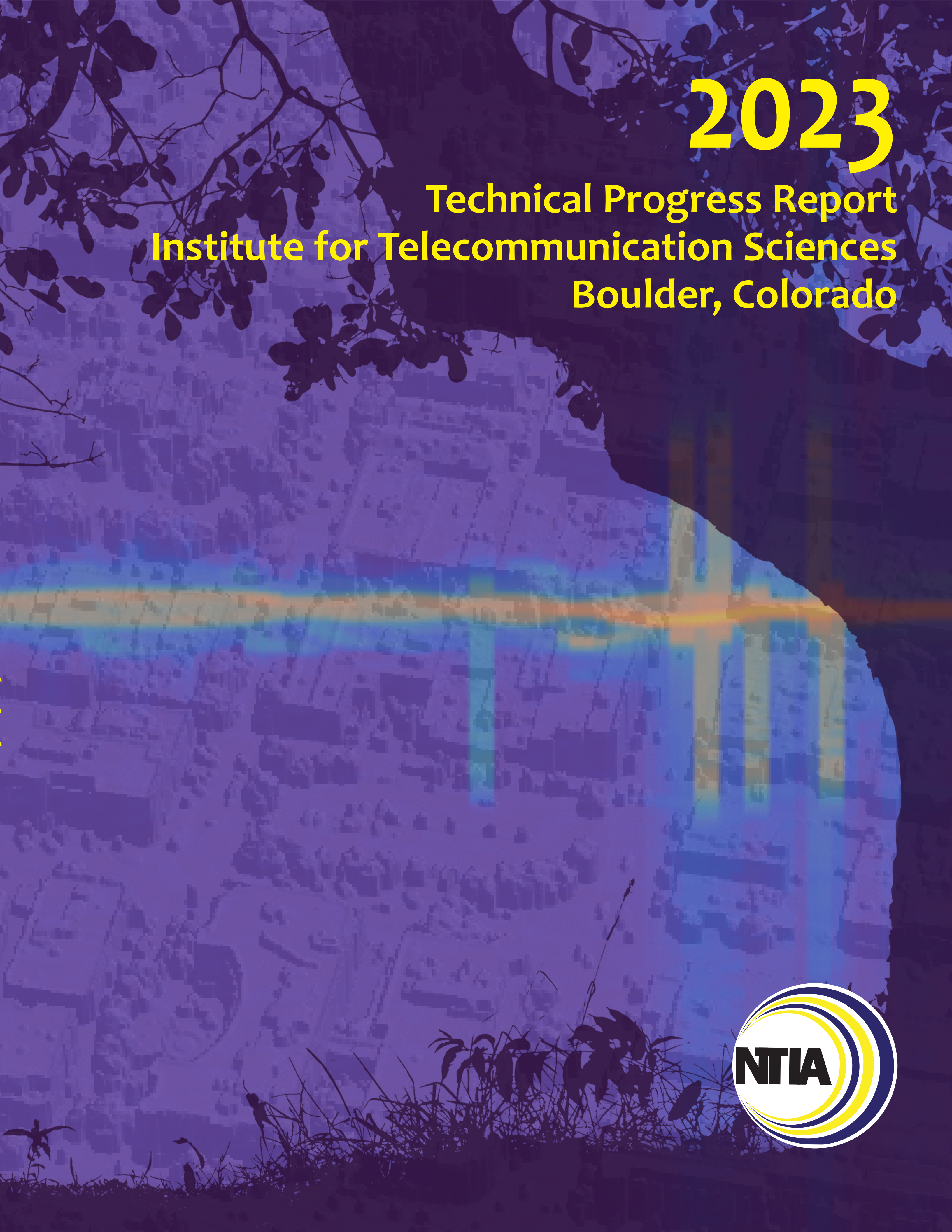
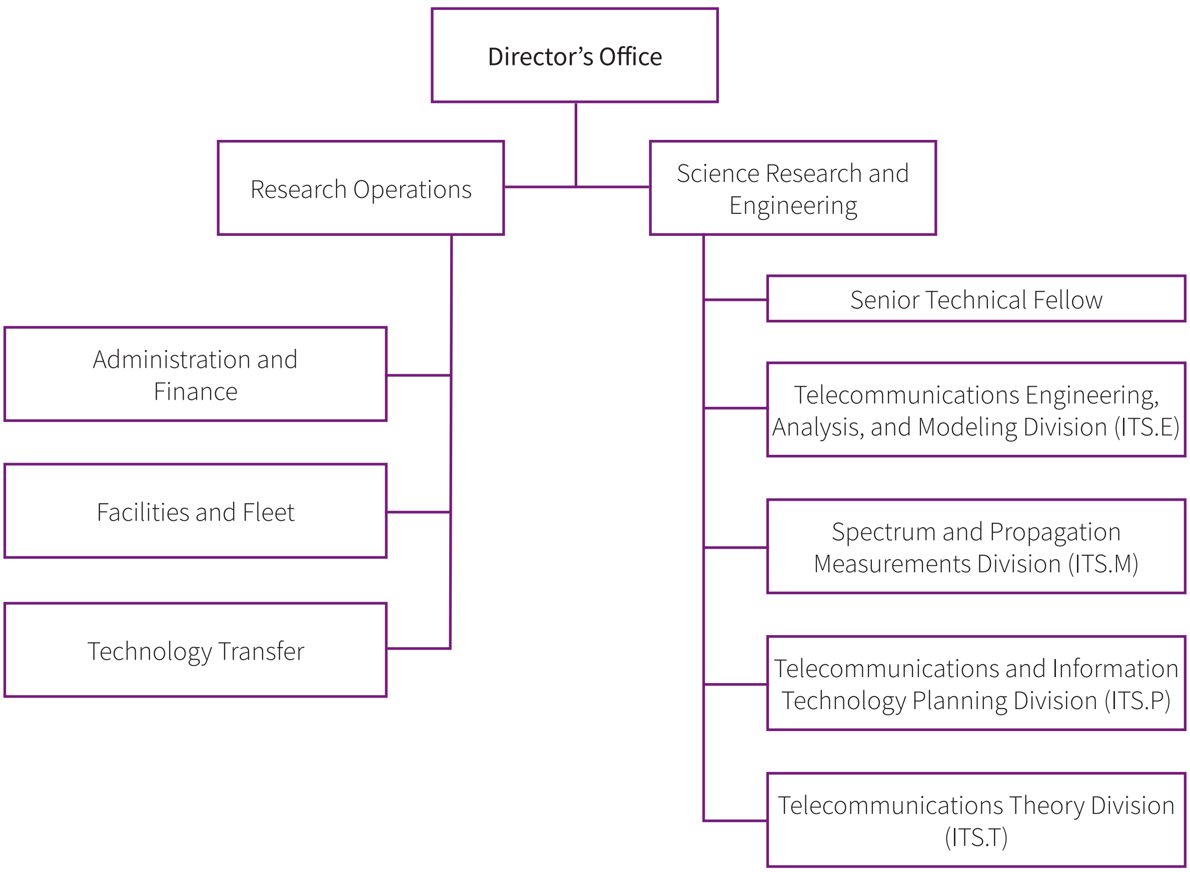
2023

Technical Progress Report
Institute for Telecommunication Sciences
Boulder, Colorado



ITS: The Nation's Spectrum and Communications Lab

Realizing the full potential of telecommunications to drive a new era of innovation, development, and productivity.



