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Panel on Physics

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

David Auston, University of California, Santa Barbara,
Anthony DeMaria, Coherent, Inc.,
Steven Larson, Memorial Sloan-Kettering Cancer Center,
Marc Levenson (retired), Saratoga, California, and
David Schultz, Oak Ridge National Laboratory.

Although the reviewers listed above have provided many constructive comments and suggestions, they were not asked to endorse the conclusions or recommendations, nor did they see the final draft of the report before its release. The review of this report was overseen by Alton D. Slay, Warrenton, Virginia. Appointed by the National Research Council, he was responsible for making certain that an independent examination of this report was carried out in accordance with institutional procedures and that all review comments were carefully considered. Responsibility for the final content of this report rests entirely with the authoring panel and the institution.

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Summary

The National Institute of Standards and Technology (NIST) is a nonregulatory agency within the U.S. Department of Commerce whose mission is to promote U.S. innovation and industrial competitiveness by advancing measurement science, standards, and technology in ways that enhance economic security and improve the quality of life. The institutional vision is to be the world's leader in creating critical measurement solutions and promoting equitable standards, with core competencies in the areas of measurement science, rigorous traceability, and the development and use of standards. The NIST laboratories conduct research that advances the nation's technology infrastructure and is needed by U.S. industry to improve products and services continually. The mission of the NIST Physics Laboratory is to support U.S. industry, government, and the scientific community by providing measurement services and research for electronic, optical, and radiation technology. In this respect, the laboratory provides the foundation for the metrology of optical and ionizing radiation, time and frequency, and fundamental quantum processes, historically major areas of standards and technology.

The organizational structure of the Physics Laboratory for accomplishing its mission and goals includes six vertically integrated divisions:

- Atomic Physics Division,
- Electron and Optical Physics Division,
- Ionizing Radiation Division,
- Optical Technology Division,
- Quantum Physics Division, and
- Time and Frequency Division.

The Physics Laboratory also includes an Office of Electronic Commerce in Scientific and Engineering Data to coordinate and facilitate the electronic dissemination of information on the Internet. In line with the vertical integration of the laboratory, each division is further divided into groups and projects, which are considered in more detail in the following individual chapters discussing each division.

For the fiscal year (FY) 2010 assessment cycle, the National Research Council (NRC) panel assessing the NIST Physics Laboratory was asked by the NIST Director to focus its assessment on the following broad factors:

1. The technical merit of the current laboratory programs relative to current state-of-the-art programs worldwide;
2. The adequacy of the laboratory budget, facilities, equipment, and human resources, as they affect the quality of the laboratory's technical programs; and
3. The degree to which laboratory programs in measurement science, standards, and services achieve their stated objectives and desired impact.

The agreed assessment procedure consisted of panel review teams performing individual site visits to their respective Physics Laboratory divisions, with the full panel reconvening to draft a comprehensive report for the Physics Laboratory. Members of the Panel on Physics visited the six divisions of the laboratory and reviewed a selected sample of their programs and projects, with the chair of the panel participating in all visits.

The general observations of the panel relative to the assessment criteria requested by the NIST Director are presented in the following sections.

GENERAL OBSERVATIONS RELATIVE TO THE ASSESSMENT CRITERIA

The Technical Merit of the Current Laboratory Programs Relative to Current State-of-the-Art Programs Worldwide

The Physics Laboratory has had two decades or more of outstanding research accomplishments because of a group of dedicated, exceptional scientists and technical staff responding to the needs of NIST, the nation, and the world, along with an administration that fostered a collegial and intellectual climate conducive to such productivity. During this same period, the laboratory has maintained its exceptional leadership role in metrology and standards, in part because of the dedication of its staff in these areas and because of the staff's groundbreaking research. The technical merit of the laboratory's programs is particularly noteworthy in view of the fact that the Physics Laboratory is a small facility in comparison with other research-oriented federal and national institutions, with its primary commitment being to commerce and industry. At the same time, changes within the laboratory in terms of scientific and administrative personnel, organization, and infrastructure have raised issues, detailed in the report, concerning planning and resources for the maintaining and fostering of this productive environment.

The Adequacy of the Laboratory Budget, Facilities, Equipment, and Human Resources, As They Affect the Quality of the Laboratory's Technical Programs

Since the previous NRC assessment in 2008, the budget for the Physics Laboratory has generally been maintained or increased in most areas in absolute dollars. With the condition of the overall economy, this is most certainly to be lauded and represents an endorsement of the laboratory and its accomplishments. At the same time, increased costs and increased commitments such as budget line items or funding from external agencies for specific programs have resulted in serious funding decreases in major responsibilities, particularly in some areas or standards and services with reductions in key personnel and/or services. The laboratory and most divisions have updated or initiated long-term strategic plans as recommended by the panel in 2008, which helps delineate the needs, but it does not generate the financial resources.

The laboratory has new facilities in the planning stage, under construction, or completed since the previous panel report in 2008, as well as acquisitions of major equipment in key areas, in many cases partly in response to the 2008 recommendations from the NRC assessment panel. There appears to be increased commitment to the refurbishment of the existing facilities and maintenance, although there remain areas of concern for specific programs and groups as noted in the chapters on the individual divisions. There also remain major groups with facilities that negatively impact productivity, time lines, and quality. For example, despite recent renovations, the building housing the majority of the Ionizing Radiation Division remains a concern. There are also concerns about the buildings and facilities used by the Atomic Physics, Electron and Optical Physics, Quantum Physics, and Time and Frequency Divisions.

In terms of human resources, the technical scientists and staff continue to represent the major strength of this laboratory, but budget and reallocation issues appear to be impacting retention, salaries, permanent appointments, and recruitment. For example, the percentage of permanent staff appears to have remained constant or to have decreased in most groups. While an influx of junior and senior scientists is good for training and the intellectual climate, many of the temporary appointments appear to be motivated by budgetary and bureaucratic considerations. The staff of the Radiation Interactions and Dosimetry Group of the Ionizing Radiation Division has decreased, and the ratio of permanent staff to temporary, contractor, and part-time personnel is relatively low in the Optical Technology Division and declining in the Time and Frequency Division. Care should be taken to ensure that important NIST capabilities are not left understaffed or that important NIST functions, such as the establishment and maintenance of standards and related services, are not adversely affected by an insufficient number of permanent staff. The NIST management also should assess the potential impact of any changes in laboratory organization on future staffing, if they have not already done so.

The Degree to Which Laboratory Programs in Measurement Science, Standards, and Services Achieve Their Stated Objectives and Desired Impact

The availability of more strategic planning has helped in the achievement of objectives, although some groups, such as the Electron and Optical Physics Division, would benefit from additional long-term planning for balancing core activities and allocating resources. The strategic planning could suggest appropriate paths to organize personnel among divisions in the Physics Laboratory so that the talented staff can work more closely and efficiently with their collaborators in other divisions. Similarly, additional strategic planning with greater consultation with its user community would benefit the Ionizing Radiation Division. In addition, it would be helpful for the Physics Laboratory to elucidate a comprehensive plan for organizing and staffing its expanded role in the biophysics area in order to optimize its effectiveness.

New, improved, and/or more accurate services were apparent even in comparison with the panel's visit to the Physics Laboratory in 2008. However, several service and standards areas, even those with the most public visibility and recognition such as time and frequency, suffered reduced funding and reduction in services. The Ionizing Radiation Division lost one position and reassigned two others at a time when medical and industrial services and calibrations are increasing within the laboratory and are a national issue before Congress. The assessments of individual divisions are summarized in the sections below and then detailed in Chapters 2 through 7. Chapter 1 provides a description of the charge to the panel and the assessment process, and Chapter 8 provides the panel's overall conclusions.

ATOMIC PHYSICS DIVISION

The goal of the Atomic Physics Division is to investigate and exploit quantum behavior and interactions of atomic matter and radiation. The major projects are Cold Atomic Matter, Nanoscale and Quantum Metrology, Quantum Behavior of Light and Matter, and Critically Evaluated Atomic Data.

In terms of overall quality, the Atomic Physics Division is doing an extraordinarily effective job of fulfilling its charges, as laid out by the NIST Director. The Joint Quantum Institute (JQI)[1] is a major success and a powerful addition to the research enterprise at NIST. The remarkable advances in quantum information, quantum measurement, and quantum control are potentially revolutionary for science, technology, and national security.

Major accomplishments include the generation of a synthetic vector potential for cold atoms, the fabrication and metrology of novel magnetic tunnel junctions, the generation of entangled photons from distinct quantum dots, and the development of new databases for atomic spectra.

This division is one for which the salary levels are becoming uncompetitive in comparison with those at academic research universities.

ELECTRON AND OPTICAL PHYSICS DIVISION

The mission of the Electron and Optical Physics Division is to improve measurement science and to develop the measurements and standards needed by emerging science-and-technology-intensive industries. It supports emerging electronic and optical technologies, particularly precision optical measurements in the extreme ultraviolet (EUV) radiation range, using the NIST Synchrotron Ultraviolet Radiation Facility (SURF III). The programs within the Electron and Optical Physics Division are technically sound and well aligned with many other programs at NIST and beyond. This should lead to a good coordination of effort across the Physics Laboratory in crosscutting research activities.

The division's largest program is the development of measurement capabilities for EUV optics, including EUV metrology and damage issues, the maintenance of national primary standards for radiometry in the EUV and adjoining spectral regions, and the operation of national user facilities for EUV science and applications. The division's metrology program has played an important role in the calibrating of detectors on several satellites focused on monitoring solar weather. A recent result demonstrating that a popular EUV resist is twice as sensitive as previously thought is very important and underscores the value of the division's careful and precise EUV metrology efforts. The division has arrangements with several companies focused on EUV source and optics

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[1] The Joint Quantum Institute is a partnership of the University of Maryland (UM), NIST, and the Laboratory for Physical Sciences of the National Security Agency for research in the area of quantum physics. It is located on the College Park campus of UM and is staffed by researchers from both NIST and UM.

development, and its ability to test large, aspheric EUV reflection optics is unique and crucially important.

A newer research thrust area supported within the division chief's office is Coherent Matter-Wave and Quantum Information Processing Metrology focusing primarily in two areas. The first is nonlinear matter-light interactions in cold atoms, for sensors and atom interferometers; the second is a concentration in quantum communication. The group has demonstrated continuous one-time-pad encryption of a streaming video signal as well as one of the highest-speed quantum random number generation systems ever produced. Another significant achievement, which combines the division's theoretical and experimental resources, is the detection of zitterbewegung in atoms. Analogous to the predicted but unobserved effect in electrons predicted by the Dirac theory of the free electron, this is a rapid oscillation in position caused by interference between atom and antimatter atom states.

The diversity of activity in the division requires strong management and suggests development of a strategic plan to guide resource allocation and balance core activities. The EUV interferometric patterning apparatus is an important part of the EUV portfolio, and its completion should be pursued. The continued development of the SURF III EUV program will benefit from strong and focused intellectual leadership.

IONIZING RADIATION DIVISION

The goal of the Ionizing Radiation Division is to provide the foundation of ionizing radiation measurements for our nation through its mission to develop, maintain, and disseminate the national standards for ionizing radiation and radioactivity to meet national needs for health care, the environment, U.S. industry, and homeland security.

The current programs in the Ionizing Radiation Division are well recognized and are judged to be state of the art. Examples of programs that demonstrate the leadership position of the laboratory both in developing new standards and in ensuring that current and new standards intercompare favorably with those of other nations include the following: the determination of exposure and absorbed dose standards for developing medical practices involving ionizing radiation, the development of low-level radiochemistry protocols for nuclear forensics and radiochronology, the development of experiments to measure basic physical properties of the neutron, the application of neutron radiography to next-generation energy production programs, and interlaboratory comparisons of values for specific measurements which have established that the NIST values are as good as or better than those of most other national and international laboratories.

Major projects that support these programs include, in the medical area, imaging measurement standards for single-photon emission computed tomography (SPECT) and positron emission tomography/x-ray computed tomography (PET/CT), maintenance of the national mammography standard, and prostate seed brachytherapy dosimetry and calibration of miniature x-ray sources used for brachytherapy. In the radiochemistry group, a major thrust is the development, production, and dissemination of standard reference materials needed for many applications in which small quantities of radioactive materials are produced or are used as part of a measurement system. In the neutron physics area, major projects include neutron phase contrast imaging, the production of a polarized helium-3 system that provides a type of filter for the production of polarized neutrons, and the use of cold neutrons for imaging objects, such as fuel cells, in support of programs to develop alternate energy sources. All three division groups include programs of major importance to national security—these programs are the performance standards for radiation-detection devices used for the detection of nuclear explosives, and the development of national x-ray standards for security-screening systems.

The budget, facilities, equipment, and human resources available to the Ionizing Radiation Division are below those necessary to sustain the present quality of work being achieved and what is needed from this group by both internal and outside customers.

OPTICAL TECHNOLOGY DIVISION

The mission of the Optical Technology Division is to develop and provide national measurement standards and services to advance optical technologies spanning the terahertz through the infrared (IR), visible, and ultraviolet spectral regions. The division's main responsibility is to advance, maintain, and disseminate standards for the candela and kelvin base Système International (SI) units and related radiometric quantities. Its core competency in this area is evident through the execution of several high-profile projects, including the following: the Spectral Irradiance and Radiance Calibrations with Uniform Sources (SIRCUS) facility, Traveling SIRCUS, Primary Optical Watt Radiometer (POWR), and the Low-Background Infrared (LBIR) facility.

Generally, this division appears to be in good health. Energetic, highly qualified, and productive leadership is executing a diverse program of applied research and calibration services. The facilities and equipment appear to be appropriate and well maintained. The division appears to be delivering on its stated mission as witnessed by its external sponsor base, which includes other U.S. government agencies, foreign national metrology organizations, and prestigious U.S. industry and academic institutions. Additionally, its leadership and participation in international standards organizations and conferences, its capture of a relatively large number of competed NRC postdoctoral researchers, the number and quality of workshops and short courses, and the overall publication record indicate the high caliber of delivered products, services, and research accomplishments.

Although the mix between permanent staff and temporary and contract personnel appears suboptimal for long-term health and consistency in meeting strategic objectives, this issue is being addressed, and progress toward hiring additional permanent staff is being made. The existence of a vibrant and dynamic strategic planning process can be seen in the development of the division's 2010 strategic plan.

Accomplishments of this division include the continued delivery and refinement of core radiometric calibrations to external customers, including other government sponsors, as a sustainable accomplishment. The utilization of the Traveling SIRCUS calibration system to calibrate the National Polar-orbiting Operational Environmental Satellite System (NPOESS) Visible Infrared Imager Radiometer Suite (VIIRS) instrument is a recent major accomplishment. The development of the new Spectrally Tunable Lighting Facility to enable modern vision experiments using a bank of calibrated light-emitting diode (LED) sources is enabling a major advance in the understanding of lighting quality using energy-efficient LED sources.

QUANTUM PHYSICS DIVISION

The Quantum Physics Division, as an integral part of JILA[2] and of NIST, strives to be at the forefront of research and measurement science in key areas related to the division's historical strengths and developing new strategic areas: (1) cold atoms and molecules, (2) precision measurements, (3) ultrafast phenomena, (4) nanotechnology related to quantum physics, and (5) areas of biological physics that connect to the first four areas at the interface of metrology and biology. As a fully integrated part of JILA, the Quantum Physics Division operates not only to serve the NIST mission, but also to serve the broader mission of JILA. Further, because of the Quantum Physics Division connection with the University of Colorado (CU), it has an objective to help produce the next generation of scientists.

The Quantum Physics Division is a premier laboratory that can favorably compete, in most of the fields of research that it pursues, with the best academic and federal research institutions in the world.

Major accomplishments of this division include the following: (1) the world's most precise neutral atom clock, (2) the first controlled quantum demonstration of a chemical reaction, (3) the measurement of nanomechanical motion with an imprecision below the standard quantum limit, (4) the first high-resolution IR spectra of a jet-cooled phenyl radical, (5) the use of three-pulse photon echo peak shift spectroscopy as a probe of flexibility and conformational heterogeneity in protein folding, (6) optical two-dimensional Fourier transform spectroscopy to explore coherent light-matter interactions in semiconductor quantum wells, (7) Bragg spectroscopy of a strongly interacting ^{85}Rb Bose-Einstein condensate (BEC), and (8) an extension of atomic-scale tip-sample control, previously restricted to cryogenic temperatures and ultrahigh vacuum, to a wide range of perturbative operating environments.

