current situation it is already impossible to compete with the best places to attract top people. This needs to be addressed very soon when considering the need to make new hires in view of the years of service of the PIs. The panel considers this situation to be an existential issue for JILA and its continuation as a center of excellence at the forefront of science. The panel has heard that several people indeed may be thinking of leaving because of the current situation.

General Working Conditions and Safety Issues

The limited space available in the laboratories presents a serious problem for the general working conditions in the laboratories and has a negative impact on safety issues, ranging from laser safety to the safe handling and storage of chemicals.

Safety culture and compliance issues are particularly challenging at JILA owing to differences in university and NIST safety requirements. The most obvious result of these inconsistencies is that safety conditions in laboratories are far from ideal. Because Colorado is not an Occupational Safety and Health Administration (OSHA) state, the university mandates compliance with state regulations. However, NIST, being a federal institution, is required to comply with OSHA regulations. This difference, together with vastly different safety cultures within the organizations, has resulted in substandard safety conditions regarding laser, electrical, chemical, cryogenic, laboratory egress, and general working conditions.

A specific example provides some insight into the complexities and severity of these issues of laboratory safety. The panel was made aware of inconsistencies in laser safety training between students and postdocs in JILA laboratories. While this was alarming, given International Electrotechnical Commission standard Class 3R/3B/4 lasers[2] in the laboratories the panel visited, the panel felt it was important to understand whether this was an inconsistency between laboratories or whether the issue was indicative of more systemic problems. Upon further investigation, the panel became aware of NIST's ongoing efforts to improve laser safety on the JILA campus and how these efforts have resulted in safety improvements but also contribute to inconsistent training across JILA. Discussions between NIST and CU after a laser safety incident at JILA in 2021 led to the recent signing of a memorandum of understanding which documented the intention of the university to bring JILA up to American National Standards Institute (ANSI) laser safety standards. The first step in this process has been the establishment of a campus laser safety officer. The panel was both surprised to hear that the campus never had a laser safety officer—especially given the high fraction of laboratories within JILA containing International Electrotechnical Commission standard Class 3R/3B/4 lasers—and heartened that NIST and the university had emphasized this first step toward compliance with relevant safety standards. Lacking a laser safety officer has led to a patchwork approach to instituting adequate training across JILA laboratories, wherein NIST safety managers are conducting training sessions for students, postdocs, and faculty; furthermore, compliance tracking is clearly not yet where it needs to be. Again, it is clear that the intention by both organizations is to improve safety conditions, but the panel is concerned that there are no established timelines to reach compliance with the agreed-upon standards, nor are safety standards agreed upon across all areas. Furthermore, it is clear from discussions with NIST safety personnel that the intention is to use the safety memorandum to expand safety efforts into other areas; again, the panel's concern is that there is no timeline set for implementation, nor even full agreement on the areas where conditions need to

[2] See IEC 60825-1 Ed. 3.0 b:2014, https://webstore.iec.ch/publication/3587, last accessed January 17, 2024.

improve. Lastly, the facility issues mentioned elsewhere place severe constraints on the ability of the organizations to achieve safe conditions.

Recommendation 4-1: The National Institute of Standards and Technology's Office of Facilities and Property Management and appropriate University of Colorado leadership should work together to solve the serious JILA space, infrastructure, and safety problems. The two organizations need to understand what is at risk and the urgency of the issue. A special task force with representatives of all stakeholders may be useful in putting focus on this problem and finding a timely solution.

Recommendation 4-2: The Physical Measurement Laboratory and the University of Colorado Boulder should jointly establish a clear and aggressive timeline to reach American National Standards Institute laser safety standards. The panel also recommends expanding the existing memorandum of understanding to establish acceptable standards and timelines for achieving improved and adequate safety compliance in those areas.

Diversity

A lack of diversity was noted by students and postdocs in nearly every measure of diversity, including gender, race, and identity. There were few indications of measures to improve diversity, and such measures are highly likely to be affected by the individual positions of the 29 JILA Fellows. The panel is concerned that a lack of attention to improving these conditions will affect JILA's ability to bring in and, especially, retain highly qualified candidates and ensure that the teams are able to perform the highest-quality research.

EFFECTIVENESS OF DISSEMINATION EFFORTS

The division's results are distributed in the very best journals, with extremely high impact factors. Between 2018 and now the division's researchers have published more than 300 refereed papers and accumulated more than 60,000 citations, for an average h-index of 57.

Because of its involvement with UC, JILA is extremely well-posed to do public outreach. In fact, David Nesbitt is the "Chief Wizard and Program Director" of the extremely successful CU Wizards Program (https://www.colorado.edu/cuwizards). Each year, about 10 to 12 professors from different disciplines put on the wizard's hat to present shows to students.

Stakeholder Needs

Quantum physics and the mysteries of state entanglement used to be the realm of the physicists and the more esoteric and advanced aspects of technology. However, in the past 5–10 years the panel has seen a remarkable growth in interest in quantum computing and quantum security at an international and highly competitive level. Historically the stakeholders of the Quantum Physics Division and JILA effort have been the community of fundamental scientists. All of this is changing at warp speed as fundamental quantum physics begins to invade all aspects of not only high technology but daily life.

A very surprising aspect of the growing interest in esoteric quantum physics from outside the field is the development of biomarker sensing using femtosecond frequency combs. This promises to lead to the inclusion of the medical community—and indeed of the general public as well as additional stakeholders—among those invested in quantum entanglement and other aspects of quantum physics.

Owing to the unique charter of JILA among NIST laboratories, a fundamental responsibility of Quantum Physics Division and JILA is to provide essential support to a broad spectrum of stakeholders through the recruiting and training of the next generation of top students and postdoctoral researchers in quantum physics and quantum information science, broadly understood. Our textbooks and courses will need to be dramatically revised to accommodate this explosive change in quantum physics, and thus higher education will also be a stakeholder of Quantum Physics Division and JILA.

5
Quantum Electromagnetics Division

The Quantum Electromagnetics Division develops measurement devices, standards, and methodologies for use with electronic, magnetic, photonic, and quantum technologies that have national strategic importance. The division has four technical focus areas: advanced computing, new analytical tools and reference data, instrumentation for astrophysics and cosmology, and quantum information science. The division's researchers take advantage of the quantum-mechanical, electronic, magnetic, and photonic properties of materials and their interaction with electromagnetic radiation to create a wide variety of measurement tools used for such things as quantum-based electrical standards, energy-efficient spintronic devices, and high-resolution photon sensors used in imaging and spectroscopy. Innovations in metrology and in micro- and nanofabrication originating from the division have helped propel critical advances in high-performance superconducting electronics, data storage, materials development, quantum processing and engineering, nuclear forensics, and astronomical observations and have also contributed to a deeper understanding of fundamental physics. Furthermore, hardware designed and built by the division is important in such areas as artificial intelligence, superconducting quantum information, and hyper-spectral imaging.

The division has five research groups: the Device Microfabrication Group, the Quantum Calorimeters Group, the Long Wavelength Sensors and Applications Group, the Quantum Electronics Group, and the Spin Electronics Group. The division has 70 staff members, including more than 40 scientists, plus technicians, engineers, and students, to carry out pioneering research in such areas as superconducting transition-edge sensors (TESs), superconducting quantum interface device (SQUID) multiplexing, parametric amplifiers, microwave kinetic inductance detectors, and several types of advanced refrigerators.

The Device Microfabrication Group builds a wide range of microfabricated circuits including TESs, MKIDs, SQUIDs, and parametric amplifiers for both internal and external sensing and metrology needs worldwide. The Group specializes in the development of large arrays of cryogenics sensors.

The Quantum Calorimeters Group develops highly sensitive calorimetric detectors of high-energy X ray and gamma-ray radiation using highly sensitive TES devices. The high-sensitivity spectrometers form a core capability at the National Institute of Standards and Technology (NIST) and answer external needs for super-fine-energy resolution to detect isotopes, in particular, for residual low-volume isotope compositions in nuclear materials and nuclear medicines.

The Long Wavelength Sensors and Applications Group explores and implements devices and spectrometers for long wavelength low energy electromagnetic radiation with super-high sensitivity at absolute energy scale by using TES and microwave kinetic induction detector-based devices. These devices achieved an unprecedented sensitivity of 6×10^{-19} W/Hz$^{1/2}$ in the long-wavelength region and provided absolute power measurement metrology at low power levels relevant to quantum computing.

The Quantum Electronics Group develops low-noise readout techniques to enable larger arrays of more sensitive detectors. The Group designs low-noise amplifiers, multiplexing circuits, and custom room-temperature electronics in order to perform end-to-end readout of cryogenic sensors.

The Spin Electronics Group is exploring a next-generation technology to replace conventional semiconductor electronics for high-capacity data processing applications. Electron-spin torque is being explored for use in switching magnetic memory elements; if successful, the new technique could provide higher switching speeds, greater reliability, and scalability to smaller device dimensions for lower-power switching of memory bits with magnetic fields. Theoretical and experimental investigations have been performed on spin and thermal transport, interfacial structure, and the transfer dynamics of spin angular momentum in devices and across interfaces with newly developed high-frequency and optical measurement capabilities to create and characterize new materials.

The division works with stakeholders in industry, academia, and other government agencies to understand and be responsive to their measurement needs in such areas as quantum electrical standards; advanced materials analysis using X-ray sensor arrays; superconducting electronics and nanomagnetics for high-speed, energy-efficient, future-generation computing; and quantitative medical diagnostic imaging.

ASSESSMENT OF TECHNICAL PROGRAMS

The Quantum Electromagnetics Division's focuses include, among others, high-performance sensors for long-wavelength detection, X-ray detection, large-scale TES detector fabrication, and interconnects.

The Device Microfabrication Group has recently fabricated 300 wafers for sensors and interconnects yearly. The mix includes TESs, microwave kinetic inductance detectors, SQUID arrays, time-division SQUID multiplexers, microwave SQUID multiplexers, Josephson parametric amplifiers, kinetic inductance traveling wave parametric amplifiers, normal-insulator-superconductor tunnel junctions, tunable inductance bridges, and microresonators.

The TES activity at the Quantum Electromagnetics Division has matured over the past few years and ranks among the best in the world. This activity's success with larger research and development programs (e.g., the Simons Observatory and ATHENA satellite) can be a true sign of success for NIST. However, the TES activity has become very successful and is very strongly supported by a few outside programs. This is good, but the scientific and technical community at large has not taken advantage of the TES capability. It would be very satisfying to see a broadly based appreciation of TES, which would impact more than just a very small number of major named programs. Such penetration would also shield TES activity from changes in the small number of programs. It would be good if, in the coming years, the success with a small number of "name" programs would transition into programs that affect the scientific, technical, and industrial community broadly.

That the sensors and interconnect program is so successful speaks to the scientific and technical expertise behind it. However, it is important to disseminate the results to broader communities and industry beyond the current stakeholders. This would generate new needs and technology directions which will require additional support and a focus on staffing and resources.

The current funding profile of the groups in the division appears highly skewed, with 65 percent of the funding coming from outside non-NIST sources. While the panel applauds the high level of interaction of the group with the practical needs of outside stakeholders, questions arise regarding the possibility of such high levels of external funding redirecting the real priorities of the division away from NIST. There is a real danger that the level of outside funding and the outsize success of the sensor/interconnect activity could obscure new opportunities that should be pursued.

Conclusion 5-1: The Quantum Electrodynamics Division's resources, specifically funding, are currently inadequate to pursue interesting new lines of inquiry in quantum electronics and explore new opportunities should those opportunities fall in line with the Physical Measurement Laboratory's mission. Quantum electronics is a very broad field with many areas to be explored beyond what the division currently explores.