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Institute for Telecommunication Sciences

Technical Progress Report

Fiscal Year 2023

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National Telecommunications and Information Administration

United States Department of Commerce

June 2024

ITS Institute for Telecommunication Sciences

Boulder, Colorado

The Institute for Telecommunication Sciences is the research laboratory of the National Telecommunications and Information Administration, an agency of the United States Department of Commerce.

The mission of the Department of Commerce is to create the conditions for economic growth and opportunity for all communities.

The National Telecommunications and Information Administration is principally responsible for advising the President on telecommunications and information policy issues.

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Cover art by A.D. Romero.

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The mission of ITS is to
ADVANCE innovation in communications technologies,
INFORM spectrum and communications policy for the benefit of all stakeholders, and
INVESTIGATE our Nation's most pressing telecommunications challenges through research that employees are proud to deliver.

"Scientific and technological information, data, and evidence are central to the development and iterative improvement of sound policies..."[1]

"ITS has extensive capabilities in public safety, radio-spectrum sensing, propagation modeling, and interference analysis. It is recognized by other government agencies (and, to some extent, private industry) for its objectivity, expertise, and physical resources; it is the historically trusted expert in certain areas of spectrum and communication engineering; and it is an essential provider of these services to government agencies.[2]*"*

1. The White House, Presidential Memorandum on Restoring Trust in Government Through Scientific Integrity and Evidence-Based Policymaking, January 27, 2021, https://www.whitehouse.gov/briefing-room/presidential-actions/2021/01/27/memorandum-on-restoring-trust-in-government-through-scientific-integrity-and-evidence-based-policymaking/
2. National Academies of Sciences, Engineering, and Medicine. 2015. *Telecommunications Research and Engineering at the Institute for Telecommunication Sciences: Meeting the Nation's Telecommunications Needs*. Washington, D.C.: The National Academies Press. DOI: 10.17226/21867

ITS: The Nation's Spectrum and Communications Lab

The Institute for Telecommunication Sciences (ITS) manages the telecommunications technology research programs of the National Telecommunications and Information Administration (NTIA), an agency of the U.S. Department of Commerce (DoC). ITS's cutting-edge technical research informs spectrum and communication policy, has a multibillion-dollar impact on the nation's economy, and advances innovation in telecommunications technology. Sound technical input that informs NTIA policy development and spectrum management is fundamental to promoting a more agile and evidence-driven regulatory environment. It's also essential to meeting the goals laid out in the Administration's National Spectrum Strategy[1] of protecting vital federal government operations that use spectrum while at the same time supporting the growth of commercial wireless broadband technologies in the U.S.

ITS serves as a principal federal resource for investigating the most pressing telecommunications challenges of other federal agencies through cost reimbursable interagency agreements (IAAs). Advancing innovation in telecommunications technologies supports interference-free functionality of mission critical spectrum dependent systems while optimizing federal and non-federal use of an increasingly crowded and shared spectrum and facilitating coexistence of cellular technologies, radars, satellites, and myriad other systems in an expanding ecosystem of wireless devices.

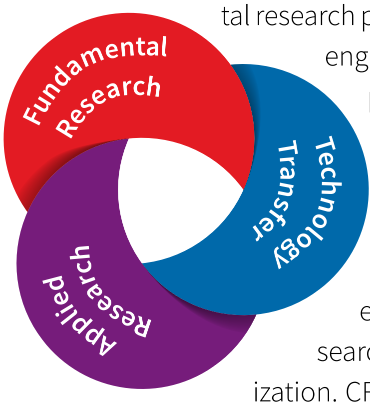
For decades, ITS's research has directly enabled spectrum sharing among a variety of mission critical federal and economically important commercial spectrum dependent systems. ITS research promoted the multibillion-dollar successes of spectrum auctions like the AWS-3 ($45B) and Citizens Broadband Radio Service (CBRS, $4.6B) auctions, and the feasibility data ITS provided to America's Mid-Band Initiative Team (AMBIT) led to a $22.5B mid-band auction.

In 2022, working under an interagency agreement with the Department of Defense (DoD) and in close collaboration with dozens of other federal and non-federal stakeholders, ITS performed groundbreaking flight tests to assess the impact of C-band 5G base stations on radio altimeters. Testing revealed substantial 5G base station transmit filtering and supported the Federal Aviation Administration's (FAA) corrective action focused on upgrading receive filters on some radio altimeters, allowing industry to realize an $81B investment in the C-band auction and earning ITS a U.S. Department of Commerce Gold Medal and the CO-LABS Governor's Award for High-Impact Research.

ITS research also advances innovation in communications technologies to expand spectrum efficiency for our Nation. In 2022 and 2023, ITS conducted a DoD-sponsored 5G Open RAN Challenge to accelerate modular, diverse, secure, interoperable 5G Open RAN networks for mission critical DoD private networks and commercial networks. Almost $9 million in cash and prizes was awarded to top competitors who achieved multi-vendor interoperable 5G Open RAN solutions. The program achieved a first-in-the-world success when two teams of four unique vendors completed rigorous mobility handover testing. This achievement shows tremendous potential for United States technical advancement for secure 5G Open RAN interoperable networks to achieve supplier diversity, lower costs, and modular development.

1 The White House, *National Spectrum Strategy,* November 13, 2023. https://www.whitehouse.gov/wp-content/uploads/2023/11/National-Spectrum-Strategy.pdf

A Portfolio of Synergistic Research Programs



ITS is both a scientific and an applied engineering laboratory. Theoretical and applied research are equally important facets of the ITS research mission that form a beneficial feedback loop. ITS's fundamental research portfolio, funded by Congressional appropriation, provides new, expanded scientific and engineering understanding of the basic physical principles upon which spectrum use depends and of the complex technologies being developed to exploit the radio spectrum, including spectrum at progressively higher frequencies. This expertise is leveraged to quickly and effectively respond to telecommunications questions brought to ITS by other federal agencies as well as by NTIA's Office of Spectrum Management (OSM).

ITS performs collaborative research with industry and academia through Cooperative Research and Development Agreements (CRADAs), which leverage ITS federal research resources to promote private sector innovation, entrepreneurship, and commercialization. CRADAs expose ITS researchers to cutting-edge industry research and development and allow industry to benefit from ITS's decades of knowledge and experience while protecting industry's intellectual property. These collaborations engender new insights and prepare all parties to meet future challenges in the U.S. telecommunications industry.

ITS staff represent U.S. interests at national and international telecommunication conferences and in standards development organizations (SDOs) as leaders and active participants in various working groups. Technical contributions by ITS experts drive innovation and contribute to the development of strong, unbiased communications and broadband standards that enable a robust telecommunication infrastructure, ensure system integrity, support e-commerce, and protect a globally competitive telecommunications marketplace.

Technology transfer through open science and formal or informal collaborations ensures that the Nation receives maximum value from the theoretical and applied research in the Institute's portfolio. NTIA scientific publications describe advances in fundamental radio science and best practices for solving real-world problems. ITS researchers publish in peer reviewed scientific journals and participate in technical conferences to engage in lively exchange of ideas and widely disseminate ITS research results. Software tools and validated propagation model implementations are released via the NTIA/ITS GitHub open-source code repository. Submissions to standards bodies further broaden the impact of ITS research.