Major projects include the following: (1) ultracold fermions and the development of ultraprecision clocks; (2) studies of dense cold polar molecules in the lowest energy state; (3) the measurement the electric dipole moment of the electron (if it exists!); (4) research on entangled atoms/spin-squeezed states; (5) the structure, interactions, and dynamics of molecules and molecular ions and quantum dots; (6) an optically stabilized atomic force microscope (AFM) as a force standard with sub-piconewton resolution; (7) high-resolution control of frequency combs to generate arbitrary optical waveforms; (8) the development of one of the world's only laboratories integrating biochemistry, cell biology, ultrafast lasers, microfluidics technologies, and optical technologies; and (9) the development of ultrasensitive force and motion detectors with precision beyond the quantum zero point of motion (of an atom in a lattice).

The accomplishments have been dramatically aided by the infrastructure of this division and by JILA scientists, and the students and postdoctoral researchers training at JILA obtain a unique educational advantage through their close interactions with expert instrument makers, electronics designers, and information technology (IT) staff. However, the state of Colorado is facing a severe budget shortfall. Likewise, the

[2] JILA is a joint research institute of the University of Colorado (CU) and NIST that is engaged in research in the areas of the physical sciences. It is supported by both CU and NIST, and its administration is overseen by a chair who is selected every 2 years, alternating between individuals from CU and NIST.

University of Colorado is facing a severe budget cut next fiscal year, after having made significant cuts in the past year. If this results in a significant reduction in CU funding to JILA, the research infrastructure (instrument shop, electronics shop, IT shop, administrative support) should be protected as much as possible, as this is a unique contributor to JILA's excellence.

TIME AND FREQUENCY DIVISION

The Time and Frequency Division is responsible for the realization and dissemination of the SI unit of time in the United States. Also, the division provides a broad range of advanced measurement services, performs research and development (R&D) for the future generations of time and frequency standards, and in addition is a key U.S. resource advancing quantum information processing.

The division represents the only organization in the world in which a complete range of time and frequency research and metrology tools can be combined for unique research and metrology. NIST provides an array of services to a very broad user community in the United States: the NIST Internet Time Service is used more than 3 billion times every day; NIST radio station WWVB is widely used to synchronize commercial timekeeping devices to NIST time; and the NIST Automated Computer Time Service helps industry meet Securities and Exchange Commission requirements to synchronize the time-stamping of hundreds of billions of dollars of electronic financial transactions to NIST time.

The Time and Frequency Division operates the world's most accurate primary frequency standard (NIST-F1), a timescale that is among the best in the world (NIST timescale), state-of-the-art femtosecond laser frequency comb systems to mediate the comparison across a factor-of-100,000 frequency range, the world's narrowest linewidth laser for precision frequency measurement, and the unique logic clock. These sorts of assets and experiments lead to unique by-products, such as improvements by a factor of 10 in setting limits on the possible time variations in fundamental constants such as the fine structure constant, and the world's most accurate tests of special and general relativity.

There has been progress in improving the existing laboratory space, an issue raised by the panel that visited the division in 2008; as a result, improved operational efficiency has been achieved. At the same time, the ratio of permanent staff to associates has been declining, and the division productivity would be improved by increasing technical support personnel. Another area of concern is the declining and inadequate funding supplied to primary standards and the NIST timescale.

1

The Charge to the Panel and the Assessment Process

At the request of the National Institute of Standards and Technology, the National Research Council has, since 1959, annually assembled panels of experts from academia, industry, medicine, and other scientific and engineering environments to assess the quality and effectiveness of the NIST measurements and standards laboratories, of which there are now nine,[3] as well as the adequacy of the laboratories' resources. In 2010, NIST requested that five of its laboratories be assessed: the Building and Fire Research Laboratory, the Manufacturing Engineering Laboratory, the Materials Science and Engineering Laboratory, the NIST Center for Neutron Research, and the Physics Laboratory. Each of these was assessed by a separate panel of experts; the findings of the respective panels are summarized in separate reports. This report summarizes the findings of the Panel on Physics.

For the FY 2010 assessment, NIST requested that the panel consider the following criteria as part of its assessment:

1. The technical merit of the current laboratory programs relative to current state-of-the-art programs worldwide;
2. The adequacy of the laboratory budget, facilities, equipment, and human resources, as they affect the quality of the laboratory's technical programs; and
3. The degree to which laboratory programs in measurement science, standards, and services achieve their stated objectives and desired impact.

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

In order to accomplish the assessment, the NRC assembled a panel of 20 volunteers, whose expertise matches that of the work performed by the Physics Laboratory staff.[4] The panel members were also assigned to six subgroups (division review teams), whose expertise matched that of the work performed in the six divisions in the Physics Laboratory: (1) Atomic Physics, (2) Electron and Optical Physics,

[3] The nine NIST laboratories are the Building and Fire Research Laboratory, the Center for Nanoscale Science and Technology, the Chemical Science and Technology Laboratory, the Electronics and Electrical Engineering Laboratory, the Information Technology Laboratory, the Manufacturing Engineering Laboratory, the Materials Science and Engineering Laboratory, the NIST Center for Neutron Research, and the Physics Laboratory.

[4] See http://www.nist.gov/physlab/ for more information on Physics Laboratory programs. Accessed May 1, 2010.

(3) Ionizing Radiation, (4) Optical Technology, (5) Quantum Physics, and (6) Time and Frequency. These division review teams individually visited Physics Laboratory facilities in Gaithersburg, Maryland, and Boulder, Colorado, for 1 day, during which time they attended presentations, tours, demonstrations, and interactive sessions with Physics Laboratory staff. Subsequently, the entire panel assembled for 2 days at the NIST facilities in Gaithersburg, Maryland (on February 25-26, 2010), during which they attended welcoming remarks from the NIST Director's representative, overview presentations on the Physics Laboratory and its divisions by Physics Laboratory managers, and an interactive session with Physics Laboratory management. The panel also met in a closed session to deliberate on its findings and to define the contents of this assessment report.

The approach of the panel to the assessment relied on the experience, technical knowledge, and expertise of its members, whose backgrounds were carefully matched to the technical areas of Physics Laboratory activities. The panel reviewed selected examples of the technological research covered by the Physics Laboratory; because of time constraints, it was not possible to review the Physics Laboratory programs and projects exhaustively. The examples reviewed by the panel were recommended by the Physics Laboratory in consultation with the NRC and the panel. The panel's goal was to identify and report salient examples of accomplishments and opportunities for further improvement with respect to the following: the technical merit of the Physics Laboratory work, its perceived relevance to NIST's own definition of its mission in support of national priorities, and specific elements of the Physics Laboratory's resource infrastructure that are intended to support the technical work. These examples are intended collectively to portray an overall impression of the laboratory, while preserving useful suggestions specific to projects and programs that the panel examined. The assessment is currently scheduled to be repeated biennially, which will allow, over time, exposure to the broad spectrum of Physics Laboratory activity. While the panel applied a largely qualitative rather than a quantitative approach to the assessment, it is possible that future assessments will be informed by further consideration of various analytical methods that can be applied.

The comments in this report are not intended to address each program within the Physics Laboratory exhaustively. Instead, this report identifies key issues. Given the necessarily nonexhaustive nature of the review process, the omission of any particular Physics Laboratory program or project should not be interpreted as a negative reflection on the omitted program or project.

2

Atomic Physics Division

MISSION

The goal of the Atomic Physics Division is to investigate and exploit quantum behavior and interactions of atomic matter and radiation. The strategy for achieving the division's mission is to develop and apply atomic-physics and condensed-matter research methods, particularly those making novel use of electromagnetic fields, to achieve fundamental advances in measurement science—including measurement at and beyond the standard quantum limit.

SCOPE

The Atomic Physics Division, located at NIST's Gaithersburg, Maryland, campus, has 3 NIST fellows, 27 scientists/engineers, 1 technician, 74 NIST associates (the associates category includes contractors, NRC postdoctoral researchers, foreign guest researchers, and guest researchers/workers from universities and industry), and 5 administrative support staff, as of January 2010. Its FY 2009 budget was about $15.4 million, 86 percent of which was scientific and technical research services (STRS) internal funding.

The scope of the Atomic Physics Division includes the following four strategic elements.

1. To advance the understanding and applications of cold atomic matter, including the study of many-body quantum systems, exotic states of matter, atomic analogs of condensed-matter systems, metrology of and with cold atoms, and quantum information;
2. To advance measurement science at the atomic and nanometer scale, focusing on precision optical metrology, quantum optics of nanoscale systems, nanoscale devices at the quantum limit, and nano-optical systems;
3. To explore fundamental aspects of the quantum nature of light and its interaction with quantum matter and to develop applications relating to metrology and other areas of NIST's mission, including measurement at and beyond the standard quantum limits; and
4. To measure, calculate, critically compile, and disseminate reference data on atomic structure and fundamental constants in support of basic research, commercial development, and national priorities.

PROJECTS

Cold Atomic Matter

The current effort in cold atomic matter focuses on the physics and applications of laser cooling and the electromagnetic trapping of neutral particles, the manipulation of ultracold atoms and Bose-Einstein condensates, and the creation of exotic states of matter through control of ultracold atoms. It includes both fundamental studies, such as the investigation of superfluidity, and applied studies, including quantum information processing and the engineering of synthetic charge along with synthetic electric and magnetic fields for neutral atoms.

The pioneering development of laser cooling and trapping techniques, much of which was done at NIST, allows exquisite control over the motion of atoms. Such control has been exploited to build more precise atomic clocks and other precision-measurement devices at NIST and elsewhere. These techniques also enable the study and manipulation of atoms and molecules under conditions in which their quantum behavior dominates. This research has revolutionized the field of matter-wave optics, given rise to the field of quantum simulation, and now allows the simulation of the behavior of charged particles using neutral atoms.

Nanoscale and Quantum Metrology

The effort in nanoscale and quantum metrology focuses on developing and exploiting precision metrology at the interface between atomic and nanoscale systems. Systems under study include quantum dots and wires, optical microcavities, the quantum optics of nanosystems, metallic nanoparticles, and those with nanoscale features induced on surfaces by highly charged ions. Such systems arise in advanced 193 nm and 157 nm lithography, plasma etching of semiconductor wafers, nanolasers, detectors, biomarkers and sensors, nanomaterials, quantum devices, and quantum information.

The research in this effort combines theory and experiment. Theory is used to extend the fundamental understanding of systems at the atomic-nanoscale interface as necessary to interpret experiments, to explore new applications in nanoscale and quantum technologies, and to motivate new and enhanced precision metrology. The researchers are developing the theoretical understanding needed to create nano-optics structures that will be needed in emerging quantum and nanoscale technologies.

Quantum Behavior of Light and Matter

The strategic element involving the quantum behavior of light and matter focuses on entangled states of light and analogous states of matter. These quantum features are studied in situations that range from the generation of quantum light in atomic vapors and condensed-matter systems, to the effect of quantum light on quantum degenerate atomic gases, to the behavior of mechanical oscillators at the quantum level.

The goals of this effort include the following: the evaluation of quantum light, atoms, and fabricated micromechanical systems for metrology beyond the standard quantum limits; the development of quantum information transfer between different physical qubit platforms according to which ones are most appropriate for a given function; and the fundamental study of quantum phenomena, such as measurement and the quantum-classical interface.

Critically Evaluated Atomic Data

The aim of the strategic element on critically evaluated atomic data is to maintain an authoritative and publicly accessible source of atomic data and related fundamental constants. Two examples of databases maintained by this group are the Fundamental Constants database and the Atomic Spectra database, but there are many other similar databases that address specific areas of high impact. Some of the data in the NIST databases are compiled from the open scientific literature. NIST adds great value through the process of critical compilation. Other data are generated by experiments at NIST, such as measurements of highly charged ions with the NIST Electron Beam Ion Trap (EBIT), the development of standard spectral sources for calibration of the next generation of space- and ground-based telescopes, and the development of new measurement platforms for improved determination of fundamental constants. Theoretical calculations also address needs for atomic data and for the improvement of fundamental constants. Theoretical work includes atomic structure calculations, studies of fundamental constants, and kinetic modeling of highly charged ions and high-energy-density plasmas.

ASSESSMENT OF THE DIVISION

As stated above, the mission of the Atomic Physics Division is to investigate and exploit the quantum behavior and interaction of atomic matter and radiation. The division succeeds in reflecting this mission. Its major projects strike a healthy balance between fundamental studies that yield new knowledge which may lead to new technologies that are important to maintaining U.S. leadership economically and scientifically, and applied studies that target high-priority needs of industry, the energy community, and the space astronomy program. The work in the division also has important positive impact on issues relevant to national security.

The major accomplishments of the division since the previous assessment, in 2008, include both institutional progress and technological accomplishments. Examples of institutional progress include the following:

- The NIST Quantum Information Program, started in 2000, is a cross-laboratory effort in quantum information science. The scope of this program was further expanded in 2006 with the establishment of the Joint Quantum Institute, a partnership of NIST with the University of Maryland and the Laboratory for Physical Sciences of the National Security Agency to study coherent quantum phenomena and quantum information science. The JQI has had and will continue to have a profound and lasting positive effect on the research efforts of the division.
- NIST is taking a leadership role in the U.S. government in delineating the opportunities for quantum information science and technology to address

national priorities. This effort includes ultrasecure encryption, code breaking, database searching, weather forecasting, drug design, and the solution of many other challenging scientific and technological problems. The chief of the Atomic Physics Division also serves as the co-director of the JQI and as coordinator of the NIST Quantum Information Science Program, and currently also leads a federal initiative in quantum information science in the Office of Science and Technology Policy.

- The Atomic Spectroscopy Group, which received funds to enhance the Atomic Data Center, has received an increase in its level of base funding.

The technological accomplishments of the division are strongly aligned with the mission of the laboratory and are of high technical merit. Technological accomplishments in the division since the previous NRC assessment of the Physics Laboratory include the following:

- Theorists in the Atomic Physics Division provided critical theoretical support for experiments at JILA that produced for the first time a dense sample of ultracold, 330 nK $^{40}K^{87}Rb$ polar molecules in their ground state of electronic, rotational, and vibrational motion. This work, which is important because it could provide new phases of matter for quantum information and quantum control, provided an important part of a successful Multi-University Research Initiative proposal from JQI funded by the Air Force Office of Scientific Research.
- NIST scientists have developed a technique for generating entangled light by four-wave mixing in atomic vapors. It produces "twin beams" of light that are more closely correlated than for any classical sources. One particularly useful feature of this technique is that entangled light can easily be made in multiple spatial modes. That is, images with quantum correlations can be produced. Pixel by pixel, the light in these pairs of images is correlated at levels better than the shot noise for the photon numbers involved.
- NIST scientists have used an Electron Beam Ion Trap to produce and study highly charged ions of heavy elements that are relevant to the development of controlled fusion energy. Atoms of the heavy elements hafnium, tantalum, tungsten, and gold were stripped of 60 or more electrons and held in the EBIT while their radiative properties and atomic structure were studied. Experimental observations in combination with sophisticated plasma kinetic modeling uncovered combinations of soft-x-ray emission lines that are suitable for use by fusion scientists in analyzing the super-hot plasmas in fusion-energy devices.

Following is the panel's assessment of the overall quality of the Atomic Physics Division (including opportunities for improvement) in terms of the three criteria as requested by the NIST Director (see Chapter 1).

Assessment Relative to Technical Merit

Cold Atomic Matter

The area of atom cooling and trapping was pioneered at NIST, leading to a Nobel Prize in 1997. This group also pioneered the confinement of cold atoms in optical lattices formed by the interaction of atoms with a standing wave of light. The trapped atoms are being explored as a possible route to quantum computation and for the quantum simulation of problems of interest in condensed matter. This work is among the best in its field.

Nanoscale and Quantum Metrology

The efforts on quantum metrology are addressing interesting issues with the potential for transformative advances. They are well integrated with other efforts in related areas around the world.

Quantum Behavior of Light and Matter

The work on entangling photons in quantum dots is among the best in the world. It is potentially extremely important for quantum communication and information applications.

Critically Evaluated Atomic Data

The atomic data evaluated and compiled by the Atomic Spectroscopy Data Center provide a definitive and accessible source of atomic spectral data for applications in areas including astronomy and fusion research. The effort could be improved even further by integrating state-of-the-art information technology advances into the effort.

