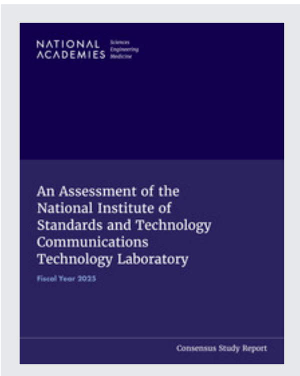

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An Assessment of the National Institute of Standards and Technology Communications Technology Laboratory

Fiscal Year 2025

Panel on Assessment of the National Institute of Standards and Technology (NIST) Communications Technology Laboratory (CTL)

Physical Sciences, Systems, and Infrastructure Program Area

Center for Advancing Science and Technology

Consensus Study Report

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PANEL ON ASSESSMENT OF THE NATIONAL INSTITUTE OF STANDARDS AND TECHNOLOGY (NIST) COMMUNICATIONS TECHNOLOGY LABORATORY (CTL)

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This Consensus Study Report was reviewed in draft form by individuals chosen for their diverse perspectives and technical expertise. The purpose of this independent review is to provide candid and critical comments that will assist the National Academies of Sciences, Engineering, and Medicine in making each published report as sound as possible and to ensure that it meets the institutional standards for quality, objectivity, evidence, and responsiveness to the study charge. The review comments and draft manuscript remain confidential to protect the integrity of the deliberative process.

We thank the following individuals for their review of this report:

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Although the reviewers listed above provided many constructive comments and suggestions, they were not asked to endorse the conclusions or recommendations of this report nor did they see the final draft before its release. The review of this report was overseen by **DAVID W. JOHNSON, JR. (NAE),** Bell Laboratories (retired), and **DAVID A. WEITZ (NAS/NAE),** Harvard University. They were responsible for making certain that an independent examination of this report was carried out in accordance with the standards of the National Academies and that all review comments were carefully considered. Responsibility for the final content rests entirely with the authoring committee and the National Academies.

Contents

Tables

Preface

Since 2014, the National Institute of Standards and Technology (NIST) Communications Technology Laboratory (CTL) has been pioneering metrology and standards research across the breadth of communication technologies, including, but not limited to, public safety communications research, radio frequency technologies, and spectrum science. The work, scientific expertise, operations, and effectiveness of its strategy to disseminate program outputs have been routinely evaluated as excellent by the National Academies of Sciences, Engineering, and Medicine (National Academies). CTL has taken feedback from the National Academies' reviews and incorporated recommendations into its research pipeline, workflow, and operational strategy when and where feasible. In 2022, the National Academies recommended that CTL conduct a strategic roadmapping activity across the organization so that individual projects can trace their activities up to the laboratory-wide vision and help identify organizational and research gaps and future growth opportunities. CTL has implemented the recommendation, and the CTL leadership team now evaluates every project as a part of the roadmap activity, from inception through technology transfer.

Unlike the 2022 National Academies' review, this 2025 review was conducted on-site, and the review panel had the opportunity to walk around the research facility and view state-of-the-art equipment and experiments. The CTL leadership and staff are using their resources extremely effectively in service to the nation and its scientific, industrial, public safety, and defense capabilities in a very competitive research environment.

The National Academies' review panelists had a productive 2.5-day visit at the Boulder, Colorado, NIST campus with a very collaborative discussion with the CTL research team. On behalf of the 2025 National Academies' panelists and staff, I would like to thank the NIST CTL leadership team for their preparation and engagement during the meeting. We specifically want to thank Ari Feldman, Anne Lane, Nada Golmie, and the staff for their hospitality, insightful, thorough, and prompt response to our probing questions, honest discussion on the state of their research operations and facility, and continued responsiveness as we prepared this report. All of this could not have happened without their willingness to be independently evaluated by the external expert panel from industry and academia and to take constructive criticism toward improving their strategic planning and operations like they did in 2022. So, we thank you for your great work, leadership, and cooperative mindset. You are making a great difference for the nation and our international partners. Similarly, the National Academies' review panel and I especially would like to thank the study staff Elizabeth (Beth) Zeitler, Catherine Wise, and Maura Walsh for their leadership and professionalism throughout the review process, for moderating the panel discussions, and for always keeping an eye toward the creation of the final report. This resulted in a strong outcome, and hopefully a valuable resource for NIST CTL as it incorporates the recommendations.

Bishal Thapa, *Chair*
Panel on Assessment of the National Institute of Standards and Technology (NIST)
Communications Technology Laboratory (CTL)

Acronyms and Abbreviations

3GPP	Third Generation Partnership Project
AI	artificial intelligence
BNC	Bayonet Neill-Concelman
BIPM	Bureau International des Poids et Mesures
CBRS	Citizens Broadband Radio Service
CHIPS	Creating Helpful Incentives to Produce Semiconductors
CRADA	Cooperative Research and Development Agreement
CTL	Communications Technology Laboratory
DOW	U.S. Department of War
EMC	electromagnetic compatibility
FY	fiscal year
GHz	gigahertz
IEEE	Institute of Electrical and Electronics Engineers
LBS	Location-Based Services
LMR	Land Mobile Radio
LTE	Long-Term Evolution
MCX	Mission Critical Services
NASA	National Aeronautics and Space Administration
NASCTN	National Advanced Spectrum and Communications Test Network
NextG	Next Generation Communications
NIST	National Institute of Standards and Technology
NMI	national metrology institute
NPL	National Physical Laboratory
NR	new radio
O-RAN	Open Radio Access Network
P25	Project 25 Radios
PREP	Professional Research Experience Program
PSCR	Public Safety Communications Research Division
PSIAP	Public Safety Innovation Accelerator Program
PTT	push-to-talk

R&D	research and development
RF	radio frequency
RFI	radio frequency interference
RFTD	Radio Frequency Technology Division
STAR	Spectrum Technology and Research Division
THz	terahertz
TRL	technology readiness level
UAS	Uncrewed Aircraft Systems
UX	User Experience

Summary

The National Institute of Standards and Technology (NIST) Communications Technology Laboratory (CTL) was established in 2014 to unify the communications research and development (R&D) efforts occurring across NIST. CTL is divided into five divisions: three based in Boulder, Colorado, and two based in Gaithersburg, Maryland. The National Academies of Sciences, Engineering, and Medicine (National Academies) were asked by the director of NIST to assemble an expert panel to assess the work of the three divisions based at the Boulder facility: the Public Safety Communications Research Division (PSCR), the Radio Frequency Technology Division (RFTD), and the Spectrum Technology and Research Division (STAR), in fiscal year (FY) 2025.[1] The assessment encompasses four primary objectives:

- assess CTL's technical programs, comparatively against world-class research, and its adequacy to reach NIST's stated objectives;
- assess CTL's scientific expertise comparatively to leading experts and adequacy to reach its stated objectives;
- assess the adequacy of budget, facilities, equipment, and human resources; and
- assess the effectiveness of CTL's dissemination of its program outputs, in terms of direction toward stakeholder needs, effectiveness of methods, and monitoring of stakeholder use and impact.

The full statement of task is included in the introductory chapter of this report. The expert panel structured its review by division, and developed overarching key conclusions and recommendations, as well as division-specific conclusions and recommendations.

[1]Complementary FY 2025 National Academies' assessments are available of the NIST Center for Neutron Research as well as the Gaithersburg divisions of the Physical Measurement Laboratory.

PUBLIC SAFETY COMMUNICATIONS RESEARCH DIVISION

The PSCR aims to “accelerate the adoption of critical communication capabilities for first responders” through five research portfolios: Mission Critical Services (MCX), User Experience (UX), Location-Based Services (LBS), Uncrewed Aircraft Systems (UAS), and the Innovation Lab. These five program areas provide services and technical expertise to the public safety community and related industries. Such service is intended to accelerate applicability of communications technologies for public safety use cases in parallel to commercial availability for the U.S. consumer. The PSCR appears to be unique among federal laboratories working on public safety communications because of its focus on local first responders, creating an ecosystem where these workers have a meaningful voice informing interdisciplinary communications research.

The MCX portfolio is meeting its technical objectives, notably with its leadership in the replacement of Land Mobile Radio (LMR) standards for push-to-talk radios with more advanced technologies on mobile broadband networks. The MCX group developed trusted and provable application readiness, specifications, equipment readiness testing, and laboratory test certification, and then transferred the work to commercial testing and evaluation companies.

The UX group takes a first-responder training point of view to develop augmented, virtual, and extended reality, heads-up displays, haptics and audio cues, and user experience research and testing methodologies, for example, simulating the experience of a firefighter entering a room. Obtaining feedback from intended end users in a frequent and convenient manner about routine and emergency uses is key to conducting successful applied research and technology transfer. The UX group has significant potential for stakeholder impact by focusing on NIST measurement science and developing guidelines to evaluate operations of third-party products in its mock-up of real-world settings.

The LBS portfolio focuses on indoor positioning, a long-standing engineering challenge for first responders, particularly in the z axis (vertically). The team is constructing an instrumented z-axis facility, which will enable R&D, testing, and unique dataset production by groups internal and external to NIST to evaluate indoor positioning solutions.

The UAS group sponsored eight prize competitions from 2018 to 2025 to advance capabilities of uncrewed aircraft systems for emergency response operations. This research area appears to align well with NIST’s metrology strengths, such as the use of standardized test methods to evaluate the UAS solutions from different competition teams, and has so far differentiated itself from other first responder–related UAS efforts nationwide.

The Innovation Lab supports the computing, networking, and radio needs of other PSCR portfolios and CTL divisions. It operates multiple LMR systems and a long-term evolution base station deployed in a test range, and it has a van outfitted with a radio tower for drive testing and high-elevation outdoor deployment.

The PSCR's expertise across the portfolio of projects in MCX, UX, LBS, UAS, and the Innovation Lab supports its objectives reasonably well despite such a small number of staff. The MCX's success in transforming an unsolved engineering and standardization problem into a final technology transfer stood out. The UX staff adequately supports its technical programs, but the group could benefit from additional staff to support a test and evaluation setup with commercial partners to assess its UX guidelines. Similarly, the LBS could better confront the numerous unsolved problems in signal processing and engineering with a larger team of researchers who have expertise in areas such as radio frequency (RF) propagation, optics, signal processing, radar, imaging, and communications. Adding more PhDs with relevant backgrounds in applied research could contribute to research depth and breadth in the PSCR. This could accelerate adoption of critical communication capabilities for first responders via enhanced cross research portfolio collaboration.

The PSCR facilities are of high quality and a major asset to the division. The equipment is likewise excellent, including the networks and capabilities provided by the Innovation Lab. A plan for maintenance of equipment that is grounded with stakeholder requirements and funding sources is needed.

The PSCR has maintained high-quality stakeholder engagement. It hosts a major public innovation summit that draws public safety organizations, industry, academia, and government partners from around the United States and across the world and serves as an example of how other parts of NIST could transfer research outputs, identify new problems, and market their work. The PSCR also performed a comprehensive survey and semi-structured interviews with the public safety community, publishing its findings in a 2018 NIST report with additional volumes published through 2023. It is developing a roadmap to address issues identified by stakeholders: budget and logistics, technological needs, and information gaps.

The PSCR subpanel's conclusions and recommendations are presented in Chapter 2. The PSCR subpanel recommends that the PSCR (1) consider updating research on the transition from LMR to newer technologies; (2) require projects to specify anticipated outcomes in measurement sciences, standards development, accelerating adoption, and reusable datasets; (3) increase the ratio of personnel with PhDs; (4) analyze costs of system upkeep and consider how to allocate those costs; and (5) consider monitoring value beyond targeted stakeholders.

RADIO FREQUENCY TECHNOLOGY DIVISION

The RFTD has four research groups: the Electromagnetic Fields Group (traceable electromagnetic field strength measurements for international standards and electromagnetic compatibility [EMC] evaluations), the Guided Wave Electromagnetics Group (fundamental electromagnetics research for advanced wireless communications), the High-Speed Waveform Metrology Group (measurement science for high-frequency communications and 5G/6G networks), and the Superconducting Electronics Group (quantum technologies for voltage standards, quantum waveform synthesis, and RF metrology). The division has key technical strengths in foundational metrology with capabilities competitive with leading national metrology institutes (NMIs)—for example, Josephson standards, and RF power and scattering-parameter measurements. Work in the RFTD impacts all time-critical systems across national security and civilian infrastructure domains, improving technology from cell phones to computer chips. The RFTD transformed RF probe calibration into atom-based primary standards, reducing uncertainties and positioning the United States as the global leader in RF quantum sensing. It has led innovation in measurement science that has launched entirely new industries—for example, Rydberg sensing with approximately 25 companies and $100 million in commercial activity based on NIST technology. It operates at the appropriate early technology readiness level, with successful technology transfer to industry implementers. The division contributes to several standards (Next Generation Communications [NextG] Channel Model Alliance, Third Generation Partnership Project, and the Institute of Electrical and Electronics Engineers). It is developing new technologies with strong external collaborations positioned to significantly contribute to future industry needs—for example, hot qubit metrology, the Creating Helpful Incentives to Produce Semiconductors and Science Act magnetic materials, and 5G/6G EMC frameworks.

The RFTD has committed staff with technical depth. It possesses strong scientific expertise across its mission areas, with recognized contributions in quantum sensing, high-frequency electronics, and calibration sciences. Staff have pioneered measurement methods including Rydberg atom electrometry, electro-optic sampling to 1 terahertz, and advanced channel sounding methodologies. Early career researchers demonstrated enthusiasm and strong capabilities, contributing to a vibrant research environment. Two areas for improvement are (1) greater connection with universities outside of Colorado and (2) succession planning or knowledge-transfer protocols, given both an aging workforce and the specialized nature of metrology expertise. Greater development and hiring of technicians could also better balance the workforce of graduate students, early career staff, and senior research staff.

The division's facilities face significant infrastructure challenges that actively compromise its ability to provide reliable national measurement standards. Multiple facilities experience planned power interruptions and unplanned power failures, uncontrolled temperature issues affecting calibration chamber stability, and inadequate environmental controls requiring makeshift solutions like open windows for equipment cooling.

The division demonstrates competence in traditional NMI dissemination methods including journal publications, conference presentations, technical reports, and standards development. Notable technology transfer successes include automation of the Josephson voltage standard, enabling adoption by other NMIs; development of primary standards lab capability within the Air Force Metrology and Calibration Program; open-source Open Radio Access Network (O-RAN) testbed tools; and NextG Channel Model Alliance data repository.

The RFTD subpanel's conclusions and recommendations are presented in Chapter 3. The RFTD subpanel recommends that (1) the RFTD develop new measurement capabilities to address current industry needs; (2) NIST address infrastructure failures through backup power and environmental control remediation; (3) the RFTD conduct a strategic industry stakeholder needs assessment; (4) the RFTD enhance its impact assessment; (5) the RFTD implement workforce practices that optimize resources and plan for technical workforce succession; and (6) CTL perform a workforce metrics analysis.

SPECTRUM TECHNOLOGY AND RESEARCH DIVISION

Launched in 2021, STAR is a relatively new division of CTL that works to increase the availability of spectrum for commercial use without impacting military applications. It contains three primary research groups: (1) Applied Systems Metrology, which develops technical foundations for spectrum science and measurement techniques for closed-box RF systems; (2) Fiber Sources and Applications, which develops fiber-laser frequency combs for a variety of precision measurement applications; and (3) Shared Spectrum Metrology, which performs research on wireless coexistence, EMC, spectrum sensing and noise, and interoperability for the 5G Open Radio Access Network (O-RAN). Together, these groups help ensure that the U.S. infrastructure for communications, spanning mobile phones to GPS, operate correctly and without interferences as the public expects.

Technical achievements of STAR include groundbreaking work in optical comb time transfer, yielding synchronization accuracies of less than a femtosecond. Spectrum sensing and sharing work is also of high quality, including both theoretical and field-tested practical capabilities. Expanding CTL's research using aerial capabilities (e.g., drones) can address metrology and standards needs in a technology area of growing importance. CTL's advanced RF instrumentation, calibrated data collection, and interference modeling provide essential tools to quantify and mitigate RF interference, ensuring measurement integrity. STAR has a wide range of stakeholders and collaborators, including government, industry, standards organizations, and academia. New directions that could be impactful for the division and its stakeholders include building off the Citizens Broadband Radio Service spectrum sensing program and branching into new bands, developing RF digital twins for controlled simulation or emulation, and developing standards for digital twins used in artificial intelligence (AI)-native wireless for 6G across the commercial industry.