Fiscal Year 2023 Research Questions

Spectrum is a unique natural resource: It is not depleted or depreciated by use, but neither can it be increased. It is impossible to "make more spectrum." To make more spectrum *available* means changing the rules for frequency allocation to permit more and different uses by allowing new services to use the same frequency bands — or near-adjacent bands — that existing users occupy. In fiscal year (FY) 2023, research funded by other agencies and OSM very directly focused on addressing spectrum sharing issues made urgent by either recently enacted or imminently pending regulatory changes. All federal agencies depend on the radio spectrum for mission critical uses, many of them safety-of-life, vital to national security, or vital to the U.S. economy. The DoD, the largest federal agency, is also perhaps the agency with the most, and the greatest variety of, spectrum dependent systems—and, consequently, DoD sharing issues motivated a large part of ITS's FY 2023 other-agency-funded portfolio. In addition to maintaining its full portfolio of fundamental research, in FY 2023 ITS performed research to resolve questions brought forward by 12 different offices of 7 federal agencies, as well as OSM.

For example, in FY 2023, ITS also continued to support the Department of Transportation (USDOT) in its aggressive pursuit of robust, secure wireless Vehicle-to-Everything (V2X) technology. Part of USDOT's overall, long-term, comprehensive approach to reducing roadway fatalities, V2X enables vehicles to communicate with one another, with other road users, and with roadside infrastructure. To realize the full lifesaving potential of V2X technology, though, vehicles and infrastructure must be able to communicate safely, securely, and without harmful interference across devices and platforms. This year's focus was on laboratory and field tests to assess the potential for adjacent channel interference from Wi-Fi® devices into the V2X band, as well as on researching radio layer security vulnerabilities. ITS also continued to assist the National Oceanic and Atmospheric Administration (NOAA) to protect the integrity of weather and environmental data transmitted by a constellation of satellites operating in an increasingly crowded spectrum. This critical data is used daily throughout the U.S. by the National Weather Service (NWS), scientists in myriad disciplines, the commercial sector, and private citizens for a wide range of applications.

ITS's Holistic End-to-End Research Approach

Between 2010 and 2020, and driven by voracious demand, Executive Order, and Congressional fiat, more than 7,500 MHz of radio frequency (RF) spectrum was repurposed. Repurposing inevitably means increased spectrum sharing among federal and non-federal users and among disparate systems—e.g., between radars and cellular phones. Yet every new spectrum dependent system that is proposed must fit into the ecosystem of incumbent technologies already operating in the same or adjacent frequency band. The evolution from analog to digital transmitters and receivers, the rise of the commercial cellular phone industry, the commoditization of wireless technologies like Wi-Fi® and Bluetooth,® and, most recently, the emergence of a 5G ecosystem with widespread machine-to-machine (M2M) communication have changed the landscape of RF spectrum use and management.

Today, new systems may contain thousands of devices, many of them mobile, that operate in the same frequencies and geographies. Cellular and M2M systems may overlap with incumbent systems of a radically different nature, such as radars. Coordinating spectrum use within such a diverse and complex ecosystem presents special challenges. ITS's holistic approach to spectrum sharing research and its end-to-end telecommunication system analysis capability uniquely equip ITS to perform the research needed to inform today's spectrum management and regulation in ways that promote successful spectrum sharing and more efficient use of spectrum.

Understanding the potential impact of new, existing, and future technologies on each other's performance requires a multi-disciplinary approach that considers everything from the physics of the radio frequency that carries the signal to digital signal processing by the codecs that compress and decompress the signal so that it can be read by the receiver, whether the receiver is a human being or another device. Investigation of a particular sharing scenario might begin with surveying current use of that frequency.

ITS's measurements and characterizations of the radio spectrum and the devices that use it provide trusted independent data to inform policymaking. Propagation models derived from first principles feed into software implementations for practical use by experts and non-experts alike. Experts' expansive knowledge of system characteristics and the radio access network (RAN) protocols that manage communications between systems supports test and evaluation of emerging communications technologies. A deep understanding of signal processing provides a foundation for new metrics of transmission quality that illuminate the trade-off between bandwidth and quality. This expansive and holistic approach to spectrum research supports end-to-end telecommunication system analysis capability and enables development of data-validated simulations to speed feasibility analyses.

Awards

Double Honors for Innovative Spectrum Compatibility Testing

A team of ITS and OSM researchers was twice honored for planning, designing, and implementing first-of-their-kind quick-reaction over-the-air 5G transmitter measurements and analyses for testing electromagnetic compatibility between 5G signals and existing radar communication used in aircraft. The 17-month project reached fruition in FY 2023. The ITS team, pictured below, along with Edward Drocella, Nickolas LaSorte, and Charles Glass of OSM, received the 2023 U.S. Department of Commerce Gold Medal for Scientific/Engineering Achievement, the highest honor granted by the Secretary for distinguished and exceptional performance.

The ITS team, based in Boulder, Colorado, was also selected to receive the CO-LABS Governor's Award for High-Impact Research, which was accompanied by a Congressional Certificate of Special Recognition from Congressman Joe Neguse's office. The award was started in 2009 by Colorado Governor Bill Ritter to celebrate those ground-breaking discoveries from Colorado's federally-funded laboratories and institutions that have significant potential for widespread societal application. The project, fully described on page 38, yielded not only highly impactful published results with multibillion-dollar consequences, but also a new measurement system that represents a state-of-the-art advancement for conducting repeatable spectrum coexistence engineering measurements, studies, and analyses.

GOVERNOR'S AWARDS FOR HIGH–IMPACT RESEARCH 2023

From left, Kenneth J. Brewster, Frank H. Sanders, Geoffrey A. Sanders, Kenneth R. Tilley, Kenneth R. Calahan, and Savio Tran at the Denver Museum of Nature and Science, where they received the CO-LABS Governor's Award for High-Impact Research,on Wednesday, October 11, 2023. (Photo © Liz Copan/Studio Copan.)

ITS Peer Awards

For decades, the ITS internal awards have offered ITS employees the opportunity to recognize colleagues for exceptional performance. The ITS Outstanding Publication, ITS Outstanding Technical Achievement, and ITS Director's Cornerstone awards are peer-nominated and peer-adjudicated. This recognition by those who have the most technical understanding of the intensity of an effort or the brilliance of a solution, which may not be readily apparent to non-scientists, is highly valued.

In FY 2023, two internal awards went to the same team that received the DOC Gold Medal and the Governor's Award also received an ITS Outstanding Technical Achievement award for designing and executing flight tests and a new measurement system to collect data on potential interference between 5G systems and radio altimeters. Colleagues recognized the unique challenges that the team overcame in record time, from obtaining needed Special Temporary Authorizations (STAs) to transmit, to coordinating among multiple agencies, to installing the specially built system into helicopters for fly-overs.

Four members of the team also received the ITS Outstanding Publication award for the report on the measurement campaign. NTIA Technical Report TR-22-562 "Measurements of 5G New Radio Spectral and Spatial Power Emissions for Radar Altimeter Interference Analysis" provided timely, critical insights into the most prominent spectrum sharing issue in decades: the delay imposed on full 5G commercial deployment in the C-band due to FAA and DoD concerns about potential interference from 5G base stations into radio altimeters.