Assessment Relative to Adequacy of Resources

Staffing

The Atomic Physics Division has had one staff member depart and has made two promising hires of permanent staff over the past 2 years. One-third of the permanent scientific staff was new to the division over the course of the past decade. The total number of permanent staff has been constant in recent years even though the level of funding increased during that time; this is because of the inflation, not included in the division's base budget, that increased the cost to support each investigator. An increasingly important problem is that salaries at NIST are becoming more and more uncompetitive with those paid by major research universities, particularly for senior scientists.

The JQI has had an extremely positive impact on the number of graduate students and postdoctoral researchers contributing to the scientific efforts of the division. The JQI effort effectively leverages the expertise of the Atomic Physics Division staff, exposing young physicists to the important missions of the laboratory as aligned with national priorities and increasing the overall impact of the division.

One concern is that hiring qualified non-U.S. citizen scientists who have green cards is extremely difficult, slow, and time-consuming. To remain competitive on a global scale, it is critically important for the division to be able to hire the most highly qualified scientists.

Major Equipment, Facilities, Ancillary Support, and Resources

The status of equipment, facilities, and ancillary support and resources in the division is good overall, but some of the buildings housing experiments in the division are in need of renovation. Laboratory management is aware of infrastructure needs and is working hard to address them.

The current equipment of the division is state of the art. The older general-purpose laboratories do have problems, particularly in the areas of humidity control (which leads to serious condensation problems), temperature control, and air quality. The other facilities are excellent and are well maintained. The Advanced Measurement Laboratory building provides state-of-the-art facilities for the Cold Atomic Matter activity and for parts of the Nanoscale and Quantum Metrology activity. These activities receive significant outside funding—a recognition of the importance of the research to outside funding agencies. This laboratory is maintained and used at a high level. The Joint Quantum Institute is constructing a new building on the campus of the University of Maryland at College Park that will provide new laboratory space for this group.

Assessment Relative to Achievement of Stated Objectives and Desired Impact

The Atomic Physics Division is doing an excellent job of achieving its objectives. The high impact of its work is demonstrated on multiple fronts, including the large number of highly prestigious awards given to investigators in the division and the large number of articles published in high-impact journals.[5] In addition, the use of the Atomic Spectroscopy Data Center continues to increase, with more than 45,000 hits per month over the past year. The impact of this division is also seen in the formal training provided by division staff for the 27 postdoctoral fellows (of which 23 are associated with the JQI) and the 19 graduate students (18 are associated with the JQI). The number of

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[5] V. Boyer, M. Marino, R. Pooser, and P.D. Lett, "Entangled Images from Four-Wave Mixing," *Science* 321:544, 2008; G.K. Campbell, M.M. Boyd, J.W. Thomsen, M.J. Martin, S. Blatt, M.D. Swallows, T.L. Nicholson, T. Fortier, C.W. Oates, S.A. Diddams, N.D. Lemke, P. Naidon, P.S. Julienne, J. Ye, and A.D. Ludlow, "Probing Interactions Between Ultracold Fermions," *Science* 324:360, 2009; K.P. Helmerson, "Surviving the Transition," *Nature* 455:880, 2008; Y.J. Lin, R.L. Compton, K. Jimenez-Garcia, J.V. Porto, and I.B. Spielman, "Synthetic Magnetic Fields for Ultracold Neutral Atoms," *Nature* 462:628, 2009; A.M. Marino, R.C. Pooser, V. Boyer, and P.D. Lett, "Tunable Delay of Einstein-Podolsky-Rosen Entanglement," *Nature* 457:859, 2009; K.-K. Ni, S. Ospelkaus, M.H.G. de Miranda, A. Pe'er, B. Neyenhuis, J.J. Zirbel, S. Kotochigova, P.S. Julienne, D.S. Jin, and J. Ye, "A High Phase-Space-Density Gas of Polar Molecules in the Rovibrational Ground State," *Science* 322:231, 2008; J.V. Porto, "Improving Correlations Despite Particle Loss," *Science* 320:1300, 2008; S. Ospelkaus, K.-K. Ni, D. Wang, M.H.G. de Miranda, B. Neyenhuis, G. Quéméner, P.S. Julienne, J.L. Bohn, D.S. Jin, and J. Ye, "Quantum-State Controlled Chemical Reactions of Ultracold Potassium-Rubidium Molecules," *Science* 327:853, 2010.

postdoctoral fellows and students has increased significantly owing to the new partnership with the JQI. This training of future scientists in the mission-oriented work aligned with national priorities is a particularly valuable contribution. Every effort should be made to support the factors that encourage such training, particularly financial support for the new Joint Quantum Institute.

Cold Atomic Matter

The Cold Atomic Matter team continues to make world-leading breakthroughs. One recent example is the generation of a synthetic vector potential for cold atoms.[6] This work is important because it enables the cold atom system to be used to simulate the behavior of charged particles in the presence of a strong magnetic field, potentially enabling a new level of understanding of the properties of complex materials.

Nanoscale and Quantum Metrology

The Nanoscale and Quantum Metrology team's use of highly ionized atoms to control properties of tunnel junctions is novel. The work on the complementary metal oxide semiconductor-compatible process for silicon devices for low-noise applications is potentially extremely important.

Quantum Behavior of Light and Matter

The team working on Quantum Behavior of Light and Matter has made important breakthroughs. These include the demonstration of entanglement between photons from different sources and entanglement of nanomechanical and optical degrees of freedom.

Critically Evaluated Atomic Data

The NIST work in the area of Critically Evaluated Atomic Data sets the standard for the world. The critically evaluated data from the scientific literature and targeted original investigations that are combined and made available to the public provide a definitive standard in this area.

CONCLUSIONS AND RECOMMENDATIONS

The technical merit of all of the groups in the Atomic Physics Division continues at a very high level, driving the current state of the art in the relevant research areas. The Joint Quantum Institute is a major success and a powerful addition to the research enterprise at NIST. The remarkable advances in quantum information, quantum measurement, and quantum control are potentially revolutionary for science, technology,

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[6] Y.J. Lin, R.L. Compton, K. Jimenez-Garcia, J.V. Porto, and I.B. Spielman, "Synthetic Magnetic Fields for Ultracold Neutral Atoms," *Nature* 462:628, 2009.

and national security. One concern is that hiring qualified non-U.S. citizen scientists who have green cards is extremely difficult, slow, and time-consuming.

3

Electron and Optical Physics Division

MISSION

The goal of the Electron and Optical Physics Division is to support emerging electronic, optical, and nanoscale technologies, particularly precision optical measurements in the EUV radiation range using the NIST Synchrotron Ultraviolet Radiation Facility (SURF III). A number of very interesting supplementary research efforts are also pursued, as described below.

SCOPE

The Electron and Optical Physics Division, located at NIST's Gaithersburg, Maryland, campus, has 1 Senior Executive Service (SES) staff member, 12 scientists/engineers, 1 technician, 43 NIST associates, and 1 administrative support staff, as of January 2010. Its FY 2009 budget was about $4.9 million, 81 percent of which was STRS funding.

There are several primary research focuses within the scope and mission of the Electron and Optical Physics Division. The largest program is that on the development of measurement capabilities for EUV optics, including both EUV metrology and damage issues; the maintenance of national primary standards for radiometry in the EUV and adjoining spectral regions; and the operation of national user facilities for EUV science and applications. A second focus area provides measurements and data to enable the development of atom and photon technology in sensors, atom interferometers, and quantum information-processing devices.

PROJECTS

The division has invested in upgrades of the SURF III facility that have made it an ideal source of extended ultraviolet radiation, and this facility now forms an important resource for several different activities. SURF III supports long-standing efforts in vacuum ultraviolet (VUV) and EUV detector calibration, which are an important part of the division's core mission. Strong collaborations with the National Aeronautics and Space Administration (NASA) over several decades, and more recently with the National Oceanic and Atmospheric Administration (NOAA), have been essential to many different satellite missions. The implementation of a cryogenic radiometry capability has improved the accuracy of these calibrations by nearly an order of magnitude. Future improvements that will extend this methodology to shorter wavelengths will be very valuable.

EUV detector, source, and optical metrology activities have grown in recent years in support of the nation's EUV photolithography technology. There are collaborations with several industrial partners that involve a unique capability to characterize large-area, large-numerical-aperture (NA), aspherical, multilayer-coated EUV reflection optics that are crucially important to the EUV program. This work cannot at present be done elsewhere in the United States; it is made possible by recent upgrades to the SURF III facility and experimental capabilities.

A key barrier to the broad implementation of EUV lithography technology involves the development of new EUV photoresists, the generally polymeric materials into which a pattern is written when one is making small electronic devices. Successful implementation of EUV lithography is currently of dominant importance to the semiconductor industry. As yet, no photoresist offers the required combination of radiation sensitivity, spatial resolution, and low line-edge roughness. The division is actively pursuing some of these issues as well. A recent result demonstrating that a popular EUV photoresist is twice as sensitive as previously thought is very important and demonstrates the value of the division's careful and precise EUV metrology efforts. The division has also established a collaborative program designed to further the understanding of resist photochemistry at the level of fundamental polymer chemistry. This is an important effort that will have a long-term impact on efforts to optimize resist performance. At present, the division does not have any EUV patterning capability. A grating-based EUV interferometer that can employ sources of limited spatial coherence to pattern lines with widths on the order of 10 nm has been designed and partly constructed. This instrument will be an important complement to existing capabilities, as it can be used to test the lithographic performance of existing and candidate photoresists. Completion of this apparatus should be pursued aggressively, along with synergistic collaborations with photoresist vendors and the Polymers Division in the Materials Science and Engineering Laboratory at NIST.

The recent implementation of autonomous operation of the SURF III accelerator with about 0.3 A of circulating current, also a unique capability, has significantly expanded the capacity of the facility. This capacity represents an underutilized resource, and the division should consider research areas that might be developed in which it could have a major long-term impact.

EUV surface photochemistry cuts across many different disciplines and laboratories, including plasma physics, space physics, optics, materials science, and several areas of chemistry. The SURF III-based EUV program is a common ingredient in all of these disciplines, and it increasingly acts as a focal point for EUV activities inside and outside NIST. The division should continue the active pursuit of more collaborations and connections to the growing industrial base focused on EUV lithography. There is a need for the development of a clear plan for central oversight of the entire NIST EUV program.

In an additional VUV-based project, the division has participated in developing a new kind of neutron detector based on the production of vacuum ultraviolet radiation following the $n + {}^{3}\text{He} \rightarrow {}^{1}\text{H} + {}^{3}\text{H}$ nuclear reaction. By producing multiple photons per neutron that can be detected with a low-noise phototube, very high detection efficiency is possible. While originally thought to be hydrogen Lyman-alpha photons, more recent work suggests that the VUV light is related to noble gas excimers, which will significantly limit the bandwidth of the detector because of their long decay time and will limit the range of linearity with neutron intensity. This development should be pursued further to evaluate the advantages and disadvantages relative to existing neutron detectors.

One of the newer research thrust areas supported within the Office of the Division Chief is Coherent Matter-Wave and Quantum Information Processing Metrology, which has focuses primarily in two areas. This first is nonlinear matter-light interactions in cold atoms, for sensors and atom interferometers; the second is a concentration on quantum communication.

In the nonlinear cold atoms area, there are efforts in both theory and experiment. The theoretical program is well integrated with JQI activities supported by the Atomic Physics Division in the area of modeling magneto-optical atom traps and lattices loaded to an atomic density high enough that quantum effects are of primary importance.

The experimental group in this research thrust area has developed a unique magneto-optic trap capable of creating high column densities of ultracold atoms. This trap can be used as a testbed for studying new quantum optical effects that will lead to new applications in quantum technologies. For example, the group is working on information storage and retrieval, and on fast gates utilizing this system and building on the insights that have come from quantum optical investigations of slow light in this system. Another fundamental investigation that combines both theoretical and experimental resources in the division is the detection of zitterbewegung in atoms. Analogous to the predicted but unobserved effect in electrons predicted by the Dirac theory of the free electron, this is a rapid oscillation in position caused by interference between atom and antimatter atom states.

This experimental effort, though small, can take advantage of the large community at NIST of atomic physicists interested both in the fundamental aspects of ultracold atoms and in applications, particularly in quantum information. It is important that those connections be made as strong as possible in order to optimize the impact of this work.

There is another small group within this thrust area, studying quantum key distribution (QKD) at high rates. This is a collaboration with several groups both within and outside NIST. The researchers are aiming at the development of transmission through the atmosphere of a polarization-encoded QKD system with a clock rate of over 1 GHz. Efforts have focused on optimizing the speed of avalanche photodiode detectors without sacrificing the quantum efficiency. This project involves a sophisticated integration of the optical and electronic system and custom high-speed electronics that adapt telecommunications clock-recovery techniques.

This group has demonstrated continuous one-time-pad encryption of a streaming video signal, as well as one of the highest-speed quantum random number generation systems ever produced. It has taken successful live demonstrations to the highly visible DEFCON conference (the world's largest hacker convention) for the past 2 years.

The plans of this group are growing in response to increased interest to overcome a technical roadblock in the deployment of quantum information and communication systems. The division is pursuing several of these:

- A key future advance in this technology will come from moving to the Balmer-alpha wavelength of 656 nm, where light from the Sun is attenuated by 7 dB in a narrow interval, greatly improving the fidelity of daylight operation of free-space QKD systems.

- This group is also developing a fiber-laser-based source of correlated photon pairs, in collaboration with the JQI and the University of Illinois.
- The data rates are sufficiently high that pixel-by-pixel entanglement of video images is possible, and the group is working to demonstrate this new video quantum image as a new milestone in quantum information.

These efforts in quantum optics and quantum information within the Electron and Optical Physics Division are technically sound and well aligned with many other programs in the Physics Laboratory. They provide a strong conduit for communication among scientists in different divisions. This asset should lead to good coordination of effort across the Physics Laboratory in the crosscutting research activities.

STAFFING

The division currently supports 14 full-time-equivalent scientific staff, about half of whom are involved with SURF III operations and EUV technology development. This appears to fit the current diverse research scope reasonably well, although the ratio of research thrusts to scientific staff is low, and this suggests the need for some thought and organizational planning.

The emergence of the SURF III facility as an important resource for EUV technologies suggests the need for a reexamination of the current management structure. The present arrangement, with the division director assuming primary responsibility for SURF/EUV operation, is not optimal. The overall program will benefit from strong and focused intellectual leadership and robust outreach to other NIST divisions and the broader EUV community in the United States.

MAJOR EQUIPMENT, FACILITIES, ANCILLARY SUPPORT, AND RESOURCES

The Electron and Optical Physics Division supports a state-of-the-art quantum telecommunications laboratory, as discussed above. The speed records of the system here are impressive; the division's current move to develop sources of entangled and correlated photons for future studies is appropriate. Ongoing and/or planned connection of this effort to such source development elsewhere at NIST (e.g., the Optical Technology Division) is encouraged.

The division operates the SURF III facility and supports a variety of beam lines devoted to detector and instrument calibration as well as EUV optics testing, as discussed above. Several of these beam lines provide unique and important capabilities. Twenty years ago, this facility was used extensively for VUV spectroscopy. In the early 1990s, however, many of those programs migrated to newer facilities around the country, leaving SURF III with a mission focused primarily on the core activity of detector and instrument calibration. The emergent role of EUV radiation in next-generation lithography has offered the facility a new mission of national prominence. This area should continue to be a major focus of this division.

ASSESSMENT OF THE DIVISION

Following is the summary of the panel's assessment of the overall quality of the Electron and Optical Physics Division (including opportunities for improvement) in terms of the three criteria as requested by the NIST Director (see Chapter 1).

Assessment Relative to Technical Merit

The unique and state-of-the-art capabilities of the division include the following:

- The precision reflectometry of large-area and large-NA multilayer-coated EUV optics for at-wavelength testing and characterization;
- The provision of transfer standard EUV photodiodes and the development of cryogenic radiometric capability, which improved calibration accuracy by an order of magnitude;
- The primary national standard for source-based optical radiometry in the EUV regime;
- On-site calibration capabilities for satellite EUV detectors;
- The integration of EUV optical measurements with surface analytical photochemistry capabilities;
- The high-rate testbed for secure quantum encryption key distribution in free space; and
- The highest-column-density 60 mm-long magneto-optical trap for quantum optics and quantum information applications.