The scientific expertise within STAR is of very high quality and fits the variety of technical programs conducted by a range of researcher types, from early career scientists and engineers to midlevel staff, to senior staff of international repute. One strength of the division is the support of management for principal investigators to propose high-risk, high-reward, curiosity-driven research, which is essential for the continued vitality of the science and engineering of a national laboratory. The division staff would be expected to grow as spectrum sensing becomes more critical and to expand the division's expertise into needed areas like AI-native wireless/RF digital twins.

The facilities and laboratories at STAR are well equipped and maintained, and field-testing facilities are well designed. Laboratory equipment is generally state of the art, but the absence of backup power for some laboratories is a problem. Additional facilities may be required if STAR takes on future work from any government sponsor that requires controlled access. The division has one secure facility but no associated secure laboratory.

The division's publication record is strong, producing journal articles, conference presentations, technical reports, standards, validated datasets, and even short courses for the community at large. Three gaps were identified in STAR's dissemination strategy: collaboration with other government entities to share data, widely sharing and evaluating validated data, and technology transfer.

The STAR subpanel's conclusions and recommendations are presented in Chapter 4. The STAR subpanel recommends that STAR (1) better engage with the U.S. Department of War (DOW), National Science Foundation (NSF), and commercial stakeholders; (2) investigate the use of techniques beyond radiometric detection for spectrum sensing; (3) contribute to the technical evaluation and gap or security analysis of emerging technologies; (4) better define, track, and value its technology transfer strategy; (5) better share validated data; (6) lead the development of standardized frameworks for use of digital twins in AI-native 6G wireless systems; and (7) employ its radiometry expertise to space research applications.

OVERARCHING CONCLUSIONS AND KEY RECOMMENDATIONS

A set of overarching conclusions and key recommendations that spans all the CTL divisions under review is as follows:

Overarching Conclusion 5-1: The Communications Technology Laboratory (CTL) research is of top quality. It has profound implications for the relevant research communities, industries, and government stakeholders. Continuing to pursue new topic areas within CTL's strengths in measurement science is critical to meeting stakeholder needs.

Overarching Conclusion 5-2: Even with limited research staff, the Communications Technology Laboratory's in-house scientific expertise is among the best in the field. However, hiring more researchers with diverse backgrounds and educational lineage from across the country as permanent staff will advance multiple areas. In particular, additional PhD researchers in the Public Safety Communications Research Division could help to accelerate application of new technologies for community use cases.

Overarching Conclusion 5-3: The existing Communications Technology Laboratory (CTL) facilities in Boulder are maintained and utilized to the best of the CTL staff's ability given available resources. Some infrastructure issues, particularly the lack of reliable power supply have interrupted research and experimental work. With ever-growing research and development infrastructure and service maintenance cost, current resources for infrastructure repair and improvement are insufficient, and CTL needs more capital investment to repair, improve, and expand its research facility.

Overarching Conclusion 5-4: The dissemination of Communications Technology Laboratory (CTL) program outputs via publications, presentations, and certain datasets is aligned with best practices for industry standards and academic expectations. There is insufficient coordination with institutions who are working in similar problem spaces (e.g., the National Telecommunications and Information Administration), where CTL can take the lead on metrology and inform standards. CTL curation of additional open radio frequency, public safety, and spectrum sharing and sensing datasets could support stakeholder needs. Opening datasets and sharing them with the greater open research community is a mountainous effort but of great value. No group is better suited and placed to undertake this than CTL.

From the above overarching conclusions stem these key recommendations:

Key Recommendation 5-1: The Communications Technology Laboratory (CTL) should examine the division-specific recommendations for research topic growth areas that would advance CTL's mission and leverage its technical strengths.

Key Recommendation 5-2: The Boulder-based divisions of the Communications Technology Laboratory (CTL) should engage with a wider range of universities and

students to supplement the recruitment opportunities presented by the Professional Research Experience Program.

Key Recommendation 5-3: Communications Technology Laboratory (CTL) leadership should prioritize addressing backup power needs for critical instruments and experiments, given the frequent planned and unplanned power outages at the Boulder campus, and its negative impact on calibrations, experiments, and the CTL mission.

Key Recommendation 5-4: The Communications Technology Laboratory should build on its success in hosting and curating open, validated datasets for research use. Areas of growth include sharing reusable datasets from the Public Safety Communications Research Division's User Experience portfolio, analyzing how datasets support industry development in the Radio Frequency Technology Division, developing reliable data in new areas of the Spectrum Technology and Research Division's work such as for digital twins, and developing shareable data from otherwise inaccessible datasets like those containing various forms of controlled information.

1
Introduction

The National Institute of Standards and Technology (NIST) Communications Technology Laboratory (CTL) unifies decades of research on communications technologies across NIST. CTL conducts work across a range of research levels, from fundamental science for improved metrology to standardization of tools and techniques used by current and future industry. It aims to serve as "an independent, unbiased arbiter of trusted measurements and standards to government and industry" by "developing precision instrumentation and creating test protocols, models, and simulation tools to advance communications technology" (CTL 2025a). CTL is comprised of five divisions—the Public Safety Communications Research Division (PSCR), the Radio Frequency Technology Division (RFTD), the Spectrum Technology and Research Division (STAR), Smart Connected Systems, and Wireless Networks—and houses the National Advanced Spectrum and Communications Test Network, a collaborative effort with other federal agencies to tackle challenges in spectrum sharing (CTL 2025a). To inform its research efforts and align them with stakeholder needs, CTL has been developing strategic roadmaps in the areas of 6G communications, radio frequency metrology and calibration services, quantum communications, public safety communications, spectrum science, and space communications (Feldman et al. 2025a).

As of September 2025, CTL employed 299 staff members, including career and term-limited federal employees, contractors, guest researchers, postdoctoral fellows, and students (CTL 2025b; Feldman et al. 2025b). This represents a slight decrease since fiscal years (FYs) 2023 and 2024, when CTL staff numbered 338 and 341, respectively (Feldman et al. 2025b). CTL's appropriations have also been decreasing over the past several FYs—from $62.4 million in FY 2023, to $59.8 million in FY 2024, to $54.7 million in FY 2025 (CTL 2025b; Feldman et al. 2025b). In addition to the base appropriations, CTL divisions can (and often do) receive additional funding through other congressionally mandated activities (e.g., Creating Helpful

Incentives to Produce Semiconductors and Science Act programs), internal NIST-funded initiatives (e.g., NIST's Innovation in Measurement Science Program), other federal agency initiatives, and/or cooperative research and development agreements.

STATEMENT OF TASK

The National Academies of Sciences, Engineering, and Medicine (National Academies) have been conducting independent assessments of NIST laboratories since 1959 at the direction of Congress and in response to requests from the NIST director. There have been three prior reviews of CTL, in FYs 2015, 2019, and 2022. For this 2025 assessment, the National Academies convened the Panel on Assessment of the NIST Communications Technology Laboratory (the panel) to evaluate the three CTL divisions located in Boulder, Colorado: Public Safety Communications, Radio Frequency Technology, and Spectrum Technology and Research. The panel was responsible for responding to the following statement of task:

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

NIST has requested that the laboratories be assessed against the following broad criteria:

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

- How well does the organization's scientific expertise support the organization's technical programs and the organization's ability to achieve its stated objectives?

3. Assess the adequacy of the organization's budget, facilities, equipment, and human resources.
   - How well do the facilities, equipment, and human resources support the organization's technical programs and its ability to achieve its stated objectives? How could they be improved?
4. Assess the effectiveness by which the organization disseminates its program outputs.
   - How well are the organization's research programs driven by stakeholder needs?
   - How effective are the dissemination methods and technology transfer mechanisms used by the organization? Are these mechanisms sufficiently comprehensive?
   - How well is the organization monitoring stakeholder use and impact of program outputs? How could this be improved?

CONDUCT OF THE ASSESSMENT

The panel comprised 12 experts aligned with the scientific and technical work performed by the CTL divisions being assessed. The volunteer panel convened in Boulder, Colorado, September 16–18, 2025, for an on-site evaluation of CTL, which involved presentations from the CTL leadership and staff, laboratory tours, and discussions with early career individuals. These interactions, as well as overview material provided by CTL and its divisions and written responses to panel inquiries, informed the qualitative assessment presented in this report. The panel also relied on its own expertise and experience in commenting on the quality of CTL's research, staff, and facilities and the effectiveness of dissemination efforts. Conclusions and recommendations focused on opportunities and challenges related to CTL's current work. It is important to underscore that NIST maintains a distinct advisory entity, the Visiting Committee on Advanced Technology, which is charged with addressing broader questions related to strategic direction and research alignment across the agency's laboratories. Further, given the broad, interdisciplinary nature of research at CTL, measuring the laboratory's outcomes and impacts can be challenging.

STRUCTURE OF THE REPORT

Following this introductory chapter, the report includes chapters focused on three CTL divisions being assessed. The PSCR is discussed in Chapter 2, the RFTD is discussed in Chapter 3, and STAR is discussed in Chapter 4. Chapter 5 presents the committee's conclusions and recommendations, including division-specific and key crosscutting conclusions and recommendations.

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2
Public Safety Communications Research Division

BACKGROUND ON THE PUBLIC SAFETY COMMUNICATIONS RESEARCH DIVISION

Established in 2002, the Public Safety Communications Research Division (PSCR) aims to "advance communications technologies in support of the public safety community through strategic, forward-looking research that balances near-term operational needs with long-term innovation" (Feldman et al. 2025, p. 9). To advance this objective, the division has established five technical program areas, or "research portfolios": Mission Critical Services (MCX), User Experience (UX), Location-Based Services (LBS), Uncrewed Aircraft Systems (UAS), and the Innovation Lab. The five PSCR program areas provide services and technical expertise to the public safety community and related industries that are intended to accelerate applicability of communications technologies for public safety use cases in parallel to commercial availability for the U.S. consumer. Table 2-1 provides an overview of the objectives of each of these research portfolios. Supporting these portfolios, the PSCR's fiscal year (FY) 2025 combined budget was $12,148,900 with a total of 32 staff (25 federal, 7 associate) (Feldman et al. 2025; PSCR 2025).

Early PSCR work (2002–2007) focused on Land Mobile Radio (LMR). Long-term evolution (LTE) enabled an expansion into emerging broadband technologies from 2007 to 2012. The PSCR's efforts accelerated with the $300 million Public Safety Innovation Accelerator Program (PSIAP) funding between 2016 and 2022 and a series of UAS prize challenges from 2019 to 2025. The PSCR also works closely with the FirstNet Authority, which oversees the dedicated nationwide broadband network for first responders to support public safety and ensure connectivity during emergencies (FirstNet Authority n.d.). In this collaboration, the National Institute of Standards and Technology (NIST) targets work at technology readiness levels (TRLs) of roughly 1–6 (i.e., research and development looking out 5–15 years), and FirstNet

Authority targets work at TRLs 6–9 (i.e., investment and deployment into technology 0–5 years ahead). The division's goals for the next year include utilizing new criteria for FY 2026 planning, narrowing focus, sunsetting FY 2025 projects, and maintaining alignment with FirstNet Authority.

PSCR leadership shared crisp communication technology objectives for each of the public safety community program areas, copied into Table 2-1. These objectives were used to guide this assessment.

TABLE 2-1 Overview of the Public Safety Communications Research Division (PSCR) Research Portfolios

Program Area	Objective
Mission Critical Services	Advance the availability and performance of mission-critical services for first responders, forging partnerships to expand research in this area, and actively influence standards within the public safety community, particularly as broadband technology becomes prevalent for public safety use.
User Experience	Research and develop tools and technologies designed around first responders' specific needs and requirements, using user-centered design and feedback. Collaborate with the public safety community, stakeholders, and vendors to drive innovation and create reliable, intuitive technology that enhances first-responder communications technologies.
Location-Based Services	Accelerate the pace of technological development in the fields of indoor mapping, tracking, and navigation for the public safety community and remove barriers to adopting these technologies.
Uncrewed Aircraft Systems (UAS)	Advance the capabilities of UAS through cutting-edge research to provide safe, effective, and reliable solutions for first responders in their crucial missions and emergency response operations.
Innovation Lab	Provide an innovative research laboratory and network that accelerates next-generation communications technology development and adoption by optimizing a fast, reliable, and secure network platform with advanced testing capabilities to support all PSCR and Communications Technology Laboratory–wide communications research.

SOURCE: Committee generated using PSCR (2025a,b,c,d,e).

TECHNICAL PROGRAMS

The PSCR's five research portfolios, introduced above, focus on high-importance research areas that have a clear impact on real-world public safety problems. The PSCR's research includes both low-TRL, long-term work and high-TRL, short-term work. The PSCR has performed initial roadmapping efforts in public safety analytics research and development (R&D), user interface R&D, and location-based services R&D (Benson et al. 2017; Felts et al. 2015, 2016). The PSCR also aligns its roadmap with that of FirstNet Authority, which updated its roadmap in 2020 and 2023 in response to evolving communication challenges (CTL 2025).

NIST PSCR appears to be unique among federal laboratories working on public safety communications because of its focus on local first responders. First responders primarily operate in local contexts, which is why PSCR has leveraged relationships with FirstNet (federal perspective) and with local first responders (state and local perspective) in targeting relevant outcomes for federal, state, and local agencies. PSCR has created an ecosystem where these workers have a meaningful voice informing interdisciplinary communications research.

Examples from each research portfolio, as well as work performed under the PSIAP, are described in the following sections.

Mission Critical Services

The MCX portfolio is the most mature and strongest of the five portfolios and meets its stated objectives. The broadband mission-critical push-to-talk (PTT) modernization stands out as a PSCR success story. PTT radios are viewed as indispensable by many public safety officers. Unlike mobile phone calls, which require entering digits to initiate a voice call, PTT systems give the officer the feeling of constant connectivity because a quick button push opens a voice channel. PTT radios date back almost to the invention of radio, and public safety officers have depended on PTT provided by LMR for instant reliable communications.

The MCX and its partners were able to shepherd conformance testing through the Third Generation Partnership Project (3GPP), develop standards-based conformance testing scripts, and transfer this work to commercial testing and evaluation companies. This high-impact work stands out because the MCX played a critical role from inception to commercialization. The most common LMR standard in the United States involves Project 25 (P25) radios, which gained widespread use during the transition from analog to digital waveforms in the 1990s. LMR has been used for decades by both police and fire, saving numerous lives by providing connectivity in life-threatening situations. Today, P25 is an approximately 35-year-old standard that is frozen. It does not utilize the innumerable physical, medium access, and network layer improvements that have been available for around 15 years in commercial wireless broadband standards, such as 3GPP LTE. A switch to a wireless broadband network such as LTE or 5G New Radio (NR), available for around 5 years, would lower cost, improve voice performance, and provide improved spectral efficiency.

Despite the widespread availability of LTE and 5G NR, LMR is still widely used in the United States by public safety organizations, primarily resulting from a lack of trust in alternatives—for example, equivalent ruggedized devices. LMR decommissioning will depend on feature equivalency of a replacement system. One gap preventing this transition away from LMR to new technologies is reach beyond the current radio coverage. Technical solutions such as sidelink and satellite are being considered. The PSCR's MCX portfolio has recognized this trust issue and has aimed to overcome it through a mixture of provable broadband mission-critical PTT application readiness, specification development, equipment readiness testing, and laboratory test certification.

User Experience

The User Experience (UX) group approaches its objectives (see Table 2-1) from a first responder–training point of view. Key areas of focus include augmented and virtual reality and extended reality technologies for public safety; heads-up displays, haptics, and audio cues for effective interaction; and user experience research and testing methodologies for new technologies. As an example of stakeholder engagement for user centered design and feedback, the UX team ran the "CommanDINGTech Challenge" that ended in March 2023. The UX team shared that outcomes from this event influenced future R&D directions for NIST PSCR and are incorporated into the commercial space. The UX group incorporated the learning when developing studies to take place in the Public Safety Immersive Test Center with a mock-up of an apartment in a hazardous materials situation. First responders use augmented and virtual reality equipment and 3D-printed faux test equipment to recreate a real-world setting. The mock-up laboratory has limited capacity to provide firsthand first-responder training experience. However, the UX team has significant potential to increase stakeholder impact by focusing on

NIST measurement science and development of guidelines to evaluate operations of third-party products in the mock-up real-world setting given the unique location measuring capabilities of NIST's mock-up setting. NIST might consider providing guidance for first responders on requirements for purchase and deployment of systems that include the researched user experience technologies. Obtaining feedback from intended end users in a frequent and convenient manner about routine and emergency uses is key to conducting successful applied research and technology transfer.