Recognizing that the extensive media coverage of the disagreements between the cellular carriers and the FAA would attract a much broader audience than is typical for NTIA Technical Reports, the authors included an especially comprehensive treatment of the nature of the problem, the nature of the two spectrum dependent systems seeking to coexist in adjacent frequency bands, and the methods used to conduct the electromagnetic compatibility analysis, as well as developing new 3D visualizations to illustrate the received 5G power throughout the helicopter flight paths.

A second ITS Outstanding Technical Achievement award went to the seven-person team of Kenneth J. Brewster, Mike Chang, John Ewan, Adam Hicks, Robert T. Johnk, James McLean, and Linh Vu for the design, development, and deployment of the first prototype of a troposcatter measurement system to support critical propagation model development work. Troposcatter, or, more formally, tropospheric scatter, was extensively studied in the mid twentieth century in order to model over-the-horizon radio links that might span several hundred, even 1,000, kilometers.

As the distance between transmitter and receiver increases, so does the impact of the atmosphere on the propagation of the radio wave. After the first satellite deployments during the 1960s, though, interest in measuring and modeling tropospheric effects waned. With the deployment of satellite constellations numbering in the thousands 70 years later, interest in understanding troposcatter has revived—but there is a worldwide dearth of relevant measurement data. So the team proceeded to systematically—and successfully—design, construct, bench test, characterize, and field test an entirely new measurement system.

The Director's Cornerstone award recognizes that award-winning research depends in part on award-winning behind the scenes support. The FY 2023 award went to Bradley Eales, ITS's lead data scientist, for architecting and driving the implementation of a versatile, security fenced machine learning (ML) platform. He engaged with the research teams to design the most flexible and cost-effective machine learning software and hardware environment that would meet their scientific objectives, interpreted the requirements to NTIA's IT Division, and oversaw installation of the testbed. His efforts enabled teams in different specialty areas to explore ML techniques for applicability to a broad variety of research problems, from assessing audio quality to modeling propagation through clutter.


INSTITUTE FOR TELECOMMUNICATION SCIENCES
RADIO SPECTRUM MEASUREMENT SYSTEM
NTIA

Propagation Measurement

The fundamental physics that describe how radio waves propagate (travel in space) and how they can be made to carry information (sound, images, data) as they propagate has not changed since ITS first started researching radio waves more than 100 years ago. But both our ability to acquire information about the behavior of radio waves and our ability to predict their behavior have greatly expanded as the capability and sophistication of measurement and computing devices has increased. Being able to accurately measure the power, frequency, and propagation of known and unknown signals is fundamental to understanding today's RF environment and essential to calculating whether different transmitters might feasibly coexist in the same or adjacent spectrum. The interrelated disciplines of propagation measurement and propagation modeling provide scientific data to analyze the feasibility of sharing and make the design decisions that will allow interference-free spectrum sharing.

Radio Spectrum Measurement Sciences

ITS's Radio Spectrum Measurement Sciences (RSMS) program builds on 100 years of experience in RF measurements to develop, implement, and disseminate best practices for capturing accurate radio frequency measurements. The expertise and capabilities cultivated in the RSMS program support the NTIA and other federal agencies by developing and maintaining the Institute's ability to perform critical, time-sensitive radio frequency (RF) measurements for purposes including:

- Spectrum and channel usage surveys and monitoring
- Equipment characterization and compliance
- Interference resolution and electromagnetic compatibility
- Signal coverage and quality

Spectrum surveys and spectrum monitoring measure and analyze the geographic and temporal distribution of RF signals within a spectrum band and provide empirical data to help determine which RF bands are good candidates for sharing in space or time. Spectrum surveys span multiple frequency ranges, last for one or more months, and measure spectrum occupancy, or the percentage of time that RF spectrum is being used within a given geographic area. Spectrum monitoring produces long-term, continuous observations of occupancy within a particular band from multiple sensors, provides real-time information about the use of a narrow range of frequencies across broad geographic areas, and enables observation of historical trends and events. If a band is unused within an area, then geographic sharing of that band is possible. If band occupancy is low, then that band is a candidate for sharing; a newcomer system could use the band when it is unoccupied by incumbent systems.

Two RF spectrum dependent systems with overlapping or near adjacent coverage may or may not interfere with each other. The analysis of whether coexistence is feasible begins with gathering the transmitter and receiver parameters of both systems. Transmitter power and receiver sensitivity, as well as information about the digital modulation, antenna characteristics, and bandwidth of both receiver and transmitter must be analyzed and understood. Electromagnetic compatibility analysis (EMC) uses all that information to establish the interference protection criteria (IPC): the engineering parameters that specify combinations of frequency and geographic separation which enable two RF systems to coexist.

OSM and ITS's other federal agency partners leverage RSMS expertise and capabilities to prevent and, if necessary, resolve interference problems involving federal systems. ITS's body of knowledge is applied to troubleshooting incidents of interference between systems and existing capabilities are tailored to specific situations. In FY 2023, technical directions for the RSMS program included:

- Develop new and improved propagation measurements to support model development in areas with man-made structures and foliage
- Expand capabilities for generating characteristic waveforms used to evaluate the performance of sensors employed in spectrum sharing devices
- Automate routines for capturing emissions from devices being introduced into a band for use in electromagnetic compatibility (EMC) analyses

ITS work in these areas is transferred to the broader research community through reimbursable research partnerships with the National Aeronautics and Space Administration (NASA), the National Institute of Standards and Technology (NIST), NOAA, the FCC, the FAA, the DoD, and OSM, among others.

The RSMS-4 measurement vehicle capturing emissions data on a 5G cell on wheels (CoW) while a portable RSMS data-collection system, operated by an ITS engineer, flies in a helicopter at the Table Mountain Federal Advanced Communications Test Site. (Photo credit: Kenneth R. Tilley.)

In FY 2023, the RSMS program completed the software integration of a new 18–26 GHz high-dynamic-range RF preselector. The RSMS program designs and constructs custom preselectors to address complex spectrum-sharing scenarios. This specific preselector enables ITS to perform spectrum measurements and EMC studies against 5G wave gNodeBs. RSMS uses similar preselectors from 100 MHz to 18 GHz to perform EMC studies for various sub-18 GHz systems (e.g. radars, 5G systems, land mobile radio, telemetry, and many one-of-a-kind communication systems).

Also in FY 2023, the RSMS program made incremental software updates to the RSMS Fifth Generation (RSMS-5G) measurement suite. This internally-built tool enables the RSMS program to perform automated and manual instrument control. The RSMS-5G tool choreographs data collection among spectrum sensors, preselectors, and various ancillary accessories (such as antenna rotators). The tool itself is built on MathWorks® MATLAB® software platform and allows the RSMS program to leverage MathWorks' significant research and development investments. Many of the analyses performed by the RSMS team are performed with MATLAB, so collecting the data and performing the analyses within a single application has led to increased efficiencies in data collection and quick-reaction measurements. The program also upgraded key test instruments and components used in spectrum-related research. These investments will allow ITS to continue to tackle spectrum-sharing challenges involving federal systems and state-of-the-art wireless technologies.