Assessment Relative to Adequacy of Resources

The SURF III upgrades have been very successful and useful, and the development of the quantum telecommunications laboratory has been very productive. The building that houses most division activities, including SURF III, is old and lacks optimal environmental controls. Although this is probably not a large impediment to most existing programs, it clearly affects program efficiency and, to a lesser extent, the morale of personnel. The implementation of the EUV interferometric lithography capability, as strongly recommended above, may be limited by environmental constraints.

The primary reason that the EUV interferometric patterning apparatus has not been completed is budgetary limitations and the consequent lack of staffing. This is an important part of the EUV portfolio and should be pursued.

Continued development of the SURF III EUV program will benefit from a group leader who will provide strong and focused intellectual leadership.

Assessment Relative to Achievement of Stated Objectives and Desired Impact

The Electron and Optical Physics Division supports an active and very useful service activity, combined with several application-driven research programs that will prove useful in facilitating future developments. The service activities amount to about

30 percent of the aggregate effort. Each year, about 20 external users use SURF III, mostly for instrument calibration; about 30 photodiode and 5 deuterium gas (D_2) lamp calibrations are performed; the reflectivities of between 50 and 100 EUV optics are measured; and the radiation damage testing of EUV optics is done for about 2,000 hours per year. The last three of these activities are performed on a cost-recovery basis and are supported by vendors, mostly in the developing EUV sector. This support offers good evidence of the value of the SURF III EUV programs. The division has a robust record of publication and presentations. Several workshops in the EUV technology area have been organized.

CONCLUSIONS AND RECOMMENDATIONS

The Electron and Optical Physics Division integrates a valuable, and in several cases essential, service component with cutting-edge, application-driven R&D. The division maintains a diverse portfolio of activities, and most collaboration is with researchers from other NIST divisions or from outside NIST. There is a need for strategic planning in which the division should consider what it wants to look like in 5 and 10 years and should address the following issues:

- The improvements to SURF III operations will lead to increased EUV activity in the near term, and the division should develop strategic objectives and a leadership plan to make the best use of this resource.
- The EUV lithography effort has gone in the direction of analysis of photoresists and analysis of damage to EUV optics. Both of these are bringing with them the need for increased local expertise in EUV photochemistry. The division should consider how best to organize this activity, through either strategic hiring or collaboration with chemistry and materials groups.
- SURF capabilities are distinct from other user-facility sources in the EUV such as laser-plasma sources or VUV free-electron lasers. The division should consider how it integrates its activities with those of other sources. Current examples include support roles such as sharing calibration standards and collecting and distributing accurate data. As EUV applications expand, in both the commercial and the research sectors, new ways should be found to utilize the special value of the NIST activities. For example, a longer-term program in "EUV surface photochemistry" could be considered.
- This division could play a leading role in the deployment of quantum communications and cryptography. The division currently houses an important primary resource in experimental quantum optics at NIST, and ways should be found to develop that leadership position to integrate this activity across NIST as well as in the emerging community of users of this technology.
- The division should develop a strategic plan to help guide decisions about how to balance and strengthen the core activities properly and to decide on what is the correct balance of staffing and projects. All of the division's individual projects are functioning at a very high level, but they are quite

diverse. Synergy among projects in the division needs to be fostered. A solid strategic plan could suggest appropriate paths for organizing personnel among divisions in the Physics Laboratory so that the talented staff can work more closely with their collaborators in other divisions with a procedure that would more explicitly delineate the accomplishments of the contributing divisions and institutions.

4

Ionizing Radiation Division

MISSION

The goal of the Ionizing Radiation Division is to provide the foundation of ionizing radiation measurements for the nation through its mission to develop, maintain, and disseminate the national standards for ionizing radiation and radioactivity to meet national needs for health care, the environment, U.S. industry, and homeland security.

SCOPE

The Ionizing Radiation Division, located at NIST's Gaithersburg, Maryland, campus, has 39 scientists/engineers, 5 technicians, 125 NIST associates, and 4 administrative support staff, as of January 2010. Its FY 2009 budget was about $13.4 million, 43 percent of which was STRS funding.

The major programs in the division include the following:

- *Standards and calibrations*—The division is a recognized world leader in the area of radiation standards. The importance of this function is currently growing, with increased needs in the medical imaging, therapy, and homeland security areas.
- *Neutron physics*—The division has a unique program in basic nuclear physics that has several important experiments currently underway and a number of unique studies awaiting execution.
- *Medical imaging and therapy*—Although this activity has been a focus in the division for a number of years, through the work in mammography and brachytherapy calibrations, it has recently become a wider program with the impending installation of a PET/CT scanner.

PROJECTS

Radiation Interactions and Dosimetry Group

The mission of the Radiation Interactions and Dosimetry Group is to develop dosimetric standards for x-rays, gamma rays, and electrons based on the Système International (SI) unit, the gray, for homeland security, medical, radiation processing, and radiation protection applications. These standards are disseminated by means of calibrations and proficiency testing services provided to maintain quality assurance and traceability. The projects in the group are classified in six areas: theoretical dosimetry, quantum metrology, medical dosimetry, homeland security applications, industrial applications, and protection and accident dosimetry. Work on homeland security issues has continued since the previous panel review, in 2008. There has, however, been an increasing focus on standards, calibrations, and traceability with respect to medical imaging.

Significant progress has been made in a number of the group's measurement standards and calibration services, including the following:

- *Low-energy absolute x-ray calibration wavelength metrology*—production of data needed in a number of areas in quantum metrology;
- *Maintenance of the national mammography standard*—necessary to ensure that the radiation doses delivered in this medical imaging technique are consistent and safe;
- *The development of dosimetry systems for industrial applications*—necessary to meet the growing need for accurate dosimetry in the radiation sterilization of medical disposables and the treatment of food and other biological materials;
- *Prostate seed brachytherapy dosimetry*—necessary to ensure that the radiation doses delivered during radiation treatment for certain cancers are accurate in intensity and spatial distribution; and
- *The calibration of miniature x-ray sources used for brachytherapy*—necessary to establish a national primary air-kerma-rate standard for this developing technique for in situ irradiation of cancerous tissue in humans.

The group regularly compares its standards for radiation dose with those of other national and international standards laboratories, and in most cases they compare to within 0.5 percent with the averaged measurements of these other laboratories. This is an excellent outcome.

Two new projects of major need for the nation with respect to the safety of patients and technicians are calibration and dosimetry for part- and whole-body diagnostic studies and the calibration and ongoing monitoring of external radiation therapy (linear particle accelerators [LINACs] producing beams of x-rays, electrons, and, more recently, protons and heavier charged particles for conventional and conformal delivery systems, and cobalt-60 [Co-60] systems). This undertaking has priority for action commencing immediately. These needs have arisen in a fashion similar to the brachytherapy calibration and mammography work now successfully underway.

Budget and staffing are critical issues for this group, which is experiencing decreases in personnel and funding. Three researchers left the group in February 2010—one retired and two transferred to other groups owing to a lack of funding. This decrease in staff is occurring even as the workload for calibrations is increasing. This attrition should be reversed.

Radioactivity Group

The mission of the Radioactivity Group is to develop, maintain, and disseminate radioactivity standards, develop and apply radioactivity measurement techniques, and engage in research to meet the requirements for new standards. This mission leads to the development, maintenance, and dissemination of the national measurement standards for ionizing radiation and to engagement in research for meeting the requirements for new standards needed by industry, medicine, and government. Further, it provides standards for the radioactivity based on the SI unit, the becquerel, for homeland security, environmental, medical, and radiation protection applications.

There are a number of good, technically advanced programs in the Radioactivity Group. The following are notable examples. The Low-Level Radiochemistry Program is involved in many research projects dealing with analysis of low levels of radioactivity. These include the investigations of methods for radionuclide speciation in soil, techniques for isolation in the characterization of various radioactive particles in cells and sediments, the development of rapid radioactivity screening methods for emergency situations, including approaches to assess internal contamination by radionuclides that are difficult to measure.

Through the Medical Imaging Standards Program, NIST has taken up the national need for the calibration and standardization of nuclear medicine imaging systems by the acquisition of a PET/CT instrument that will provide the platform for the development of calibration phantoms to be used by manufacturers and clinics for instrument-performance calibrations. An international collaboration program through the International Atomic Energy Agency has been initiated so that both primary institutions and second-world countries can have materials and protocols for instrument-performance assessments and calibrations. This work is encouraged by the panel, and it is important to note that the national needs go beyond phantom creation and calibration standards for PET/CT. Indeed, the current instrumentation being commercially produced requires standardization for the safety and quality of medical diagnostics. These standardization needs include the robustness of attenuation correction, motion compensation, and scatter correction. In addition, this program should include single photon emission tomography and standard multidetector x-ray CT within its charge. SPECT instruments have additional algorithmic components, such as depth-dependent collimator response, truncation compensation, and methods of attenuation compensation. (For clarity, it is noted that NIST is not involved in the development of the instruments themselves or their applications, except to the extent of understanding their operation and applications sufficiently to establish standards.)

The investigators have carried out significant work on the development of standards for radionuclides employed in SPECT positron emission tomography and nuclides used directly for therapy. These studies have resulted in a significant number of publications in appropriate journals. A PET/CT scanner for humans has been ordered to allow the assessment both of the standards developed for PET/CT and of phantoms developed to determine the characteristics of the various PET/CT scanners being utilized. This is an important project, and the group is well qualified to carry out these studies. At present, the group involved in this work consists of three staff members; however, other individuals are being transferred to this program.

Neutron Interactions and Dosimetry Group

The mission of the Neutron Interactions and Dosimetry Group is to maintain and disseminate measurement standards for neutron dosimeters, neutron survey instruments, and neutron sources, and to improve neutron cross-section standards through both evaluation and experimental work. This effort will provide neutron standards and measurements needed for worker protection, nuclear power, homeland security, and fundamental applications and will provide the world's most accurate measurements of neutron coherent scattering lengths, important to materials science research and the modeling of the nuclear potentials.

Eight permanent scientific staff, 2 technicians, and approximately 20 visiting scientists with various residence times comprise the personnel involved in neutron innovative physics experiments and the neutron dosimetry and calibration program of NIST. The facility's major resource is a 20 MW reactor with nine beam lines available for a variety of experiments. The program plans an expansion to extended space and additional beam lines.

This program is responsible for a number of very significant accomplishments. The neutron radiography program relies on the unique characteristics of neutrons to penetrate metals and interact with light elements as well as with structural aspects of the medium (e.g., metal fine structure) so as to allow high-sensitivity detection of water, boron, lithium, and so on as well as regional defects in metals. This program has major projects of national importance. The industrial applications have recently gone beyond the fuel cell evaluation of water distribution to the study of lithium-ion batteries. Resolution is obtainable at 10 micrometers. A new development, first in the world, is neutron phase contrast imaging. The contrast mechanisms leading to good target-to-background images are based on material property changes associated with stressed metals or the carbon/hydrogen composition of biological objects. The images show unprecedented results. Other advances are the production of a polarized helium-3 system that provides a type of filter for polarized neutrons that enables physics experiments not otherwise possible. The NIST technology serves programs both at NIST and at the Oak Ridge National Laboratory. The unique aspect is the preparation of neutron polarizer cells available to a wide range of fundamental physics experimenters.

The service component of the Neutron Interactions and Dosimetry Group includes the best-in-the-world results of calibration using the unique manganese sulfate ($MnSO_4$) bath as well as the new smaller but portable $MnSO_4$ system. The assessment of their excellence is based on a comparison at an international intercomparison with 10 other facilities. The current and planned calibrations and evaluations of dosimeters using the group's californium-252 (Cf-252) neutron sources as well as its innovations in a scintillation/lithium dosimeter are significant advances that make this one of the best service centers in the world.

Some of the service projects have been canceled. For example, reactor-materials dosimetry calibrations related to commercial power plants are no longer provided by NIST, and another project was not pursued owing to a lack of personnel. The service component of the neutron group is extremely important to the nation and should be expanded as warranted either by perceived need or by customer requests.

Programs Important to National Security

Programs in all three groups in the Ionizing Radiation Division that are of major importance to national security are the performance standards for radiation-detection devices (portal screening and handheld devices) used for the detection of nuclear explosives, and the development of national x-ray standards for security-screening systems. These projects are essential activities for activities of the Department of Homeland Security's Domestic Nuclear Detection Office.

ASSESSMENT OF THE DIVISION

Following is the summary of the panel's assessment of the overall quality of the Ionizing Radiation Division (including opportunities for improvement) in terms of the three criteria as requested by the NIST Director (see Chapter 1).

Assessment Relative to Technical Merit

In general, the programs currently underway in the Ionizing Radiation Division are as good as or better than those in other national and international laboratories. Examples include the neutron radiography and basic physics programs, the development of standards and calibration techniques in which the results obtained generally agree extremely well with those of other laboratories, and calibration programs supporting advanced medical imaging techniques such as PET/CT.

Assessment Relative to Adequacy of Resources

Budget

The funding of the Ionizing Radiation Division is not adequate at this time, when the need for its services is increasing. It is the panel's understanding that, subsequent to its visit to the Ionizing Radiation Division for this assessment, two members of the Radiation Interactions and Dosimetry Group were transferred to other groups for budgetary reasons and the group leader has retired, with his responsibilities being assumed by an existing lead.

The Radiation Interactions and Dosimetry Group's losses come at a time when the needs for standards and the demand for calibrations are increasing. Moreover, the Neutron Interactions and Dosimetry Group's loss of two researchers to retirement in the past years comes at a time when new reactor beam lines are being constructed for the specific use of this group. Although attrition is to be expected, there appears to be no plan to replace the losses.

Facilities

The building in which the majority of the division is housed is old and in need of a major upgrade. With the confirmation of a new chief for the division, an aggressive strategic plan should be put in place by the chief that will ensure the continuation of the high quality of work being done by the division and increase funding for the group.

Human Resources

The Ionizing Radiation Division currently has 48 full-time staff and 125 NIST associates. The high number of associates versus full-time employees is a matter of concern; the full-time staff should be expanded in the future at the expense of associates. Clearly, there are budgetary issues associated with this recommended change.

Assessment Relative to Achievement of Stated Objectives and Desired Impact

The Ionizing Radiation Division is recognized worldwide for its expertise in the measurement of standards related to radiation.

The mission, projects, and performance of the Ionizing Radiation Division are good. The situation with respect to major equipment has improved since the previous panel review, in 2008. Since that review, some older, unreliable equipment has been decommissioned, and other equipment has been moved. These changes have freed up space for the installation of a high-power LINAC needed to do the high-dose calibrations required for industrial processes. In addition, new beam lines for neutron physics are under construction, and a PET/CT scanner has been ordered that will greatly enhance the medical imaging capability. The time required to complete some projects appears to be longer than might be desired, but much of this is due to staff and budget constraints.

Building 245, where most of the Ionizing Radiation Division is housed, is one of the oldest on the NIST campus. During the 2008 panel review, it became very clear that the condition of this building was very poor, as was noted in the panel's 2008 report. Since that time, the building has seen some improvement, but it still needs a major upgrade.

The following comments pertain to the division's responses to items raised by the panel that conducted the 2008 review:

- *Much of the division's radiation-producing equipment is obsolete or in poor condition and should be modernized or replaced.*—The division has made significant progress in this area since the 2008 review. The decommissioning of old equipment has freed up space for a new high-power LINAC and the installation of a PET/CT scanner. Further, the construction of an extension to the existing experimental hall at the NIST Center for Neutron Research's (NCNR's) neutron-producing reactor facility will allow the installation of more experiments in this facility.
- *The NCNR experimental hall is being enlarged and the Neutron Interactions Group will be acquiring new beam lines. These new facilities will require new experimental equipment and staff.*—Little progress has been made in this regard, but construction at the NCNR has been delayed, so there is no need for the equipment and staff at this time. Purchase of the equipment is budgeted for FY 2010.
- *The Neutron Interactions Group should pursue interagency agreements as a means of getting increased funding and manpower for additional neutron experiments.*—This suggestion is being vigorously pursued.
- *External Advisory Committees should be appointed to help the Radioactivity Group select and prioritize research projects.*—There appears to be some resistance to this suggestion, and there may be some legal issues related to implementing this recommendation, as there are federal regulations restricting NIST and other government entities from having outside advisory committees.