Location-Based Services

The LBS portfolio focuses on indoor positioning, which is a long-standing engineering challenge in both commercial and government settings. For indoor mapping, tracking, and navigation, the LBS group has generated results using light detection and ranging and artificial intelligence (AI) techniques. The LBS group is looking to make a major step forward in removing barriers to technology adoption with its new z-axis positioning test facility. Indoor positioning is a widely known problem that to date does not have a widespread solution. In outdoor areas, global navigation satellite systems such as the Global Positioning System can be used for accurate positioning. Public safety settings, however, require officers to enter buildings in scenarios where both the public and first responders' lives are in danger. Global navigation satellite systems are unreliable indoors because accurate timing estimation requires line-of-sight connectivity. In a building, the existence of spatially varying relationships and unknown multipath propagation make it difficult to track officers and to radio in information. This is particularly a problem when trying to locate an object or position in height or by building floor (i.e., the z axis), especially in disaster recovery scenarios. When the z-axis positioning facility is completed, the LBS group will be able to host organizations to support research and development, testing, and unique dataset production, and to establish clear guidelines on how to support, test, and evaluate indoor positioning solutions.

Uncrewed Aircraft Systems

To achieve its objective of advancing capabilities of uncrewed aircraft systems for emergency response operations, the UAS group functions as a competition-focused center, having sponsored eight prize competitions between 2018 and 2025. The UAS group formulates unmanned aerial challenges with set objectives and rules, which are then opened to teams across the world, with multiphase down selections and funding. The UAS group does not specify how teams design their unmanned systems other than providing broader guidelines on competition objectives. As a result, limited up-front funding for materials and supplies catalyzes large numbers of highly skilled research teams performing a significant amount of R&D for UAS, with the top-performing teams receiving additional monetary awards. The UAS portfolio is then able to harness the observations and data from these challenges to inform its outcomes.

The UAS research area appears to align well with NIST's metrology strengths, such as the use of standardized test methods for evaluating UAS solutions from different competition teams. It has so far differentiated itself from other UAS efforts nationwide and capitalized on NIST's strengths for sustained impact in improving first-responder UAS services. Collaboration with other UAS research initiatives, such as the National Science Foundation's Aerial Experimentation and Research Platform for Advanced Wireless, with a focus on PSCR use cases, may help to accelerate capability for first responders. Still, drone detection and tracking is an emerging use case that is top of mind for national security, critical infrastructure, DOW, and disaster recovery situational awareness. The 5G/6G telecommunications network's Integrated Sensing and Communication (ISAC) capability is being standardized now for multi-vendor interoperability. PSCR could consider applying best practices in UAS metrology to the drone detection and tracking use case which would have relevance beyond the current public safety mission. Addressing 5G/6G ISAC capability for first responder communications technology, and standards and metrology for UAS communications technology could be opportunities for new or increased cross-division collaboration. For example, MCX in collaboration with the Radio Frequency Technology Division (RFTD) could influence standards development of sensing APIs for public safety, and LBS and MCX could collaborate with the RFTD to develop ISAC-enabled location sensors for first responders.

Innovation Lab

The Innovation Lab supports the computing, networking, and radio needs of the other PSCR portfolios and CTL divisions. It operates LMR systems from multiple vendors and an LTE base station deployed at a test range, and it maintains a van outfitted with a radio tower for drive testing and high-elevation outdoor deployments. The Innovation Lab also contains fully functional systems necessary to exercise system interoperability, including

- A 4G/5G cellular network system,
- A P25 phase 1 and 2 LMR system,
- Radio frequency (RF) chambers for testing devices,
- A mission-critical Voice Quality of Experience system, and
- A mobile research vehicle for field measurements.

Per the Cybersecurity and Infrastructure Security Agency, communications systems are operational technology, and the Innovation Lab operates under a NIST Authority to Operate in accordance with the Federal Information Security Modernization Act. The breadth of laboratory capabilities and ability to work with NIST's information technology department and other government agencies to meet the PSCR's radio test capabilities indicate that the Innovation Lab is achieving its stated objectives.

PUBLIC SAFETY INNOVATION ACCELERATOR PROGRAM

As mentioned above, the PSCR received $300 million in public safety trust funds through the Middle Class Tax Relief and Job Creation Act from 2016 to 2022 and established the PSIAP. To expand research breadth, the PSCR used PSIAP funds to capitalize on the expertise of researchers nationwide and outside the United States in the form of grants and prize challenges. Of the $300 million public safety trust funds, $108.76 million was used to provide external grants to other researchers, and $5.3 million was used for prize challenges (246 winning teams among 20 challenges), with $8.1 million having been spent to date, including Scientific and Technical Research and Services funds made available following the close of the $300 million supporting two additional challenges. The PSCR funding also supported a relatively small number of distinct non-U.S. participants with complementary expertise, but inclusion of a U.S. partner in the prize challenge team was a requirement for funding.

SCIENTIFIC EXPERTISE

The PSCR's expertise across the portfolio of projects in the MCX, the UX, the LBS, the UAS, and the Innovation Lab supports its objectives reasonably well. The MCX's success in taking the broadband mission-critical PTT from an unsolved engineering and standardization problem to a final technology transfer stood out to the panel among the PSCR portfolios. While the UX staff is adequately supporting its technical programs, the portfolio could benefit from additional staff to support a test and evaluation setup for commercial partners. Similarly, the LBS group could better confront the numerous unsolved problems in signal processing and engineering with a larger team of researchers with expertise in areas such as RF propagation, optics, signal processing, radar, imaging, and communications. The UAS group operates much differently than the other portfolios, borrowing organization and management models aligned more closely to the Defense Advanced Research Projects Agency Grand Challenges.

Across research portfolios, approximately 8 percent of the PSCR federal employees have a PhD, which is relatively low compared to the Communications Technology Laboratory (CTL) average of 47 percent. This discrepancy can be attributed to some extent to the applied nature of the work at the PSCR, which requires close engagement with the first-responder community. Adding more PhD researchers with relevant backgrounds in applied research could contribute to research depth led by the PSCR and accelerate adoption of critical communication capabilities for first responders via enhanced cross research portfolio collaboration. Nonetheless, the PSCR produces many publications (75 out of 384 total publications for the CTL from 2022 to 2025, amounting to 19.5 percent), which is commendable. As further testament to its high-impact work, the PSCR received a 2023 Gold Medal from the Department of Commerce for "development and execution of a $300 million intramural and extramural R&D program that enabled the advancement of critical public safety communications technology," where funds were used to "pioneer technological innovation, accelerate cutting-edge communications research, and set critical communications standards" (NIST n.d.).

The infusion and then expiration of PSIAP funding required the PSCR to expand and then downsize its personnel, from 9 federal staff and 21 associates in 2015, to 38 federal staff and 40 associates in 2020, down to 25 federal staff and 7 associates in 2025. This short-term scaling up and scaling down of staff may have impacted PSCR's ability to assemble a more diverse team of MS and PhD researchers in areas such as communications, sensing, control, augmented reality, and computer science. Consequently, the PSCR appears to have limited ability to adequately formulate and address the myriad public safety R&D challenges within its remit. It is surprising that the organization has achieved such great impact with such a small headcount.

FACILITIES, EQUIPMENT, AND HUMAN RESOURCES

Facilities, equipment, and human resources support the needs of the PSCR's technical programs and assist the division in achieving its stated objectives. The PSCR's facilities stood out as a major positive feature for the division. For example, as introduced above, the LBS portfolio is building a stairwell outfitted with an infrared system for high-accuracy (x,y,z) indoor positioning. This state-of-the-art z-axis positioning test facility will provide unique capabilities for conducting z-axis testing at a subcentimeter resolution in a tightly controlled environment (i.e., for indoor location-based services). If successfully completed and marketed to outside groups, the LBS facilities will have significant impact on solving the public safety indoor positioning problem and could be used by both NIST and outside organizations for testing.

The PSCR portfolios have excellent equipment, which is likely a result of the past $300 million investment through Public Safety Immersive Test Center PSIAP. The Innovation Lab provides access to radio networks and measurement capabilities that meet or exceed those of any top research-focused organization. Multiple portfolios utilize infrared positioning cameras for ground-truth or augmented and virtual reality work. The portfolios seem to have adequate computing capabilities.

The Innovation Lab has the responsibility to secure operation of the equipment, including equipment for interoperability, which requires systems to be kept reasonably current. The maintenance of public safety systems—including hardware and software fees and the services to perform upgrades—requires significant funding. A plan for maintenance of equipment that is grounded with stakeholder requirements and funding sources is needed.

The PSCR currently faces a cultural change from administering grants and prize challenges to performing early TRL work. Between 2022 and 2023, with the expiration of PSIAP funding, the PSCR underwent a major transition, having to juggle priorities and transition smoothly to end projects, decrease team size, and maintain researcher morale. The division has succeeded in its transition, including upholding the morale of remaining employees, and the PSCR leadership is commended for maintaining a strong program in such a difficult situation.

The PSCR could be strengthened by increasing the organization's staff to a level where a holistic and multifaceted public safety research program could be conducted.

EFFECTIVENESS OF DISSEMINATION OF PROGRAM OUTPUTS

Stakeholder Engagement

The PSCR prioritizes involving public safety stakeholders, as evidenced by its innovation summit, close collaboration with FirstNet, and community outreach. The division was founded on stakeholder input, with past stakeholder events charting the work done today. The division currently works with stakeholders in multiple ways, including conferences and other convenings, roadmapping activities, surveys, and interviews. The PSCR's "5×5: The Public Safety Innovation Summit" (5×5 Summit) draws public safety organizations, equipment manufacturers and industry innovators, academia, and federal government partners from around the United States and across the world and is an example for how other NIST laboratories and divisions can transfer their research outputs, identify new problems, and advertise their work.

The PSCR has leveraged insights from its stakeholders in developing its roadmap. Between 2015 and 2017, they met with companies, universities, and agencies to collect input for their roadmapping exercises. The PSCR also held follow-up workshops and roundtables between 2018 and 2024, which resulted in a variety of published NIST reports on highly mobile deployable networks, Internet of Things, wildland–urban fire response, cybersecurity and AI risk management in UAS, and mission-critical voice. The PSCR also performed a comprehensive survey of communication technology experiences with more than 7,000 participants from the first-responder community and published the findings in a 2022 NIST report (Pintar et al. 2022). Subsequently, NIST held more than 80 semistructured interviews with the incident response community (fire, law, emergency medical services, dispatch) with around 93 hours of interview time, which revealed that open problems can be explained by three factors: budget and logistics, technological needs, and information gaps.

Several stakeholder engagement activities within individual research portfolios are worth highlighting. The MCX staff identified stakeholder concerns that were serving as a barrier for adoption of public safety mobile broadband. They then worked with partners to get conformance testing through 3GPP and later transition it to commercial partners. This serves as the best example of working with end users, commercial manufacturers, network operators, and international standardization bodies. In addition, as described above, the UAS group conducts unmanned vehicle challenges with competitors from around the globe. These challenges integrate stakeholder use cases into short development cycle unfunded tests, giving stakeholders quick experimental feedback. The UX staff has conducted numerous interviews and other training laboratory interactions with fire departments throughout the United States.

At the division level, the PSCR convenes an annual 2-day meeting for its leadership—including portfolio leads and program managers—to track impact, project objectives, partnerships, and engagements. The PSCR executed four rounds of a 12-week commercialization accelerator program for 34 emerging technology companies that support the public safety and first-responder sectors. Among the 28 participants in the first three cohorts, 16 have received follow-on funding from external agencies and the private sector, in amounts totaling over $27 million, which is a notable success (data are still being collected for the fourth cohort). The PSCR also works closely with FirstNet Authority, meeting annually to discuss alignment between objectives.

The priorities for stakeholder engagement have been shifting because the PSIAP grant money has ended. The PSCR has been focusing on more structured collaborations with the community. The staff plan to meet stakeholders to conduct portfolio workshops and update their roadmap. The PSCR currently has nine active Cooperative Research and Development Agreement (CRADA) partners and two Memorandum of Understanding partners for close collaborations. Some CRADA partners, both past and in development, have previously worked with the PSCR as past grant awardees, showing the impact of past engagements through PSIAP funding. Because the PSCR works closely with stakeholders, it closely monitors stakeholder use and impact. The only way to improve this would be to substantially increase the staffing.

Dissemination and Technology Transfer

The PSCR is very effective at dissemination and technology transfer despite its small size. Its dissemination includes traditional mechanisms and nontraditional approaches—with laboratory tours; roundtables and workshops; working groups; CRADAs; external events and conferences; grants and prize challenges; and its annual flagship event, the 5×5 Summit. The 5×5 Summit has drawn up to 600 attendees in years past. It involves a broader stakeholder community and features presentations and technical demonstrations of developed technologies by the PSCR and FirstNet Authority staff and partners, including the PSCR grantees and prize challenge awardees. Participants have noted that the quality of the event has been improving each year. The PSCR has funded a large number of academic institutions, as indicated in its award recipient database (CTL n.d.)https://www.nist.gov/ctl/pscr/funding-opportunities/award-recipient-database). The PSCR also has a good record of technology transfer, having supported partners in advancing their prototypes toward commercialization by pairing them with subject-matter experts about topics such as building financial projections, assessing their team and human resources plans toward growth, and creating and refining their business pitches and other business growth strategies. An independent economic analysis examined the impact of the $230 million investment in the form of the PSCR grants, prize challenges, small business innovation research, and internal research between FY 2016 and FY 2020, finding that they generated 4,280 jobs and $513 million in total economic output (Nadeau et al. 2021). Using the same algorithm to analyze additional investments made as of October 2022, of the $348.8 million invested, the PSCR has generated 6,043 jobs and $807.1 million in total economic output.

CONCLUSIONS AND RECOMMENDATIONS

The PSCR-focused conclusions and recommendations are based on the judgement of the panel regarding the alignment of the material presented during the assessment with the PSCR Division objectives presented in Table 2-1. The panel recognizes the relevance of the public safety mission in the context of the broader national security mission. Thus, recommendations primarily address amplification, dissemination, and acceleration.

> *Conclusion 2-1: The MCX portfolio is the most mature and strongest of the five PSCR portfolios. The MCX and its partners were able to shepherd conformance testing through the Third Generation Partnership Project (3GPP), develop standards-based conformance testing scripts, and transfer this work to commercial testing and evaluation companies. This high-impact work stands out because the MCX played a critical role from inception to commercialization. The Mission Critical Services (MCX) portfolio has prioritized forging partnerships and achieving impactful outcomes. The activities of the portfolio have helped make Long-Term Evolution and 5G New Radio–based first-*

responder networks viable alternatives to traditional Land Mobile Radio (LMR) systems. However, lack of trust and feature parity have slowed the decommissioning of LMR systems. The MCX portfolio also deals with complicated and evolving standards, and they could play a key role in guiding first-responder radio and network evaluation. What PSCR has been able to accomplish with very little resources is not only impressive but may be a best practice to replicate.

Recommendation 2-1: When developing the next evolution of the Mission Critical Services research beyond conformance, the Public Safety Research Division leadership should add or update research on the minimum feature parity necessary for first-responder agencies to trust the transition from Land Mobile Radio to newer technologies. Examples include trust in the ruggedized device and reach beyond radio coverage (e.g., via satellite or device to device mechanisms).

Conclusion 2-2: The User Experience (UX) portfolio has made a focused effort at creating a realistic scenario for first-responder training via mock-up of an apartment in a hazardous materials situation. Training techniques like this hold much potential for improving the way first responders are trained nationwide, but the number of first responders who can directly benefit from the NIST environment is limited. The impact of the UX portfolio could be increased by broadening its focus toward dissemination of learning, e.g., to assist with measurement sciences, standards development, guidelines for adoption of critical communications capabilities for first responders, and interface specifications for reusable datasets.