Federal Advanced Communications Test Site (FACTS)

Closely related to the RSMS program is the Federal Advanced Communications Test Site (FACTS) program, established in FY 2023 as a complement to and extension of the RSMS program. FACTS will use precision test equipment to perform accurate and actionable over-the-air measurements of techniques, technologies, or systems to promote increased spectrum sharing. Tests and measurements conducted in FY 2023 to assess the effect of C-band 5G base stations on adjacent band radar altimeters illustrated both the need and the requirements for a permanent facility for characterizing transmitter emissions of federal and next generation commercial systems and assessing harmful interference thresholds for these systems *(see 5G Coexistence with Radars in C-band on page 38)*.

FACTS will support development and validation of spectrum sharing models for feasibility studies, rulemakings, and interference mitigation. Using ITS's 1700 acre Table Mountain site *(see Table Mountain Radio Quiet Zone on page 76)*, FACTS will enable robust, open-air testing to: (1) measure emissions from federal spectrum dependent systems and commercial wireless base station and user equipment to support spectrum sharing modeling and analyses; (2) measure the levels at which commercial wireless systems cause harmful interference to federal systems and vice-versa; and (3) investigate artificial intelligence/machine learning (AI/ML) capabilities to facilitate dynamic spectrum sharing between federal systems and next generation (e.g., 5G, 6G, xG) systems.

Commercial mobile network operators (MNOs) must have access to a full array of spectrum bands to maintain U.S. leadership in advanced communications (e.g., 5G, xG). Many, perhaps eventually all, these bands will be shared with federal agency systems. To successfully implement the National Spectrum Strategy (NSS), to establish spectrum-sharing arrangements, and to support science-based objective decision-making, federal agencies and MNOs need to understand the characteristics of transmitter emissions and receiver performance. Newly deployed spectrum-monitoring sensors and state-of-the-art test equipment will enrich the creation of new spectrum optimization AI/ML capabilities that will curate, manage, and disseminate comprehensive spectrum measurement datasets for use by authorized government and non-government researchers.

As a national test range, FACTS is staffed with ITS subject matter experts, and the AI/ML based evolved spectrum sharing capabilities will increase commercial access to spectrum. FACTS will leverage ITS's Table Mountain field site, which is the only radio quiet zone in the U.S. with open-air transmission capability. Using this unique asset, FACTS' initial focus will be on mid-band spectrum sharing options. In coordination with OSM and in support of the NSS, FACTS engineers will proactively address knowledge gaps that impair accurate spectrum sharing modeling and that can be resolved by over-the-air measurements. Evolving NSS priorities will motivate research outside of mid-band spectrum.

Future Research

FACTS startup activities in FY 2023 focused on tooling up: procuring test equipment, obtaining commercial 5G telecommunications equipment and support services, and contracting for Table Mountain infrastructure improvements. Research planned for FY 2024 includes:

- Measurements of aggregate signals generated by large deployments of C-band 5G base stations which, when compared to interference model predictions, will provide a gauge of the accuracy of those models. Confidence in aggregate interference models, the crux of spectrum sharing feasibility studies, is an essential precursor to successful rulemakings and spectrum auctions.

- Publication of a survey of current federal research into applications of AI/ML to promote dynamic spectrum sharing through control of the 5G physical layer. This activity will promote coordination and collaboration between the federation of test ranges supporting dynamic spectrum sharing research.
- Development of a pilot AI/ML program to address a relevant gap in the AI/ML research portfolio.
- Investigation of the characteristics of 5G advanced antenna systems to formulate methods of statistically describing their effective isotropic radiated power (EIRP). This addresses a significant gap in electromagnetic compatibility modeling that arose upon the introduction of new 5G based antennas which constantly adjust transmitted power and directionality to focus energy on users.

An Army Blackhawk helicopter probes the space surrounding a 5G base station to determine the effects of 5G emissions on an on-board radar altimeter. (Photo credit: Eric Nelson)

Spectrum Monitoring

The RSMS and FACTS programs offer the most advanced, sophisticated, and versatile RF measurement instruments and methods. These capabilities are designed to scientifically investigate potential future sharing scenarios, nascent technologies, and the need to continuously build a more detailed and expansive understanding of the physics of radio waves across multiple frequencies. The need for real-time awareness of how spectrum is being used in specific frequencies and geographies becomes more pressing as the RF environment becomes more crowded and sharing becomes increasingly complex. Data generated through spectrum monitoring are used by spectrum managers to coordinate use and enforce rules. Monitoring is also essential to optimize efficient use of the spectrum, now and in the future.

ITS's Spectrum Monitoring Program aims to provide spectrum stakeholders with more effective, evolvable, and scalable monitoring solutions to enable distributed, persistent, and automated monitoring of spectrum occupancy (the percentage of time that the band is being used) in specific frequency bands. Over the course of a decade of development, ITS has iterated prototypes to improve sensor performance while decreasing the physical footprint and hardening the sensors for fully outdoor deployments.

Scaling spectrum monitoring requires inexpensive sensors that can operate unattended for long periods of time. ITS designs, prototypes, tests, builds, and deploys RF sensors using software defined radios (SDRs) and other commercially available RF components. The sensors can be easily adapted to new requirements with different antenna, preselector, connectivity, and onboard computer configurations.

Incorporating lessons learned from early prototype deployments, a multi-agency team that included ITS researchers from the Spectrum Monitoring program deployed validated, reliable, robust production-level spectrum monitoring systems that offer secure real-time continuous data for authorized data clients, advanced data analytics and visualization to characterize the wireless ecosystem, and alerts on potential interference events. These systems were implemented to support a long-term monitoring initiative in the Citizens Broadband Radio Service (CBRS) band. They include all the characteristics that are needed for effective spectrum monitoring:

- Heterogeneous, low cost, rugged sensors
- Standardized interfaces
- Secure open-source software implementations
- Common metadata
- Automated provisioning, deployment, and maintenance
- Data analytics incorporating artificial intelligence and machine learning

Software integration of different components (e.g., new SDR models) and new single- and multi-sensor algorithms evolves the capabilities of the overall infrastructure. Automated calibration routines calculate the gain, equivalent noise bandwidth, noise figure, and 1 dB compression point for each sensor. These routines are independent of the underlying hardware to allow any sensor to be quickly calibrated before it is fielded. Resulting calibration tables are uploaded to the sensor software to allow for calibrated power measurements to be performed in the field.

Prior years' research and development produced the Spectrum Characterization Occupancy Sensing (SCOS) sensor and manager software, standardized as IEEE 802.15.22.3 in an effort led by ITS. The SCOS sensor software provides a common Application Programming Interface (API) that interacts with distributed heterogeneous sensors and that is agnostic as to the manufacturer, cost, and capabilities of the sen-

A variety of ITS-developed spectrum monitors designed to monitor different radio frequencies.

sors. To better enable sharing of datasets, ITS also developed [sigmf-ns-ntia](), a namespace extension to the core SigMF standard for storing recorded signal datasets. sigmf-ns-ntia enriches the metadata available for sharing and analyzing datasets.

Crowdsourcing

Also in FY 2023, the Spectrum Monitoring Program began exploring the possibility of crowdsourcing as an avenue to collect spectrum occupancy data. The Crowdsourcing and Citizen Science Act of 2016 ([15 U.S.C. §3724]()) granted federal laboratories explicit authority to use crowdsourcing and citizen science as appropriate to advance agency missions. In 2017, the ITS audio quality program reported that crowdsourced speech intelligibility testing using anonymous, self-selecting subjects in uncontrolled environments listening via internet attained results nearly identical to those obtained in highly-controlled laboratory environments. That year also, the ITS public safety communications research program reported the successful development of a cellphone app that allowed public safety stakeholders to collect robust data on in-building LTE coverage in the band dedicated to the FirstNet nationwide public safety network.