Device Microfabrication Group

The fabrication activity perhaps ranks among the best-in-class, in terms of both breadth and quality of the output, which is attested by the fact that the sensors and amplifiers produced by this group are sought by users worldwide and form the critical components of two well-known astrophysics programs—the Simons Observatory and the ATHENA (Advanced Telescope for High Energy Astrophysics) satellite program for space X-ray spectroscopy.

Wafers with many high-pixel-count TES sensor arrays are required for Simons Observatory. The group has successfully transitioned many processes to 150 mm wafer size. Achievement of readout for so many complex sensors is a tour de force for the quantum electronics group and other divisions. The device fabrication group works intimately with other groups on device design, read-out, testing, packaging, and system users to optimize the TES devices and circuits to deliver the world's best performance for the stakeholders.

Opportunities and Challenges

Fabrication facilities appear to be state-of-the-art for the current fabrication needs. However, questions remain regarding continuous upgrade of the capabilities, especially two dedicated special superconductor deposition systems are needed to meet future advances in performance requirement and capacity needs.

> **Recommendation 5-1: The Physical Measurement Laboratory should prioritize renovations and improvements to the device fabrication facility of the Quantum Electromagnetics Division. The present facilities are fully used and aged to the point that they require major renovations to increase the capacity to deliver on current expanding research projects and to acquire new capabilities to embark on leading-edge research in the future.**

Quantum Calorimeters Group

The extension of TES applications to highly sensitive calorimetric detection of X rays and gamma rays promises to revolutionize precision detection. The group develops and disseminates sensors and spectrometer instruments to detect single photons, particles, and radioactive decays, particularly active in X-ray and gamma-ray wavebands, and in decay energy spectroscopy. These devices are used for internal metrology projects including X-ray tomography of integrated circuits and efforts to improve the realization of the becquerel.[3] X-ray and gamma-ray spectrometers are also used for collaborative external projects at X-ray light sources and nuclear facilities. The high sensitivity spectrometer instruments are a core capability of NIST, used for determining more precise and more accurate reference data for both internal (NIST) and external needs of other government agencies, for example.

Accomplishments

The TES calorimeter demonstrated the ability to reduce thermal noise at ultra-low temperatures (less than 100 mK). The high sensitivity provides super energy resolution to detect isotopic composition, in particular, the ratio of Pu-238/Pu-239/Pu-240, which is critical to detecting residual low-volume isotope compositions in nuclear materials and nuclear medicines.

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[3] The becquerel is a measure of radioactive decay. More information can be found at https://www.nrc.gov/reading-rm/basic-ref/glossary/becquerel-bq.html, last accessed January 17, 2024.

Long-Wavelength Sensors and Applications Group

This group is responsible for the high-sensitivity infrared detectors, whose success with the Simons Observatory was described above. The most remarkable success was clearly the unprecedented achievement of detection sensitivity of approximately 6×10^{-19} W/Hz$^{1/2}$ in the long-wavelength region together with the capability of absolute power measurement. The group develops arrays of multichroic microwave polarimeters for very challenging detection of faint infrared radiation from the cosmic microwave background. These new devices and measurement techniques are well suited to perform new spectroscopic metrology into the deep long wavelengths which are absent today beyond the micron-scale infrared regime. The long wavelength measurement techniques will provide detailed characterization and understanding of materials and compounds to develop many industrial and bio-medical applications.

Recommendation 5-2: The Quantum Electromagnetics Division should broaden its advanced long-wavelength sensing technologies to many other long-wavelength applications at elevated temperatures, such as for far-infrared long wavelengths and nuclear isotopic compositions.

Accomplishments

The group demonstrated TES bolometers and SQUID multiplexed readout to advance cosmology for measurements of the cosmic microwave background radiation by supplying more than 80,000 units of TES sensors and more than 130,000 units of SQUID multiplexed readout channels to U.S. research collaboration partners to perform detailed mapping of dark matter. Arrays of microwave kinetic inductance detectors enable new astrophysics applications.

The group demonstrated a highly sensitive TES bolometer intended to achieve absolute power sensitivities as small as 100 aW in support of quantum computing. The high sensitivity is enabled by achieving ultralow thermal conductance between the thermal bath and the sensing element. Similar devices would enable single photon counting at frequencies of tens of terahertz.

A new, highly sensitive microwave kinetic inductance detector was implemented to enable measurement of far-infrared radiation (0.1–10 mm). Advanced silicon platelet feedhorn arrays and meta-material lenslet arrays have been developed for coupling long-wavelength radiation to sensors.

Opportunities and Challenges

The mix of technical talent in the Long-Wavelength Sensors and Applications Group is outstanding. However, it would be valuable for the group to explore long-term plans for maintaining cutting-edge technology. It would also be useful if the team considered increasing their exposure to reach broader audiences to help recruiting. As the current experienced workforce are aging with limited additions of junior and mid-career staff, succession plans should be developed to close experience gaps.

Quantum Electronics Group

The Quantum Electronics Group develops advanced, world-class, low-noise, high-bandwidth multiplexed readouts for cryogenic quantum sensor arrays. It also performs fundamental research on the detection of weak signals based on quantum coherence and quantum entanglement. The group has strong capabilities in designing firmware, analog and microwave electronics, highly sensitive low-noise readout electronics, and parametric amplifiers, with close collaborations with internal and external partners for applications. For example, TES arrays with SQUID multiplexers have been inserted in X-ray spectrometers for the Intelligence Advanced Research Projects Activity’s RAVEN (Rapid Analysis of Various Emerging Nano-electronics) and the BESSY-II (Berliner Elektronenspeicherring-Gessellschaft fur Synchrotronsstrahlung) synchrotron; gamma-ray spectrometers for the Los Alamos, Oak Ridge, and

Idaho National Laboratories; in microwave polarimeters for the Simons Observatory, and for the ATHENA X-ray satellite being developed by the National Aeronautics and Space Administration (NASA) and the European Space Agency.

Accomplishments

The group developed time-division SQUID multiplexers to read out TESs for the ATHENA satellite's X-ray integral field unit (X-IFU), which were certified as technology readiness level (TRL) 5 by NASA in 2023.

The group demonstrated highly sensitive and compact microwave readout design and instrument deployment for mixing baseband signals up to 4–8 GHz for 1,054 channels. It implemented high-bandwidth readout of near-infrared and optical TESs used for quantum information science.

Single-photon detection was demonstrated with a new integration of microwave SQUID multiplexing and kinetic inductance current sensors. The integration of traveling wave parametric amplifiers and TES array provides amplification and mode selection to enable high-detection sensitivity approaching the standard quantum limit (SQL) and dissipates less power.

The Boulder Cryogenic Quantum Testbed is a project within the Quantum Electronics Group that is intended to explore materials limitations to the performance of supercomputing quantum computers. There appears to be good collaboration with a Google group that has been at the forefront of commercial quantum supercomputing activities. The team also engages with at least one of the Department of Energy quantum centers. The program is at the starting gate, and the panel sees a great future here if nurtured properly. The partnership with academia has helped to educate young students and to train junior researchers from the University of Colorado and other universities to utilize this unique testbed. Many industrial companies are participating to perform experiments at the testbeds and transferring some knowledge back to the companies. Additional staff support to optimize the loss and readouts in the testbed and funding of students and junior postdoctoral researchers with additional operational expenses to strengthen the collaboration for this effort should be strongly considered.

Recommendation 5-3: The Boulder Cryogenic Quantum Testbed should add additional personnel and resources. In particular, it should seek to develop an enhanced capability that offers a unique resource by funding additional staff for the testbed and adding internships for students and junior researchers to strengthen and broaden the collaborations and partnerships with academia and with the emerging quantum computing and sensing industry.

Spin Electronics Group

After the 2018 National Academies' assessment (NASEM 2018), the Nanoscale Spin Dynamics Group was dissolved. The current Spin Electronics Group is planned to move to the Applied Physics Division in fiscal year (FY) 2023. The technical focus areas are to develop novel electrical and optical metrology techniques for microelectronics and to explore novel devices relevant to advanced and future computing. In FY 2023, the group has four active projects on nanoscale magnetic devices, extreme ultraviolet optical metrology, cryogenic neuromorphic circuits, and hybrid ferromagnetic and superconductor systems. The group also developed 3D X-ray tomography techniques to provide high resolution images of layers metal interconnections in a microelectronic integrated circuit.

Accomplishments

The group demonstrated spin sensitivity and can resolve a single spin in 10^{19} using a hybrid superconductor-ferromagnet system. They are developing time-resolved measurement of stochastic spin-torque magnetic tunneling junction devices for application of random code generation for novel stochastic computing applications. They are using extreme ultraviolet pulses to image the dynamics of nanoscopic heat flow and material properties in active microelectronic devices.

Opportunities and Challenges

Since the previous reorganization, the group has initiated many new diverse research directions on in situ characterization of dynamic properties of spin-based materials, and highly sensitive quantum sensing and quantum computing with promising advances. This small group is spread very thin and it is not adequate to cover these new areas in stochastic spin-based computing. It will require additional personnel and resources to attain a critical mass for it to be truly competitive worldwide.

Recommendation 5-4: The Spin Electronics Group should add additional personnel and resources. In particular, it should consider increasing exposure to reach broader audiences in recruiting. With a small and aging workforce to cover many new and competitive research directions, it should also consider succession and recruitment plans to establish a critical mass and close experience gaps in pursuing new research fields in spin-based quantum computing and device characterization.

ASSESSMENT OF SCIENTIFIC EXPERTISE

The Quantum Electromagnetics Division has world-class expertise in harnessing electromagnetic technologies for practical and fundamental scientific use cases. This is demonstrated, in part, by the awards won by division staff. These include the 2023 Keithley Award from the American Physical Society, a 2022 R&D100 award, two Nancy Grace Roman Technology fellowships, an Institute for Electrical and Electronics Engineers (IEEE) Magnetics Distinguished Lectureship, and various Department of Commerce medals. There have been 21 awards in total since the past assessment.

The division is delivering unique and complex sensing systems in a research environment that is simultaneously multi-disciplinary, multi-institution, and multi-agency. The scientific innovation of the division ranges from applied material science to technologies for quality assurance of integrated assemblies. The panel finds that the U.S. scientific ecosystem continues to be accelerated by the products of the division.

The Quantum Electromagnetics Division has used its unique sensor expertise to underpin a shared mission among U.S. agencies to foster broad American technical superiority. Advancing nuclear material accountancy is a key achievement for the division; which includes mobile spectrometers fielded at Oak Ridge National Laboratory, the analytical laboratory at Idaho National Laboratory, and soon the Pacific Northwest National Laboratory. Engaging in an interdisciplinary manner, the division has introduced a leap forward for detector resolution in the Microcalorimeter Gamma Spectrometer—a new platform for nondestructive nuclear material analysis.

The division successfully takes advantage of longstanding NIST leadership—for instance, the design and fabrication of SQUID arrays—while innovating on new sensing modalities and materials. One encouraging finding is that by acting as the central hub of sensing activity, the division is proactively extending its capabilities through calibration, for example, through the development and integration of phonon band-gap filters within bolometer sensors, which has been initially explored through external collaborations.

A major milestone for the division has been the recognition of a TRL assessment of TRL-5 by NASA for the sensor baselined for the upcoming ATHENA space mission, meaning that the sensor and readout component has passed the bar for integrated system testing. This accomplishment is the culmination of decades of accumulated experience and expertise and an important waypoint toward a successful space mission.

Indeed, the collaboration with NASA and other astrophysics projects is a key driving force behind the group's groundbreaking work. The panel was encouraged to see that in most cases, clear and ambitious targets were set for new technology development. Additional internal resources could bolster the balance between work in the service of specific science missions and work that is strictly curiosity-driven exploration.