Recommendation 2-2: To amplify the potential impact for society, PSCR leadership should require each project, for example the User Experience portfolio's mock-up training environment, to specify the anticipated amplification outcomes in all four Public Safety Communications Research Division research value areas as appropriate:

- **a. Measurement sciences,**
- **b. Standards development,**

c. **Accelerating the adoption of critical communication capabilities for first responders, and/or**
d. **Reusable datasets.**

Conclusion 2-3: One of the challenges for Land Mobile Radio transition to newer 5G/xG technologies was trust in the device. There is a need for focused basic research on public safety radios within the United States; the Public Safety Communications Research Division could be the leading U.S. research and development organization on this topic if it was properly resourced. For example, the Location-Based Services group could better confront the numerous unsolved problems in signal processing and engineering in indoor adverse situations with a larger team of researchers with expertise in areas such as RF propagation, optics, signal processing, radar, imaging, and communications. The Mission Critical Services (MCX) team could lead the evolution of MCX application programming interfaces to take advantage of Integrated Sensing and Communications.

Recommendation 2-3: The Public Safety Communications Research (PSCR) Division leadership should increase the ratio of personnel with PhDs to expand its research depth. Given the PSCR division's success in connecting with relevant stakeholder feedback, hiring more PhD researchers with diverse backgrounds may help to accelerate application of new technologies, such as integrated sensing and communications, for PSCR community use cases while also addressing the device trust concerns expressed by stakeholders.

Conclusion 2-4: There is significant maintenance cost to keep current each Public Safety Innovation Lab subsystem (Project 25 Land Mobile Radio [LMR] systems two companies, 4G/5G systems, radio frequency chambers, interoperability systems between LMR and Long-Term Evolution, Mission-Critical Voice Quality of Experience system, and Mobile Research Vehicle). A better understanding of the projects and active grant proposals dependent on each subsystem is needed to better understand the business tradeoff between the maintenance cost of each system and relevance of the system for the PSCR mission moving forward.

Recommendation 2-4: To make a business decision on when to decommission each Public Safety Innovation Lab system, the Public Safety Communications Research Division leadership should analyze the cost to keep each system current and its ability to allocate these costs to ongoing research projects and future grant awards. The visibility to the dependencies and maintenance costs should be shared with stakeholders.

Conclusion 2-5: The Public Safety Communications Research Division (PSCR) aims to play a key role nationally in guiding public safety radio development, radio evaluation, radio testing, first-responder training, and new technology integration. Research and development in these areas could also impact commercial radio networks and training and communication systems in other industries (e.g., mining, oil and gas, railways). The PSCR prioritizes interaction with targeted stakeholders, and stakeholder use of the PSCR infrastructure, outcomes, and guidelines appears well monitored. The PSCR may benefit from measuring or documenting each portfolios' impact to the broader community, beyond the targeted stakeholders. Visibility to indirect impact may bring to the surface additional societal challenges.

Recommendation 2-5: The Public Safety Communications Research Division leadership should consider monitoring value beyond the targeted stakeholders—for example, those to whom the information was disseminated—in addition to monitoring stakeholder value. For example, a mapping of potential ripple effects from dissemination of each portfolio's outcome may highlight areas of potential cross portfolio collaboration need.

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3
Radio Frequency Technology Division

The Radio Frequency Technology Division (RFTD) at the National Institute of Standards and Technology (NIST) Communications Technology Laboratory (CTL) maintains strong capabilities in metrology science and calibration services, with recognized contributions in quantum sensing and high-frequency electronics. RFTD work impacts all time-critical systems across national security and civilian infrastructure domains, improving technology from cell phones to computer chips. This assessment evaluates the division's performance against the mission of a national metrology institute (NMI), comparing capabilities with peer institutions and assessing whether the division adequately supports U.S. industry and research needs.

BACKGROUND ON THE RADIO FREQUENCY TECHNOLOGY DIVISION

The RFTD operates through four research groups: the Electromagnetic Fields Group, the Guided Wave Electromagnetics Group, the High-Speed Waveform Metrology Group, and the Superconducting Electronics Group. Table 3-1 provides an overview of the objectives of each of these research groups.

TABLE 3-1 Overview of the Radio Frequency Technology Division Research Groups

Program Area	Objective
Electromagnetic Fields Group	Provide traceable electromagnetic field strength measurements for international standards and electromagnetic compatibility evaluations
Guided Wave Electromagnetics Group	Provide fundamental electromagnetics research (measurements, modeling, and theory) for advanced wireless communications and other priorities in electromagnetics at radio, microwave, and millimeter-wave frequencies
High-Speed Waveform Metrology Group	Advance measurement science in high-frequency communications to enable accurate characterization of signals critical to 5G and 6G networks
Superconducting Electronics Group	Leverage quantum technologies to develop voltage standards, quantum waveform synthesis, and radio frequency metrology techniques

SOURCE: Committee generated using CTL (2025).

Technical work is organized around metrology portfolio areas, aligning long-term activities with national metrology needs:

- RF Metrology and Calibrations—standard reference instruments, measurement standards, and calibration services spanning power, impedance, field strength, antenna calibration, and quantum voltage standards;
- High-Speed Microelectronics—metrology for Next Generation Communications (NextG) wireless, high-speed microelectronics, and quantum communications; and
- Quantum Communications—quantum sensing, computing, and networking measurement techniques.

The division maintains international standards contributions through multilateral measurement intercomparisons, participation in France's Bureau International des Poids et Mesures (BIPM) key comparisons, and collaborations with national metrology institutes including the National Institute of Advanced Industrial Science and Technology in Japan for antenna metrology at 140–220 gigahertz (GHz), the Korea Research Institute of Standards and Science for quantum computing metrology, and the National Institute of Aerospace Technology in Spain for Josephson voltage standards deployment.

TECHNICAL PROGRAMS

The RFTD manages four primary portfolios—Calibration, NextG, High-Speed Microelectronics, and Quantum—with a $24 million budget (approximately $9.2 million in base funding) and 51 federal employees out of 108 total staff. The division has achieved notable success in establishing new measurement capabilities and enabling technology transfer, although questions exist about strategic priorities and resource allocation.

Quality of Research Compared to World-Class Standards

The Rydberg sensor development represents a paradigmatic success for NIST's measurement science mission. NIST established SI-traceable RF field measurement methods that enabled an entire industry sector—approximately 25 companies with $100 million in commercial activity now build upon NIST's measurement foundations. This exemplifies the appropriate NMI model: NIST develops measurement science at low technology readiness level (TRL), and industry implements commercial systems at high TRL. Since 2021, NIST's Rydberg sensor program has secured approximately $14 million in external direct funding, earned multiple Department of Commerce awards, and delivered more than 50 publications, conferences, and patents—highlighting both scientific excellence and translational impact. By pioneering atoms as calibrated metrology artifacts, NIST transformed RF probe calibration into atom-based primary standards, reducing uncertainties and positioning the United States as the global leader in RF quantum sensing. Beyond metrology, the program has demonstrated novel applications including atom-based receivers, RF imaging, angle-of-arrival sensing, and blackbody/voltage standards, underscoring its broad technical reach.

NIST maintains foundational voltage standard capabilities with uncertainties at parts in 10^{12}. International comparisons with BIPM, the National Metrology Institute of Japan, and NIST achieved agreement within 5 parts in 10^{12} (Rufenacht et al. 2018). NIST systems are replicated globally by other NMIs, demonstrating sustained technical leadership comparable to Physikalisch-Technische Bundesanstalt in Germany and the National Physical Laboratory in the United Kingdom. Since 2010, NIST has disseminated more than 25 programmable Josephson voltage standards, 20 cryopackaged systems, and 8 Josephson arbitrary waveform synthesizers worldwide, supporting NMIs, national laboratories (NASA Houston, Sandia National Laboratories, Oak Ridge National Laboratory), and industry leaders (HP, Keysight, Fluke, Boeing). These platforms deliver quantum-accurate references up to 10 volts (V) direct current (DC) and multivolt alternating current (AC) waveforms, with DC–DC comparison reproducibility of 3×10^{-11}, underscoring NIST's role in setting and maintaining the global benchmark for voltage metrology.

The Electro-Optic Sampling system provides waveform characterization up to 1 terahertz (THz) with 100 femtosecond (fs) resolution, establishing measurement capabilities that surpass commercial instruments, which typically operate below 100 GHz. It delivers traceable magnitude and phase references that support calibration of oscilloscopes, analyzers, and network systems, with possibility of traceability greater than 250 GHz and high spatial waveform imaging. The program has produced peer-reviewed results (e.g., Bosworth et al. 2023; Cheron et al. 2022), although high-impact publications are still limited, secured CRADAs with industry, and established calibration pathways for the Department of War (DOW) and six companies, underscoring its technical rigor and measurable impact.

NIST's cryogenic RF calibration program leads internationally by integrating probe stations inside dilution refrigerators for on-wafer measurements below 0.1 K, enabling calibrated scattering-parameter and modulated-signal characterization of quantum devices. The group has developed cryogenic microelectromechanical systems switch networks for high-throughput calibration, as well as standard qubits, power sensors, and single-photon sources to support round-robin interlaboratory comparisons. With multiple peer-reviewed demonstrations since 2020 and commercial prototypes already tested down to 0.1 K, NIST provides unique capabilities unmatched by other NMIs.

Critical Gaps in Supporting Emerging Industry Needs

The panel's assessment of gaps, summarized below, is based on division presentations and early career researcher posters representing examples of ongoing work. These may not reflect the complete scope of division capabilities, and additional programs exist beyond those presented during the review.

6G Frequency Range: Measurement Science Gap

NIST capabilities in channel sounding and general RF metrology remain largely below 100 GHz, while 6G standards development targets 100–300 GHz (THz bands). The division demonstrates antenna metrology work at 140–220 GHz through bilateral comparisons with the

National Institute of Advanced Industrial Science and Technology in Japan, indicating partial capability in this frequency range for antenna-specific applications. However, Third Generation Partnership Project (3GPP 2025) TR 38.901 Release 19 now covers 0.5–100 GHz, and industry consortia are planning systems across the broader 100–300 GHz range for channel characterization, device testing, and system validation.

Assessment: This discrepancy represents a measurement science gap—U.S. industry developing 6G technologies may lack NIST-traceable measurement methods beyond the antenna-specific capabilities already demonstrated. NIST should either develop broader THz measurement capabilities to support U.S. 6G development across channel sounding and device characterization or explicitly determine that these frequencies fall outside mission scope and that industry must develop measurement methods independently.

Hot Qubit Metrology: Development Program in Progress

The division's 100 GHz/1 K hot qubit program is in active development, targeting qubit frequencies of 10–100 GHz to enable approximately 1 K operation versus standard <50 mK requirements. Early career researchers report infrastructure development with external collaborations, including University of Colorado, Dartmouth College, Google, and Fermilab/Brookhaven National Laboratory, with five publications, one patent, and ongoing measurement system development. However, academic institutions, including University of Chicago/Stanford University and TU Delft, have demonstrated operational high-frequency and elevated-temperature qubit systems several years ahead of NIST's current development status.

Assessment from NMI perspective: The program demonstrates appropriate strategic positioning through strong external collaborations and active infrastructure development. However, NIST is several years from providing operational measurement support for industry. If quantum computing platforms transition to elevated-temperature operation in the near term, U.S. industry may require measurement capabilities before NIST systems reach maturity. The division should undertake a hot qubit metrology program strategic review to clarify (1) the anticipated timeline for operational measurement services, (2) whether its development pace matches projected industry needs, and (3) the decision criteria for resource allocation given the multiyear gap between current status and demonstrated academic capabilities (Recommendation 3-1).

Quantum Transduction: Mission Alignment Question

Literature searches reveal that NIST participates primarily in theoretical quantum transduction work, while experimental demonstrations with reported end-to-end efficiency come from international institutions.

Assessment from NMI perspective: The critical question is whether quantum transduction represents a measurement science need (NIST's role) or a quantum device development need (not NIST's role). If U.S. quantum networking efforts require standardized transduction measurement methods, NIST could develop them. If transduction is purely a device engineering challenge, NIST's theoretical contributions may be sufficient NMI support. The division should clarify the industry need and whether current activities appropriately address it.

Strategic Resource Allocation

A fundamental strategic issue emerges from resource allocation: approximately 50 percent of researcher effort is devoted to performing calibration services rather than developing new measurement capabilities. While providing calibrations is a core NMI function, this raises efficiency questions. Are highly skilled PhD researchers the appropriate workforce for routine calibrations, or should technicians perform these services? Does the current calibration fee structure (up to 900 percent markup) provide sufficient cost recovery to support both service provision and capability development?

The division's stated goal to enable others to perform NIST-level calibrations aligns well with NMI best practices. The Air Force Metrology and Calibration Program has successfully developed primary standards capability, exemplifying this model. However, no systematic plan exists to transition additional routine calibrations to qualified secondary laboratories, which would free NIST researchers to focus on developing measurement capabilities for emerging technologies.

Channel Sounding: Mission Alignment and Deployment Limitations

The Next Generation Communications program includes the design, construction, and use of channel sounders in a millimeter-wave and sub-THz bands. Channel sounders are critical in providing an experimental basis for channel models used to assess communication (and, more recently, sensing) system performance. This is an important and natural role for CTL, as it helps derisk commercial use of these bands. The sounder equipment is state of the art, covering all relevant signal properties (path loss, polarization, angles of arrival and departure, etc.). The primary accomplishment is system integration of various components and collection of channel sounding data in select environments. However, the resulting sounder is physically large and heavy so as to restrict measurement to short-range, indoor locations where a cart can be pushed on a level floor. Commercially important environments, such as macrocells, which have rooftop or tower-mounted antennas, are thus not measurable using such a sounder. This restricts the applicability and impact of the resulting data and conclusions. Additionally, the current use of a BNC coaxial cable to synchronize the sounding transmitter and receiver limits the range of the system. The next iteration of the sounder design can be improved by exploring use of any of the NIST optical clock technology to remove this restriction.

SCIENTIFIC EXPERTISE

The RFTD possesses strong scientific expertise across its mission areas, with recognized contributions in quantum sensing, high-frequency electronics, and calibration sciences. Staff have pioneered measurement methods including Rydberg atom electrometry and electro-optic sampling to 1 THz, and have advanced channel sounding methodologies. Early career researchers demonstrate enthusiasm and technical depth, contributing to a vibrant research environment.

World-Class Expertise Assessment

The Rydberg sensor development team exemplifies NIST's capacity for pioneering measurement science. Starting as exploratory work in 2010 that was difficult to justify for funding, this program has established an entirely new measurement field and enabled commercial sector development, demonstrating NIST's culture of supporting long-term technical vision with high-risk, high-reward potential. The high-frequency electronics group's work on characterizing heterogeneous (3D) microelectronics helps position NIST to support semiconductor industry measurement needs, particularly the Creating Helpful Incentives to Produce Semiconductors and Science Act objectives. This work now underpins a $100 million U.S. commercial sector and has reduced RF field measurement uncertainties. The team's more than 100 publications, 8 patents, and the Department of Commerce Gold Medal and Ron Brown Innovation Award confirm global scientific leadership, while approximately $14 million in recent external funding (Defense Advanced Research Projects Agency, Department of Energy, DOW) highlights broad impact. Beyond metrology, NIST has demonstrated atom-based receivers, RF imaging, angle-of-arrival sensing, and traceable power and voltage standards, bridging fundamental physics and applied measurement needs.

As another example, the Electro-Optic Sampling team demonstrates world-class expertise in high-frequency waveform calibration, developing the first traceable system reaching up to 1 THz with 100 fs resolution—well beyond the below 100 GHz limit of commercial tools. Their methods provide absolute magnitude and phase references for oscilloscopes, analyzers, and network systems, with calibration services already adopted by DOW and industry partners. Recent advances in modulation traceability (Institute of Electrical and Electronics Engineers [IEEE] 1765 EVM), photodiode calibration to 250 GHz, and on-wafer imaging confirm NIST's leadership in waveform metrology.

In the area of quantum voltage standards, NIST's superconducting electronics group maintains foundational voltage standards with uncertainties at parts in 10^{12}, comparable to or exceeding Physikalisch-Technische Bundesanstalt and the National Physical Laboratory (NPL). International comparisons with BIPM, the National Metrology Institute of Japan, and NIST agree to within 5 parts in 10^{12}. The dissemination of more than 25 programmable Josephson systems and 8 waveform synthesizers since 2010 demonstrates sustained leadership. These platforms provide quantum-accurate references up to 10 V DC and multivolt AC waveforms, establishing NIST as the global benchmark in electrical metrology.