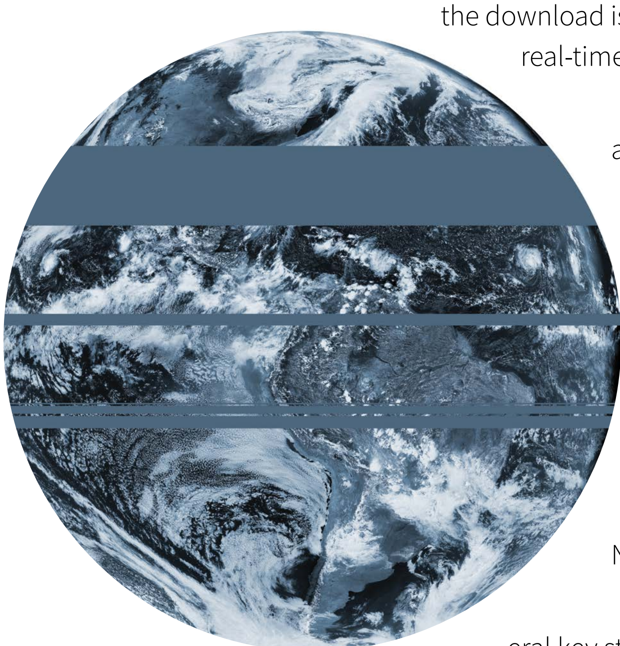
Building on those successes, the program began exploring the unique opportunity presented by mobile phone ubiquity to expand the diversity and quantity of spectrum occupancy data by adding crowdsourcing as method of collection. Both LTE and 5G networks broadcast a known set of reference signals to enable mobile phones to identify and attach to a network, and mobile phones continuously measure the power of these signals when seeking the optimal connection.

These reference signal measurements present an untapped and abundant signal of opportunity for high quality RF measurement data. A series of experiments In FY 2023 compared the accuracy of such measurements performed by several different mobile phone models to measurements performed with a commercial-grade LTE network scanner. The results were encouraging for future research.

Radio Frequency Interference Monitoring System Support

For a number of years, ITS has supported the testing and deployment of an advanced spectrum monitoring system for the National Oceanic and Atmospheric Administration (NOAA). Radio Frequency Interference Monitoring Systems (RFIMS) facilitate spectrum sharing between NOAA and commercial carriers in the 1695 to 1710 MHz band, referred to as AWS-3, where weather satellites currently transmit to NOAA earth stations as well as to private and commercial users across the United States.

The data transmitted from both Polar Operational Environmental Satellites (POES) and Geostationary Operational Environmental Satellites (GOES) is critical for weather forecasting, severe weather tracking, search and rescue, and environmental monitoring. It also supports investment and resource utilization in dozens of economic sectors— agriculture, transportation, fisheries, energy, construction, insurance, emergency management, and hazard mitigation, to name a few. Data are permanently lost if the download is interrupted, since they are transmitted in a continuous real-time stream.

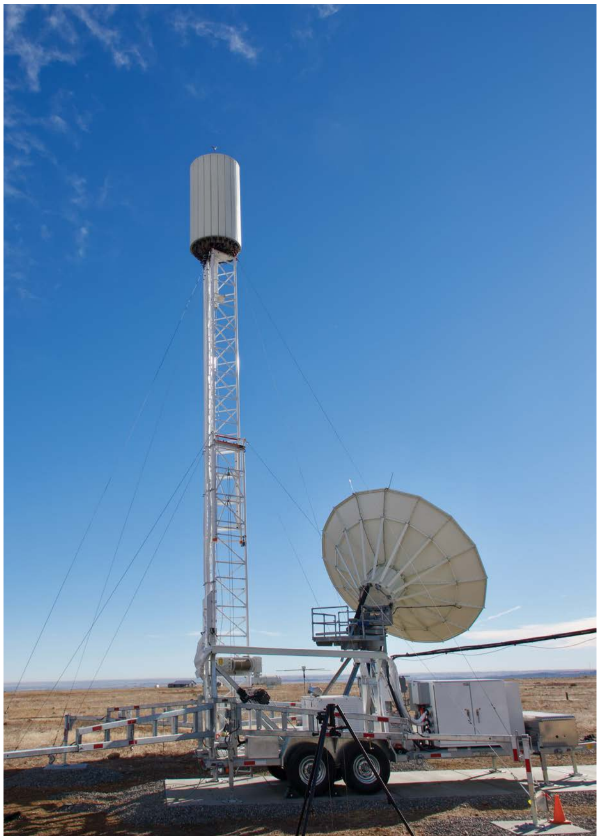


NOAA started development of RFIMS systems immediately following the 2015 auction of the AWS-3 band, with the aim of developing continuously operating near-real time monitoring, data collecting, and reporting methods to implement cooperative spectrum sharing. The goal was and is to share information in real time between the wireless carriers entering that spectrum band and NOAA. The shared information will enable the carriers to deconflict their operations through active supervision and management of signal power spectral densities to prevent interference to NOAA ground station operations.

In FY 2023, the RFIMS Support Program performed several key studies to facilitate spectrum-sharing between NOAA and commercial wireless carriers. ITS completed new studies on NOAA earth station systems located at ITS's Table Mountain field site to assess interference artifacts related to the respective systems. The systems were methodically tested against synthesized 5G signals and the results analyzed and disseminated to the NOAA RFIMS program management office.

Table Mountain hosts one RFIMS for long-term testing, research, and development. Originally deployed in 2021, the Table Mountain RFIMS was initially designed and optimized to detect 4G Long Term Evolution (LTE) signals. Subsequently, 5G has become the de facto standard for terrestrial wireless service. In 2022, the contractor that developed the RFIMS performed an engineering upgrade to make the system capable of detecting 5G wireless signals.

In 2023, ITS engineers spent a substantial amount of time working alongside NOAA engineers to perform capability assessment tests of the new 5G-capable RFIMS. Using ITS's Table Mountain infrastructure, measurements were conducted while vector signal generators were autonomously instructed to transmit synthesized waveforms using different transmit waveforms and scenarios. These long-term tests were crucial to the joint NOAA-ITS studies.



In the fall of 2023, mobile network operators began the deployment of wireless services in the 1695–1710 MHz portion of AWS-3 in Colorado. ITS engineers worked to determine the locations of these cellular towers and capture real-world, in situ signals from them. These signals were used to evaluate and refine assumptions made with the ITS-synthesized interference waveforms used to test the RFIMS.

Looking forward to FY 2024, ITS will assist NOAA with the development and fielding of a compact monitoring system, similar in capabilities to the RFIMS, that will be deployed at two NOAA sites in Florida and Hawaii. These compact monitoring systems, based on vector signal analyzer technology, will run autonomously and have the ability to capture both spectral and in-phase and quadrature (I/Q) recordings for offline analysis.