Accomplishments

The Quantum Electromagnetics Division is tackling ambitious programmatic targets at the forefront of science. This focus has resulted in new expertise and innovations, such as the frequency trimming of multiplexed resonators after precharacterization, as well as new sensing capabilities, such as absolute power measurement for atto-watt, and new directions, such as a standard for the becquerel unit. The division effectively shares expertise between sensing modalities such as electronics, firmware, and component design, accumulating incremental progress to extend its leadership.

Opportunities and Challenges

The work of the division relies on an increasingly rare set of scientific expertise. It is remarkable what the division has accomplished at the size of the current group. A key challenge remains recruiting and retention. In some areas, such as cryogenics development, the division's expertise resides in a single individual whose technical background is increasingly sought after by the industry. The additional workforce could enable succession planning for critical expertise and extend the division's efforts to apply sensing technologies in new directions, such as applications in the development of quantum computing components.

The collective expertise of the people in the division is extraordinary, and extra care needs to be given to recruit and retain them, especially the guest staff. Researcher morale is high, and many temporary researchers have been employed for a long time and express a desire to stay. If would be useful if the Physical Measurement Laboratory were to institute clear and open policies and practices for guest postdoctoral and visiting researchers to obtain permanent government employee positions. Furthermore, given that many researchers work in their own small groups with little interaction with the broader NIST community, the institute could improve retention and achieve broader research collaborations by encouraging broader interactions among researchers through NIST-wide seminar series and activities and the development of common meeting areas such as a cafeteria.

Conclusion 5-2: Clear and open policies and practices across the organization on recruiting permanent government employee positions and promoting interactions and collaborations would be useful in helping the Physical Measurement Laboratory in recruiting and retaining the world-class workforce that it needs. In particular, the open positions could be made available to staff and guest researchers across the organization. NIST-wide seminars and activities to promote inter-group interactions and collaborations could also be helpful.

BUDGET, FACILITIES, EQUIPMENT, AND HUMAN RESOURCES

The division's budget is approximately $28 million, but only one-third of that is provided by NIST. The division's budget is adequate for its current work. However, the majority of the budget is connected to specific projects with expected deliverables that are funded by external organizations (e.g., the Simons Observatory, and NASA for the ATHENA Project). The amount of external funding speaks to the importance and quality of the science and engineering research and technology development done in the division. At the same time, a low ratio of internal to external funding prevents the division and, as a result, the organization from reinvesting in facilities.

The facilities housing the division's laboratories are well used and fully equipped with state-of-the-art equipment. Most of the equipment is uniquely designed to provide metrology for the projects under way. Most of this equipment (i.e., the cryogenic testbed open to government scientists and engineers) is unique in the country or plays unique roles and needs to be sustained. It may be appropriate to seek funding from other federal programs dedicated to the further development and sustainment of unique instrumentation and infrastructure that can be available to users funded by federal funds, centers, hubs, or commons. The present facilities are fully utilized and aged to the point that they require major renovations to increase the capacity to deliver current expanding research projects and to acquire new capabilities to embark on future research.

The Quantum Electromagnetics Division develops highly precise measurements and instrumentation using devices such as SQUID amplifiers, microcalorimeters, and microbolometers fabricated in the Boulder Microfabrication Facility. This designed and developed equipment is a marvel of engineering and science, reflecting the fact that the quality of the researchers in the division is unique and important to the future of NIST. The quality of the technology and engineering solutions is superb and difficult to find in any other laboratory in this area. The collective expertise of the people is extraordinary, and extra care needs to be given to retaining them. However, the science and engineering staff see their positions as temporary, and they need more assurance than rather vague promises for possible retention. Without a well-developed plan for turning their qualified science and engineering employees into permanent positions, the team risks losing significant technical expertise. The division has the opportunity to retain the highly talented guest researchers, who all expressed interest in remaining with NIST. However, clearer policies and practices are needed for moving from a guest researcher to a permanent government employee position.

There appears to be a disconnect between the NIST leadership comments on the difficulties with recruiting and retention permanent staff versus the panelist discussions with guest researchers. There does not appear to be a retention problem for guest researchers, as their morale was high, and many guest researchers have been employed for a long time and expressed no desire to leave. For recruitment for permanent staff, NIST has ample opportunity to select from the many outstanding guest researchers they currently employ. Many postdocs said they are interested in government positions but must learn to identify and apply for permanent positions. A predictable path for postdoctoral and visiting researchers to become permanent NIST employees would be useful. Discussions with the researchers identified the need for a clear policy for becoming a permanent NIST employee. In addition, NIST may want to use its relationship with the University of Colorado Boulder (CU) and JILA to identify graduate student opportunities. Several students the panel talked to said they felt isolated and commented that there was no strong sense of community among the graduate students at NIST. One consideration could be a targeted seminar series open to all CU graduate students to foster community, expand their understanding of NIST's work, and give early career researchers a venue to speak. Perhaps this could be opened to CU as an additional recruiting opportunity. NIST also does not appear to have a mechanism to support "gap year" students between receiving their bachelor's degree and applying to graduate school. A formal program may bolster workforce development and allow a new onboarding process to introduce early career researchers to NIST.

EFFECTIVENESS OF DISSEMINATION EFFORTS

The Quantum Electromagnetics Division has an impressive dissemination record. Its staff has authored 423 total publications in the past 4 years. The division's publications have been cited a total of 5,379 times in 69 journals and the division's staff has an h-index of 35 over the past 4 years. In addition, there have been 659 co-authored papers in the past 4 years with collaborators such as the Department of Energy, NASA, Stanford University, Cardiff University, the University of Chicago, and the University of California, Berkeley. The division has 3 licenses, 20 patents, and 9 disclosures since the past assessment.

Stakeholders are the primary drivers of the research portfolios of the Quantum Electromagnetics Division, as 65 percent of the funding ($15.6 million) comes from external sources. The team noted that this percentage of external funding was unusually high for PML. In FY 2023, 31 out of 70 group members are guest researchers, and the team has three National Research Council postdoctoral fellows.

The team disseminates its results via high-visibility publications and by transitioning technology to the stakeholders. Some technology transfer efforts are occurring through patents and licensing agreements. Currently, the groups work extensively with academia, industry, and government agencies so future technology dissemination and transfer efforts can be further accelerated, particularly in areas of quantum sensing and readout. NIST has sufficient technology transfer mechanisms, some of which are used by the team.

The team works effectively with stakeholders to develop critical technologies to attain program goals. Because most of the work is supported by stakeholder investment, the team is in close contact to delineate technical plans to meet stakeholders' system requirements. The team also uses previous program outputs to implement next-generation devices and plan future research directions. No improvements are needed in this process.

Opportunities and Challenges

The sensors and interconnect program is very successful in meeting the goals of the stakeholders with great transmission of the scientific and technical expertise behind it. Outside of some good publications in selective scientific and technical journals, however, it is important to disseminate the results to a broader audience and industry beyond the current stakeholders and associated communities. This could generate new research projects to support industrial needs while helping recruit future staff. For example, this may be realized by a NIST-led industry–academia partnership program to develop advanced design, measurement, and metrology technologies in emerging devices and materials or quantum sensing and computing applications by using resources from academic centers, investment of commercial partners, and ongoing government initiatives such as the Quantum Initiative and CHIPS program.

The members of the division must disseminate their advanced quantum electromagnetic metrology and measurement standards through active participation in pan-industry standard bodies such as IEEE, the International Telecommunication Union, etc.

REFERENCE

NASEM (National Academies of Sciences, Engineering, and Medicine). 2018. *An Assessment of Four Divisions of the Physical Measurement Laboratory at the National Institute of Standards and Technology: Fiscal Year 2018.* Washington, DC: The National Academies Press. https://doi.org/10.17226/25281.

6
Time and Frequency Division

Accurate time and frequency services are vital for U.S. critical infrastructure and long-term U.S. economic growth and global leadership. The Physical Measurement Laboratory's (PML's) Time and Frequency Division has a clear mission to "develop and distribute the highest accuracy time and frequency measurements and related technologies to support commerce, research, national priorities, and the public." The division's activities fall into three primary areas: (1) accurately and precisely realizing official U.S. time and frequency, (2) operating a wide range of measurement services to distribute time and frequency and related quantities, and (3) performing basic research and developing technology to improve time and frequency standards and related technologies. An important feature of scientific and technical work in the division is collaboration across multiple groups to achieve results and produce scientific products.

The Time and Frequency Division is in Boulder, Colorado, with some staff located in Fort Collins, Colorado, and Kauai, Hawaii. The division has 137 staff, including 7 in administrative support, 38 NIST scientists, and 92 associates. The division consists of seven groups: (1) Ion Storage, (2) Phase Noise Metrology, (3) Time Realization and Distribution, (4) Quantum and Nonlinear Nanophotonics, (5) Precision Photonic Synthesis, (6) Neutral Atom Optical Clocks, and (7) Atomic Devices and Instrumentation. The fiscal year 2023 division budget is $27.9 million, of which almost $18 million is scientific and technical research and services, with 33 percent of those services being sourced outside of the National Institute of Standards and Technology (NIST).

The Time and Frequency Division is continuing its long history of excelling in its mission. The quality and impact of the research being produced is vital to the continued leadership of NIST in this arena, both nationally and internationally. Additionally, the division is providing critical operational services for multiple stakeholders including U.S. commerce, defense, industry, and the general public. Notably, the division has played a leading role in ushering in quantum computing and quantum technology. Significant services and research results have been identified along with some targeted areas that could be strengthened and improved for the continued excellence and leadership of the division into the future.

ASSESSMENT OF TECHNICAL PROGRAMS

The overall collection of scientific and technical work being carried out in the Time and Frequency Division in the NIST PML is of the highest quality. This is exemplified by the wide range of areas where the division leads the world in the development of novel scientific techniques to advance time and frequency measurements and related technologies. The quality and quantity of high-impact publications generated by the division is exceptional, including 16 papers published in *Nature* and *Science* and 30 papers published in *Physical Review Letters* over the past 5 years. Some scientific highlights include:

- The world-leading accuracy of the aluminum ion clocks in the Ion Storage Group and the world-leading precision of the ytterbium (Yb) lattice clocks in the Neutral Atom Optical Clocks Group as well as the development of a portable Yb optical lattice clock as a new tool for high-precision optical clock comparisons.

- World-leading frequency ratio values were obtained between the Al+ and Yb optical clocks at NIST and the strontium (Sr) optical clock at JILA. The measurements involved several groups in the Time and Frequency Division combining their efforts. The results have provided an important step toward the redefinition of the second in the International System of Units (SI) as well as placing new constraints on the nature of dark matter.
- The pioneering techniques originally developed in the Ion Storage Group have given rise to an entirely new industry of quantum computing. The group continues to remain at the forefront of innovation, with recent progress in areas such as microwave gates, multi-species techniques, molecular ions, and new ion trap designs that are supporting industry efforts and also opening new directions in the field.

The Time and Frequency Division also provides a number of unique and critical technical services to stakeholders in the private and public sectors. These include:

- The Time Realization and Distribution Group generates NIST's realization of Coordinated Universal Time, called UTC(NIST). UTC(NIST) is well recognized globally for its stability and is disseminated via multiple techniques, including the widely used NIST Internet Time Service, remote calibration services based on the Global Navigation Satellite System common view, radio broadcasts, and now via two new services, Time over Fiber and Time over Satellite.
- The Phase Noise Metrology Group provides valuable microwave phase noise calibration and measurement services to industry and the Department of Defense.