The division's publication output of 103 papers over 3 years for 51 federal employees translates to roughly 0.67 publications per researcher per year. This rate must be contextualized: research staff dedicate approximately 50 percent of their efforts to calibration services, meaning the effective publication rate reflects half-time research capacity. The division has received significant recognition through the Arthur S. Flemming Award and Presidential Rank Award, demonstrating individual research excellence. The division contributed five patents from 2022 to 2025 and maintains international engagement with BIPM, the Korea Research Institute of Standards and Science, and Japan's National Institute of Advanced Industrial Science and Technology through bilateral antenna metrology comparisons at 140–220 (GHz), Josephson voltage standards deployment to Spain's National Institute of Aerospace Technology, and participation in standards development including IEEE P1765 and 3GPP.

Expertise Development Needs

The division shows limited recruitment connections with universities beyond the local region. The formal Professional Research Experience Program (PREP) partnerships are administered by the NIST International and Academic Affairs Office and are restricted to four institutions which are partners on the current grant for the Boulder facility: three Colorado universities (University of Colorado Boulder, University of Colorado Denver, and Colorado School of Mines) and New Mexico State University. Some researchers from other institutions work at Boulder through mechanisms such as the National Research Council postdoctoral program or individual collaborations. In contrast, peer NMIs demonstrate broader formal academic engagement: Physikalisch-Technische Bundesanstalt engages more than 30 universities where doctoral students maintain academic supervisors, and the NPL's Postgraduate Institute collaborates with approximately 35 UK academic institutions. This difference in partnership breadth may limit the division's access to emerging research areas and diverse talent pools.

Between January and September 2025, CTL experienced a reduction of 19 federal staff members (10.7 percent), declining from 178 to 159 employees. These dates were selected to capture the impact of recent government-wide voluntary workforce reduction policies. This includes the Voluntary Early Retirement Authority program and other voluntary departures across the tenure spectrum. The reduction was not distributed uniformly across divisions: Smart Connected Systems was disproportionately affected with a 33 percent reduction (from 27 to 18 staff), while RFTD lost 11 percent of its workforce (from 54 to 48 staff). The tenure statistics reveal concerning patterns. While average years at NIST increased by 0.61 years and average time in grade increased by 0.63 years—both slightly below the expected 0.75-year increase from the 9-month elapsed time—the average years since the last degree *decreased* by 0.53 years. This counterintuitive decrease indicates the loss of more experienced researchers, as natural progression should have increased this metric. Additional context is provided by looking at data from January 2024. It is clear that the hiring freeze during 2025 kept CTL from replacing departed staff with more junior new hires as was done in 2024.

Additionally, the retirement of key personnel, such as the main architect of the uncertainty software, highlights institutional knowledge risks. No formal succession planning process or knowledge transfer protocols were described during the review. Given the specialized nature of metrology expertise, loss of senior staff without planned knowledge transfer could compromise NIST's ability to maintain measurement capabilities.

Workforce stability is also a concern. Associates and permanent staff in probationary status face job uncertainty because of recent government actions. This is likely to impact performance and project continuity. The division reports good diversity in recruitment mechanisms with 57 associates including postdoctoral researchers, PREP researchers, and international associates, but retention becomes difficult once they complete degrees, given very limited availability of permanent positions at NIST. The combination of recent workforce reductions, loss of experienced researchers, ongoing institutional knowledge risks, and continued uncertainty for associates and probationary staff creates a compounding challenge for maintaining CTL's technical capabilities. The committee recommends tracking workforce metrics quarterly to evaluate stabilization and guide strategic workforce planning (Recommendation 3-6).

FACILITIES, EQUIPMENT, AND HUMAN RESOURCES

Infrastructure Deficiencies Compromising Metrology Mission

The division's facilities face significant infrastructure challenges that actively compromise its ability to provide reliable national measurement standards—the core NMI function. Multiple facilities experience power failures (both planned and unplanned), uncontrolled temperature issues affecting calibration chamber stability, and inadequate environmental controls requiring makeshift solutions like opening windows for equipment cooling. The absence of backup power systems represents a fundamental failure for an NMI to provide the foundation of U.S. measurement traceability and protect national standards.

Infrastructure failures directly threaten NIST's ability to provide reliable calibration services and maintain measurement standards. Industry and government customers rely on NIST for measurement traceability—these failures undermine this core function. Despite inquiries about facility repair and improvement funding, no concrete plan exists to address these deficiencies beyond attempting to "minimize impacts" of ongoing issues.

Equipment Limitations

Laboratory equipment generally supports current measurement services across the frequency spectrum. Notable systems include material measurement systems for RF and microwave frequencies of 1 megahertz to 100 GHz, antenna testing facilities, and integrated circuit characterization capabilities. However, equipment limitations may constrain the division's ability to support emerging U.S. industry needs, particularly for cryogenic RF measurements where the NPL has demonstrated capabilities to tens of millikelvin.

Human Resource Challenges

The division faces a persistent technician shortage, a challenge that extends across the laboratory. This shortage has resulted in graduate students and postdoctoral researchers filling roles that could be performed by technicians in support of both research and calibration services. Retention becomes difficult once these individuals complete their degrees, creating an ongoing cycle that has not been addressed through systematic workforce planning. The absence of a stable technician workforce requires PhD researchers to spend significant time on routine calibration tasks rather than advancing measurement science. Developing high school apprenticeship programs leading to technician certification and/or partnering with relevant technical training programs could provide a sustainable solution to this persistent workforce gap.

Cost Recovery Model

Despite high calibration fees, cost recovery remains insufficient to support both facility needs and capability development. This suggests fundamental issues with overhead and wrap rate structures, or that the current service volume cannot sustainably fund both operations and innovation.

EFFECTIVENESS OF DISSEMINATION OF PROGRAM OUTPUTS

Dissemination Strengths

The division demonstrates competence in traditional NMI dissemination methods including journal publications, conference presentations, technical reports, and standards development. Notable technology transfer successes include automation of the Josephson voltage standard, enabling adoption by other NMIs; development of primary standards lab capability within the Air Force Metrology and Calibration Program; development of open-source Open Radio Access Network (O-RAN) testbed tools, and development of the NextG Channel Model Alliance data repository. Testbed tools and research for 5G O-RAN are a potential area of new or increased collaboration with the Spectrum Technology and Research Division. These examples demonstrate appropriate NMI technology transfer: NIST develops measurement methods and makes them available for implementation by others.

Strategic Planning and Stakeholder Engagement Framework

CTL has established systematic strategic planning processes including roadmap development with stakeholder engagement (surveys, interviews, working groups); formal project planning with 2–3-year horizons; and quarterly reviews tracking research progress, budget, and risks. This systematic approach addresses 2022 National Academies' recommendations for R&D roadmaps and demonstrates proactive planning aligned with industry needs. Impact assessment could be improved by estimating economic value of calibration services, systematic tracking of measurement method adoption in commercial products, and examination of industry development based on NIST dataset support. This could be accomplished via an industry survey to identify priority U.S. measurement requirements, perform gap analysis of NIST's capabilities versus industry needs, and create an evidence base to rank priorities.

Opportunities for Enhanced Impact Assessment

While the division tracks research outputs through quarterly reviews (publications, standards contributions, conferences attended, laboratory tours provided, Cooperative Research and Development Agreements established), opportunities exist to strengthen demonstration of economic value and industry adoption. Quantifying calibration cascade economic impact (e.g., 25 power calibrations enabling 30,000 DOW calibrations annually), systematically tracking technology adoption in commercial products, and analyzing how datasets support industry development would provide stronger evidence of mission impact. International metrology institutes like the NPL and the National Metrology Institute of Japan provide models for comprehensive impact assessment and economic value quantification.

CONCLUSIONS AND RECOMMENDATIONS

CTL's RFTD is a global leader in metrology and has pioneered many advanced technologies, even leading to completely new industries. The subpanel frames its conclusions and recommendations to highlight strengths and address critical issues for the division's advancement.

Conclusion 3-1: The Radio Frequency Technology Division has strengths in metrology, measurement sciences, and technology development:

- *Strong foundational metrology capabilities (e.g., Josephson standards and radio frequency power and scattering-parameter measurements, competitive with leading peer national metrology institutes);*
- *Successful measurement science innovation enabling new industries (e.g., Rydberg sensing); and*
- *Active development programs with strong external collaborations positioning for future industry needs (e.g., hot qubit metrology with industry, national laboratories, universities, magnetic materials, 5G/6G electromagnetic compatibility frameworks).*

Conclusion 3-2: The Radio Frequency Technology Division effectively disseminates its work by

- *Demonstrating an appropriate technology transfer model (the National Institute of Standards and Technology develops measurement science for low technology readiness level (TRL), and industry implements systems at high TRL) and*
- *Contributing effectively to standards development (e.g., Next Generation Channel Model Alliance, Third Generation Partnership Project participation, Institute of Electrical and Electronics Engineers standards development).*

Conclusion 3-3: The National Institute of Standards and Technology (NIST) has world-class expertise in Rydberg sensor science, defining the state of the art in atom-based radio frequency metrology. Emphasis on higher frequency (>110 gigahertz) and deployable system integration would help NIST to sustain its leadership.

Recommendation 3-1: Based on confirmed industry needs, the Radio Frequency Technology Division should develop terahertz-frequency measurement capabilities for 6G support or determine that the frequencies fall outside its mission scope; conduct a hot qubit metrology program strategic review to determine industry need and timeline, pace of NIST measurement capability development, and resource allocation decision criteria; and assess cryogenic radio frequency measurement requirements for the quantum computing industry.

Conclusion 3-4: Power failures, absent backup systems, and environmental control deficiencies represent an infrastructure crisis, and actively compromise the National Institute of Standards and Technology's ability to provide reliable national measurement standards. This threatens the core national metrology institute (NMI) function and risks loss of international credibility in key comparisons with other NMIs such as Germany's Physikalisch-Technische Bundesanstalt, the United Kingdom's National Physical Laboratory, and the National Metrology Institute of Japan.

Recommendation 3-2: The National Institute of Standards and Technology should install backup power systems for all measurement standards facilities; remediate environmental controls; stabilize temperature control for calibration chambers; and develop a multiyear capital facilities plan with dedicated funding.

Conclusion 3-5: Several programs show active development with appropriate external collaborations (hot qubit metrology, terahertz frequency extensions, cryogenic radio frequency), but timelines to operational capability may not align with U.S. industry needs. Early career researcher presentations demonstrate progress, but multiyear gaps may exist before measurement services reach maturity. Strategic clarification is needed on development pace versus anticipated industry demand, particularly for quantum computing and 6G technologies where academic and international capabilities are advancing rapidly.

Conclusion 3-6: The Radio Frequency Technology Division has established strategic planning with stakeholder engagement and quarterly tracking of research activities (publications, standards contributions, conferences, Cooperative Research and

Development Agreements). Opportunities exist to enhance impact assessment beyond activity metrics to include economic value quantification of calibration services, systematic tracking of measurement method adoption in commercial products, and analysis of how datasets support industry development. These enhanced metrics would strengthen demonstrated value and inform resource allocation.

Recommendation 3-3: The Radio Frequency Technology Division should conduct a strategic stakeholder needs assessment based on a comprehensive industry survey to identify priority U.S. measurement requirements; perform gap analysis comparing capabilities against industry needs; and develop an evidence-based priority ranking.

Recommendation 3-4: The Radio Frequency Technology Division should enhance its impact assessment by implementing comprehensive tracking of calibration service reach and economic value; develop technology adoption metrics; create systematic industry feedback mechanisms; and publish its annual impact assessment to demonstrate mission effectiveness.

Conclusion 3-7: The current model with PhD researchers spending a large percentage of time performing routine calibrations while calibration fees prove insufficient for facility or capability needs appears unsustainable. Peer national metrology institutes use different workforce models and cost recovery structures that may better support both service provision and innovation.

Recommendation 3-5: The Radio Frequency Technology Division should optimize its workforce by implementing or partnering with an existing technician training program for routine and high-volume calibrations and review cost recovery models for sustainability; conduct a comprehensive workforce assessment including experience demographics and retirement impact; develop succession plans for critical positions; and expand university recruitment relationships beyond the local region.

Recommendation 3-6: The Communications Technology Laboratory (CTL) should perform a workforce metrics analysis, tracking workforce metrics semiannually—

including headcount by division, average years at the National Institute of Standards and Technology, time in grade, and years since the last degree—to evaluate workforce stabilization, assess the ongoing impact of recent reductions, and guide strategic workforce planning.

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4
Spectrum Technology and Research Division

BACKGROUND ON THE SPECTRUM TECHNOLOGY AND RESEARCH DIVISION

The Spectrum Technology and Research Division (STAR), launched in 2021, performs research and development on "innovative measurement methods and tools to promote novel and efficient use of spectrum through improved access, sharing, atmospheric sensing, and precision timing" (Coder 2025, p. 5). STAR work increases the availability of spectrum for commercial use without impacting the military applications. The division is split into three primary research groups: Applied Systems Metrology, Fiber Sources and Applications, and Shared Spectrum Metrology. Together, these groups help ensure that the U.S. infrastructure for communications, spanning mobile phones to GPS, operate correctly and without interferences as the public expects. Table 4-1 provides an overview of the objectives of each of these research groups. The STAR also hosts the National Advanced Spectrum and Communications Test Network (NASCTN), in coordination with the National Telecommunications and Information Administration and other members of the steering committee, which provides testing and validated data for spectrum sharing technologies. As of September 2025, the division had 25 federal employees (19 permanent and 6 term limited) and 22 associates, domestic and international guest researchers, for a total of 47 staff members.

TABLE 4-1 Overview of the Spectrum Technology and Research Division Research Groups

Program Area	Objective
Applied Systems Metrology Group	Develop measurement techniques to evaluate deployed commercial and closed-box communication systems operating in congested and dynamic RF environments.
Fiber Sources and Applications Group	Advance the development and application of fiber-laser frequency combs for precision measurement in optical clocks, frequency transfer, ranging, and spectroscopy.
Shared Spectrum Metrology Group	Develop advanced measurement tools and methodologies to address challenges in the overcrowded RF spectrum.

SOURCE: Committee generated using CTL (2025).

Each of the three subdivisions has its own unique mission and research aims. The Applied Systems Metrology group develops technical foundations for spectrum science and measurement techniques for closed-box radio frequency (RF) systems. Research aims include interference susceptibility metrology and in situ field measurements of RF systems. The Fiber Sources and Applications group develops fiber-laser frequency combs for a variety of precision measurement applications, aiming to enable global-scale, femtosecond-level synchronization and open-path dual-comb spectroscopy. The Shared Spectrum Metrology group performs research on wireless coexistence, electromagnetic compatibility, spectrum sensing and noise, and interoperability for the 5G Open Radio Access Network (O-RAN) to inform standards and regulatory policy that address RF spectrum overcrowding.

TECHNICAL PROGRAMS

STAR is contributing to the National Institute of Standards and Technology (NIST) Communications Technology Laboratory (CTL) mission in fundamental metrology as well as current and future technology applications such as spectrum sensing and sharing. STAR is conducting groundbreaking work in its optical comb time-transfer project. This research is yielding synchronization accuracies—at widely separated locations up to several tens to hundreds of kilometers—of less than a femtosecond. This is orders of magnitude better than the accuracy that can be achieved with current satellite systems such as the Global Positioning System. In addition to precise network timing for quantum communications applications, this work will also enable more accurate geodesy, with potential use in earthquake and volcano monitoring. In dual-comb spectroscopy, NIST's Spectrum Technology and Research Division demonstrates strong atmospheric sensing measurement capabilities with 14.5 km city-scale open-path measurements and 155× compression factors (Giorgetta et al. 2024). NIST's focus on practical field implementation and SI-traceable measurement methods represents an appropriate NMI role—establishing measurement foundations that industry and academia build upon.

Work in spectrum sensing and sharing is also of high quality. Investigations include theoretical studies as well as field testing, the latter being one of the more comprehensive measurement campaigns to date. Development of field equipment for data collection exemplifies a high-value practical outcome for NIST and for the community at large. This work will also likely drive new theoretical and numerical investigations to advance the field. Work at STAR in spectrum sensing is going beyond conventional radiometric energy detection to explore more sensitive techniques such as correlation and cyclostationary processing. It could benefit STAR and the community at large to consider additional techniques such as interferometric (two-antenna) detection, feature detection, correlation (e.g., Durbin-Watson), and matched filtering, as these techniques are superior in performance to energy detection, at the cost of some additional complexity. Collaboration with the greater remote sensing community (e.g., space and airborne sensing platforms) is beneficial, as this community has a long history of success in both weak signal detection and interference mitigation. Expanded work in this area could benefit both the remote sensing community and terrestrial (e.g., cellular) spectrum sharing and sensing systems, potentially unifying the variety of processing techniques to gain new insights that can lead to improved performance.