CONCLUSIONS AND RECOMMENDATIONS

Conclusions

1. The Ionizing Radiation Division may be losing its leading position in the national and international radiation measurements community as a result of an increasing workload in the standards area and a lack of funding to cover this increase, and the loss of personnel due to retirements and the transfer of personnel to other, fully funded programs.
2. Interviews with division management and employees conveyed the overall impression that more frequent and open communications with NIST administration on staffing, funding, and technical direction would be of benefit in giving direction to the division and in discovering ways to increase funding.
3. The process through which the Ionizing Radiation Division prioritizes and selects projects to pursue is of concern. For example, in the medical imaging area, input on clinical experience should be considered.
4. The physical plant occupied by most of the Ionizing Radiation Division equipment and personnel (Building 245) is still substandard, although some improvements have been made.

Recommendations

1. NIST in general and the Ionizing Radiation Division in particular need to develop a mechanism whereby the critical standards work of importance to the nation receives the necessary funding to maintain quality standards assessments.
2. The division chief and others in the division should seek advice on programs and priorities from experts in the field outside the NIST laboratory. Such advice may assist the division chief in determining which programs will allow the division to develop cutting-edge research projects to support and advance the measurements of standards in the field.
3. The Ionizing Radiation Division's nuclear measurements and research programs are of the highest quality. Funding for these efforts should be maintained or, preferably, increased. Although there is the potential for work of Nobel Prize quality, the major goal is and should be to serve the nation in measurements, standards, and safety that underpin advances in technology throughout the country.
4. A major upgrade of Building 245 must be a priority for NIST.

5

Optical Technology Division

MISSION AND STRATEGIC PLAN

The mission of the Optical Technology Division (OTD) is to develop and provide national measurement standards and services to advance optical technologies spanning the terahertz through the infrared, visible, and ultraviolet spectral regions. In particular, this division is charged with maintaining two primary standards: (1) the unit of luminous intensity, the candela; and (2) the unit of temperature, the kelvin, above 1234.96 K. The strategic elements of the OTD are (1) to maintain and advance optical radiation standards traceable to the SI system of units, (2) to advance optical radiation measurement science to solve problems in critical and emerging technology areas of national importance, and (3) to disseminate optical radiation measurement technology and standards to industry, government, and academia.

SCOPE

The Optical Technology Division, located at NIST's Gaithersburg, Maryland, campus, has 42 scientists/engineers, 81 NIST associates, and 6 administrative support staff, as of January 2010. Its FY 2009 budget was about $18.5 million, 61 percent of which was STRS funding.

The division's projects and sustained activities fall roughly into three main categories: development and refinement of optical radiation standards, optical measurement methods, and the provision of optical measurement services.

Optical Radiation Standards

The OTD provides the optical radiation measurement science and standards to aid the advancement and application of optical technology.

Unique capabilities of the division include (1) the Spectral Irradiance and Radiance Calibrations with Uniform Sources facility, coupled with cryogenic radiometry; (2) the Low-Background Infrared facility, developed to calibrate user-supplied blackbodies that are used in turn to characterize low-background IR detectors; and (3) the Spectrally Tunable Lighting Facility for studies of spectrally tunable light-emitting diode lighting.

Optical Measurement Methods

The OTD strives to improve the accuracy, quality, and utility of optical measurements in burgeoning technology areas. Its accomplishments include the following: (1) spectral and spatial stray-light correction in optical systems, (2) follow-on satellite instrument-calibration conference, (3) bacteria identification with the quantum dot method, (4) long chains of magnetic nanoparticles, and (5) an efficient, correlated two-photon source.

Optical Measurement Services

The OTD builds and maintains optical radiation measurement facilities that are among the best in the world in order to meet the continued need for standards and specialized measurements by governments and industry.

Selected accomplishments in this area include the following: (1) a hyperspectral image projector for the calibration of remote sensing instruments; (2) a goniospectrometer that tackles translucence and other color challenges; (3) perceived and measured colors of retroreflective materials in traffic signs; (4) the Missile Defense Transfer Radiometer, employing a cryogenic Fourier transform spectrometer and an absolute cryogenic radiometer; and (5) improvements to the transportable SIRCUS system (Traveling SIRCUS). SIRCUS is a reference calibration facility to calibrate detectors and radiometers for spectral irradiance responsivity and spectral radiance responsivity from the UV to the IR. Tunable lasers are coupled to integrating spheres with an exit port to produce either uniform irradiance at a reference plane or uniform radiance within the sphere exit port at high levels.

PROJECTS

The projects and sustained activities of the Optical Technology Division are listed below in the subsections on the individual groups, although there is extensive intergroup collaboration underlying much of this work.

Optical Thermometry and Spectral Methods Group

The Optical Thermometry and Spectral Methods Group maintains, improves, and disseminates the national scales for the spectroradiometric measurement of radiation sources and temperatures. Methods developed for extremely accurate determination of aperture areas are important for Earth-orbiting sensors of the solar irradiance. A new activity in optical medical imaging involves members of this group. They are also engaged in basic research aimed at applying new techniques in quantum optics to revolutionize future radiometry standards.

Optical Properties and Infrared Technology Group

The Optical Properties and Infrared Technology Group establishes and disseminates primary measurement scales for the transmittance and reflectance of materials in the IR spectral region; it studies optical properties of materials in the near-, mid-, and far-IR spectral regions; it provides blackbody calibrations, research and development of accurate, high-precision radiometric measurements in low and ambient thermal background environments; and it develops and calibrates transfer standard radiometers to be used for on-site NIST-traceable measurements of missile defense sensor test chambers. The LBIR radiometry system is used for the latter activity. It is a unique resource for calibrating sensors—a capability that must be maintained for customers of the future.

Optical Sensor Group

The Optical Sensor Group establishes the national measurement scale for the SI unit the candela; it provides measurements of the absolute spectral responsivity of optical detectors in the spectral region from 200 nm through the IR traceable to a high-accuracy absolute cryogenic radiometer. Solid-state lighting, a critical component of future energy-efficiency improvements, is an important thrust of this group. The group is developing novel test methods for high-power LEDs and developing new metrics to evaluate the color rendering of light sources in general.

Laser Applications Group

The Laser Applications Group advances laser technology for applications in optical radiation and optical properties of materials measurements. This group developed the SIRCUS facility and the Primary Optical Watt Radiometer system. The Traveling SIRCUS development is currently being used for the calibration of future space-based instruments that are designed for long-term, high-accuracy measurements of radiance and/or irradiance. It will play an increasingly important role in instrument calibration.

Biophysics Group

The Biophysics Group develops advanced spectroscopic and microscopic measurement methods, nano-optical probes, and imaging technologies and associated theoretical models to solve important biophysics and bio-nanotechnology measurement science problems. The new activity in optical medical imaging involves members of this group. Group members are also involved in spectroscopic studies in the terahertz spectral region.

STAFFING

There are 42 full-time technical staff members in the Optical Technology Division; 3 more permanent staff will be added by the end of 2010. In addition, a far greater number of temporary, contractor, and part-time personnel than of permanent staff also contribute to this division. For example, there are 81 NIST associates. In the 2008 panel report, a concern was expressed that the ratio of permanent staff to total staff was quite low. This is being addressed.

MAJOR EQUIPMENT AND FACILITIES

Major facilities of the Optical Technology Division associated with maintaining national standards include the following:

- *National Standard for Optical Power: POWR*—provides the optical power standard to 0.01 percent;
- *LBIR Facility*—maintains the NIST infrared radiometric standard for instruments that need to be calibrated in background environments that are 80 K and below;
- *SIRCUS*—a tunable laser-based facility for the absolute calibration of optical instruments, with the companion Traveling SIRCUS, used at external sites;
- *Facility for Spectral Irradiance Calibration of Sources (FASCAL 2)*—provides the NIST spectral irradiance scale, covering the 200 nm to 2500 nm wavelength range;
- *Spectral Tri-function Automated Reference Reflectometer Facility*—maintains the national scale of reflectance, including the bidirectional reflectance distribution function;
- *Telescope Calibration Facility*—for the laboratory testing and evaluation of telescopes and telescope radiometric calibration methods; and
- *Spectrally Tunable Lighting Facility*—for the study of spectral properties of LED lighting sources related to the effects of chromaticity, color rendering, and other aspects of spectra on lighting quality. Research results are coupled with LED "wall-plug efficiency" characteristics (as they evolve with continuing improvements in LED fabrication) to evaluate the overall energy efficiency of a variety of lighting sources.

These facilities are at the core of the NIST mission. Research on new methods is also being carried out, with the possibility that new approaches (e.g., single-photon source and photon-counting detection) may supplement or substitute for certain of the current facilities.

ASSESSMENT OF THE DIVISION

Following is the summary of the panel's assessment of the overall quality of the Optical Technology Division (including opportunities for improvement) in terms of the three criteria as requested by the NIST Director (see Chapter 1).

Assessment Relative to Technical Merit

The Optical Technology Division maintains a long-term core commitment to high-accuracy measurements in radiometry, photometry, and spectroradiometry. The division's continuing efforts to develop new approaches to calibration over a wide spectral range, from the far infrared through the ultraviolet, are commendable. The division has invested significant resources in these areas, and it justifiably places emphasis on maintaining the laboratory investments as well as careful measurement methodologies as tools for external customers in the private and government sectors.

The division has the institutional responsibility for maintaining two base Système International units: the unit of temperature, the kelvin, above 1234.96 K; and the unit of luminous intensity, the candela. The division also maintains the national scales for other optical radiation measurements and ensures their relationship to the SI units. These measurement responsibilities include derived photometric and radiometric units, the radiance temperature scale, spectral source and detector scales, and optical properties of materials, such as reflectance and transmittance. The division has maintained spectral irradiance standards and has validated through international comparisons that the achieved uncertainties are the lowest in the world over a wide spectral range. The POWR system has enabled the standard for optical power to be provided with an accuracy of 0.01 percent. The division has undertaken several collaborative projects for the calibration of satellite-based sensors. Its impact on space-based climate change assessments should grow in the future owing to these collaborations with NOAA and NASA.

A core activity of the Optical Technology Division is the development of technical standards for industries relying on optical technologies. The division also has research programs to develop optical and spectroscopic tools for the improved understanding of processes required to support evolving technologies in industries such as the semiconductor, solid-state lighting, biotechnology, and health science industries. The division has led efforts in the development of new American National Standards Institute (ANSI) standards of the chromaticity of solid-state lighting products.

In view of the wide range of activities in optical technology, the distinctiveness and relation to similar activities elsewhere must be examined using differing criteria. Within the area of optical standards, the activities in the Optical Technology Division are clearly distinctive in the United States. The facilities for maintaining standards that have been developed in the division do not exist elsewhere in the nation. The natural technical point of comparison for the optical standards lies in the research carried out in national laboratories in Europe. The division staff members are very well aware of comparable research and, indeed, engage in ongoing international comparisons and cross-calibration. Many of the other activities in optical technology, while not involving specific international optical standards, rely on highly refined measurement capabilities. Here the uniqueness of the activities results from the choice of the problems addressed as well as from the distinctiveness of the measurement capabilities themselves. One common standard of technical merit is the number and quality of publications in the technical literature and presentations at conferences. The division has a good record in this regard. The activities of the overall program constitute forefront research in areas that are relevant to the NIST mission.

Assessment Relative to Adequacy of Resources

Facilities

Laboratory space has been much improved over the past few years. The division appears to have adequate resources to undertake its stated mission and objectives. Several laboratories are in new locations, and in general the overall increase in floor space offers much more flexibility and a much-improved environment in which the researchers work with their equipment. In 2008 it was known that the residents of the Advanced Measurement Laboratory, in large part the new Biophysics Group, would have to move in order to create space for a new center. Laboratory moves are always disruptive to some degree. The affected personnel have made the move. There have been a few start-up transients in the new locations; however, the staff is up and running in the new locations.

Equipment

The equipment and instrumentation are of high quality, evidence of healthy spending on equipment over the past few years. The equipment budget appears to be adequate, and the staff appears to be making insightful decisions in the vendor-selection process.

Human Resources

The permanent staff is capable, experienced, and motivated. Their results attest to their commitment to high-quality research and products. The panel does not review the capabilities and productivities of the short-term staff and contractors. The percentage of the research and technical population who are permanent staff is low, much less than 50 percent. The relatively low permanent staff population appears to be partially related to the NIST overhead structure, which places the preponderant portion of the overhead on the permanent staff, with little or no overhead being attached to the other technical personnel or the office or laboratory space usage. Another factor appears to be related to the extent to which support depends on external funding sources, which can create a mood of conservatism regarding hiring.

The permanent members are the leaders of the division. There are many tasks and responsibilities of an institutional nature that they alone are capable of assuming. They also direct and mentor the other technical staff. Obviously the smaller the number of permanent staff, the greater the proportion of time required to fulfill these responsibilities. The risk is high that, in the event of the loss of one or two permanent staff, a multimonth disruption in progress would occur. It takes continuity and flexibility both to maintain a laboratory of outstanding quality and to be able to respond to new needs and new opportunities. Both capabilities are at risk with a low ratio of permanent staff to total researcher population.

This issue is being addressed, and progress is being made toward the hiring of additional permanent staff. The division management has exhibited the confidence in the future needed to commit to offering additional permanent positions to a select group of very capable people. This is the start of a trend that should continue.

Assessment Relative to Achievement of Stated Objectives and Desired Impact

The research program in the Optical Technology Division in large part reflects careful strategic planning to respond to NIST and national priorities. The existence of a vibrant and dynamic strategic planning process can be seen in the development of the division's 2010 strategic plan. Additionally, the development of the Solid State Lighting, Vision Science, and Greenhouse Gas measurement efforts demonstrate agility in addressing national priorities.

The Optical Technology Division also demonstrates a commitment to developing technology that could be foundational in future standards, as evidenced by its continued investment in its quantum measurement program and related activities. Although these single-photon-based technologies may not be integrated into the larger standards effort for some time, the compact prototype units being developed by the Optical Thermometry and Spectral Methods Group could be deployed in the near future to help streamline calibration activities for research groups relying on single-photon-counting detection.

Whereas several years ago there was no OTD work related to biological sciences, staff and projects are now in place (with extensive external collaborations) to address this strategic thrust. Also, in a related vein, the frontier of optical spectroscopy of nano- and molecular-scale objects has been impressively extended.

The Optical Technology Division makes use of a variety of effective means for delivering the technical output of the division. For long-term research, the means are primarily the traditional methods of publication in the technical literature and presentations at conferences. For standards work, the division's output takes the form of providing calibrations of customer sources and detectors and making available transfer standards.

Several additional forms of disseminating the technical capabilities of the division have also been implemented. Notable among these are the organizing and/or hosting of specialized courses, tutorials, and workshops and the dissemination of specialized software. The latter has been implemented very effectively with respect to the analysis of optical scattering data. This flexible analysis program, developed in the division, has been very popular, with more than 1,000 downloads. The division evidently places a healthy emphasis on publicizing and disseminating much of its technical output.

The OTD has an excellent balance, meeting immediate needs while developing new long-term programs. This approach will keep the division at the technical forefront and ensure significant long-term impact. The standards work has an impact through a widespread chain of technology, since calibration is essential for a wide spectrum of applications. Similarly, fundamental advances in the optical characterization of materials have broad impact beyond the immediate field of optical science.

NIST has identified biosciences as a strategic area of emphasis. Activities of the Biophysics Group in this division are distributed among diverse optical technologies in applications related to biology. This diversity is elaborated in the expanded group descriptor of "Biophysics, Nanobiotechnology, and Biophotonics." Altogether, this is a nascent effort, still in early stages of development. It is a vigorous enterprise as is evident from its appeal to postdoctoral fellows (five NRC fellows and three National Institutes of Health [NIH] fellows currently) as well as graduate students (two currently). Although currently a small number, the research personnel are a very capable group and obviously enthusiastic about their research. The biosciences thrust in the OTD relies heavily on multidisciplinary and interdisciplinary research. Collaborations are in place with NIH and university groups. A more formalized association with biologists is recognized as beneficial, but efforts to effect such an association with the Center for Advanced Research in Biotechnology (CARB) are currently on hold, as CARB's own association with the University of Maryland is undergoing reorganization.

One particularly promising new project within the biophysics focus is a NIST Director's Innovations in Measurement Science program in optical medical imaging. A team of division scientists is working to achieve an enhanced surgical lighting environment for obtaining images with optimal human-vision contrast. Well-calibrated hyperspectral images of normal and diseased tissues are being acquired through collaborations with partners at various universities, and algorithms are being developed for quantifying disease and tissue states.