The division is also world-leading in the development of cutting-edge time- and frequency-related technologies with higher technology readiness levels that are industry and application oriented and are also relevant to other scientific disciplines:

- The Atomic Devices and Instrumentation Group vigorously innovates in the area of compact, low-power quantum sensors and clocks and leads research efforts in the $10 million/year NIST on a Chip program. Among other important efforts, the group is developing a rubidium two-photon optical clock targeted to replace or supplement the hydrogen maser, the current workhorse for realizing UTC across the planet, and yet one that's harder to acquire and maintain as industry phases such masers out. This group continues to demonstrate close ties to industry and strong levels of technology transfer.
- The Quantum and Nonlinear Nanophotonic Systems Group is developing integrated photonics and making important advances into miniaturized, integrated optical clocks (including subsystems such as microcombs and tunable lasers) that are potentially very important for next-generation time-keeping.
- The Precision Photonic Synthesis Group has demonstrated world-record-setting low-phase noise microwave generation from optical sources and is producing cutting-edge miniaturized ultrastable optical cavities through new fabrication techniques.

The quality of the technical programs makes the Time and Frequency Division well-suited to reach its stated technical objectives. However, there are several opportunities for improvement:

- A national standards institute of this caliber should be operating a cesium (Cs) fountain primary frequency standard to provide regular contributions to the International Bureau of Weights and Measures (BIPM) for inclusion in the computation of UTC. The division is aware of this and has been working to remedy the situation by setting up and characterizing a new Cs fountain (NIST-F3), as well as refurbishing an older fountain (NIST-F4). In parallel, the division is also working to develop a robust Sr+ optical ion frequency standard that can serve the same needs, acting as a

secondary representation of the SI second. The panel encourages the division to prioritize these developments to ensure that NIST can provide measurement results that are traceable to the SI second with the lowest uncertainty and be able to regularly contribute to international time scales.
- There are important opportunities for expanding the phase noise characterization services and capabilities performed by the Phase Noise Metrology groups to higher frequencies (terahertz) and optical phase noise measurements in conjunction with the Precision Photonic Synthesis Group, to keep pace with the development of new and emerging communications and metrology technologies.
- The compact Sr lattice clock project under development in the Quantum and Nonlinear Nanophotonic Systems Group is very promising and represents an important future technology with a wide variety of applications. Currently, the project is externally funded, and the focus is only on some components of a clock. The effort could benefit from additional internal funding to support the development of other aspects, such as the photonic integration of lasers, active optics, and light distribution, which are not covered by the current external support.
- While the time distribution service is currently serving millions of customers and expanding to additional platforms, the staff and infrastructure seem to be operating at maximum capacity with little room for needed growth in this important service. It would be valuable if the architecture and infrastructure of this service were to be evaluated and modernized with an eye toward growth, security, and robustness.

In light of these considerations, the panel offers the following recommendations:

Recommendation 6-1: The Time and Frequency Division should prioritize development of its Cs fountain primary frequency standards, its Sr+ secondary standard, or both to ensure that the National Institute of Standards and Technology can regularly contribute to international time scales. The division should ensure the continuation of its recent progress with the addition of new personnel to these efforts.

Recommendation 6-2: The architecture and infrastructure of the time distribution service should be evaluated and modernized with an emphasis on growth, security, robustness, and adequate staffing of this crucial service for the country.

ASSESSMENT OF SCIENTIFIC EXPERTISE

The Time and Frequency Division has world-leading experts in all seven of its groups. This results in high-impact scientific research and enables the delivery of unique products and services, while also attracting new generations of high-caliber junior scientists; when interviewed, junior scientists in the division expressed their enthusiasm for working with leaders in their field as one of the primary motivations for joining the division. The scientific expertise across the division is further evidenced by the outstanding number of prestigious external prizes and fellowships that have been awarded to staff members.

The group leaders demonstrate deep technical knowledge and enthusiasm for the areas they oversee. The division chief is to be particularly commended for her leadership of the technical direction while also focusing on improving the diversity and representation of the workforce. Based on discussions with staff and the previous report, the division morale, the division community, and the quality of the facilities have all improved under her leadership.

The staff also ensure that NIST has an influential voice in relevant international committees. Of particular note is the strong NIST representation on the Consultative Committee for Time and Frequency and its working groups. Important topics under discussion at the moment include the redefinition of the SI second, the future of leap seconds, and the mutual benefit of UTC and global navigation satellite system.

Decisions made in these committees will have long-term implications for time and frequency needs in the future, so it is important that NIST is able to influence that future direction.

The organization's technical programs are greatly enhanced by the scientific expertise of the staff members. In fact, the continued success of the division is strongly dependent on its staff and thus it is important to preserve the division's technical expertise in the long-term. In some cases, there is a large concentration of expertise in a small number of outstanding individuals, making the division vulnerable to a lack of continuity in critical knowledge and services if these individuals depart. Given that, the panel offers the following recommendation:

Recommendation 6-3: The Time and Frequency Division should ensure that succession plans are put in place and that knowledge and responsibilities are shared and distributed among the wider members and teams. The Physical Measurement Laboratory's new succession funding program is encouraging, but all critical areas should be evaluated to identify and mitigate potential single points of failure.

BUDGET, FACILITIES, EQUIPMENT, AND HUMAN RESOURCES

NIST's budget for the Time and Frequency Division appears to be sufficient to maintain facilities, equipment, and staff for the existing services and research developments. All of the division group leaders reported strong support from the division chief and are content with their respective current budgets. It was noted by the panel that some of the groups (such as the Phase Noise Metrology Group) depend heavily on external funding (more than 60 percent of their budget is through external funds), which could contribute to issues related to finding and retaining staff because of the uncertainty of yearly budgets. In addition, some staff members expressed concerns that it is gradually becoming more difficult to secure funding for new research directions, due in part to the lengthy process at NIST that often delays the acceptance of funds from other government agencies, such as the Defense Advanced Research Projects Agency. The delay sometimes takes so long that funds cannot be accepted in the fiscal year in which they were targeted for, prompting their withdrawal.

The Time and Frequency Division has a majority of its laboratories located in the Katharine Blodgett Gebbie Laboratory Building 81 and the Radio Building 01 in Boulder. The cutting-edge facilities and equipment located in Building 81 are of very high quality and support both the time-keeping services and fundamental research being conducted in the division and are a direct result of the relatively recent construction (within the past 15 years). The Atomic Devices and Instrumentation and the Time Realization and Distribution groups' laboratories are still housed partially in Building 01 (Wing 1 and the Spine), which appear to be adequate for current research efforts. However, owing to the nature of renovations and the clear limitation of existing space, many of division staff's office spaces have heating, ventilation, and air conditioning issues (portable heaters and air conditioners are necessary), are subject to construction noise, have experienced flooding, have issues with pests, and can be located very close to actual construction, causing disturbances to workflows or incurring safety issues. It has also been noted by key staff that once the renovations have been completed, all available laboratory and office space will likely be completely filled, with no room for growth or innovation (this was referenced by one NIST staff scientist as "The renovations will be appropriate for 2010 needs, not 2030 needs"). There was also mention of critical infrastructure (including the sewer) of Building 01 that needs to be addressed for the health and safety of the staff as well as power outages in many of the buildings affecting the research laboratories.

Recommendation 6-4: The Physical Measurement Laboratory should act to improve the critical infrastructure of Building 01 as well as to mitigate power outages in many of the buildings affecting the research laboratories or find other suitable space to house these groups.

Because time keeping is a core function of the Time and Frequency Division, it would be beneficial to have better infrastructure for connecting remote facilities that support time distribution, such as direct links (fiber and free-space) to key U.S. timekeeping facilities including the U.S. Naval Observatory, Fort Collins, and the NIST Gaithersburg campus. Similarly, as noted in Recommendation 6-2, the Time Realization and Distribution Group needs more funding and personnel dedicated to its time services, commensurate with the crucial role these serve for the country.

The human resources in the Time and Frequency Division are of the highest quality for the types of services and research being performed at NIST. This ranges from the staff scientists to postdocs and graduate students. The high quality is demonstrated by both the cutting-edge research and the critical time-keeping services performed in the division. The recent addition of a highly qualified safety officer (who is also a Time and Frequency Division staff scientist) is a very important step toward ensuring that the laboratories and experiments are as safe as possible for the division personnel while also allowing high-quality research to continue. While advances have been made to increase the representation of certain minority demographics (e.g., women under 30 years of age and Latinos) at NIST, the division still has a long way to go to achieve a level of diversity that reflects the current diversity of those receiving PhDs in physics, let alone the society at large. One example of this is that African Americans appear to be dramatically underrepresented in the division. While this is a complex problem, outreach and recruiting at colleges and universities with statistically higher populations of minorities for collaborations, as well as workforce development, may solve this problem. In fact, the division has initiated a new recruiting relationship with a historically black college and expects to have two African American visiting staff members next year; this is a good start.

Despite the excellence the panel found in the staff throughout all of the groups in the Time and Frequency Division, it did find a few main concerns: (1) the ability to find and obtain new and high-quality postdocs and graduate students; (2) the processes associated with hiring permanent staff; (3) a shortage of staff in key service areas; and (4) a shortage of administrative staff to allow the technical staff to focus on technical and scientific responsibilities. Finding and acquiring new staff has been most challenging at the postdoc and graduate student level; this has been attributed to the growth in the quantum computing industry. In some respects, NIST is a victim of its own success in terms of advancing the industry with which it now finds itself competing for personnel. Within the limits of government-set pay schedules and the realities of PML's staffing and budget situation, offering higher salaries is a possible solution for this problem. Another possible solution, within the same limits, is to increase the opportunities for the conversion of postdocs to permanent staff. For the more service-oriented groups, and if these areas are no longer able to attract a consistent stream of postdocs and graduate students, a few more permanent positions could keep these critical areas flourishing for the nation. Concerning the process associated with hiring permanent staff, it was noted that there can be serious restrictions in adding new positions, including, but not limited to, the federal requirements for posting new positions (which can lead to reduced quality and size of the applicant pool), the internal size of NIST's Human Resources (HR) Department (which was leading to significant delays in the hiring process but is perhaps somewhat improved now), communication between HR and applicants during the submission process (applicants were not being told if their submissions were inadequate and therefore disqualified), and proper advertisement of these positions (postdocs at NIST currently express frustration about not knowing when new positions were available). Lastly, some of the permanent division staff did admit the amount of administrative duties they are burdened with can affect their ability to conduct their research. Additional administrative personnel would directly improve the staff's ability to get more research accomplished.

One additional area that PML could improve is to facilitate even more communication among research groups. While individual research groups are run very efficiently to achieve industry-leading research, and junior researchers report excellent mentorship and a respectful environment with easy access to collaborate with experts across the division, postdocs only stay for a few years and are very busy so do not get enough in-depth exposure to their colleagues. Several individuals spoke about the benefit of attending the poster presentation prepared for this panel. In response, the division chief will consider ways to enhance knowledge sharing, such as mini poster sessions during weekly coffee hours or reinstituting the annual poster session that stopped during the COVID-19 pandemic. It was clear that the expertise and collaborative environment was key in attracting top talent to the postdoc pool, so it is important that everything be done to maintain this.

EFFECTIVENESS OF DISSEMINATION EFFORTS

The Time and Frequency Division has a comprehensive approach for communicating with its stakeholders in all three of the scientific, technological, and service areas related to time and frequency. The scientific output of the division is widely disseminated through publication in top-tier scientific journals and in conferences related to atomic physics and fundamental physics and those specifically catering to the time and frequency community. The division output is also highlighted to the public at large through articles and news releases in the popular press, as appropriate. With regard to the conferences, all staff members (including associates) have the opportunity to attend conferences and present their work. Division staff also actively participate and serve in various committees within the scientific, engineering, and international organizations that relate to the field of time and frequency. In particular, the division has taken an active role in the committee organized by BIPM to transition the definition of the SI second with the advent of new optical clocks. The division also does an excellent job of promoting the accomplishments of its staff members by nominating them for various awards and recognitions, within both NIST and the Department of Commerce and also through national and international professional organizations.