In the past, STAR has explored the feasibility of using drones (uncrewed aircraft systems [UASs]) for in situ characterization of antenna arrays and spectrum systems. UASs are currently used to provide unique vantage points for spectrum measurements in the NASCTN Citizens Broadband Radio Service (CBRS) Sharing Ecosystem Assessment project, and to demonstrate some free-space spectroscopy techniques in the dual-comb spectroscopy project in the Fiber Sources and Applications group. Other explorations of aerial capabilities include a possible collaboration with an external partner to develop new electromagnetic compatibility measurement techniques to qualify high-altitude balloon payloads ahead of flight, and recent work funded by NASA and in collaboration with industry and universities to develop a novel noise-temperature calibration target based on a metamaterial design aimed to make a calibration target suitable for flight on a cubesat. Developing metrology and standards for communications technologies related to drones, low-altitude aircraft, and other emerging technologies like reconfigurable intelligent surfaces is a growth area for STAR, as these are becoming a bigger part of the communications technology landscape.

Radio frequency interference (RFI) poses a critical threat to spaceborne microwave radiometry, where even minor interference can lead to costly errors and compromised weather and environment data collection. As spectrum congestion grows, unwanted signals increasingly disrupt satellite observations. NIST CTL's advanced RF instrumentation, calibrated data collection, and interference modeling can provide essential tools to quantify and mitigate RFI, ensuring measurement integrity. RFI detection and mitigation is important with increasing spectrum use by emerging 6G nonterrestrial networks, low earth orbiting satellite constellations, and airborne platforms. With its leadership in precise radiometry, NIST is uniquely positioned to collaborate with the National Oceanic and Atmospheric Administration and NASA programs, advancing digital radiometry, onboard RFI mitigation, and small satellite calibration. This can strengthen the scientific community's ability to safeguard Earth observation systems.

STAR has a very wide range of stakeholders and collaborators including government, industry, standards organizations, and academia, addressing a diverse portfolio. The quality of the technical programs within STAR is adequate for the division to achieve its technical objectives, but continued improvement in these programs is required for any world-class organization, including NIST. Extending the CBRS spectrum sensing to new bands—for example, 7–8 gigahertz—is a good example of future planning. As the CBRS program matures, providing new understanding of how to effectively employ spectrum sensing would be useful to more rapidly deploy spectrum sharing systems in other bands, accelerating network efficiency and supporting economic growth. This knowledge can be obtained by studying RFI in a controlled simulation or emulation environment using RF digital twins. Commercial 5G companies have built digital twins in their laboratories to study the spectrum sharing impact on Department of War (DOW) radars but they usually do not have a higher-fidelity model of DOW radars. NIST may be better placed to work with DOW to use a high-fidelity model of their radars to interact with a digital twin at their facility.

Artificial intelligence (AI)-native wireless for 6G is emerging as a key trend, integrating AI across the communication stack for smarter, more efficient systems. Digital twins are also central to this vision, yet the lack of standards and reliable datasets limits progress. CTL is uniquely positioned to lead in establishing these standards by leveraging its advanced RF instrumentation and calibrated propagation data to create benchmarks for ray-tracing and other (e.g., AI-developed) models. AI for 6G is a ripe area for new or increased inter-division collaboration. Specifically, the RFTD can contribute heavily to the 6G AI-Native Channel Modeling work in STAR. CTL and the STAR would benefit from a strategic analysis of how they can contribute to metrology, data, and standards for emerging technologies in spectrum sharing including AI-based systems as well as millimeter wave and terahertz technology, within the growing NIST AI metrology and standards efforts. By collaborating with federal, industry, and academic partners, STAR can accelerate the adoption of AI-native wireless technologies, enable standardization of digital twins for communications, and position itself as a key partner in shaping 6G research.

SCIENTIFIC EXPERTISE

The scientific expertise within STAR is of very high quality. This expertise fits the variety of technical programs via a range of researcher types, from early career scientists and engineers to midlevel staff, to senior staff of international repute. As noted, the fundamental work in time transfer with optical combs is award winning. The project was clearly explained, including techniques and goals. This project used expertise from fundamental physics, through engineering, to implementation, and illustrates the practical value that can develop from curiosity-driven research. The optical comb time transfer work has evolved over decades from fundamental research which was awarded a Nobel Prize to technology transfer for NIST, for which the research team received NIST’s 2024 Excellence in Tech Transfer award (Hall 2006 and NIST 2024).

NIST has several internal mechanisms to encourage and recognize excellent science. Within the STAR, the encouragement from managers for principal investigators to propose “seedling” projects that are high risk, high reward is great to motivate innovation and keep talented scientists and engineers interested. Such curiosity-driven research is essential to ensure the continued vitality of the scientific inquiries and engineering solutions of a national laboratory. The NIST Fellow award is an excellent way to recognize career achievement.

The STAR's scientific and engineering expertise is well qualified to support the division's mission. Given the broadening scope of the division's work, additional staff will likely be required in the future; for example, as spectrum sensing becomes more widely used, a larger suite of techniques would be investigated. This may require additional expertise (e.g., in statistical signal processing). Similarly, exploring the most effective use of digital twins and aerial drones for multiple intelligence disciplines sensing for various use cases and applications will likely require additional staff.

FACILITIES, EQUIPMENT, AND HUMAN RESOURCES

The facilities at the STAR are mostly good. The laboratories are well equipped and maintained, and field-testing facilities are well designed. Laboratory equipment is generally state of the art, but the absence of backup power for some laboratories is a problem. Some of the facilities (e.g., buildings and infrastructure) need renovation. Additional facilities may be required if STAR takes on future work from any government sponsor that requires controlled access. The division has a secure facility, but no associated secure laboratory.

Human resources are managed effectively. The early career scientists and engineers with whom the panel met were excited about their work and spoke very highly of the expertise and mentoring from senior colleagues. Technical staff, particularly primary investigators who lead projects, are highly qualified in science and engineering, but less so in technical marketing and sales. A growth opportunity for STAR is to provide greater services to DOW, which has many research needs aligned with STAR expertise. In the near-term, STAR leadership and principal investigators with good technical marketing and sales skills could engage the DOW stakeholders to leverage the opportunity to conduct dual-use research that benefits the fundamental mission of NIST and addresses DOW challenges.

EFFECTIVENESS OF DISSEMINATION OF PROGRAM OUTPUTS

Dissemination of STAR results through publications is very good. This includes journal publications, conference presentations, technical reports, standards, validated datasets, and even delivery of short courses. For example, STAR shared an extensive list of reports that it published since 2022 in connection with its NASCTN: Citizens Broadband Radio Service Sharing Ecosystem Assessment project. This activity sets a high bar for the other STAR projects that would benefit from a similar level of publication frequency and exposure. Three gaps were identified in the division's dissemination strategy: collaboration with other government entities to share data, widely sharing and evaluating validated data, and technology transfer.

First, STAR is not collaborating efficiently with other parts of the community to share work publicly, including commercial companies, DOW, and NSF. The DOW Chief Information Officer helped charter the NIST-hosted NASCTN in 2015. Presently, DOW leans heavily on the National Spectrum Consortium (NSC) for advanced spectrum and wireless technology development. Sometimes, NSC projects seem to be better suited for CTL's STAR. STAR would be well served by exploring more potential Pentagon-related opportunities and collaboration with the DOW Chief Information Officer or Office of the Deputy Under Secretary for Research and Engineering, which could be a source of external funding. Opportunities could include expanding its work on CBRS spectrum sharing for civilian use cases to defense use cases and learning from DOW about requirements from a defense perspective (e.g., based on real battlefield conditions) to inform future research directions. STAR can consider collaborations that would allow DOW program datasets to be made available publicly or within a U.S.-based researcher community if the dataset is International Traffic in Arms Regulations controlled. This would aid in NIST's dissemination of validated datasets to advance work in government and industry.

Over the past decade, NSF has made substantial investments in spectrum science through program initiatives such as Spectrum Efficiency, Energy Efficiency, and Security; Spectrum and Wireless Innovation Enabled by Future Technologies—Satellite-Terrestrial Coexistence; Next Era of Wireless and Spectrum; and Verticals-enabling Intelligent Network Systems. NSF started a directorate for Technology, Innovation, and Partnership to better align its research with its stakeholder needs. STAR can better align its research portfolio in spectrum research and strategic direction with the outcomes of these parallel efforts conducted by NSC, NSF, and others. For example, NIST could take a more proactive role in engaging with the research community and leveraging the impactful results generated by these programs. Similar to how NIST utilized a risk-based approach to managing multiple-stakeholder projects under the CBRS effort, it should utilize risk-based approaches to modify new Spectrum Research and 5G Network Slicing program plans to work around stakeholder limitations to reduce long program delays (see Recommendation 4-1). This may involve increased costs and reduction in scope but would avoid producing results that arrive too late to be impactful.

STAR's relationship with some federal entities remains unclear. For example, the distinction between the National Telecommunications and Information Administration's Institute for Telecommunications Sciences and NIST CTL's STAR is understood by the staff but is not clear across the CTL online resources. The webpages of the two organizations seem to indicate that there is significant overlap in their missions. Clarifying this would benefit both organizations by enabling public and private entities to understand the differences between them, potentially streamlining the distribution of future work among them.

Second, sharing its validated data more effectively will increase STAR's visibility and enable the wider community to test algorithm development on realistic data. NIST-validated data are essential to the spectrum sharing community because most other data collections are proprietary and do not enable fundamental research across the entire community. Currently, some STAR data are shared but are not readily and/or publicly available. Several venues and approaches could improve sharing of validated data, including through relevant Institute of Electrical and Electronics Engineers societies' forums, or via a competition that could test and evaluate STAR's data and algorithms. The division could, as an example, host booths with hands-on tutorials at conferences and expos that utilize and then give a dataset for researchers to use. This would provide the STAR research leaders with more opportunities to showcase their work to a large audience, attract young researchers and engineers to NIST, and share their hands-on research expertise more often with the community at large. This outreach could involve follow-up workshops at NIST as other divisions have done in the past.

Third, technology transfer is underemphasized in STAR. Greater focus on technology transfer and increased outreach to relevant companies for technology licensing would increase the visibility of STAR and could yield national economic benefits (e.g., spawning new products, start-up companies). Technology transfer can be facilitated within STAR by better defining it in the strategic planning of the division and tracking its return on investment, such as by mapping the number of the division's Cooperative Research and Development Agreements with actual technology transitions. Internally valuing it, such as through using technology transfer metrics in project assessment, would help convey its external value in the division's decision making with regards to continuing certain technical efforts based on their technology transition priority. STAR could also consider holding dedicated events targeted toward technology entrepreneurs and companies to showcase their research outputs, or leverage existing events, such as the National Telecommunications and Information Administration's International Symposium of Advanced Radio Technologies, for this purpose.

FEEDBACK ON ROADMAPPING AND STRATEGY DEVELOPMENT

The benefits of technical roadmaps are well known: roadmaps align research and development efforts with organizational goals, enabling better prioritization, stakeholder alignment, and efficient resource allocation. NIST's unique position sustained by long-term federal funding, working on very difficult or long-term technical problems, with benefits across many national and global community applications magnifies the advantages that well-strategized roadmaps would provide. Based on a recommendation from the 2022 National Academies' review, a formal roadmapping and strategy development effort was started—which is excellent. Roadmapping exercises engaged staff and industry stakeholders to identify gaps in the divisional research spaces and outlined five goals for each research area that align with CTL's capabilities and industry needs.

Many organizations conduct roadmapping activities every year and make it an iterative process, allowing the strategy and the technology roadmap to evolve. One-off or once every 3 or 5 year roadmap activities defeat the key purpose of a roadmapping exercise because, in such a case, the roadmap becomes stale long before the final outcome strategy from the roadmapping activity is implemented.

CTL projects require formal annual approval through a proposal that aligns with CTL's scope, demonstrates value to NIST and CTL, and outlines milestones, impacts, and associated risks. Quad charts that address the project need and problem statement are submitted before project planning. Approved projects are planned, including technical and funding aspects. Division chiefs review ongoing projects annually for alignment with strategic goals, budget, staffing, progress, and emerging challenges, and the quad charts are updated quarterly. Despite these extensive planning processes, the panel found it difficult to understand how the research project presentations and papers it received and reviewed fit into the overall context of STAR's research strategy, roadmap, and mission objectives. As STAR finalizes the roadmaps it started in spring of 2025, its researchers would benefit from answering these four questions at the very beginning of each presentation or paper generated for internal and external consumption:

1. What is this project trying to do or prove?
2. Why is this project important?
3. How does this project fit into the organization's short- and long-term research and technology strategy and roadmap?
4. What potential practical outcome or benefit accrues if this project is successful?

Customers need to understand clearly not only what the organization is doing but why and how that work fits into the overall research context and eventual desired outcome. That needs to be implicit and explicit starting at the lowest level to stay on the roadmap once it is adopted. In effect, every researcher needs to become the salesperson for his or her project, and focusing on the four questions above would help with that. Being able to address such questions would aid in prioritizing research projects. This simple approach would also improve dissemination outcomes with existing and new customers.

CONCLUSIONS AND RECOMMENDATIONS

Conclusion 4-1: The current engagement with the Department of War (DOW), National Science Foundation (NSF), and commercial stakeholders is insufficient. There is a changing focus within DOW to align even fundamental research with national security–relevant causes. Finding opportunities for dual-use research at the National Institute of Standards and Technology (NIST), engaging with DOW and NSF stakeholders more often, and aligning the internal research project investments to also contribute to DOW and NSF mission sets when applicable could advance both NIST and DOW or NSF goals.

Recommendation 4-1: The Spectrum Technology and Research Division (STAR) should collaborate more effectively with Department of War (DOW), National Science Foundation, and commercial stakeholders. More STAR-related DOW collaborations should implement a risk-based approach to manage multistakeholder

programs as is done in the Citizens Broadband Radio Service program. This approach avoids producing results that arrive too late to be impactful even if it means slightly more cost and reduction in scope.

Conclusion 4-2: Radiometric (energy) detection is the standard method for spectrum sensing, but there are multiple other techniques that are superior, particularly when the signals being detected are completely known (e.g., standard waveforms). Cyclostationary detection is one example that the Spectrum Technology and Research Division is considering.

Recommendation 4-2: The Spectrum Technology and Research Division should investigate the potential use of other techniques beyond radiometric detection, e.g., interferometric (two-antenna) detection, feature detection, correlation (e.g., Durbin-Watson), and even matched filtering for spectrum sensing.

Conclusion 4-3: The panel review meeting and follow-up materials described limited projects involving drones or other low-altitude aircraft (e.g., NASA's Advanced Air Mobility program), or involving reconfigurable intelligent surfaces, which are being intensively studied for use in 6G. This is a key focus area within the 6G network standard.

Recommendation 4-3: The Spectrum Technology and Research Division should develop projects involving drones, low-altitude aircraft, and other emerging technologies of national importance. Research and metrology in these areas should be conducted to influence 6G network architecture and the design of objective, rigorous technical evaluation of these technologies and inform gap and security vulnerability analysis.

Conclusion 4-4: The Spectrum Technology and Research Division's tracking of technology transfer, and empowerment of the technical staff to achieve such technology transfer, seems ad hoc.

Recommendation 4-4: The Communications Technology Laboratory should better define its technology transfer strategy, track programs for return on investment,

value technology transfer internally, and prioritize it as a tracked mission effectiveness measure. Implementation could involve engaging with industry to develop commercial uses cases for their technologies, undertaking one-to-one mapping with Cooperative Research and Development Agreements after the technology transfer, and making technology transfer a significant portion of program success criteria.

Conclusion 4-5: One of the objectives of the Spectrum Technology and Research Division is to provide validated data that improve spectrum sharing models and interference testing. National Institute of Standards and Technology–validated data are of high value for the spectrum sharing community because they are unbiased and nonproprietary. Sharing data can help publicize and increase visibility of the Communications Technology Laboratory's work.

Recommendation 4-5: The Spectrum Technology and Research Division should share validated data more effectively, through venues such as Institute of Electrical and Electronics Engineers societies, perhaps in a competition, so that people can test and evaluate their algorithms.

Conclusion 4-6: The feasibility of communications digital twins is rapidly increasing because of advances in computational capabilities, and their relevance is growing with the rise of artificial intelligence (AI). As digital twins become more prominent, standardizing their design and validating their performance in AI-native wireless for 6G are emerging as critical areas of research. The broader research community would greatly benefit from the National Institute of Standards and Technology's active involvement in shaping standards and validation frameworks for communications digital twins.