Another effort applies biophotonic-based measurement science to support research into biomolecular structure, function, and interactions in cells and tissues. Recent accomplishments include a NIST Integrated Colony Enumerator, which may be a useful tool, and developments in the molecular imaging of cells based on fluorescent nanocrystal (nanodot) probes, which have been tested in malaria-infected red blood cells.

Another division effort with biological implication concerns the physicochemical characterization of engineered nanoparticles. Raman spectroscopy and other measurements are being used to characterize carbon nanotubes and other nanoparticles with an aim to establishing improved standards. Such data are key to the assessment of the environmental, health, and safety impact of nanomaterials. Another component of the group is concerned with the molecular modeling of nanoscopic properties. Quantum mechanics and molecular dynamics simulations are used in coordination with experimental observations to establish force standards. Demonstrations include work on single-molecule extensions of deoxyribonucleic acid (DNA) in comparison with observations by atomic force microscopy.

Finally, the terahertz metrology project is studying applications to protein misfolding. These studies are complicated by spectroscopic challenges from water, which is typically essential for biological systems.

Additional Considerations

The projects and sustained activities in the Optical Technology Division are well publicized and articulated in terms of the participation of the personnel—for example, in technical conferences, workshops, and short courses—and in terms of publications.

In general, the division leadership was responsive to the findings expressed in the 2008 NRC panel report. Some particulars are discussed in the following paragraphs.

It was stated in the 2008 NRC panel report that although the Biophysics Group seemingly fits into the Optical Technology Division, several other division chiefs included the activities of this group in their presentations of division activities. This brought up questions about the present and future "ownership" of this promising group. The 2008 panel suggested that it would be helpful to address this issue and to articulate the understanding of the extent of the "sharing" of the objectives and products of the biophysics thrust among the various divisions. A concern was the perception of a lack of coordination of efforts in this research area. It suggested that it would be helpful for the Physics Laboratory to elucidate a comprehensive plan for organizing and staffing its expanded role in the biophysics area to optimize its effectiveness.

The Optical Technology Division has been responsive to this issue. It has provided more clarity about the application in this division of its expertise in spectroscopy, imaging, and remote sensing to biophysics investigations. It was clear that personnel in the Biophysics Group are in touch with ongoing biophysics investigations in the Quantum Physics Division (e.g., in developing biological force standards capabilities). This appears to be healthy collaboration, with promising results.

The Optical Technology Division has outstanding measurement capabilities in the terahertz spectral region, originally based on traditional Fourier transform techniques, more recently developing forefront capabilities for measurements using laser sources, including both frequency-domain and time-domain approaches. The suite of measurement capabilities is outstanding. A significant investment has been made in the terahertz laser source technology resident in this division, and it is attracting a number of outstanding postdoctoral fellows.

It was stated in the 2008 NRC panel report that the terahertz research appeared to be at a crossroads. It was obvious (and still is) that the senior researchers in this area are very capable and are internationally recognized for their research in spectroscopy. The 2008 panel had questions about the future applications and future customers of this capability in this division.

The principals on the permanent staff are associated with the new Biophysics Group and have been investigating potentially relevant applications of terahertz spectroscopy. They have been addressing the obvious problem associated with application of terahertz tools to biological research, namely, the very strong water absorption throughout the terahertz region of the spectrum. The terahertz spectroscopic study of the amino acid L-proline molecule within a reverse micelle is an interesting way of mitigating the water absorption problem. The observed terahertz resonances will be used to refine a structural model of this protein building block in an aqueous environment.

Terahertz spectroscopy is also being applied to other investigations not related to biophysics. This appears to be of the nature of curiosity-driven research. One application area, related to submillimeter-wave and terahertz observations of Earth's atmosphere from space, may become an area of emphasis as observations in this spectral region become increasingly important in climate change studies.

The expansion of the Traveling SIRCUS capability is an ongoing activity. The OTD is pursuing this expansion by using American Recovery and Reinvestment Act of 2009 (ARRA; Public Law 111-5) funding to commercially acquire advanced laser systems and other associated equipment. Once the equipment is delivered, the system will be configured. The new system will permit the deployment of the Traveling SIRCUS to two additional facilities simultaneously.

CONCLUSIONS AND RECOMMENDATIONS

Conclusions

The Optical Technology Division is successfully maintaining its long-term core commitment to high-accuracy measurements in radiometry, photometry, and spectroradiometry. This capability is central to the NIST mission. Core facilities continue to be operational, and new methods and techniques are continuing to be developed. The OTD has engaged in strategic planning that involves new areas of emphasis. The staff are capable and motivated; however, the mix between permanent staff and temporary and contract personnel appears suboptimal for long-term health and consistency in meeting strategic objectives.

The calibration and sensor facilities have only two or three peers worldwide and clearly no domestic equivalents. One notable example of the use of this capability as an important element of the climate change initiative is highlighted. SIRCUS—Spectral Irradiance and Radiance Calibrations with Uniform Sources—is designed to provide a means of absolute calibration of optical instrumentation. The combination of coupling the light from stabilized tunable lasers with integrating spheres has led to a revolutionary facility for irradiance and radiance calibration. The Primary Optical Watt Radiometer system is an element of SIRCUS. The Traveling SIRCUS version can support a wide range of activities, including system calibration for satellite sensors, including calibration of total solar irradiance sensors. The staff reported that the Traveling SIRCUS and several members of staff were involved in the calibration of the NPOESS Visible Infrared Imager Radiometer Suite instrument, a very important sensor that has the potential to provide valuable data for the study of climate change, if properly calibrated.

The advanced research effort in the area of Quantum Information Science is also of high quality, comparable to major academic programs throughout the country. The research into the radiometric applications of correlated photon states is unique.

Concerns remain regarding the relatively small number of permanent staff—that is, those who must be counted on to continually lead the effort to achieve the core mission and realize the strategic plan of the division. The staffing issue is being addressed, and a trend in the right direction has begun.

Recommendations

A specific recommendation relates to the Greenhouse Gas Measurements thrust, a recent OTD initiative with the aim of quantifying greenhouse gas emissions from distributed-area sources. The instrumentation in this laboratory is in the early stages of development. At present the laboratory is developing direct absorption methods using differential absorption lidar. Although this laboratory has potential, considerable effort will be required to accomplish its objectives. Additional funding will be required to upgrade the instrumentation currently available in the laboratory. Care must also be taken in the efforts to measure quantities such as greenhouse gas fluxes using a limited number of ground-based sensors. The researchers should also take care in designing the proposed differential absorption lidar testing facilities to make certain that the test range will provide the necessary absorption paths to meet the needs for the required validation.

6

Quantum Physics Division

MISSION

The goal of the Quantum Physics Division is to make transformational advances at the frontiers of science, in partnership with the University of Colorado at JILA. (JILA is a joint research institute of CU and NIST that is engaged in research in the areas of the physical sciences. It is supported by both CU and NIST, and its administration is overseen by a chair who is selected every 2 years, alternating between individuals from CU and NIST.) The Quantum Physics Division's mission includes helping to produce the next generation of scientists and to investigate new ways of precisely directing and controlling light, atoms, and molecules; measuring electronic, chemical, and biological processes at the nanoscale; and manipulating ultrashort light pulses.

SCOPE

The Quantum Physics Division, located at JILA on the campus of the University of Colorado in Boulder, has 4 NIST fellows, 13 scientists/engineers, and 3 administrative support staff, as of January 2010. Its FY 2009 budget was about $10.0 million, 77 percent of which was STRS funding.

The strategic elements of the Quantum Physics Division are as follows:

- To develop measurement science tools and their applications to technology;
- To exploit Bose-Einstein condensation, quantum degenerate Fermi gases, and cold molecules for metrology and ultralow-temperature physics;
- To advance ultrafast science and apply it to physics and biophysics;
- To apply cutting-edge measurement science to biological systems;
- To apply laser spectroscopy to important problems in chemical physics and biophysics; and
- To educate a supply of top-quality scientists for NIST and elsewhere.

PROJECTS

Essentially all of the research projects pursued by the Quantum Physics Division are very well conceived and conducted, and proven to be relevant to and enhancing of the stated mission of the Physics Laboratory and NIST. The atomic and molecular physics at JILA has received top rating by *U.S. News and World Report*. Projects are described in detail in the section "Major Projects," below.

STAFFING

The division and JILA expect that the current number of 29 JILA fellows will remain approximately constant. But many of the current fellows are in the early stages of their careers, and both their expressed plans and historical trends indicate that their group sizes are likely to grow significantly, as allowed by the new space added by the new building.

JILA and the Quantum Physics Division have an excellent shop infrastructure, including the following:

- An advanced instrument shop with seven highly experienced and capable instrument makers. The JILA instrument shop participates directly and substantially in designing complex instruments, based on general ideas and needs expressed by the researchers.
- An advanced electronics shop, with five experienced and talented staff. As with the instrument shop, electronics shop staff design complex systems based on general descriptions of need from the researchers.
- An experienced and capable information technology staff providing direct support to complex computing needs (clusters, etc.) and interfacing equipment with computers.
- A highly qualified administrative staff helping to manage the complex activities of JILA, including crucial grant application processes.

The success of division and JILA scientists is dramatically aided by this infrastructure, and the students and postdoctoral researchers training at JILA obtain a unique educational advantage through their close interactions with expert instrument makers, electronics designers, and IT staff. This substantial infrastructure is supported by all JILA researchers—in the division and at CU—and any loss of the infrastructure would be highly detrimental to the division.

However, the state of Colorado is facing a severe budget shortfall, as is the case for most states, and state funding for the university is gravely threatened. The University of Colorado is facing a severe budget cut in FY 2011, after making significant cuts in FY 2009. If this results in a significant reduction in CU funding to JILA, the research infrastructure (instrument shop, electronics shop, IT shop, administrative support) should be protected as much as possible, as this infrastructure is a unique contributor to JILA's excellence.

MAJOR EQUIPMENT

In addition to the shop infrastructure and staff component discussed in the section "Staffing," above, new, significant equipment purchases are also important to the division's ongoing and future work. American Recovery and Reinvestment Act funds are being used to purchase a new state-of-the-art femtosecond laser system; a new state-of-the-art atomic force microscope; and a new state-of-the-art scanning electron microscope (SEM) with a resolution of 1.0 nm, imaging voltages from 200 V to 30,000 V, a precision stage with five-axis motion control, and capability for electron beam lithography (EBL).

The new SEM/EBL will not only substantially improve imaging capabilities for nanotechnology applications, but will also provide new precision fabrication capabilities to extend nanotechnology research and measurements further.

FACILITIES

It is clear that inadequate facilities have severely hampered the progress on and efficiency of research in the Quantum Physics Division in two major areas: (1) Poor control of air temperature, air cleanliness, vibration, and other environmental conditions in the outdated laboratories has seriously compromised precision measurements. (2) Insufficient laboratory and office space prevents the expansion of research activities.

The staff provided suggestions of factors that hinder research:

- "We've come to a point where we could progress faster if we had a laminar flow of dust-free air over our optical tables. We're holding off on installing this technology pending resolution of uncertainties about the new building."
- "Temperature control has been an issue."
- "Space is limited."
- "Our state-of-the-art AFM is housed in an unrenovated basement dating back to 1962 with all the expected problems with temperature stability and noisy ventilation."

These are indeed serious issues. The planned JILA expansion should help solve the problem with lack of space overall, and should resolve the environmental problems for those fortunate enough to move into the new laboratories. However, the new building creates two pressing needs for funding, namely:

- Costs of moving complex laboratories into the newly constructed space, and
- Renovations of the existing laboratories to bring them up to current standards—especially urgent because it is easier to renovate the laboratories vacated by the move before staff moves back in.

NIST and the University of Colorado should be working together to identify sufficient funding for both the relocation and the start of renovations of vacated laboratories in FY 2012.

ANCILLARY SUPPORT AND RESOURCES

There is always the problem in a very successful program such as the Quantum Physics Division and JILA that the fellows become ingrained. In the past, JILA had a vigorous Visiting Fellows Program funded by the division that brought top scientists from around the world to work at JILA for periods of a few months to a year. This program was highly effective in the past for both JILA and the visitors. An active JILA Visiting Fellows Program provides the opportunity to spread knowledge, insights, technology, and NIST culture more widely and to bring new knowledge, insights, and technology into NIST. Over the past decade or so, the number and quality of interested visitors have significantly declined, and the value of the Visiting Fellows Program has likewise declined. Staff offered the following comment regarding this decline in the fellows program:

- "If I were to put in a personal word, I would say that the JILA Visiting Fellows Program has been substantially reduced over the past 10 years, due to understandable budgetary pressures. However, this is a program which has traditionally gotten absolutely top scientists (say, in chemical physics) to come on sabbatical and work with us in our labs—this has a superbly nonlinear impact on how quickly science proceeds and evolves into exciting new areas at JILA and should be supported as best as one can."

That comment suggests that this aspect of the success of the Quantum Physics Division is being neglected.

MAJOR PROJECTS

Ultracold Atoms and Molecules

In the area of ultracold atoms and molecules, a dramatic experiment has converted highly interacting pair states of colliding cold atoms into polar molecules in their lowest bound state by removing the appropriate energy with an optical Raman process. This opened up the field of ultracold single state-to-state chemical reactions. Reaction rates have been dramatically changed by polarizing the molecules with electric fields, changing the internal hyperfine state, and raising the temperature.

Work continues on a difficult, high-payoff experiment to measure the dipole moment of the electron in a trapped polar molecule. This experiment has the possibility of contributing to fundamental extensions of the Standard Model of high-energy physics. The work has also involved the study of fundamental elementary excitations of a Bose-Einstein condensate such as vortices. Another example is the confinement of a BEC in two dimensions to access the interesting (and somewhat controversial) physics that happens in restricted geometries.

Ultracold clouds of Fermi atoms are also studied. In this system correlated pairs of atoms form, and the pairs can Bose condense, similar to the formation of Cooper pairs in a superconductor. The ability to tune the pair interaction has led to a wealth of phenomena.

In one experiment, a sudden pulse of magnetic field puts pairs of atoms into a novel quantum superposition, which oscillates in time between bound and unbound states. Another study explores the variation from the BEC regime, where localized pairs could form a Bose condensate to the Bardeen-Cooper-Schrieffer (BCS) regime, where pair formation is mediated by the surrounding condensate atoms and the size of the pair could become very large.

This BEC-BCS crossover is important theoretically, and its understanding could impact the theory of high-critical-temperature (T_c) superconductivity. This work has been enabled by novel techniques developed for extracting information on the pair correlations from noise in absorption images of the cold atomic cloud.

Development of New Systems and Techniques in Frequency Measurement

The laser frequency comb has produced a revolution in optical frequency measurement and is key to the development of ultra-stable optical atomic clocks. Current work in the Quantum Physics Division applies the frequency comb technique to a new atomic clock system composed of an optical lattice of laser-cooled strontium atoms. This novel optical clock features a large number of atoms responding identically, thus providing the precision of a single atom with enhanced signal-to-noise ratio. Fractional frequency instability of 1.5×10^{-17} has already been achieved. The frequency comb is also being extended to the VUV and is approaching 50 nm.

Another experiment addresses a problem of fundamental interest and great applicability, that of measuring the center of a resonance line to better precision than is allowed by the shot noise due to having only N atoms. Modern techniques of quantum information have provided routes to this; a squeezing approach is being adopted and is close to demonstration.

Approaching Quantum Limited Nanoscale Mechanical and Electronic Measurement

In the effort of approaching quantum limited nanoscale mechanical and electronic measurement, the quantum limits to microwave measurement, amplification, and interferometry are tested in a series of elegant experiments that use novel microwave interferometers and nonlinear Josephson devices to explore the concept of microwave quantum optics. A microwave Fabry-Perot interferometer has been fabricated containing the microwave equivalent of a nonlinear Kerr medium composed of a metamaterial built from a series of 400 Josephson junctions. This device is a phase-sensitive parametric amplifier, capable of the near-noiseless amplification of one quadrature of a microwave signal. It can also be used to generate squeezed states of the microwave field, and as much as 85 percent phase-dependent noise suppression has been observed.

Using related technology, a low-noise, superconducting quantum interference device (SQUID) multiplexer has been developed for the readout of arrays of low-temperature astronomical sensors. This multiplexer has the potential to read out an array of thousands of detectors in a single channel with gigahertz bandwidth, and could have application to novel detector arrays used in nuclear and particle physics, materials science, and astronomy.