The Time and Frequency Division is the only organization in the nation that provides an annual seminar on time and frequency to support the industry and others working in the field. This is a valuable enterprise, and currently there are no other educational opportunities that provide the needed training and education in this very specialized field. The two service groups also remain in close contact with the calibration customers and provide information about new capabilities as they are being developed.

The division also produces patents and intellectual property in support of commercialization. There are several instances of either licensing patents to industry or putting them in the public domain, both of which have led to development and commercialization of related products.

In general, the Time and Frequency Division does an excellent job of disseminating information to the stakeholders. However, the impact of the division's efforts could be further amplified through improved outreach to industry. There are several examples of techniques and instrumentations, in addition to patents and intellectual property, that the division has developed, such as the new phase noise measurement instrumentation based on a field-programmable gate array, that are mostly disclosed through conference papers. Members of industry may not regularly attend academic or technical conferences, so access to that type of information is limited for them, which reduces the number of stakeholders who could benefit from these new developments. It would be helpful if such information was made available through the website or notices sent via email (e.g., subscription mailing lists) to notify industry. Monitoring traffic to these website areas and subscriber lists would also add to the numerous ways the division already employs to measure stakeholder impact, such as tallying 100 billion network time protocol requests per day, more than 60 subscribers to Time and Frequency Measurement and Analysis Services, and the division's numerous publications, citations, publication journals, collaborators, patents, licenses, and disclosures. Despite collecting all these positive impacts, the division would further benefit from doing a better job of illustrating the significant long-term impact of its work and the benefit to the U.S. economy, to U.S. leadership, and to the general public. An example here is the evolution of the quantum computing industry from early research at NIST. This is a valuable national asset that needs to be recognized as such.

7
The Physical Measurement Laboratory's Responses to the Recommendations of the 2018 Assessment Report

Five years ago, in 2018, this report's predecessor report, *An Assessment of Four Divisions of the Physical Measurement Laboratory at the National Institute of Standards and Technology: Fiscal Year 2018* (NASEM 2018; hereafter "*FY 2018 Assessment*") offered four key recommendations to the National Institute of Standards and Technology (NIST) regarding the operation of the Physical Measurement Laboratory (PML) and, in particular, the four PML divisions that have been reviewed again in this report: the Applied Physics Division, the Quantum Physics Division, the Quantum Electromagnetics Division, and the Time and Frequency Division. Two of the recommendations were aimed generally at all four of the PML divisions in the review, while the other two were intended for specific divisions. The 2018 report also offered some observations about what might act to improve specific divisions that did not rise to the level of recommendations.

In preparation for visits from the committee working on this current report, NIST staff provided descriptions of how NIST and PML had responded to the recommendations in the 2018 report. The responses are reproduced below (unedited, without citations)—organized into responses to the two general recommendations and then responses to recommendations and observations relating to each of the four divisions.

GENERAL RECOMMENDATIONS

FY 2018 Assessment:

> **Recommendation 1: The Physical Measurement Laboratory (PML) should develop with National Institute of Standards and Technology 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.**

NIST response:

> NIST and PML recognize the important of infrastructure to meeting our mission. The *Technical Assessment of the Capital Facility Needs of the National Institute of Standards and Technology* states that a substantial number of facilities, in particular the general purpose laboratories, have functional deficiencies in meeting their environmental requirements for temperature and humidity, and of electrical systems for stability, interruptibility, and for life safety. The assessment concluded that these deficient functionalities of NIST's facilities constitute a major threat to its mission performance and thereby, to our nation's economy, national security, and quality of life. While some progress has been made to remedy issues since the 2018 review, such as construction of Wing 5 on the Boulder campus which is expected to completed in the summer of 2023, more needs to be done.
>
> In recognition of the needs, the President's FY 2024 budget request includes an increase of $128.6 million to address NIST facilities needs and $3.5 million in inflationary adjustments for the most critical utility infrastructure issues:

Repair and Revitalization of NIST Facilities. The FY 2024 budget request includes an increase of $48.6 million to support infrastructure improvements and enhancement of research spaces, ensuring that NIST can support a leading-edge research and development program that advances U.S. innovation in quantum information science, biotechnology, artificial intelligence, advanced manufacturing, cybersecurity, privacy, 5G and 6G telecommunications, and other critical programs.

Gaithersburg Central Utility Plant (CUP) Modernization. The FY 2024 budget request includes an increase of $50.0 million to provide for the full modernization of the CUP to replace all existing infrastructure and older equipment with new state-of-the-art sustainable systems.

Multiple Heating, Ventilation, and Air Conditioning] System Replacements. The FY 2024 budget request includes an increase of $30.0 million to ensure air handling units and related heating, ventilation, and air conditioning distribution systems in most buildings across the Gaithersburg, Maryland, campus provide clean, temperature-controlled air at proper ventilation rates.

FY 2018 Assessment:

Recommendation 2: The Physical Measurement Laboratory (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.

NIST response:

All NIST staff, including PML staff, are required to disclose their inventions to management and to our Technology Partnership Office (TPO). TPO assesses the invention for commercial potential and—for PML inventions—recommends to the PML Director, Jim Kushmerick, whether a patent should be sought. PML management works closely with TPO to reach equitable decisions on patenting promising inventions.

APPLIED PHYSICS DIVISION

FY 2018 Assessment:

Recommendation 3: Physical Measurement Laboratory (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.

NIST response:

At this stage, the procurement and maintenance costs of a regular clinical magnetic resonance imager was deemed inappropriate given NIST’s limited capabilities to perform extensive animal and/or human research, which would leave such a machine under-utilized. Instead NIST has established close collaborations with CU Boulder and Anschutz Medical Campuses, both of which provide NIST with more cost-effective access to clinical systems. We also maintain collaborations with researchers at the NIH, where we perform animal-based research on both clinical MRI scanners as well as higher field systems, and with MGH/Harvard Medical School where human studies are performed on a home-built low-field scanner. Additionally, NIST has procured a less expensive low-field Hyperfine clinical system with which we are able to conduct limited in-house phantom and human studies.

QUANTUM ELECTROMAGNETICS DIVISION

FY 2018 Assessment:

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.)

NIST response:

See responses to Recommendations 1 and 2.

TIME AND FREQUENCY DIVISION

FY 2018 Assessment:

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: Physical Measurement Laboratory (PML) should continue its work to develop methods for distributing time over long distances at the newly attainable levels of precision.

NIST response:

The TFD is pursuing two main methods to compare frequency standards at the precision offered by optical clocks: through two-way frequency-comb based comparisons (over free space and optical fibers) and through the development of a transportable ytterbium optical lattice clock.

For the comb-based optical time transfer measurements, TFD has collaborated with JILA and the Fiber Sources and Applications Group in NIST's Communications Technology Laboratory to perform the most accurate frequency ratio measurements made to date (*Nature*, 2021). These measurements used fiber-optic based frequency transfer. The teams also performed an optical clock comparison through turbulent air (*Physical Review Research*, 2020), showing that they can perform comparisons below the 10–18 level.

The NIST portable Yb lattice clock has been under development since 2018 and became operational in 2022. Deployment of the portable Yb clock at the US Naval Observatory (USNO) in Washington DC in March of 2023 was the system's first remote frequency comparison. The portable Yb clock was measured against a USNO Rb atomic fountain (one of their most stable systems) over several days, with a focus on characterization of the frequency stability and phase noise between the two systems. The measurements are consistent a frequency stability of 1 × 10-15 at 10,000 seconds, limited by the Rb fountain. This work will be presented at the [joint conference of the European Frequency and Time Forum & the IEEE International Frequency Control Symposium] in May. After the uncertainty budget is evaluated and published, planned future experiments include using the portable system with optical time transfer over free space to measure the gravitational redshift between Boulder and the summits of Flagstaff Mountain and Mount Evans. The system will also be used to validate the performance of frequency standards that are being developed at other institutes through the [Defense Advanced Research Projects Agency] A-Phi and ROCk'N programs.

Finally, the portable clock will eventually be deployed internationally for optical clock frequency ratio measurements at other NMIs.

QUANTUM PHYSICS DIVISION

FY 2018 Assessment:

> 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.

NIST response:

> The short distance (2 miles) between JILA and the NIST campus has an impact on scientific interactions, with JILA's position on the CU campus enabling a different set of interactions for its researchers. However, since the previous review, the large BACON Collaboration has operated a network of three optical atomic clocks in Boulder, consisting of a TFD aluminum-ion clock (Hume), a TFD ytterbium lattice clock (Ludlow), and a QPD strontium lattice clock (Ye), and a TFD optical network (Fortier). In addition, there are now highly productive QIS collaborations between the TFD ion storage group (Bollinger and Slichter) and the QPD Rey and QPD Kaufman groups, and between the TFD Atomic Devices and Instrumentation Group (Kitching) and the QPD Thompson group. The QPD is also collaborating on numerous projects with other NIST divisions. Finally, these efforts are all two-way collaborations between groups with different expertise and styles, but of similar overall quality, that bring added value to all researchers.

REFERENCE

NASEM (National Academies of Sciences, Engineering, and Medicine). 2018. *An Assessment of Four Divisions of the Physical Measurement Laboratory at the National Institute of Standards and Technology: Fiscal Year 2018.* Washington, DC: The National Academies Press. https://doi.org/10.17226/25281.

8
Overarching Themes, Key Recommendations, and Division-Specific Recommendations from This Assessment

OVERARCHING THEMES AND KEY RECOMMENDATIONS

The Panel on the Assessment of the National Institute of Standards and Technology (NIST) Physical Measurement Laboratory (PML) organized itself into four largely independent sub-panels to assess the divisions included in this report in parallel. In the course of their work, three overarching themes emerged that apply to all of PML. These are the adequacy of facilities and equipment, adequacy of staffing, and safety posture.

Adequacy of Facilities and Equipment

Each of the four sub-panels identified facilities and infrastructure as a crucial area to address. The 2018 report that assessed the PML division and Boulder (NASEM 2018), and the more recent National Academies' report *Technical Assessment of the Capital Facility Needs of the National Institute of Standards and Technology* (NASEM 2023), both highlight the aging facilities and infrastructure that present severe impediments to PML research staff continuing to produce the high quality of work for which they are known.. Of particular note, the 2023 report found that NIST research staff are devoting 10 to 40 percent of their time on workarounds and do-it-yourself repairs. This comes at the cost of research time and may impact PML's status as a world-leading institution, along with its ability to attract high-quality talent.

For the Applied Physics Division, the sub-panel identified the electrical supply and the water system as particular areas in need of upgrades. The Quantum Physics Division sub-panel pointed to serious space and infrastructure problems at JILA. The Quantum Electromagnetics Division sub-panel identified renovations and improvements to the division's device fabrication facility as a priority. The Time and Frequency Division sub-panel called out improvements in Building 01 and the mitigation of power outages in multiple buildings as being critical to the division's future success.

Key Recommendation 1: The Physical Measurement Laboratory (PML) should work with the National Institute of Standards and Technology's Office of Facilities and Property Management to identify facilities and infrastructure with critical infrastructure issues. Infrastructure and facilities that are critical in supporting the scientific mission of PML should be considered in assessing remodeling and upgrading needs.

Adequacy of Staffing

Attention needs to be paid to staffing, both now and in the future. Several programs currently have insufficient staffing levels, and retirements could lead to a loss of knowledge and expertise unless effective succession plans are put in place. The sub-panel that reviewed the Quantum Electromagnetics

Division identified the Spin Electronics Group as needing additional personnel and resources. It also recommended that this group consider succession plans to close experience gaps. Similarly, the sub-panel evaluating the Time and Frequency Division recommended the development of succession plans and furthermore called for knowledge and responsibilities to be shared and distributed among members and teams to guarantee that knowledge was preserved if key members left. That sub-panel was also concerned about inadequate staffing, in particular for the division's time distribution service. The Applied Physics Division sub-panel emphasized the importance of addressing personnel issues in a timely fashion and, to that end, recommended that PML ensure that the division has one or more excellent Human Resources professionals onsite.