Recommendation 4-6: The Spectrum Technology and Research Division should lead the development of standardized frameworks for use of digital twins in artificial intelligence–native 6G wireless systems by leveraging the Communications Technology Laboratory (CTL)'s advanced radio frequency instrumentation and calibrated propagation data. This effort should focus on the National Institute of

Standards and Technology and CTL strengths and priorities in defining interoperability standards, creating benchmark datasets, and establishing validation protocols to ensure accuracy and reproducibility.

Conclusion 4-7: The long-standing expertise of the Spectrum Technology and Research Division (STAR) in microwave radiometry and precise noise calibration makes it uniquely qualified to lead pilot projects on radio frequency interference detection and mitigation. STAR's proven capabilities applied to spaceborne and airborne platforms can ensure high-fidelity measurements, protect mission-critical data for existing and future spaceborne microwave radiometry assets, and expand into emerging areas such as unmanned aerial vehicle sensing within 6G Non-Terrestrial Network frameworks. This will strengthen Earth observation and environmental monitoring efforts.

Recommendation 4-7: The Spectrum Technology and Research Division should employ its radiometry expertise to space research applications. A critical component of this expansion is the accurate detection and mitigation of radio frequency interference, which is essential for preserving the integrity of passive radiometric measurements in space-based and airborne platforms. The space work could expand to the unmanned aerial vehicle domain within the 6G Non-Terrestrial Network construct.

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5
Panel Conclusions and Recommendations

The committee's conclusions and recommendations are described in the preceding chapters, including key conclusions and recommendations in the summary and the conclusions and recommendations specific to each division which appear in Chapters 2–4.

OVERARCHING CONCLUSIONS AND KEY RECOMMENDATIONS

The committee observed several crosscutting conclusions in its review of the technical work, expertise, and operations at the Communications Technology Laboratory (CTL). These are summarized in four overarching conclusions. Four key recommendations also stem from these summary and crosscutting issues.

Overarching Conclusion 5-1: The Communications Technology Laboratory (CTL) research is of top quality. It has profound implications for the relevant research communities, industries, and government stakeholders. Continuing to pursue new topic areas within CTL's strengths in measurement science is critical to meeting stakeholder needs.

Overarching Conclusion 5-2: Even with limited research staff, the Communications Technology Laboratory's in-house scientific expertise is among the best in the field. However, hiring more researchers with diverse backgrounds and educational lineage from across the country as permanent staff will advance multiple areas. In particular, additional PhD researchers in the Public Safety Communications Research Division could help to accelerate application of new technologies for community use cases.

Overarching Conclusion 5-3: The existing Communications Technology Laboratory (CTL) facilities in Boulder are maintained and utilized to the best of the CTL staff's ability given available resources. Some infrastructure issues, particularly the lack of reliable power *supply have interrupted research and experimental work. With ever-growing research and development infrastructure and service maintenance cost, current resources for infrastructure repair and improvement are insufficient, and CTL needs more capital investment to repair, improve, and expand its research facility.*

Overarching Conclusion 5-4: The dissemination of Communications Technology Laboratory (CTL) program outputs via publications, presentations, and certain datasets is aligned with best practices for industry standards and academic expectations. There is insufficient coordination with institutions who are working in similar problem spaces (e.g., the National Telecommunications and Information Administration), where CTL can take the lead on metrology and inform standards. CTL curation of additional open radio frequency, public safety, and spectrum sharing and sensing datasets could support stakeholder needs. Opening datasets and sharing them with the greater open research community is a mountainous effort but of great value. No group is better suited and placed to undertake this than CTL.

From the above overarching conclusions stem these key recommendations:

Key Recommendation 5-1: The Communications Technology Laboratory (CTL) should examine the division-specific recommendations for research topic growth areas that would advance CTL's mission and leverage its technical strengths.

Key Recommendation 5-2: The Boulder-based divisions of the Communications Technology Laboratory (CTL) should engage with a wider range of universities and students to supplement the recruitment opportunities presented by the Professional Research Experience Program.

Key Recommendation 5-3: Communications Technology Laboratory (CTL) leadership should prioritize addressing backup power needs for critical instruments and experiments, given the frequent planned and unplanned power outages at the Boulder campus, and its negative impact on calibrations, experiments, and the CTL mission.

Key Recommendation 5-4: The Communications Technology Laboratory should build on its success in hosting and curating open, validated datasets for research use. Areas of growth include sharing reusable datasets from the Public Safety Communications Research Division's User Experience portfolio, analyzing how datasets support industry development in the Radio Frequency Technology Division, developing reliable data in new areas of the Spectrum Technology and Research Division's work such as for digital twins, and developing shareable data from otherwise inaccessible datasets like those containing various forms of controlled information.

DIVISION-SPECIFIC CONCLUSIONS AND RECOMMENDATIONS

Public Safety Communications Research Division

Conclusion 2-1: The MCX portfolio is the most mature and strongest of the five PSCR portfolios. The MCX and its partners were able to shepherd conformance testing through the Third Generation Partnership Project (3GPP), develop standards-based conformance testing scripts, and transfer this work to commercial testing and evaluation companies. This high-impact work stands out because the MCX played a critical role from inception to commercialization. The Mission Critical Services (MCX) portfolio has prioritized forging partnerships and achieving impactful outcomes. The activities of the portfolio have helped make Long-Term Evolution and 5G New Radio–based first-responder networks viable alternatives to traditional Land Mobile Radio (LMR) systems. However, lack of trust and feature parity have slowed the decommissioning of LMR systems. The MCX portfolio also deals with complicated and evolving standards, and they could play a key role in guiding first-responder radio and network evaluation. What PSCR has been able to accomplish with very little resources is not only impressive but may be a best practice to replicate.

Recommendation 2-1: When developing the next evolution of the Mission Critical Services research beyond conformance, the Public Safety Research Division leadership should add or update research on the minimum feature parity necessary

for first-responder agencies to trust the transition from Land Mobile Radio to newer technologies. Examples include trust in the ruggedized device and reach beyond radio coverage (e.g., via satellite or device to device mechanisms).

Conclusion 2-2: The User Experience (UX) portfolio has made a focused effort at creating a realistic scenario for first-responder training via mock-up of an apartment in a hazardous materials situation. Training techniques like this hold much potential for improving the way first responders are trained nationwide, but the number of first responders who can directly benefit from the NIST environment is limited. The impact of the UX portfolio could be increased by broadening its focus toward dissemination of learning, e.g., to assist with measurement sciences, standards development, guidelines for adoption of critical communications capabilities for first responders, and interface specifications for reusable datasets.

Recommendation 2-2: To amplify the potential impact for society, PSCR leadership should require each project, for example the User Experience portfolio's mock-up training environment, to specify the anticipated amplification outcomes in all four Public Safety Communications Research Division research value areas as appropriate:

- **a. Measurement sciences,**
- **b. Standards development,**
- **c. Accelerating the adoption of critical communication capabilities for first responders, and/or**
- **d. Reusable datasets.**

Conclusion 2-3: One of the challenges for Land Mobile Radio transition to newer 5G/xG technologies was trust in the device. There is a need for focused basic research on public safety radios within the United States; the Public Safety Communications Research Division could be the leading U.S. research and development organization on this topic if it was properly resourced. For example, the Location-Based Services group could better confront the numerous unsolved problems in signal processing and engineering in indoor adverse situations with a larger team of researchers with expertise in areas such as RF *propagation, optics, signal processing, radar, imaging, and communications. The Mission Critical Services (MCX) team could lead the evolution of MCX application programming interfaces to take advantage of Integrated Sensing and Communications.*

Recommendation 2-3: The Public Safety Communications Research (PSCR) Division leadership should increase the ratio of personnel with PhDs to expand its research depth. Given the PSCR division's success in connecting with relevant stakeholder feedback, hiring more PhD researchers with diverse backgrounds may help to accelerate application of new technologies, such as integrated sensing and communications, for PSCR community use cases while also addressing the device trust concerns expressed by stakeholders.

Conclusion 2-4: There is significant maintenance cost to keep current each Public Safety Innovation Lab subsystem (Project 25 Land Mobile Radio [LMR] systems from two companies, 4G/5G systems, radio frequency chambers, interoperability systems between LMR and Long-Term Evolution, Mission-Critical Voice Quality of Experience system, and Mobile Research Vehicle). A better understanding of the projects and active grant proposals dependent on each subsystem is needed to better understand the business tradeoff between the maintenance cost of each system and relevance of the system for the PSCR mission moving forward.

Recommendation 2-4: To make a business decision on when to decommission each Public Safety Innovation Lab system, the Public Safety Communications Research Division leadership should analyze the cost to keep each system current and its ability to allocate these costs to ongoing research projects and future grant awards. The visibility to the dependencies and maintenance costs should be shared with stakeholders.

Conclusion 2-5: The Public Safety Communications Research Division (PSCR) aims to play a key role nationally in guiding public safety radio development, radio evaluation, radio testing, first-responder training, and new technology integration. Research and development in these areas could also impact commercial radio networks and training and communication systems in other industries (e.g., mining, oil and gas, railways). The

PSCR prioritizes interaction with targeted stakeholders, and stakeholder use of the PSCR infrastructure, outcomes, and guidelines appears well monitored. The PSCR may benefit from measuring or documenting each portfolios' impact to the broader community, beyond the targeted stakeholders. Visibility to indirect impact may bring to the surface additional societal challenges.

Recommendation 2-5: The Public Safety Communications Research Division leadership should consider monitoring value beyond the targeted stakeholders—for example, those to whom the information was disseminated—in addition to monitoring stakeholder value. For example, a mapping of potential ripple effects from dissemination of each portfolio's outcome may highlight areas of potential cross portfolio collaboration need.

Radio Frequency Technology Division

Conclusion 3-1: The Radio Frequency Technology Division has strengths in metrology, measurement sciences, and technology development:

- *Strong foundational metrology capabilities (e.g., Josephson standards and radio frequency power and scattering-parameter measurements, competitive with leading peer national metrology institutes);*
- *Successful measurement science innovation enabling new industries (e.g., Rydberg sensing); and*
- *Active development programs with strong external collaborations positioning for future industry needs (e.g., hot qubit metrology with industry, national laboratories, universities, magnetic materials, 5G/6G electromagnetic compatibility frameworks).*

Conclusion 3-2: The Radio Frequency Technology Division effectively disseminates its work by

- *Demonstrating an appropriate technology transfer model (the National Institute of Standards and Technology develops measurement science for low technology readiness level (TRL), and industry implements systems at high TRL) and*

- *Contributing effectively to standards development (e.g., Next Generation Communications Channel Model Alliance, Third Generation Partnership Project participation, Institute of Electrical and Electronics Engineers standards development).*

Conclusion 3-3: The National Institute of Standards and Technology (NIST) has world-class expertise in Rydberg sensor science, defining the state of the art in atom-based radio frequency metrology. Emphasis on higher-frequency (>110 gigahertz) and deployable system integration would help NIST to sustain its leadership.

Recommendation 3-1: Based on confirmed industry needs, the Radio Frequency Technology Division should develop terahertz frequency measurement capabilities for 6G support or determine that the frequencies fall outside its mission scope; conduct a hot qubit metrology program strategic review to determine industry need and timeline, pace of NIST measurement capability development, and resource allocation decision criteria; and assess cryogenic radio frequency measurement requirements for the quantum computing industry.

Conclusion 3-4: Power failures, absent backup systems, and environmental control deficiencies represent an infrastructure crisis, and actively compromise the National Institute of Standards and Technology's ability to provide reliable national measurement standards. This threatens the core national metrology institute (NMI) function and risks loss of international credibility in key comparisons with other NMIs such as Germany's Physikalisch-Technische Bundesanstalt, the United Kingdom's National Physical Laboratory, and the National Metrology Institute of Japan.

Recommendation 3-2: The National Institute of Standards and Technology should install backup power systems for all measurement standards facilities; remediate environmental controls; stabilize temperature control for calibration chambers; and develop a multiyear capital facilities plan with dedicated funding.

Conclusion 3-5: Several programs show active development with appropriate external collaborations (hot qubit metrology, terahertz frequency extensions, cryogenic radio *frequency), but timelines to operational capability may not align with U.S. industry needs. Early career researcher presentations demonstrate progress, but multiyear gaps may exist before measurement services reach maturity. Strategic clarification is needed on development pace versus anticipated industry demand, particularly for quantum computing and 6G technologies where academic and international capabilities are advancing rapidly.*

Conclusion 3-6: The Radio Frequency Technology Division has established strategic planning with stakeholder engagement and quarterly tracking of research activities (publications, standards contributions, conferences, Cooperative Research and Development Agreements). Opportunities exist to enhance impact assessment beyond activity metrics to include economic value quantification of calibration services, systematic tracking of measurement method adoption in commercial products, and analysis of how datasets support industry development. These enhanced metrics would strengthen demonstrated value and inform resource allocation.

Recommendation 3-3: The Radio Frequency Technology Division should conduct a strategic stakeholder needs assessment based on a comprehensive industry survey to identify priority U.S. measurement requirements, perform gap analysis comparing capabilities against industry needs, and develop an evidence-based priority ranking.

Recommendation 3-4: The Radio Frequency Technology Division should enhance its impact assessment by implementing comprehensive tracking of calibration service reach and economic value, develop technology adoption metrics, create systematic industry feedback mechanisms, and publish its annual impact assessment to demonstrate mission effectiveness.

Conclusion 3-7: The current model with PhD researchers spending a large percentage of time performing routine calibrations while calibration fees prove insufficient for facility or capability needs appears unsustainable. Peer national metrology institutes use different workforce models and cost recovery structures that may better support both service provision and innovation.

Recommendation 3-5: The Radio Frequency Technology Division should optimize its workforce by implementing or partnering with an existing technician training program for routine and high-volume calibrations and review cost recovery models for sustainability; conduct a comprehensive workforce assessment including experience demographics and retirement impact; develop succession plans for critical positions; and expand university recruitment relationships beyond the local region.

Recommendation 3-6: The Communications Technology Laboratory (CTL) should perform a workforce metrics analysis, tracking workforce metrics semiannually—including headcount by division, average years at the National Institute of Standards and Technology, time in grade, and years since the last degree—to evaluate workforce stabilization, assess the ongoing impact of recent reductions, and guide strategic workforce planning.

Spectrum Technology and Research Division

Conclusion 4-1: The current engagement with the Department of War (DOW), National Science Foundation (NSF), and commercial stakeholders is insufficient. There is a changing focus within DOW to align even fundamental research with national security–relevant causes. Finding opportunities for dual-use research at the National Institute of Standards and Technology (NIST), engaging with DOW and NSF stakeholders more often, and aligning the internal research project investments to also contribute to DOW and NSF mission sets when applicable could advance both NIST and DOW or NSF goals.

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Recommendation 4-6: The Spectrum Technology and Research Division should lead the development of standardized frameworks for use of digital twins in artificial intelligence–native 6G wireless systems by leveraging the Communications Technology Laboratory (CTL)'s advanced radio frequency instrumentation and calibrated propagation data. This effort should focus on the National Institute of Standards and Technology and CTL strengths and priorities in defining interoperability standards, creating benchmark datasets, and establishing validation protocols to ensure accuracy and reproducibility.

Conclusion 4-7: The long-standing expertise of the Spectrum Technology and Research Division (STAR) in microwave radiometry and precise noise calibration makes it uniquely qualified to lead pilot projects on radio frequency interference detection and mitigation. STAR's proven capabilities applied to spaceborne and airborne platforms can ensure high-fidelity measurements, protect mission-critical data for existing and future spaceborne microwave radiometry assets, and expand into emerging areas such as unmanned aerial vehicle sensing within 6G Non-Terrestrial Network frameworks. This will strengthen Earth observation and environmental monitoring efforts.

Recommendation 4-7: The Spectrum Technology and Research Division should employ its radiometry expertise to space research applications. A critical component of this expansion is the accurate detection and mitigation of radio frequency interference, which is essential for preserving the integrity of passive radiometric measurements in space-based and airborne platforms. The space work could expand to the unmanned aerial vehicle domain within the 6G Non-Terrestrial Network construct.