Ultrashort Femtosecond Laser Pulse Interactions with Matter

The work on ultrashort femtosecond laser pulse interactions with matter is divided into three areas: interactions between alkali atoms in the gas phase, condensed-matter systems, and spintronics dynamics.

In the gas dynamics work, the effort is primarily on the study of the collision dynamics of potassium atoms. Potassium atoms are illuminated with a sequence of two pulses. The first excites the atom to a specific state, and the second has a frequency that is absorbed only by the excited atoms and thus induces emission, as long as the excited atoms have not lost their energy by collision. The intensity variation as a function of delay provides a measure of collision dynamics.

The condensed-phase work involves cross-correlation two-dimensional near-IR spectroscopy of excitons in semiconductors using three, femtosecond, near-IR pulses to generate excitons in semiconductors such as gallium arsenide (GaAs). The correlation between absorption and emission was determined in a plot of wave patterns and frequency. This two-dimensional spectroscopy method is capable of determining correlated oscillation of two groups in a molecule or lattice. Using this rather new two-dimensional spectroscopic method, the structure of groups of large biological molecules and also the electronic properties of semiconductors may be revealed, which would be impossible when only the normal one-dimensional spectroscopic methods are used. The knowledge obtained on GaAs and other semiconductors by this method may lead to better electronic devices. This work is at the leading edge of work in the broader community.

The spintronics work involves developing the capability of maintaining electron spin direction for several nanoseconds while being transported micron distances, and is of paramount importance for high-capacity storage and other devices. A group at JILA has determined that the spin direction is more stable when confined in the defects of semiconductors and that it loses alignment fast when embedded in a perfect single-crystal environment. It was determined that the place of highest spin stability is located in a crossover "magic" point somewhere between perfect crystal and defect. This work is also leading edge.

Laser Spectroscopy Kinetics and Dynamics of Organic Molecular and Nanoparticle Systems

The area of laser spectroscopy kinetics and dynamics of organic molecular and nanoparticle systems involves ultrashort, femtosecond laser pulse interactions with matter and has a close connection with chemistry and biological physics that is described below.

The techniques determine basic chemical-reaction dynamics by means of laser spectroscopy of jet-cooled molecular ions and radicals, intermolecular energy surfaces, and low-temperature radical and ion dynamics. In addition, a considerable effort is made in the study of single-molecule kinetics and microscopy. These techniques have been used to study single quantum dot emission kinetics of cadmium sulfide and silver involved in nanoparticle lithography.

This group has been very active and is successful in the design of new equipment and devices and the improvement of standard equipment for use in specific experiments. For example, it developed, designed, and built a novel, near-field, apertureless scanning optical microscope capable of less than 10 nm resolution that finds use in many areas of physics, chemistry, and biology. Utilizing their slit jet discharge spectrometer, the researchers have studied high-resolution vibrational spectra of jet-cooled large organic radicals that were obtained for the first time.

Biological Physics

The two main biological physics groups have quite different areas of expertise and interact with different groups within JILA and at the University of Colorado. Both groups study single molecules, but the second group uses fluorescence energy transfer techniques whereas the leader of the first group is a world expert in the use of optical tweezers and lately of atomic force microscopes in the incredibly precise measurements of subnanometer motions of biological molecules. This researcher's recent work on the molecular motor RecBCD (a protein consisting of three polypeptides RecB, RecC, and RecD) is an example of how much is yet to be learned about how nanomotors move along biological polymers. The questions of the step sizes of these motors, the role of thermal noise, and the basic physics of very small displacement measurements all come into play here.

The first main group in biological physics is working to improve the resolution of optical tweezers by increasing sensitivity while reducing system noise, which is clearly connected to the JILA tradition of precision measurements. This group has explored the use of a more stable optical design (with improved laser-pointing stability and reduced microscope-stage drift), active sample stabilization, and the introduction of a grid of nanofabricated fiducial marks.

One researcher with this first group has made significant progress in the past 2 years. His microfluidic work, aimed at increasing the ability to screen fluorescent proteins, is an important and needed means for the judicious selection of the appropriate fluorescing proteins from the rather vast collection available. The work on single-molecule spectroscopy, microscopy, and dynamics is very interesting research but not unique; nonetheless, it has the potential of yielding surprising, excellent data. This researcher's ultrafast research would be enhanced by closer collaboration with one of the laser groups—but not enough to provide the system(s) and the in-depth expertise that he needs to perform the rather intricate structural and dynamics experiments on biological systems that he is pursuing.

The second group described above has built on its expertise in single-molecule optical detection to elucidate the folding conformational thermodynamics of single ribonucleic acid (RNA) molecules and single DNA molecules in electrophoresis. The group has used fluorescence energy transfer techniques at the single-molecule level to measure distances of 2 to 8 nm between specifically labeled sites on the RNA. This information is crucial to understanding RNA-based enzymes, or ribozymes. In the future, the group's techniques should make it possible to probe the folding and unfolding of biomolecules in chemically active states.

Finally, an outstanding example of the cross-fertilization of technologies developed at JILA for the core mission of the development of measurement science tools is the extension of John Hall's Nobel Prize-winning work on optical combs to another researcher's application of this technology to biomolecule detection. This research group invented cavity-enhanced direct frequency comb spectroscopy, and it has shown that it can perform ultrasensitive detection of unknown chemicals. It has recently developed a more sensitive, smaller, and less costly fiber laser for this system, which can perform ultrasensitive and fast detection of organic molecules using a simple charge-coupled-device camera, opening the door for using this technique for medical and for homeland security applications.

ASSESSMENT OF THE DIVISION

Following is the summary of the panel's assessment of the overall quality of the Quantum Physics Division (including opportunities for improvement) in terms of the three criteria as requested by the NIST Director (see Chapter 1).

Assessment Relative to Technical Merit

The Quantum Physics Division is a premier laboratory that favorably competes, in most of the fields of research that it pursues, with the best academic and federal research institutions in the world, and the graduate school of the University of Colorado was recently ranked in a national rating as number one in atomic physics. The laser frequency comb work and the cold atom and now the new cold molecule research are definitely among the best in the world. The division has attracted applicants with competing offers from top-five U.S. institutions in areas identified for expansion, such as biological physics and nanoscale physics.

Assessment Relative to Adequacy of Resources

Facilities remain a problem for the continued excellence of the division. The new building should provide the needed space to expand present crowded laboratories and make vibration-free areas and, hopefully, clean rooms available for ultrafast and other experiments. The JILA shops, by general opinion, provide service that is unmatched in pure university environments in the design and construction of various types of mechanical and electronic equipment, and it is absolutely critical that they be maintained at that high level. However, there are severe financial pressures being exerted on the division that must be addressed, as noted above.

Assessment Relative to Achievement of Stated Objectives and Desired Impact

The impact of the Quantum Physics Division is outstanding as measured against its stated goal and mission of making important advances at the frontiers of science that enable future precision measurement technology and in producing graduates that form a talented pool of scientists who are now dispersed throughout the NIST laboratories and elsewhere. These researchers are also having significant impact through applications of their technology outside NIST—for example, in sensitive, high-resolution frequency comb spectroscopy for trace detection and molecular fingerprinting and in the development of technology for multiplexed low-temperature detector arrays for astronomy.

Additional Considerations

The comments and recommendations resulting from the panel's 2008 visit to the division were very seriously considered both by the Quantum Physics Division and by NIST. In the 2008 review, the panel expressed three key concerns, which are identified below, along with the Quantum Physics Division's 2010 response.

1. *The first concern expressed by the panel in the 2008 review:* The increased emphasis on nanotechnology needs to be supported by upgrades to better instrumentation, especially an improved scanning electron microscope with a state-of-the-art field emission source. The existing SEM available to the Quantum Physics Division at JILA was evaluated not as state of the art, and it was proposed by the panel that JILA needed in-house a very high quality SEM for the imaging of the nanostructures and to do nanolithography.

   The response of the division: The American Recovery and Reinvestment Act funding for NIST equipment purchases includes funding for a new, state-of-the-art scanning electron microscope with resolution of 1.0 nm, imaging voltages from 200 V to 30,000 V, precision stage with five-axis motion control, and capability for electron beam lithography. The new SEM/EBL will not only substantially improve imaging capabilities for nanotechnology applications, but it will also provide new precision fabrication capabilities to further extend nanotechnology research and measurements. The procurement is underway at this time, and the group (Lehnert group) hopes to take delivery within several months.

   In addition to being used for the SEM/EBL, ARRA funds are also being used to purchase the following for the Quantum Physics Division:

   - A new, state-of-the-art femtosecond laser system to support research and measurements on the structure and dynamics of enzymes that could be used for the high-efficiency production of biofuels and to extract cleaner energy sources from petroleum and other fossil fuels;
   - A new, state-of-the-art femtosecond laser system to support research and measurements on the interaction of ultrafast laser pulses with solid-state systems and other matter; and
   - A new, state-of-the-art atomic force microscope for especially challenging measurements and research on biological samples in both air and fluid environments, with the best available control of positioning, temperature, and vibration isolation.

   In total, an estimated $1.7 million of new ARRA-funded research and measurement equipment is being procured to support Quantum Physics Division programs.

2. *The panel noted the following in its 2008 review:* The interaction with the astrophysics group at the University of Colorado is of some concern; it should be enhanced and the number of researchers of this group should be increased.

   The response of the division: JILA fellows, representing both the University of Colorado and NIST researchers, have recently jointly agreed on a revised JILA strategic plan. One of the key issues identified in the plan is the need to improve integration of the collaborative astrophysics research into the other JILA activities. As one approach to this integration, the strategic plan identifies a preference for hiring an experimental astrophysicist who would focus on developing innovative imaging and measurement technologies. Such a new member of the division and JILA would be well positioned to help foster collaborations among the existing astrophysics research and other traditional strengths in JILA such as experimental atomic, molecular, and optical physics and experimental chemistry.

   There was also agreement among the group that the current size of JILA is nearly optimal, given expectations for future financial resources and space, and in recognition of the challenges of maintaining a coherent organization as the organization's size increases. Thus JILA does not expect to grow appreciably in the foreseeable future. Instead, it will focus on improving the balance of various research areas through replacements as fellows retire or otherwise leave JILA.

3. *The third issue raised by the panel in its 2008 review:* Steps should be taken at JILA to ensure that space limitations do not create potentially unsafe working conditions detrimental to productivity. It was recommended that funding to build additional space be provided in a timely fashion. It was acknowledged that the Joint Quantum Institute had plans for a new building that would provide new laboratory space for the Laser Cooling and Trapping Group, and these plans should be brought to completion. The panel concluded that it was critical for the Quantum Physics Division that funding for the new JILA building be provided; the lack of space was detrimental to productivity, created potentially unsafe working conditions, and could affect the ability to attract and hire top-class scientists in the future. This was to be considered a top-priority item for this division. It was critical that funding for the new JILA building be put in place and that the plans for design and construction move forward.

   The response of the division: Construction of the JILA Expansion (also known as the JILA X-Wing) will begin in May 2010. The new building will add approximately 50,000 square feet of laboratory, office, and meeting space, expanding the total JILA space by about 50 percent. The new laboratory space will include high-performance labs with tight control of temperature, vibration, and air quality, to facilitate the most demanding research and measurements.

The total cost of the new building is currently estimated at approximately $35 million, although the actual cost will not be known until final construction bids are received in late February 2010. NIST has already contributed $22.5 million to the construction, and the University of Colorado has committed to providing the balance of the required funds.

Construction of the JILA Expansion is currently scheduled to begin May 2010, with building occupancy tentatively scheduled for January 2012.

The additional space is planned to accommodate approximately 30 JILA fellows and their research groups, based both on polling of the current JILA fellows about their plans for group size and using historical trends. There are many early-career researchers among the current 29 JILA fellows, and their research groups are expected to grow significantly. Thus the JILA Expansion is intended to support the natural growth of research groups for the current fellows, but it is not intended to support a significant increase in the number of fellows. The growth in staff will be almost entirely among students, postdoctoral researchers, visitors, and other temporary staff.

Meeting current standards of air cleanliness and temperature control and freedom from vibration in the new laboratories does nothing to improve the poor conditions in the old laboratory. Since the space vacated by groups moving to the new building is now empty, it is most economical to renovate its air system as soon as possible—certainly prior to moving new groups into that space.

CONCLUSIONS AND RECOMMENDATIONS

Conclusions

The Quantum Physics Division remains one of the premier fundamental research physics laboratories in the world, a jewel in the crown for NIST and the Physics Laboratory. Although severe economic pressures are being brought to bear on NIST, the Quantum Physics Division, and JILA, at present there has been a strong response by NIST that will strengthen and maintain the level of excellence for the near future.

The Quantum Physics Division has been growing in scope over the past few years, but this growth cannot continue forever, and there is concern that JILA cannot grow larger without sacrificing its strong sense of community. Atomic, molecular, and optical physics and biological physics should not continue to expand, but rather the Quantum Physics Division should maintain the present levels of excellence in its present fields of endeavor.

Recommendations

It is recommended that the Physics Laboratory should continue a high level of funding for the Quantum Physics Division, renovate the laboratories in the old building, increase the number of visiting fellows by shortening visits for one or two weeks, and seek both established experts and highly talented young researchers (e.g., postdoctoral researchers).

7

Time and Frequency Division

MISSION

The mission of the Time and Frequency Division is to advance measurement science and to provide time and frequency standards and measurement services to commerce, industry, and the public.

SCOPE

The Time and Frequency Division, located at NIST's Boulder, Colorado, campus, has 3 NIST fellows, 32 scientists/engineers, 4 technicians, 52 NIST associates, and 6 administrative support staff, as of January 2010. Its FY 2009 budget was about $15.6 million, 68 percent of which was STRS funding.

The programs of the Time and Frequency Division are effectively focused on achieving its stated objectives. Accordingly, the division programs focus on four principal thrusts: (1) the realization of national and international time and frequency standards (Coordinated Universal Time, UTC) with the greatest accuracy and precision; (2) the dissemination of time and frequency through a wide variety of measurement services directed to customers at all levels, from industrial and research customers with the most stringent needs to the general public; (3) research on future time and frequency standards and dissemination methods; and (4) quantum computing with trapped ions, which evolved directly from research on new atomic clocks and which has become a major NIST-wide focus area.

The division has established itself as a leader in these areas, providing a level of organizational performance (e.g., demonstrated frequency accuracy and stability, scope and quantity of time dissemination services, publication of scientific results) which exceeds that of any metrologic laboratory in the world. The division's outstanding staff members have produced the world's best time standard, the world's smallest atomic clock, and the world's most popular time dissemination system.

There has been progress in improving the existing laboratory space, and improved operational efficiency has been achieved as a result. The new building under construction will be available for occupancy in 2012 and will further improve the performance and reliability of the laboratory space. It is recommended that efforts to maintain and upgrade existing laboratory facilities continue, even after the new building is completed.

The division has an exceptionally talented group of permanent and temporary staff members to perform its primary responsibilities. This is particularly true in the areas of fundamental improvements to primary frequency standards and in the field of quantum logic. However, the ratio of permanent staff to associates has been declining, thereby producing less opportunity for a new generation of staff with long-term focus on the NIST mission. This imbalance in the ratio is influenced by the current structure of the overhead for permanent and associate staff.

Examples of the division's high-impact accomplishments include the aluminum ion "logic clock" (best in the world for precision), the femtosecond laser frequency combs enabling the world's most precise intercomparisons, with a wide range of other applications in diverse fields such as astronomy and biological/chemical detection, remote time and frequency calibrations (best-in-the-world accuracy and usability), phase-noise metrology, NIST network time services, and chip-scale atomic clocks and sensors.

An important area of concern is related to the declining and inadequate funding supplied to division core services, such as network time services, radio stations, time and frequency calibrations, and maintaining the operation of the F-1 time standard.

ASSESSMENT OF THE DIVISION

Following is the panel's assessment of the overall quality of the Time and Frequency Division (including opportunities for improvement) in terms of the three criteria as requested by the NIST Director (see Chapter 1).