Key Recommendation 2: The Physical Measurement Laboratory should act to ensure adequate staffing at the four divisions now and for the future and, as part of that, should work to improve the ways it addresses personnel issues. This would include having an excellent Human Resources professional(s) onsite who can address an array of personnel issues in a timely fashion within the context of the PML culture.

Key Recommendation 3: The Physical Measurement Laboratory should establish clear and open policies and practices across the organization on recruiting permanent government employee positions and promoting interactions and collaborations. In particular, the open positions should be made available to staff and guest researchers across the organization. National Institute of Standards and Technology–wide seminars and activities should be established to promote inter-group interactions and collaborations.

Safety Posture

The safety posture of PML does not adequately ensure the safety of PML staff and visitors. Initial steps to improve safety have been taken by PML staff, but improvements need to accelerate. Safety inspections and standards need to be reevaluated with the goal of bringing safety across the divisions to a level that is comparable with major industrial companies. The sub-panel that reviewed the Applied Physics Division recommended that the frequency of safety inspections be increased and that the PML leadership should reach out to major industrial companies for advice on improving laboratory safety. The Quantum Physics Division sub-panel identified laser safety as a particular concern and recommended that NIST and the University of Colorado Boulder jointly establish a clear and aggressive timeline for meeting American National Standards Institute laser safety standards.

Key Recommendation 4: The Physical Measurement Laboratory should address persistent safety concerns related to safety inspections and standards, particularly within the Applied Physics Division and the Quantum Physics Division.

DIVISION-SPECIFIC RECOMMENDATIONS

Applied Physics Division

Recommendation 3-1: The Applied Physics Division should consider incorporating artificial intelligence (AI) expertise within the division, rather than just relying on the National Institute of Standards and Technology's Information Technology Laboratory. Such expertise would allow for the development of a strategic plan for AI capabilities to be organically rolled into the Physical Measurement Laboratory's work where appropriate.

Recommendation 3-2: The Physical Measurement Laboratory should invest in additional upgrading of the division's facilities and infrastructure. In particular, the electrical supply needs to be upgraded to avoid the frequent interruptions that have been setting back and ruining experiments, and the water system needs to be improved to avoid pipe breaks.

Recommendation 3-3: The Applied Physics Division should further expand its materials characterization capabilities, as these are critical in constructing some of the devices used in the division's experiments.

Recommendation 3-4: The Physical Measurement Laboratory (PML) should have excellent Human Resources professionals onsite who can address an array of personnel issues in a timely fashion within the context of the PML culture.

Recommendation 3-5: The frequency of safety inspections by the Physical Measurement Laboratory (PML) should be increased and PML leadership should reach out to major industrial companies for advice on improving laboratory safety. In particular, the leadership should look to those companies that are recognized as having among the best safety programs in the world. Large chemical and petrochemical companies, for instance, are widely recognized as having very high-quality safety programs and may be willing to share key aspects of their safety practices.

Quantum Physics Division

Recommendation 4-1: The National Institute of Standards of Technology's Office of Facilities and Property Management and appropriate University of Colorado leadership should work together to solve the serious JILA space, infrastructure, and safety problems. The two organizations need to understand what is at risk and the urgency of the issue. A special task force with representatives of all stakeholders may be useful in putting focus on this problem and finding a timely solution.

Recommendation 4-2: The Physical Measurement Laboratory and the University of Colorado Boulder should jointly establish a clear and aggressive timeline to reach American National Standards Institute laser safety standards. The panel also recommends expanding the existing memorandum of understanding to establish acceptable standards and timelines for achieving improved and adequate safety compliance in those areas.

Quantum Electromagnetics Division

Recommendation 5-1: The Physical Measurement Laboratory should prioritize renovations and improvements to the device fabrication facility of the Quantum Electromagnetics Division. The present facilities are fully used and aged to the point that they require major renovations to increase the capacity to deliver on current expanding research projects and to acquire new capabilities to embark on leading-edge research in the future.

Recommendation 5-2: The Quantum Electromagnetics Division should broaden its advanced long-wavelength sensing technologies to many other long-wavelength applications at elevated temperatures, such as for far-infrared long wavelengths and nuclear isotopic compositions.

Recommendation 5-3: The Boulder Cryogenic Quantum Testbed should add additional personnel and resources. In particular, it should seek to develop an enhanced capability that

offers a unique resource by funding additional staff for the testbed and adding internships for students and junior researchers to strengthen and broaden the collaborations and partnerships with academia and with the emerging quantum computing and sensing industry.

Recommendation 5-4: The Spin Electronics Group should add additional personnel and resources. In particular, it should consider increasing exposure to reach broader audiences in recruiting. With a small and aging workforce to cover many new and competitive research directions, it should also consider succession and recruitment plans to establish a critical mass and close experience gaps in pursuing new research fields in spin-based quantum computing and device characterization.

Recommendation 5-5: The National Institute of Standards and Technology (NIST) should establish clear and open policies and practices across the organization on recruiting permanent government employee positions and promoting interactions and collaborations. In particular, the open positions should be made available to staff and guest researchers across the organization. NIST should establish organization-wide seminars and activities to promote inter-group interactions and collaborations.

Time and Frequency Division

Recommendation 6-1: The Time and Frequency Division should prioritize development of its Cs fountain primary frequency standards, its Sr+ secondary standard, or both to ensure that the National Institute of Standards and Technology can regularly contribute to international time scales. The division should ensure the continuation of its recent progress with the addition of new personnel to these efforts.

Recommendation 6-2: The architecture and infrastructure of the time distribution service should be evaluated and modernized with an emphasis on growth, security, robustness, and adequate staffing of this crucial service for the country.

Recommendation 6-3: The Time and Frequency Division should ensure that succession plans are put in place and that knowledge and responsibilities are shared and distributed among the wider members and teams. The Physical Measurement Laboratory's new succession funding program is encouraging, but all critical areas should be evaluated to identify and mitigate potential single points of failure.

Recommendation 6-4: The Physical Measurement Laboratory should act to improve the critical infrastructure of Building 01 as well as to mitigate power outages in many of the buildings affecting the research laboratories or find other suitable space to house these groups.

REFERENCES

NASEM (National Academies of Sciences, Engineering, and Medicine). 2018. *An Assessment of Four Divisions of the Physical Measurement Laboratory at the National Institute of Standards and Technology: Fiscal Year 2018.* Washington, DC: The National Academies Press. https://doi.org/10.17226/25281.

NASEM. 2023. *Technical Assessment of the Capital Facility Needs of the National Institute of Standards and Technology.* Washington, DC: The National Academies Press. https://doi.org/10.17226/26684.

Appendixes

A
Acronyms and Abbreviations

AFM	atomic force microscopy
AI	artificial intelligence
ANSI	American National Standards Institute
APS	American Physical Society
BESSY-II	Berliner Elektronenspeicherring-Gessellschaft fur Synchrotronsstrahlung
BIPM	International Bureau of Weights and Measures
CMR	construction and major renovations
CRF	construction of research facilities
CU	University of Colorado Boulder
CUP	Central Utility Plant
DARPA	Defense Advanced Research Projects Agency
DEIA	diversity, equity, inclusion, and accessibility
DIAL	Differential Absorption Light Detection and Ranging
FY	fiscal year
HR	Human Resources
IEEE	Institute of Electrical and Electronics Engineers
LIDAR	Light Detection and Ranging
MGH	Massachusetts General Hospital
MKID	microwave kinetic inductance detector
MML	Materials Measurement Laboratory
MRI	magnetic resonance imaging
NCNR	NIST Center for Neutron Research
NEP	noise-equivalent power
NIH	National Institutes of Health
NIST	National Institute of Standards and Technology
NSF	National Science Foundation
OSHA	Occupational Safety and Health Administration
PECASE	Presidential Early Career Awards for Scientists and Engineers
PFC	Physics Frontier Center

PI	principal investigator
PML	Physical Measurement Laboratory
PPE	personal protective equipment
QED	Quantum Electromagnetics Division
QPD	Quantum Physics Division
RAVEN	Rapid Analysis of Various Emerging Nano-Electronics
RF	radio frequency
SCMMR	safety, capacity, maintenance, and major repairs
SEM	scanning electron microscope
SI	International System of Units
SQL	standard quantum limit
SQUID	Superconducting Quantum Interface Device
TES	transition-edge sensor
TFD	Time and Frequency Division
TPO	Technology Partnership Office
TRL	technology readiness level
USNO	U.S. Naval Observatory
UTC	Coordinated Universal Time
VCAT	Visiting Committee on Advanced Technology
X-IFU	X-ray integral field

B
Panel Biographical Sketches

ROBERT H. AUSTIN (NAS), *Chair*, is a professor of physics in the Department of Physics at Princeton University. His research spans three areas: protein dynamics and conformational statistics, DNA dynamics and base pair sequence elastic variability, and applications of micro and nanofabrication technology to cellular and molecular biology. He is a master at combining physical tools and theories with biochemical techniques to attack fundamental problems in protein and nucleic acid dynamics and function. His observations of single DNA molecules using microlithography led to an understanding of their physical properties, which are important in biology and biotechnology. He is a fellow of the American Physical Society (APS) and the American Association for the Advancement of Science (AAAS) and a member of the National Academy of Sciences (NAS). He received his BA in physics from Hope College, and his MS and PhD in physics from the University of Illinois at Urbana-Champaign.

RYAN E. BAUMBACH is a research faculty at the National High Magnetic Field Laboratory (NHMFL) and an associate research professor at Florida State University (FSU). He is focused on new materials physics, with an emphasis on structural, magnetic, and electronic states that derive from transition metal, lanthanide, and actinide elements. He follows an approach based on (1) development of design principles; (2) crystal growth methods; and (3) measurement of structural, electronic, and thermodynamic quantities. He is a leader in studies of transuranic magnetism, with many pioneering measurements of molecular crystals containing Np-Cf. He is also a champion for the advancement of society through science. He regularly serves as a guest lecturer at schools and community lecture and demo activities. He recently served as a key team member for a National Science Foundation (NSF) Engine proposal. To foster diversity, equity, and inclusion, he is a member of the graduate affairs and Advanced Photon Source bridge program committees in the FSU Department of Physics, and on the NHMFL Diversity Committee. He also is the research supervisor for diverse individuals including postdoctoral researchers, graduate, undergraduate, high school, and middle school students. Lastly, he makes many contributions to the profession, where a recent example is his service on a committee reviewing the High-Pressure Collaborative Access Team.

HARISH B. BHANDARI is currently the director for the Advanced Thin Film Technologies Group at Radiation Monitoring Devices, Inc., where he directs the thin film materials research laboratory. With more than 15 years of experience in chemical synthesis, sputtered thin film synthesis, and atomic layer deposition, Dr. Bhandari has extensive expertise in thin films. His research has focused on developing high-quantum efficiency photocathodes, conformal passivation coatings for semiconductors, and large-area, low-cost scintillators, among other applications. Dr. Bhandari has received numerous patents for his innovations and is a member of the American Vacuum Society (AVS) and the Materials Research Society. He received his PhD in chemical engineering from the University of Alabama in 2005 and was a postdoctoral fellow and research associate at Harvard University from 2006 to 2010, where he identified novel materials and processes for the advancement of integrated circuit interconnect technology.