Appendix
Biographical Sketches of Panel

Chair

BISHAL THAPA is a recognized research leader in the field of cognitive wireless communication networks and wireless security. Dr. Thapa joined Raytheon BBN in 2011. He got his PhD in wireless communication and security from Northeastern University. His PhD thesis work focused on jamming and antijamming of wireless communication. Since he has been with BBN, he has been a principal investigator (PI) or a technical lead on many Defense Advanced Research Projects Agency (DARPA), Intelligence Advanced Research Projects Activity, Department of Defense Services tactical data networking projects, and Intelligence Community wireless security projects. Currently he is a PI on a multidomain tactical Internet project that connects seabed sensors with space networks in situ. He is also the networks lead on the ongoing 5G Network Enhancement and Radar/OpenRAN 5G Spectrum Sharing Project. He won a best paper award from ACM WiSec in 2011, was nominated as one of the 50 DARPA Risers from across the U.S. defense and academic institutions in 2015, won Raytheon Technical Excellence and Innovation awards, and recently received the Presidential Coin. He participated in DARPA Hackfest and the DARPA Spectrum Challenge, where his team won the first prize in the cooperative spectrum challenge. He also recently led a team to a second-place win in the Navy's Project Overmatch AINETX Networking challenge. He is an open-source GNURadio and Battle of Meshes enthusiast. He served on the National Academies' National Institute of Standards and Technology Communications Technology Laboratory Review Panel in 2022. He is an Institute of Electrical and Electronics Engineers and Association for Computing Machinery senior member.

Members

DARMINDRA ARUMUGAM is a senior research technologist at NASA's Jet Propulsion Laboratory (JPL) and the technical supervisor of the Radar Concepts and Formulation Group. He is also the founding chief technologist of the Applied Physics Laboratory at JPL, which advances high-impact radio and radar remote sensing technologies for NASA and other U.S. agencies. Dr. Arumugam specializes in quantum sensors, electromagnetics, and remote sensing, with a present focus on Rydberg atom and optical-to-microwave sensors for remote sensing using signals of opportunity. His work in wireless signal detection, spectrum sensing, and precision metrology aligns with the National Institute of Standards and Technology (NIST) Communications Technology Laboratory's efforts in next-generation wireless, spectrum sharing, and electromagnetic measurement science. He has demonstrated how quantum-based sensors harness multiband signals for passive spectrum monitoring, resilient communication, and quantum-enhanced metrology. With more than 60 peer-reviewed publications and more than 25 patents, he has advanced sensing technologies to higher readiness levels, supporting NASA missions and commercial space applications. Dr. Arumugam is a NASA NIAC fellow and a former technical advisor to the Department of Homeland Security Science and Technology Directorate, bringing expertise in advanced sensing and navigation technologies. He has received prestigious honors, including the NASA Exceptional Technology Achievement Medal (2019), the NASA Lew Allen Award (2016), and the NASA Voyager Award (2015). His contributions to GPS-denied navigation technologies have also earned recognition beyond the scientific community, including the *Popular Mechanics* Breakthrough Award (2017). Dr. Arumugam earned his PhD in electrical and computer engineering, with a focus on applied physics, from Carnegie Mellon University in 2011. Since 2021, Dr. Arumugam has led annual nationwide planning and consensus studies on Rydberg atom sensing for space-based remote sensing, bringing together experts from academia and U.S. national laboratories, including NIST and the U.S. Army Research Laboratory. His efforts have shaped national discussions, fostered cross-disciplinary collaboration, and guided the integration of Rydberg sensors into next-generation space sensing technologies.

NATHAN BROOKS has more than 20 years of experience in electromagnetics and numerical optimization. He conducted research at esteemed institutions such as the National High Magnetic Field Laboratory, the Center for Advanced Power Systems, and CERN (European Organization for Nuclear Research). He began his industry career with Argon ST, a Boeing subsidiary, and is currently a Boeing senior technical fellow focused on electromagnetic and antenna system architectures. Dr. Brooks provides technical expertise and leadership for Boeing's signal intelligence capabilities, as well as leading and consulting on electronic warfare antenna system development. He has played a key role in securing and executing advanced capability program contracts from military, government, and commercial customers, including the Defense Advanced Research Projects Agency and Intelligence Advanced Research Projects Activity. Dr. Brooks has led various 3D system performance modeling and simulation efforts and has been involved in site survey, system design, and installation teams worldwide. He recently led a team of executive technical fellows to address aviation interference issues from 5G and future telecommunication systems. Dr. Brooks holds a BS and PhD in electrical engineering from Florida A&M University and has received multiple awards, including the 2019 National Society of Black Engineers Golden Torch Lifetime Achievement in Industry Award and the 2020 Boeing Defense Engineer of the Year. He actively contributes to improving the science, technology, engineering, and mathematics workforce and has been a member of National Academies' review panels and boards.

DMITRY CHIZHIK is a Distinguished Member of Technical Staff at Nokia Bell Labs, with expertise in wave propagation modeling and measurements applied to wireless communications, multiple-input, multiple-output channels, and radar sensing. His prior work was at the Naval Undersea Warfare Center, New London, Connecticut, where he did research in acoustic scattering from the ocean floor, geoacoustic modeling of porous media, and shallow water acoustic propagation. Dr. Chizhik is a fellow of the Institute of Electrical and Electronics Engineers and is a recipient of the Bell Labs President's Award. Dr. Chizhik received his BS and MS in electrical engineering and a PhD in electrophysics in 1991 from Polytechnic University, Brooklyn, New York (now NYU). At present, Dr. Chizhik is a contributor to the Next Generation Alliance, developing channel models for sensing and in new bands.

BRENDA CONNOR has a dual appointment at Texas Tech University (TTU) as a professor of practice in the Department of Electrical and Computer Engineering and as the senior technical managing director for the TTU Critical Infrastructure Security Institute. Dr. Connor joined TTU in January 2025 after a 30-year career with Ericsson as the chief engineer of Mission Critical Systems. She is focused on applied research to accelerate the critical infrastructure operator's business case to deploy a private cellular network. Her research areas include critical infrastructure security and operational efficiency via private cellular artificial intelligence (AI)-enabled Integrated Sensing and Communications (ISAC) and SCADA IO processing capability for national security with dual-use relevance for the Department of War, and NVIDIA-based AI model and algorithms development and reuse. Dr. Connor is a telecom security expert with Certified Information Systems Security Professional certification. She has worked with smart city, intelligent transportation systems, public safety, utility, and oil and gas verticals. Dr. Connor leverages her PhD in engineering management with her MS in computer engineering and BS in computer engineering from Boston University to lead and contribute to innovations with impact for society.

ISMAIL GUVENC is a professor in the Department of Electrical and Computer Engineering at North Carolina (NC) State University, where he has been since 2016, after serving at Florida International University (FIU; 2012–2016), DOCOMO Innovations (2006–2012), and Mitsubishi Electric Research Labs (2005). He became a full professor in 2020. His recent research interests include 5G wireless systems, communications and networking with drones, spectrum sharing, and wireless testbeds. He has published more than 350 conference and journal papers and book chapters, and several standardization contributions. Dr. Guvenc is an inventor or co-inventor in some 30 U.S. patents, and he is a senior member of the National Academy of Inventors. He is a recipient of the NC State Alcoa Distinguished Engineering Research Award (2023), University Faculty Scholar Award (2021), NC State ECE R. Ray Bennett Faculty Fellow Award (2019), FIU College of Engineering Faculty Research Award (2016), National Science Foundation CAREER Award (2015), Ralph E. Powe Junior Faculty Enhancement Award (2014), and University of South Florida (USF) Outstanding Dissertation Award (2006). He is a fellow of the Institute of Electrical and Electronics Engineers (IEEE). Dr. Guvenc earned his PhD in electrical engineering from USF (2006), MS in electrical and computer engineering from the University of New Mexico (2023), and BS in electrical and electronics engineering from Bilkent University (2001). He previously served on the National Academies' committee on the review of the National Institute of Standards and Technology's Communications Technology Laboratory in 2019. Dr. Guvenc published various conference and journal papers in the past 5 years related to spectrum monitoring and sharing and submitted comments to the Department of Commerce in 2023 on the matter of the implementation of the National Spectrum Strategy.

KEVIN KORNEGAY is currently the Eugene DeLoatch Endowed Professor and the director of the Cybersecurity Assurance and Policy Center at Morgan State University in Baltimore, Maryland. He has expertise in radio frequency (RF) and mixed-signal integrated circuit design, system-on-chip design, secure embedded systems, and reverse engineering. He received a BS in electrical engineering from Pratt Institute, Brooklyn, New York, in 1985, and an MS and PhD in electrical engineering from the University of California, Berkeley, in 1990 and 1992, respectively. He serves on the technical program committees of several international conferences, including the Institute of Electrical and Electronics Engineers (IEEE) Symposium on VLSI Technology and Circuits and the Association for Computing Machinery (ACM) Great Lakes Symposium on VLSI. He has served on the National Institute of Standards and Technology (NIST) Internet of Things Advisory Board and the NIST Industrial Advisory Council R&D Workforce Working Group. He currently serves on the State of Maryland Cybersecurity Council. He has received numerous awards, including the National Science Foundation CAREER Award, IBM Faculty Partnership Award, National Semiconductor Faculty Development Award, and the General Motors Faculty Fellowship Award. He was a participant in the 5th Annual Symposium on Frontiers of Engineering and organizer of the 5th German-American Symposium on Frontiers of Engineering, National Academy of Engineering. He is a fellow of the American Association for the Advancement of Science, a life senior member of the IEEE, and a member of the Eta Kappa Nu, Sigma Xi, and Tau Beta Pi engineering or scientific research honor societies.

MEHMET KURUM received his BS in electrical and electronics engineering from Bogazici University, Istanbul, Turkey, in 2003, followed by his MS and PhD in electrical engineering from The George Washington University in 2005 and 2009, respectively. He held postdoctoral and research associate positions with the Hydrological Sciences Laboratory, NASA Goddard Space Flight Center. From 2016 to 2022, Dr. Kurum served as an assistant professor at Mississippi State University and subsequently he held the position of associate professor and the Paul B. Jacob Endowed Chair until 2023. Currently, he is an associate professor in electrical and computer engineering at the University of Georgia. Dr. Kurum's research involves microwave remote sensing from satellite scales to small aerial platforms in environmental sustainability, especially in agriculture. His current research focuses on changing the paradigm of remote sensing methods and developing next-generation technologies and ideas that are more spectrum efficient, are more effective, and meet the challenges of the present and future spectrum congestion. His portfolio encompasses development of retrieval algorithms and forward electromagnetic model simulations in support of NASA's Soil Moisture Active Passive (SMAP), Signals of Opportunity P-band Investigation (SNOOPI), NASA-ISRO Synthetic Aperture Radar (NISAR), and Cyclone Global Navigation Satellite System (CYGNSS) satellite missions. He has previously served as the principal investigator on a multitude of research grants funded by federal agencies such as the Department of Defense, NASA, the National Science Foundation, and the U.S. Department of Agriculture.

DAVID J. LOVE is the Nick Trbovich Professor of Electrical and Computer Engineering at Purdue University. He received a BS (with highest honors), MSE, and PhD in electrical engineering from The University of Texas at Austin in 2000, 2002, and 2004, respectively. His research interests are in the design and analysis of broadband wireless communication systems, 6G and beyond wireless systems, multiple-input. multiple-output (MIMO) communications, integrated sensing and communications, nonterrestrial networks, millimeter-wave and higher-frequency wireless, software-defined radios and wireless networks, coding theory, and MIMO array processing. He is one of the inventors of codebook-based precoding, which is found in all 4G and 5G wireless systems. His early work on millimeter-wave beamforming and massive MIMO have found widespread use in 5G. He holds 32 issued U.S. patents. He has been recognized as a fellow of the Institute of Electrical and Electronics Engineers (IEEE), American Association for the Advancement of Science, and the National Academy of Inventors, and a

Thomson Reuters Highly Cited Researcher (2014 and 2015). He has received awards from the IEEE Communications Society (2016 Stephen O. Rice Prize, 2020 Fred Ellersick Prize, and 2024 William R. Bennett Prize), IEEE Signal Processing Society (2015 IEEE Signal Processing Society Best Paper Award), and IEEE Vehicular Technology Society (2010 Jack Neubauer Memorial Award). He was an invited participant of the 2011 National Academy of Engineering (NAE) Frontiers of Engineering Education Symposium and the 2016 EU-U.S. NAE Frontiers of Engineering Symposium.

DAVID W. MATOLAK received a BS from The Pennsylvania State University, MS from the University of Massachusetts, and PhD from the University of Virginia all in electrical engineering. He has more than 25 years of experience in communication system research, development, and deployment, with industry, government institutions, and academia, including AT&T Bell Labs, L3 Communication Systems, MITRE, and Lockheed Martin. He has more than 290 publications and 11 patents. He was a professor at Ohio University (1999–2012), and since 2012 has been a professor at the University of South Carolina. He has been the associate editor for several Institute of Electrical and Electronics Engineers (IEEE) journals and has delivered several dozen invited presentations at a variety of international venues. His research interests are radio channel modeling and communication techniques for nonstationary fading channels, and secure communications. Professor Matolak is a fellow of the IEEE, a member of standards groups in RTCA and the International Telecommunication Union (ITU), and a member of Eta Kappa Nu, Sigma Xi, Tau Beta Pi, the International Union of Radio Science (URSI), the American Society for Engineering Education (ASEE), and the American Institute of Aeronautics and Astronautics (AIAA).

MARK A. MCHENRY is the chief executive officer of Shared Spectrum Company. He has extensive experience in military and commercial communication systems design, including research on the next generation of advanced wireless networks. He founded two high-tech wireless research and development companies. In 2000, he founded Shared Spectrum Company (SSC), which is developing automated spectrum sharing technology. SSC develops advanced technologies for government and industry customers with challenging radio frequency and networking needs. It specializes in dynamic spectrum management applications. Dr. McHenry was also a co-founder of San Diego Research Center, Incorporated (SDRC), which focused on Department of Defense (DoD) test and training systems. SDRC was acquired by Argon ST in 2006. Dr. McHenry was a program manager at the Defense Advanced Research Projects Agency, where he managed multiple tactical wireless related programs. Dr. McHenry received the Office of Secretary of Defense Award for Outstanding Achievement in 1997 and the Office of Secretary of Defense Award for Exceptional Public Service Award in 2000. Dr. McHenry was an engineer at SRI International, Northrop Advanced Systems, McDonnell Douglas Astronautics, Hughes Aircraft, and Ford Aerospace. Dr. McHenry was named Engineer of the Year by the District of Columbia Council of Engineering and Architectural Societies in February 2006. He was appointed by the Secretary of Commerce, Carlos Gutierrez, to serve as a member of the Commerce Spectrum Advisory Committee in December 2006. Dr. McHenry received a BS in engineering and applied science from the California Institute of Technology, an MS in electrical engineering from the University of Colorado, and a PhD in electrical engineering from Stanford University.

RICHARD (RICK) L. REASER, JR., has been a self-employed, independent aerospace engineering consultant who provides consulting services on satellite navigation and general space technology, as well as technical and market due diligence on aerospace technology innovations to a variety of clients since 2019. Previously, he led Raytheon Space and Airborne Systems' Spectrum Management and Electromagnetic Environmental Effects (E3) Department for 13 years. Prior to that, he served 28 years in the United States Air Force, retiring as a colonel, where he served as Navstar Global Positioning System (GPS) Joint Program Office deputy system program director and chief engineer. He has relevant expertise in spectrum management, communications-electronics laboratory management, operations and technology, wireless system testing and technology, and systems engineering. Mr. Reaser received his BS in engineering mechanics from the United States Air Force Academy in 1978, an MS in systems technology (command, control, and communications) from the Naval Postgraduate School in 1989 and an MS in national resource strategy from National Defense University in 1998. He is a Department of Defense (DoD) Level III Certified Acquisition Professional in Program Management, Engineering, as well as Test. He was awarded the DoD Legion of Merit in 2006, Department of State Superior Honor Award in 2005, Air Force Systems Engineering Unit of the Year in 2004, and Defense Superior Service Medal in 2000. From 2021 to 2022, he was a member of the National Academies' committee that reviewed Federal Communications Commission order FCC 20-48, which authorized Ligado Networks to operate adjacent to the GPS frequency band. In 2015 he was selected by the National Research Council to serve on a congressionally directed committee that provided scientific, technical, and management recommendations regarding the Department of Commerce's telecommunications laboratories. He served on the Secretary of Commerce Spectrum Management Federal Advisory Committee from 2009 to 2019. Since 2022, he has served on the National Science Foundation's SpectrumX External Advisory Board.