Assessment Relative to Technical Merit

The technical quality of the work of this division is among the best in the world. The Time and Frequency Division is indeed an important national asset and fills a major need. The staff is first-rate, and its accomplishments, as measured by the academic standards of publications, conferences, and professional recognition, are first-rate. Some important highlights of the division's accomplishments include the following:

- *Realization of the SI Second:*
  —Primary frequency standards: best-in-the-world accuracy with the atomic standard F-1 (3×10^{-16} frequency uncertainty reported to BIPM [the International Bureau of Weights and Measures]).
  —The upcoming cryogenic F-2 primary standard, which will improve the above accuracy by the factor three (to 10^{-16} uncertainty).
  —One of two best timescales in the world in terms of accuracy and stability.
- *Measurement Services:*
  —Remote time and frequency calibrations: best-in-the-world accuracy and usability.
  —Phase-noise metrology: unique capabilities, best-in-the-world metrology.
  —NIST network time services: the world's most heavily used Web clock (more than 3 billion hits per day).
  —NIST radio stations: best-in-the-world accuracy, stability; heavily used.
  —Global time service: low cost, ubiquitous 10 ns uncertainty service. The division has a new Web-based capability to track timescales across many laboratories in several countries around the world.
  —Time Measurement and Analysis Service: real time, 15 ns uncertainty; expanded to the Sistema Interamericano de Metrologia (SIM) Time Network.

—Timescale coordination in North, Central, and South America; Department of State funding (generates international goodwill).
—Phase-noise metrology: extending capability to 800 GHz, a capability that does not exist today, as driven by advancing Department of Defense technology requirements. Advancing the art of oscillator characterization beyond phase noise to acceleration sensitivity measurements, at frequencies and scales not achieved before.

- *Research and Development:*
  —Aluminum ion logic clock, best in the world (8.7×10^{-18} uncertainty).
  —Single-ion optical frequency standards: mercury ion second-best in the world (1.6×10^{-17} uncertainty).
  —Cold neutral atomic optical standards: calcium (excellent short stability); ytterbium lattice, one of the world's best.
  —Femtosecond laser frequency combs: the world's most precise frequency intercomparisons (1×10^{-19} uncertainty); the world's top-performing octave-plus spanning combs. Significantly advancing the range of applications with the optical comb to fields as diverse as astronomy and bio/chem detection.
  —Chip-scale atomic sensors: numerous first demonstrations (chip clock, chip magnetometer); progress in expanding the "microsensor" work from clocks, to magnetometers and gyros. The chip-scale-device activities are state of the art for miniature devices that could have significant applications in the commercial world. The next level of development of these devices to multiple device fabrication by means of clean-room-based wafer fabrication should be encouraged and supported.
- *Quantum Information Processing:*
  —Sole technology to demonstrate all seven DiVincenzo criteria for scalable quantum computing; first single-atom quantum logic gate; first deterministic entanglement; first robust error correction; first quantum teleportation of massive particles; first quantum Fourier transforms.
  —The ability to perform quantum processing and an extensive demonstration of quantum logic operations is very significant.

Assessment Relative to Adequacy of Resources

Human Resources

The Time and Frequency Division has an exceptionally talented group of permanent and temporary staff members, well suited to perform its primary responsibilities. This is particularly true in the areas of fundamental improvements to primary frequency standards and in the field of quantum logic. However, the ratio of permanent staff to associates has been declining, thereby producing an older and more experienced staff with fewer young developing staff and more inertia with respect to changes in the direction of work. This approach may serve the scientifically fashionable areas of research, but it does not serve the mission of NIST as it relates to advancing commerce.

The division has become overly dependent on temporary NIST associates, with over 60 percent of its staff in that category. These individuals are generally very well suited for conducting frontier research, but their awareness and interest in the fundamental mission of the division, particularly with respect to its responsibility to "our nation" is limited. A continuity of association with NIST and the Time and Frequency Division as provided by permanent employment provides the best opportunity to develop this familiarity. Such permanent staff members then have the ability to identify areas of investigation and pertinent capabilities of high relevance to serving our nation. The current overhead structure also tends to encourage the use of temporary staff. At the NIST level, changing to a more uniform burdening of salaries should result in gradually increasing the permanent-to-temporary staff ratio.

The division's productivity will be improved by increasing the number of technical support personnel. As an example, the most senior staff member associated with the establishment of the NIST timescale and Network Time Services is spending an excessive amount of his time responding to an IT audit. This work should be done primarily by IT-knowledgeable support staff, with guidance supplied by the senior staff member. Such senior staff should be focusing on improving the timescale and the NIST ability to disseminate such information. Similarly, it is desirable to have electronics technicians. The alternative is to invest graduate student and postdoctoral researchers' time in this area.

Budgets

An area of concern with respect to the Time and Frequency Division is related to the declining and inadequate funding supplied to primary standards and the NIST timescale. This area does not seem to be fully appreciated. Increased attention to clearly identifying the value that NIST products have to areas of practical impact is necessary. An increase in the level of discretionary funding at the division level would allow division leadership greater ability to address this need. Ultimately, laboratory management will have to make a conscious decision to shift resources to these areas.

The division's network time distribution continues to lead the world, with more than 3 billion automated synchronizations per day of computer clocks and network hardware, and the usage continues to grow. However, this area of core metrology has been chronically underfunded. The greatest need in this area is to hire a new staff member as an apprentice to begin learning this program from the developer and current project leader. Evidently, a lack of funds prevents this from happening, jeopardizing the long-term health of NIST's most heavily used service.

ARRA funding for a new NIST time code radio station, or for upgrading the existing WWVB time code station, should be a high priority for NIST. Attempts to identify a suitable East Coast location for a new station have failed for a variety of reasons beyond NIST's control. A major upgrade of the existing WWVB time code station appears to be the best alternative, and NIST should focus on this option and take all necessary actions to implement the upgrade.

Miniature atomic clocks and instruments are doing well with Defense Advanced Research Projects Agency (DARPA) support, but there is no budget mechanism to provide for the continuity of this work when the support runs out or takes its course to completion. This area is a good example of NIST doing its job in helping to address a major need with specialized capabilities, but the work is not high on the budgetary priority list. Budget flexibility should be developed to provide more stable support to this important area. The next level of development of these devices to multiple device fabrication by means of clean-room-based wafer fabrication should be encouraged and supported.

Three points of note remain. Resource limitations prevent the division's engaging in more extensive technology transfer; this area of the NIST mission needs more attention and support. The infusion of funds from the ARRA has been very helpful, and appears to have been used wisely. And finally, the Ion Storage Group appears to be the only group with adequate resources and adequate space.

Major Equipment and Facilities

Poorly performing laboratories have been a significant problem for the division—poor control of temperature, vibration, and other environmental conditions has seriously compromised the progress on and efficiency of research and metrology. The ongoing construction of the new advanced laboratory for Boulder should lead to major improvements for the division and for all of NIST Boulder. Progress to this end should be commended. However, the new laboratory probably will not be ready for occupation until approximately early 2012, so the division will continue to be hindered by obsolete laboratory conditions until then. With the level of accuracy and precision sought by the division, environmental control in its laboratories is critically important. There has been some progress in improving the existing laboratory space, particularly improving the temperature control for the NIST timescale. This should continue even after the completion of the new building.

Although there has been considerable improvement in the state of facilities, there remain major problems associated with the lack of space in the phase-noise measurement area and in the optical frequency standards area.

Assessment Relative to Achievement of Stated Objectives and Desired Impact

As an excellent example of serving the nation, the NIST Internet Time Service continues to grow in use, with an average of more than 3 billion automated synchronizations of computers and network devices every day. The service continues to expand the number and geographical diversity of servers across the United States to meet the continually growing demand.

Frequency combs are a major advance and a very enabling technology, transferable through optical fibers to characterize all frequencies through clockwork. Praiseworthy efforts are underway to connect this technology to problems in spectroscopy biochemistry, astronomy, the generation of arbitrary optical waveforms, and the generation of a new type of ultra-stable microwave and millimeter-wave sources.

The accuracy of the time standard has been realized, but its reliability needs to be improved. The use of highly accurate time should be promoted through sharing, portability, and new applications. Optical clocks sent through fibers appear to have much promise. The calcium clock's portability and fast stabilization are important features for expanding outside connections and opportunities.

America needs to be covered by radio time. Another group of antennas or an additional transmitter site is clearly needed to expand opportunities and commercialization. These ongoing efforts need encouragement and high-level support.

The division's research staff is doing exceptionally well in their topical areas. By all research university metrics, they are giving excellent performance. However, because they are embedded in NIST, their outreach and impact on real-world problems could be expanded. Every research staff member should be concerned about the impact that his or her work is having on the world and about the possibilities of solving previously insurmountable measurement, technical, and scientific problems with their techniques and new instruments.

NIST could do a better job of translating its science and technology into commercial value. For example, the chip-scale device activities, which could have significant commercial applications, should be supported for their next level of development. Some of its very important services require higher attention, for example, the network time services, radio time stations, time and frequency calibrations, and maintaining the operation of the F-1 time standard. The division's core metrology mission is underfunded and inadequately appreciated, as judged by its budgetary support. The human resources are primarily through contractors, who come and go without knowing what the mission really is. The transient nature of scientists' engagement with the division promotes National Science Foundation-style investigations whereby science is done for knowledge, not as a directed force to solve national problems.

A final comment is an encouragement for the Time and Frequency Division to continue to clarify the relationships between all of its technical products and commercial, military, and related scientific applications.

CONCLUSIONS AND RECOMMENDATIONS

Conclusions

The technical work in the Time and Frequency Division is excellent and serves as a model for other laboratories in the world. The physical facilities in which this work is performed have shown much improvement since the previous NRC panel visit to the division in 2008, but some of these facilities remain substandard, and inadequate space continues to be a problem. The construction of the new laboratory, appropriate for the work and technology of the division, is on schedule to be occupied in 2012 and will start a new era for expected experimental accomplishments of the division.

The Time and Frequency Division conducts a solid portfolio of efforts effectively directed toward achieving the stated division goals. The technical quality of its work in each area of emphasis is excellent and is the best or among the best in the world. The division is indeed an important national asset that fills a major need. The staff are first-rate, and their accomplishments, as measured by the academic standards of publications, conferences, and professional recognition, are of the highest quality.

Recommendations

The following recommendations address means to enhance the quality of the division's products and the ability of the division to achieve its objectives.

- Research applied toward solving problems of national interest should be encouraged by rewarding work in this area through increased recognition and increased funding and by including the concept as part of the division strategic goals.
  —The level of technology transfer should be increased and ways devised whereby technology developed at NIST over years and decades is transferred to commercial use for the best value to the public.
  —Investments in areas of research should be prioritized and reviewed so as to better serve the objectives and charge of the Time and Frequency Division and NIST as a whole.
- The goal of increasing the ratio of permanent to associate staff for the division and its management should be established.
  —An overhead structure that supports increasing the number of permanent staff should be developed.
  —The need for support staff should be reexamined to ensure that the time spent by senior researchers is best utilized.
  —The need for expanded funding for core metrology functions and services is apparent.
  —A higher level of discretionary funds should be provided for division management to help with future strategies and directions and with the current mission.
- Budgetary structures should be established that allow a smooth transition and "gap funding" between phases of externally supported work, such as work supported by DARPA.
- Adequate support should be ensured for the ongoing upgrading of facilities, both new facilities and facility renovations.

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Overall Conclusions

The following conclusions apply to the Physics Laboratory overall and are organized by the three major criteria against which the panel was charged to perform its assessment.

The Technical Merit of the Current Laboratory Programs Relative to Current State-of-the-Art Programs Worldwide

Within the United States, there is no other national laboratory or facility that focuses on the missions of the NIST Physics Laboratory, and there is no other laboratory worldwide working on the physics of standards and technology that has had the successes in physics that this laboratory has achieved during the past two decades. The laboratory has maintained this leadership position despite being among the smallest national laboratories addressing physics standards and technology, both in the number of personnel and in the size of the operating budgets. Despite its small size, it has maintained its exemplary performance by remaining focused on providing constantly improving measurement services relevant to the state-of-the-art industrial, medical, and commercial needs, keeping in close communication with its customers to anticipate their needs, and doing the research needed to improve those services and keep pace with developments in the field.

The Adequacy of the Laboratory Budget, Facilities, Equipment, and Human Resources, As They Affect the Quality of the Laboratory's Technical Programs

The budget for the Physics Laboratory has generally been maintained or increased in most areas in absolute dollars, although decreased budgets and/or decreases have been observed in some areas, with the standards and service areas appearing to be bearing a higher fraction of the burden. These reductions appear to result in part from three factors: increased operational costs, increased commitments for budget line items, and funding from external agencies for specific programs that represent a significant fraction of the increased funding. Funding restrictions are exacerbated by a continual decrease in discretionary funds at every level of NIST and the Physics Laboratory. State funding for collaborators and affiliated institutions also has begun to decrease, with further reduction expected. Despite these issues contributing to lesser support for standards and services, reduced funding for some standards and services appears in some cases to be a reallocation because of the prioritization for research.

The laboratory has new facilities in the planning stage, under construction, or completed since 2008, and it has acquired major equipment in key areas, in many cases partly in response to recommendations from the 2008 NRC assessment panel. There appears to be increased commitment to the refurbishment of the existing facilities and to maintenance, although there remain areas of concern for specific programs and groups.

There also remain major groups with facilities with shortcomings that interfere with productivity, time lines, and quality.

In terms of human resources, the technical scientists and staff continue to represent the major strength of this laboratory, and the laboratory administration has effectively applied a proactive approach that retains many of its outstanding personnel and has attracted new, highly qualified people. Budget and reallocation issues appear to be adversely affecting retention, salaries, the ratio of permanent staff to temporary appointments, and recruitment. More recently, the Office of Security within the Department of Commerce has begun reinterpreting existing policies regarding (1) out-of-hours access and (2) the unescorted access of foreign guest researchers. NIST leadership appears to be working with the Office of Security to ensure that none of these policies will be detrimental to NIST, but previous, less restrictive policies had already been noted by the panel as affecting productivity. Further constraints on the ability of foreign guest researchers to carry out their research are likely to decrease severely the number of these researchers, who are a valuable component in the Physics Laboratory's overall research program.

Salaries of permanent staff are becoming less competitive, and the complex, lengthy employment process with initial working restrictions remains a concern, although there were improvements in this area over the past 2 years. Major laboratory administrators responsible for the successes of the past decades are advancing and/or retiring. There should be an explicit plan not only for selecting exceptional people as replacements or for new projects but also for providing the training and resources needed to maintain the past level of leadership.

A generally flat and in some cases decreased budget for the laboratory may have a deleterious effect on its ability to maintain senior scientific and technical staff. Without vigilance and continued adequate support, the past and present reputation and position of the laboratory may not extend into the future. The laboratory and several of its divisions and groups have responded to budgetary pressures and to recommendations of the 2008 NRC assessment panel by developing long-range detailed strategic plans, but sufficient resources must be provided if the laboratory is going to be able to achieve its goals. Although the laboratory's strategic plan includes provisions for the increased support needed to maintain its new facilities and to upgrade and maintain the existing facilities, the inadequacy of past levels of funds for maintenance suggests that this matter deserves continued attention.

The Degree to Which Laboratory Programs in Measurement Science, Standards, and Services Achieve Their Stated Objectives and Desired Impact

Recent strategic plans at both the laboratory and division levels have succinctly enumerated objectives and, in turn, provide elucidation of the significance of the individual achievements and their contributions to these objectives. Some groups, however, would benefit from additional long-term planning for balancing core activities and allocating resources. The strategic planning could suggest appropriate paths for organizing personnel among divisions in the Physics Laboratory so that the talented staff can work more closely and efficiently with their collaborators in other divisions. New, improved, and/or more accurate services are being provided; however, some important service and standards areas have had reductions in funding, reduction in services, or increased workloads, as noted in the individual division chapters, impacting their ability to meet their responsibilities. Recently, as a result of a U.S. Government Accountability Office audit of the NIST Working Capital Fund, attorneys from the Department of Commerce General Law Division questioned the terms of the agreements by which other federal agencies transfer funds to NIST. The panel understands that NIST may be required to implement alternative procedures for accepting funding from other federal agencies. The panel recommends that any new administrative options should not reduce the efficiency or rapidity with which research addressing the needs of other federal agencies is conducted at NIST.

The panel concludes that NIST, the Department of Commerce, and the nation have been well served by the Physics Laboratory, with the past two decades being an era of exceptional accomplishment. The laboratory and its scientific, technical, and administrative personnel, as well as the service organizations and personnel supporting them, are to be lauded for their achievements.