RAINER BLATT (NAS) studied physics and received his PhD at the University of Mainz. As a postdoctoral fellow, he worked on laser cooling with John L. Hall at the University of Colorado Boulder and on single trapped ions with P. Toschek at the University of Hamburg. In 1994 he became a professor of physics at the University of Göttingen and in 1995 he accepted a chair position at the University of Innsbruck, where he works with trapped ions for quantum computation, quantum simulation, and quantum metrology. He is a research director at the Institute for Quantum Optics and Quantum Information of the Austrian Academy of Sciences in Innsbruck and the co-founder of Alpine Quantum Technologies GmbH, a company developing commercial quantum computers. Since 2021, Dr. Blatt is the scientific director of the Munich Quantum Valley. For his quantum information research, he received numerous prizes, among them the Stern-Gerlach medal of the German Physical Society (DPG) in 2012, the John-Stewart-Bell prize of CQIQC (Toronto) in 2015, and the Herbert-Walther-Prize of DPG and Optica in 2023. Dr. Blatt is a member of the Austrian Academy of Sciences, the Spanish Royal Academy of Sciences, and NAS.

GILLES BUCHS has been a senior scientist at Oak Ridge National Laboratory since 2021 and is currently the acting group leader of the Quantum Computing and Sensing Group. In his role, he contributes to establishing and leveraging a quantum edge node based on a trapped ion quantum resource to conduct research in quantum simulation and computation. From 2018 to 2021, he was a senior researcher at the quantum computing startup SQC in Sydney, Australia, conducting experimental research on analog quantum simulation with engineered donor qubits in silicon. Before this, he was a senior research and development (R&D) engineer at CSEM in Switzerland. He conducted research, developed, and managed multi-million-euro public–private projects in photonics and quantum photonics systems and quantum sensors based on atomic vapor cells for various applications in metrology and industry. In 2008, he was awarded a Marie Curie Fellowship to conduct research in quantum nanophotonics at the Kavli Institute of Nanoscience Delft in the group of Professor Val Zwiller. He is a member of APS and holds a PMP certification from the Project Management Institute. Dr Buchs received his MS in solid-state physics from ETH Zurich in 2004 before joining the Swiss Federal Laboratories for Materials Science and Technology and the University of Basel, where he earned his PhD in the field of quantum nanoelectronics in 2008.

YOUNG-KAI CHEN (NAE) is the chief scientist at Coherent Incorporated and a visiting professor at Princeton University and Cornell University. From 2017 to 2021, he was a program manager at the Defense Advanced Research Projects Agency (DARPA), and while there initiated and managed programs in advanced semiconductor electronics, artificial intelligence and machine learning processing, and secure communications. Before joining DARPA, he was a senior director at Nokia Bell Labs from 1988 to 2017, supporting R&D in the areas of high-speed electronics and optoelectronics. Dr. Chen and his teams initiated the development of integrated lasers; silicon photonics ICs; 2G, 3G, 4G, and 5G wireless backhaul transceivers; and 100G coherent optic data links. Dr. Chen received his PhD from Cornell University, MSEE from Syracuse University, and BSEE from National Chiao-Tung University in Taiwan. He is a fellow of Bell Labs, the Institute of Electrical and Electronics Engineers (IEEE), and Optica; a member of the National Academy of Engineering (NAE); and a recipient of the IEEE David Sarnoff Award and the Edison Patent Award.

DAPHNA G. ENZER has been with the National Aeronautics and Space Administration's (NASA's) Jet Propulsion Laboratory (JPL), California Institute of Technology, since 2001. She is a research technologist in the Frequency and Timing Advanced Instrument Development Group, actively working on the development of precision measurement, as well as timing and frequency systems. Dr. Enzer recently led clock system modeling for the Deep Space Atomic Clock mission and was an integral part of its Operations and Analysis team. Since then, she has been an essential member of the Data Analyst team for the Sun Radio Interferometer Space Experiment, a mission to study solar activity using a 6-spacecraft interferometer. Her other work includes the development of a cold-atom cesium space-clock and the Gravity Recovery and Interior Laboratory mission as well as support of the frequency and timing system of the NASA Deep Space Network. Dr. Enzer is serving her second year as the program chair for the

Precise Time and Time Interval Meeting. Dr. Enzer received a PhD in atomic physics from Harvard University in 1996 and a BS from Yale University in 1989.

RACHEL M. GODUN is the science area leader for the optical frequency metrology group within Time and Frequency at the United Kingdom's National Physical Laboratory (NPL). This includes optical clocks, ultrastable lasers, femtosecond frequency combs, and time and frequency transfer over optical fiber links. Dr. Godun's specialist area of research is the development of an optical atomic clock based on a trapped, single ion of ytterbium. The research aims to make frequency measurements at the highest level of accuracy to support a future redefinition of the SI second and enable tests of fundamental physics. Dr. Godun is currently a member of the Executive Committee for the European Frequency and Time Forum and a vice chair of the Scientific Committee. She is a technical expert for the European Metrology Network for quantum technologies and a member of the Institute of Physics. Dr. Godun graduated from the University of Oxford with an MPhys in 1997 and completed a DPhil in 2000, carrying out research in atom interferometry. She continued to work with ultra-cold atoms for an additional 8 years in Oxford, before joining NPL in 2008.

RICHARD A. GOTTSCHO (NAE) is the executive vice president and strategic advisor to the chief executive officer (CEO) of innovation ecosystem at Lam Research, where he develops strategies and leads collaborations to accelerate innovation in the semiconductor industry. Dr. Gottscho brings 40 years of technology leadership to his role. Previously, he was the executive vice president and chief technology officer at Lam, where he led initiatives to transform lithography and process engineering. Prior to that, he served as the executive vice president of Lam's Global Products Group, overseeing the company's deposition, etch, and clean businesses. Before joining Lam, Dr. Gottscho was a member of Bell Labs, where he oversaw research in processing, materials, packaging, and flat panel displays. He is a fellow of APS and AVS and has served on numerous committees for conferences in plasma technology. He regularly presents at universities and conferences. In recognition of Dr. Gottscho's technical achievements, NAE inducted him into its ranks in 2016. Dr. Gottscho has also been honored with AVS's Peter Mark Memorial Award, AVS's Plasma Science and Technology Division Prize, the Dry Process Symposium Nishizawa Award, and VLSI's Semiconductor Hall of Fame. He earned his PhD and BS in physical chemistry from the Massachusetts Institute of Technology and The Pennsylvania State University, respectively.

RICHARD A. HAIGHT is a research staff member at the IBM Thomas J. Watson Research Center in Yorktown Heights, New York, presently involved in IBM's quantum computation effort, where he is studying qubit materials issues and nonlinear optical communications for scaling. His prior and continuing work has involved the development and application of tunable femtosecond high harmonic photoelectron spectroscopy for studying electron dynamics in materials. He is the co-inventor of the first femtosecond photomask repair tool used in manufacturing, MARS (mask advanced repair system), which following commercialization is now in use in semiconductor companies worldwide. Dr. Haight was awarded a corporate level outstanding technical achievement award for this work. He also developed femtosecond photovoltage spectroscopy used to determine the electronic structure in buried MOS stacks, heterostructures in thin film photovoltaics, and neuromorphic devices. Dr. Haight was the principal investigator (PI) on a Department of Energy (DOE)-funded effort to develop thin-film, earth-abundant photovoltaics. He has served on committees for NSF, DOE, and the National Academies' Committee on Atomic, Molecular, and Optical Sciences. He is a fellow of APS and the Optical Society of America, edited a published two-volume set titled *Handbook of Instrumentation and Techniques for Semiconductor Nanostructure Characterization*, and co-authored the book *Industrial Applications of Ultrafast Lasers* in 2018. Dr. Haight has published more than 125 papers and book chapters and holds more than 90 U.S. and international patents with additional patent filings pending. Dr. Haight is the co–editor in chief for the *Materials and Energy* series published by World Scientific Press.

LINDA KATEHI (NAE) is the O'Donnell Endowed Chair in Engineering and a Distinguished Texas A&M Engineering Experiment Station Chair Professor of Electronics in electrical and computer engineering and material science and engineering at Texas A&M University, College Station. From 2017 until 2020, she served as the president-elect, president, and past-president of the Women in Engineering Professional Advocacy Network. She was the John Edwardson Dean of Engineering at Purdue University from 2001 to 2006, the provost of the University of Illinois at Urbana-Champaign from 2006 to 2009, and the chancellor at the University of California, Davis, from 2009 to 2016. Dr. Katehi's research focuses on designing and developing intelligent edge radio frequency (RF) electronics. This area involves analog hardware and algorithm co-design, deep machine learning, and neuromorphic computations for developing electronic components and systems that can evolve performance based on the operational space and collected data. These new research directions are founded in Dr. Katehi's broad experience in 3D integration and packaging of microwave, millimeter-wave, and sub-terahertz circuits; computer-aided design of VLSI interconnects; development and characterization of micromachined circuits for microwave, millimeter-wave, and submillimeter-wave applications including MEMS switches, high-Q evanescent mode filters, and MEMS devices for circuit reconfigurability; and the development of both frequency and time domain methods and algorithms. She is a member of NAE and received the National Academies' Simon Ramo Founders Award in 2015. She is a member of the American Academy of Arts and Sciences, the National Academy of Innovators, and a fellow of IEEE. She was the chair of the President's Committee for the National Medal of Science and the Secretary of Commerce's Committee for the National Medal of Technology and Innovation. She is a fellow of AAAS, served on the AAAS board of directors, and was the president of its Engineering Section. She served as a member of the National Higher Education Board, a member of the Higher Education Business Forum, and many other national and international boards and committees.

KATE KIRBY earned her BS in chemistry and physics from Harvard-Radcliffe College and her PhD from the University of Chicago. After a postdoctoral fellowship at the Harvard College Observatory, she was appointed as a research physicist at the Smithsonian Astrophysical Observatory and lecturer in the Harvard University Department of Astronomy. From 1988 to 2001, she served as an associate director at the Harvard-Smithsonian Center for Astrophysics, heading the Atomic and Molecular Physics Division. From 2001 to 2007, she served as the director of the Institute for Theoretical Atomic, Molecular, and Optical Physics at Harvard-Smithsonian. From 2009 to 2014, she served as the executive officer of APS. In 2015, she was appointed the first CEO of APS. She retired from that position at the end of 2020. Dr. Kirby's research interests lie in theoretical atomic and molecular physics, particularly the calculation of atomic and molecular processes important in astrophysics and atmospheric physics. She is a fellow of both APS and AAAS.

KEVIN O. KNABE is currently the director of R&D at Vescent Photonics and has extensive experience with laser stabilization and precision optical measurements. He has worked on a variety of spectroscopy experiments ranging from saturated absorption spectroscopy in hollow-core photonic crystal fibers under his graduate school advisor, Dr. Kristan Corwin, to comb-assisted spectroscopy using a quantum cascade laser in the mid-infrared (IR) for rapid broadband spectroscopy at the National Institute of Standards and Technology (NIST) under the guidance of Dr. Nathan Newbury. He also has a long history of laser stabilization with a wide range of sources (fiber and diode lasers across the visible and near-IR) to high finesse optical cavities to produce lasers that have sub-hertz linewidths and experience with integrating high performance electro-optical systems. As the director of R&D at Vescent Photonics, he oversees projects related to robust laser integration for deployed quantum applications in both government and commercial sectors.

SHIMON J. KOLKOWITZ is an associate professor and the Herst Chair in physics at the University of California, Berkeley. He was formerly an associate professor of physics at the University of Wisconsin–Madison. Dr. Kolkowitz's experimental research focuses on precision measurement, metrology, quantum sensing, and searches for new physics using atoms and atom-like systems. His research group has developed new techniques and applications for ultra-precise optical atomic clocks, and new measurement tools that make use of atom-scale defects in diamonds. He is a 2019 Packard Science and Engineering fellow, a 2022 Sloan Research fellow, and is a recent recipient of the NSF CAREER award. Dr. Kolkowitz was an undergraduate at Stanford University, graduating with distinction in 2008 with a BS in physics. He earned his PhD in experimental physics at Harvard University in 2015 with advisor Professor Mikhail Lukin, where his research focused on quantum sensing with defects in diamond. He was subsequently a National Research Council postdoctoral fellow at JILA: a joint institute of NIST and the University of Colorado Boulder, in the research group of Professor Jun Ye from 2015 to 2017, working on metrology and quantum science with optical lattice atomic clocks.