RFIMS at Table Mountain (left), with one of three earth station receiving dish antennas installed at the RFIMS over-the-air testbed at Table Mountain. (Photo credit: Kenneth R. Tilley)

Sharing Ecosystem Assessment

The Sharing Ecosystem Assessment (SEA) project strives to characterize the effectiveness of the current Citizens Broadband Radio System (CBRS) ecosystem as well as to observe the growth of commercial entrants and their effect on DoD incumbents through measurements. The project was proposed and funded by Defense Information Systems Agency Program Executive Office for spectrum (DISA PEO Spectrum) to the National Advanced Spectrum and Communications Test Network (NASCTN), a multi-agency chartered partnership that coordinates requests for research among a national network of federal, academic, and commercial test facilities. It provides testing, modeling, and analysis to develop and deploy spectrum-sharing technologies and inform future spectrum policy and regulations. SEA project execution is a collaborative effort among NIST, ITS, NASA, and The MITRE Corporation.

To characterize the effectiveness of the CBRS ecosystem, the project deployed and continues to field spectrum monitoring sensors at several key locations near coastal regions governed by spectrum sharing rules associated with the nearby dynamic protection areas (DPAs). These sensors will characterize the RF environment in the CBRS band (3.55–3.7 GHz) through data products computed at the edge and delivered to a database hosted on premises in Boulder, CO. They are designed to collect spectrum occupancy data autonomously and continuously with minimal physical intervention to provide insights for long durations. The sensors will remain deployed through 2026 to observe the evolution of the CBRS ecosystem.

The sensors' design, the outcome of ITS's long-running spectrum monitoring program, encompasses measurement and fielding best practices, implemented through a formal prototype design and validation process. Each sensor is fielded with a highly calibrated RF chain to ensure continuously accurate measurements of the band. The unique calibration methodology calls for a two-step procedure using an external probe on installation and an on-board calibration source during continuous operation. The sensor deployment is provisioned with NTIA's reference implementation of the SCOS standard which has been tailored to take amplitude summary statistics in both frequency and time on the CBRS environment of the sensor. This data is then packaged into the SigMF format to ensure data compatibility across many efforts and sent back to the on-premise server over a private LTE network, freeing sensor deployments from physical network infrastructure constraints.

FY 2023 saw the first deployments of the prototype sensor in Boulder and Virginia, offering the first look into the live system through the sensors. The sensors were operated through the entire year with a data collection rate greater than 90% during active collection campaigns. In addition, although these were prototype sensors, there were no issues that required physical intervention after installation—all issues were resolved remotely. The initial data allowed the evaluation of the derived data products and their utility to the goals of the project, including developing several example data analysis techniques and refinements to the data products as a whole.

Building on lessons learned from deployment of the prototype sensors, design revisions were made to address any shortcomings and improve the viability of the sensor. For example, a fully outdoor, weather hardened version of the sensor was designed to increase deployment flexibility. The SCOS software was improved to support additional features, data product enhancements, and stability improvements based on the year of failure mode analysis. A new round of sensors has been commissioned, verified, and is being prepared for deployment.

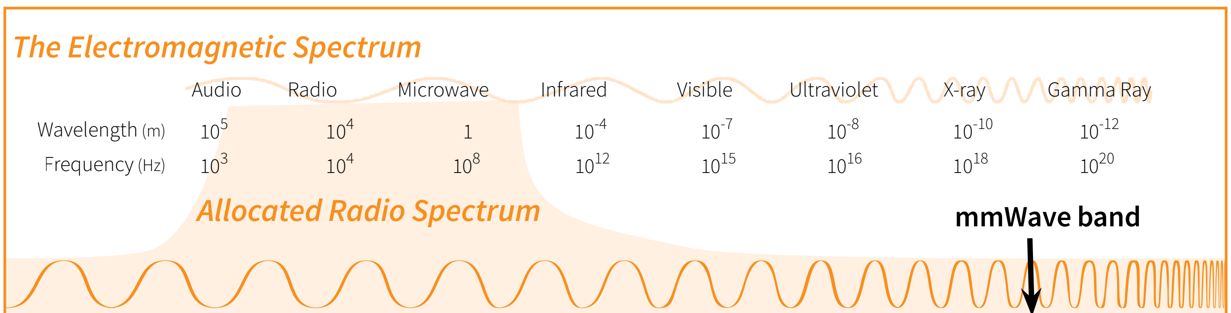
Above left, ITS Principal Investigator Todd Schuman measures antenna S-parameters during installation of a SEA prototype sensor at the Norfolk International Terminal (NIT). Right, top, SEA prototype preselector installed at the top of a NIT tower, with the door open to show internal components; bottom prototype sensor (antenna and preselector) deployed on top of a Hampton University building in Hampton, VA. (Photo credit: Anthony Romaniello)

The Institute
Propagation Measurement
Propagation Modeling
Electromagnetic Compatibility
Networks & Quality of Experience
Technology Transfer
Research Capabilities

To help site these sensors, several site surveys were carried out including returning to Camp Pendleton to finalize a deployment strategy to a reduced list of sites. Other sensor site locations were guided by modeling the environment to find locations that would provide a critical look into the ecosystem, with an overall collection strategy being developed. Once on-site, the surveys took data through a representative system as well as verified other pertinent details (backhaul service levels, installation feasibility, etc.) to begin planning an actual sensor deployment.

In addition, the first of two SEA Test Plans was briefed to the community at a community forum in March 2023. During the event, the NASCTN CBRS SEA team presented an update on the project and briefed the Test Plan to the community to garner feedback on the direction and plan. The briefing was followed by a public comment period to allow further feedback on the Test Plan. All comments were adjudicated and the updated Test Plan was released shortly into the following fiscal year. This event presented a great opportunity for the research team and stakeholders to come together and understand the goals and methods of the project, leading towards a successful data collection campaign that provides valuable data to the community.

Building on a successful year of prototype deployment and analysis as well as designs for a production system, the team will construct the next generation of sensors and look to site these sensors at the key points around the United States identified through a combination of modelling and surveys. The next Test Plan will be written and finalized in a similar manner to this year's and the research team will continue to work with the CBRS community to ensure that the project takes pertinent data that is useful to all stakeholders. This data will lead to a unique look into a live-deployed spectrum sharing ecosystem and could prove to be a template for highly dynamic spectrum sharing strategies in the future.



ITU Band	4–VLF	5–LF	6–MF	7–HF	8–VHF	9–UHF	10–SHF	11–EHF	12–THF
Frequency	3 to 30 kHz	30 to 300 kHz	300 to 3000 kHz	3 to 30 MHz	30 to 300 MHz	300 to 3000 MHz	3 to 30 GHz	30 to 300 GHz	300 to 3000 GHz
Wavelength	10 to 100 km	1 to 10 km	100 to 1000 m	10 to 100 m	1 to 10 m	10 to 100 cm	1 to 10 cm	1 to 10 mm	0.1 to 1 mm

Millimeter Wave Measurements and Modeling

Current approaches to implementing emerging 5G wireless networks and technology incorporate the use of radio spectrum both in the 6 GHz (5.925 to 7.125 GHz) and lower bands, and in the millimeter wave (mmWave) bands (24 GHz and above). Spectral congestion in the 6 GHz and lower bands means lack of availability of the wider bandwidths desired for 5G operation. This is a strong motivator for pursuing use of frequencies in the mmWave bands, where available spectrum is more abundant. The characteristics of radio wave propagation and the behavior of communication systems have been studied more extensively and are better known at lower frequencies; propagation and spectral emissions from systems operating at mmWave are not understood as well. Design, development, deployment, and regulation of 5G systems operating in the mmWave bands are dependent on a sound understanding of the radio propagation environment and the spectral emissions and active antenna characteristics of the 5G systems in those bands.