JOHN R. LOWELL is the chief engineer and quantum portfolio manager for Boeing's Disruptive Computing & Networks organization, which is leveraging core technologies in quantum communications, computing and sensing, high-performance computing, virtualization of embedded computing hardware and software, and advanced networking to develop computing and communications solutions for advanced commercial and government aerospace applications. Dr. Lowell was named to this position in October 2018. An internationally recognized expert in systems engineering of quantum, electromagnetic, or electro-optic systems, he also is a principal senior technical fellow who works across Boeing's businesses to develop quantum technology into Boeing products and services. His technical background includes work in remote sensing, precision measurements of time and frequency, inertial measurements, laser and matter interactions, photonics, optical signal processing, medical diagnostic development, and software development. Previously, he was a program manager in the Defense Sciences Office of DARPA, where he created and directed more than 10 research programs that ranged from foundational science to product development. He has served on U.S. Air Force Scientific Advisory Board studies, was an assistant professor of physics at the U.S. Air Force Academy, and a research physicist at the U.S. Air Force Research Laboratory (AFRL). Dr. Lowell is a distinguished graduate with honors from the U.S. Air Force Academy and holds an MS in physics from The Ohio State University. He also has a PhD in atomic physics from the University of Virginia.

LUTE MALEKI is the president and CEO of OEwaves, Inc. Before 2007 he was a senior research scientist at JPL, where he created and led the Quantum Sciences and Technologies Group. Dr. Maleki's research included atomic clocks, laser cooling, atom interferometers and quantum sensors, photonic oscillators, photonic signal distribution systems, crystalline whispering gallery mode microresonators, Kerr frequency combs, and tests of fundamental physics with clocks. He produced the first commercial oscillators based on a crystalline microresonator as well as oscillators based on Kerr combs and based on lowest phase noise semiconductor lasers. He has more than 65 U.S. patents and has authored and co-authored more than 150 refereed publications and more than 200 conference papers. He has been the PI of projects sponsored by DARPA, the U.S. Army, the U.S. Air Force, the U.S. Navy, and NASA. He serves on committees of international conferences in frequency and timing, and optical sciences and engineering. He is a life fellow of IEEE, a fellow of APS, and a fellow of Optica. He has co-founded three commercial companies. Dr. Maleki holds a BS, an MS, and a PhD in physics. He has received the IEEE I.I. Rabi Award and NASA's Exceptional Engineering Achievement Medal.

PIERRE MEYSTRE obtained his physics diploma and PhD from the Swiss Federal Institute of Technology in Lausanne in 1971 and 1974, respectively, and the habilitation in theoretical physics from the University of Munich in 1983. He joined the Max-Planck Institute for Quantum Optics in 1977, following a postdoctoral position at the University of Arizona College of Optical Sciences. He returned to Tucson in 1986 and became a Regents Professor of Physics and Optical Sciences in 2002 until his retirement in 2016. He then served as the Editor in Chief of the Physical Review research journals published by the APS from 2016 to 2017 after having been the lead editor of *Physical Review Letters* from 2013 to 2016. His research interests include theoretical quantum optics, atomic physics, ultracold science, and quantum optomechanics. He has published more than 330 refereed papers and is the author of *Elements of Quantum Optics*, together with Murray Sargent III, now in its fourth edition; the monograph *Atom Optics*; and the textbook *Quantum Optics, Taming the Quantum*, published in 2021. He is a recipient of the Humboldt Foundation Research Prize for senior U.S. scientists, the R.W. Wood Prize of the Optical Society of America, and the Willis E. Lamb Award for laser science and quantum optics; is a fellow of APS, the Optical Society of America, and AAAS; and an honorary professor at East China Normal University. Dr. Meystre has served on numerous national and international committees, including the Board on Physics and Astronomy of the National Academies, where he chaired its standing committee on Atomic, Molecular, and Optical Physics. He also chaired the Division of Atomic, Molecular, and Optical Physics of APS and was a council member of APS and AAAS. He served on the 2015 and 2018 National Academies' Panel on the Assessment of the Physical Measurement Laboratory at the National Institute of Standards and Technology.

JULIO A. NAVARRO is a principal senior technical fellow at the Boeing Company and a subject-matter expert in RF circuits, antennas, and heterogeneously integrated electronics. He provides technical leadership of RF and millimeter-wave technologies for Boeing's Research and Technology Division. He initiated, designed, and delivered phased array antenna (PAA) designs for unmanned aerial vehicles, aircraft, ships, submarines, satellites, and missiles. He also defines, shapes, and develops technical concepts along with product planning roadmaps to achieve breakthrough performance and efficiency gains for business unit customers. Before his current position, Dr. Navarro was a key innovator in the design, development, and transition of Ku- and Ka-band compact radar sensors, as well as the Ku-band directional network line-of-sight communication PAAs. His designs have transitioned to the Ku-band commercial SATCOM, Zumwalt DDG1000 Command-Data-Link LOS, UAE K-band and Small-Form Factor Ka-band SATCOM, and Q-band links on the Talon Hate program. For more than two decades, Dr. Navarro's integrated ceramic module served the government VIP Strategic Air Mission (SAM) fleet in the arbitrary linear-pol transmit PAAs of the Boeing Broadband SATCOM Network. The VIP SAM fleet of Boeing derivative aircraft include the VC-25, C-40, and C-32 business jets.

KAREN F. O'DONOGHUE is the director of Internet trust and technology for the Internet Society, a global nonprofit organization dedicated to an open, global, secure, and trustworthy Internet for everyone. In this role, she supports the development, deployment, and operation of technologies, standards, and best practices to improve the security of the Internet. Dr. O'Donoghue is focused on time synchronization and security of network time synchronization protocols. She has a long history of participation in the Internet Engineering Task Force, IEEE, and other standards bodies, as well as working in small multi-vendor teams to build technology demonstrations and event networks. Prior to joining the Internet Society, Dr. O'Donoghue worked for the U.S. Navy, focused on the development and application of commercial network standards and technologies to real-time Navy systems.

C. KUMAR N. PATEL (NAS/NAE) is the founder, CEO, and president of the board of Pranalytica, Inc., a Santa Monica–based company that is commercializing high-power quantum cascade lasers and highly sensitive and selective trace gas sensors for commercial, homeland security, and defense markets. He is also a distinguished professor at the University of Central Florida, as well as an emeritus professor of physics, chemistry, and electrical engineering at the University of California, Los Angeles (UCLA). From 1993 to 1999, he was the vice chancellor of research at UCLA. Until joining UCLA in 1993, he was the executive director of the Research, Materials Science, Engineering, and Academic Affairs Division at Bell Labs in Murray Hill, New Jersey. Under his leadership, Bell Labs produced some of the most critical technologies for optical communications. He is the inventor of the carbon dioxide laser and other high power gas lasers. His work at Bell Labs led to the creation of the field of high-power molecular lasers; infrared nonlinear optics; ultra-small absorption measurement techniques for gases, solids, and liquids; and laser surgery. He has authored and co-authored more than 270 publications and has been awarded 55 U.S. patents. He received the National Medal of Science given by the President of the United States in

1996. In 2012, he was inducted into the National Inventors Hall of Fame. In recognition of the CO2 laser's importance to the medical field, he was elected as an honorary member of the Gynecologic Laser Surgery Society in 1980, and in 1985 he was elected an honorary member of the American Society for Laser Medicine and Surgery. In 2018, the American Laser Study Club established the Kumar Patel Prize for Laser Surgery in honor of his invention of the carbon dioxide laser and its critical importance in laser surgery. He was named the first recipient of the prize. He is a member of NAS and NAE and is the past president of APS (1995) and Sigma Xi, the scientific research society (1993 to 1995). He co-chaired (with N. Bloembergen) the APS Study of the Science and Technology of Directed Energy Weapons. Dr. Patel received his BE in telecommunications from the College of Engineering in Poona, India, in 1958. He received an MS and a PhD in electrical engineering from Stanford University in 1959 and 1961, respectively.

MATTHEW J. REAGOR is the vice president of R&D at Rigetti Computing and the chief technology officer of the Superconducting Quantum Materials and Systems Center, one of five research centers funded by DOE as part of a national initiative with the goal to develop and deploy the world's most powerful quantum computers and sensors, headquartered at Fermilab. Dr. Reagor's research concerns applied quantum information processing techniques and algorithms for superconducting quantum devices. His PhD thesis in the Schoelkopf Laboratory at Yale introduced the first millisecond quantum memory for superconducting qubits. In the past several years, Dr. Reagor has been working toward tests of possible quantum advantage at the scale of hundreds of low-noise physical qubits.

KATHY-ANNE BRICKMAN SODERBERG is a principal research scientist at the AFRL Information Directorate in Rome, New York. Dr. Soderberg is the primary investigator and team lead for AFRL's Trapped-Ion Quantum Networking group. Dr. Soderberg received a BS in physics from the College of William and Mary, an MS and a PhD in physics from the University of Michigan, and is a postdoctoral researcher at the University of Chicago. Dr. Soderberg has more than 20 years of technical experience in atomic physics and quantum information processing. Her graduate work focused on trapped-ion quantum computing research and included key demonstrations of phonon-mediated entangling gates and proof-of-principle quantum algorithms (the Grover search algorithm). Her postdoctoral work focused on novel neutral-atom quantum computing and the difficulties associated with targeted atomic interactions and optical lattice translation and control. Before joining AFRL, Dr. Soderberg was a scientific and technical consultant for quantum information science.

JAMES (JIM) C. STEVENS (NAE) retired from Dow Chemical as the Dow Distinguished Fellow, Dow's highest scientific position, where he worked in the Core Research and Development Department. Dr. Stevens is currently the CEO of Stevens Solutions, LLC, providing scientific consulting in chemistry, materials science, photovoltaics, and battery technology. His primary field of research is in new catalysts and the high-throughput discovery of organometallic catalysts. Dr. Stevens and his team developed and commercialized numerous new polyolefin materials, which are produced on a multi-billion-pound scale annually. He is a member of NAE and has been awarded numerous awards, including the Perkin Medal, the American Chemical Society (ACS) Award in Industrial Chemistry, and the Carothers Award, and was named a "Hero of Chemistry" by ACS. Dr. Stevens has a BA in chemistry from The College of Wooster, a PhD in inorganic chemistry from The Ohio State University, and an honorary doctor of letters from Texas A&M University.

RUDOLF MARIA TROMP (NAE) received a PhD in physics and mathematics from Utrecht University (cum laude) in 1982. In 1983 he joined the IBM Thomas J. Watson Research Center as a research staff member. At IBM he has held various management positions and served as a consultant to the IBM Corporate Technology Team (an advisory body to the CEO). His research has focused on semiconductor surfaces, interfaces, and processes, epitaxial thin film growth, silicide formation, phase transitions, quantum dot and nanowire formation, thermodynamics, etc. He has developed advanced experimental techniques, including spectroscopic scanning tunneling microscopy, low energy electron microscopy, and in situ and liquid-cell transmission electron microscopy. Several of his inventions have been commercialized and are in use in laboratories worldwide. Dr. Tromp has published more than 280 refereed papers and several book chapters and has 50 U.S. and international patents. In 2006, he became (in addition to his position at IBM) a professor at Leiden University in the field of physics of surfaces and materials. Dr. Tromp is a fellow of APS, AVS, the Materials Research Society, and the Mineralogical Society of America, and a member of NAE.