To address the needs of better understanding the mmWave radio propagation environment and the spectral emissions and active antenna behavior of 5G systems operating at mmWave, ITS continues to modernize and expand its capability to perform mmWave measurements. ITS is uniquely positioned to provide objective, unbiased measurements at mmWave based on its history of leadership in mmWave research, measurements, and modeling beginning in the 1970s, in addition to its extensive experience in spectrum, propagation, interference, and noise measurements throughout the radio spectrum.

In FY 2023, mmWave work at ITS was primarily focused on preparing to deploy a mmWave 5G base station (gNodeB) at Table Mountain, with the goal of performing active antenna characterization (AAC) and out-of-band emissions (OOBE) measurements on the downlink in the future. Significant work on the development of the AAC measurement system was also completed. Another enhancement to the ITS mmWave measurement laboratory procured in FY 2023 was a new, wideband (2 GHz bandwidth) vector signal analyzer with measurement capability up to 50 GHz. This analyzer not only enables wider bandwidth measurements for characterizing the radio channel at mmWave frequencies but also serves as an essential, additional mmWave analyzer for field measurements.

The goal for the AAC measurements is to provide a measured azimuthal antenna pattern characterizing the performance of the active antenna in the mmWave gNodeB. Some limited elevation antenna pat-

Specialized antenna face mount being installed by ITS's Kenneth Brewster (right) and Ryan McCullough on the mobile antenna tower at the Table Mountain mmWave 5G test cell site.(Photo credit: Jeffery Wepman).

tern characterization will also be obtained. The goal for the OOBE measurements is to provide a depiction of the received signal power across a band of frequencies spanning from below to above the operating frequency band of the gNodeB.

ITS considered various options for conducting AAC and OOBE mmWave measurements, including measurements on an existing, commercially operational 5G cellular system, but chose to deploy an outdoor mmWave 5G test cell site on Table Mountain to be able to conduct repeatable measurements in a controlled environment. The mmWave 5G test cell site operates in the 37–40 GHz (n260) band in non-standalone (NSA) mode, which requires both an LTE base station (eNodeB) operating in LTE band 66 and a mmWave 5G gNodeB. The cell site is an expansion of the ITS Communications Research and Innovation Network (CRAIN) lab 5G testbed *(see Communications Research and Innovation Network (CRAIN) Laboratory on page 71)*, a commercial grade 5G system that consists of an NSA core, a standalone (SA) core, and sub-6 GHz 5G gNodeBs located in the Radio Building at the Boulder Labs.

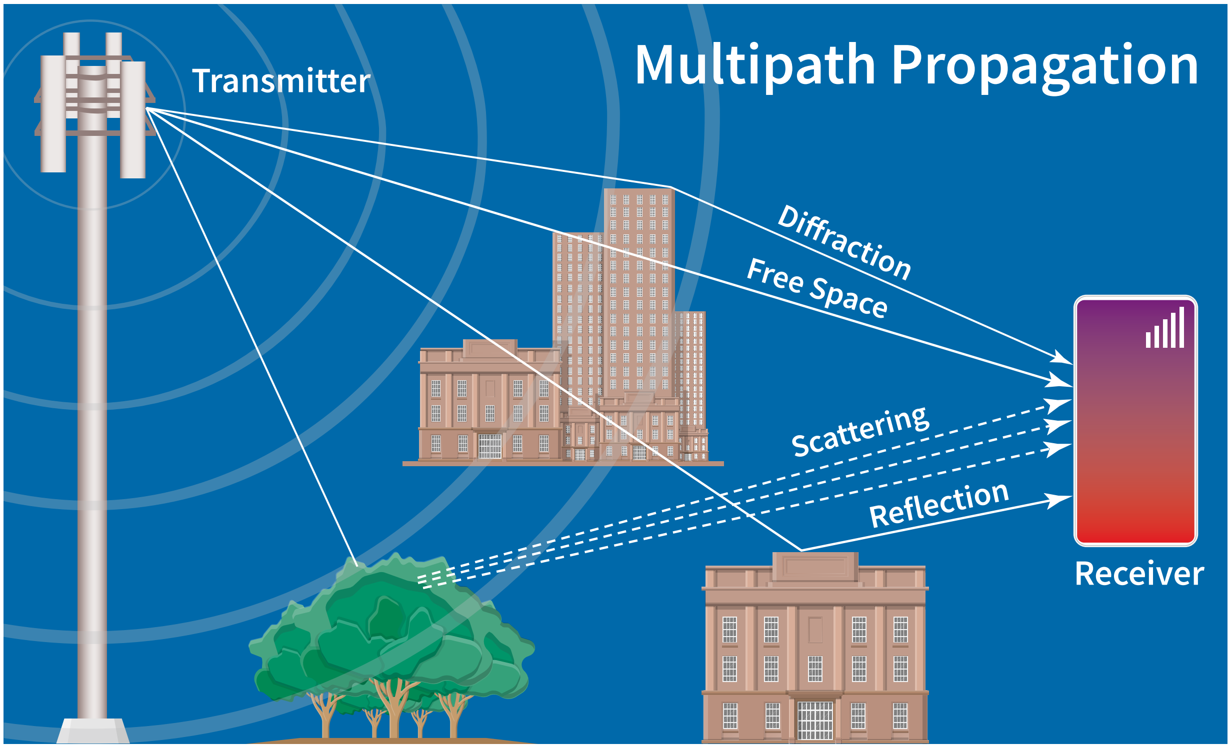
The mmWave cell site will be located at Building T2 at the Table Mountain Field Site and Radio Quiet Zone and is supported by the CRAIN lab NSA core. Building T2 is particularly well-suited for deployment of the mmWave gNodeB and conducting over-the-air RF measurements on a cellular base station: it has a significant amount of existing infrastructure required for installation, is located near the center of Table Mountain, and has proximity to existing roads to facilitate mobile drive test measurements.

Planning for the deployment of the mmWave cell site required tight coordination among the CRAIN lab, cellular equipment manufacturers, NTIA IT department, Table Mountain management, and the mmWave project (jointly funded by OSM and ITS). Significant progress was made on equipment procurement and site preparedness. The AC power in Building T2 was upgraded with a new 48-volt DC power plant to power the LTE eNodeB and 5G gNodeB. New fiber optic cable was laid from the central Table Mountain building (I10-C) to Building T2 to provide 10 Gbit/second network connectivity to the NSA core at the Boulder Labs. The required LTE eNodeB, LTE antenna, mmWave 5G gNodeB (with integrated antenna), and cabling and installation hardware were delivered and installation will begin in FY 2024.

For maximum flexibility a hydraulic tilt, 10 m antenna tower mounted on a trailer was procured and installed at the cell site. This provides a semi-permanent installation for the LTE antenna and 5G mmWave radio that can be readily moved if necessary. To accommodate mounting of the LTE antenna and mmWave 5G radio to the tower, a specialized antenna face mount was specified and obtained.

Another prerequisite that was completed for the deployment of the test mmWave cell site was obtaining the necessary experimental frequency licenses for transmission of signals for both downlink and uplink in LTE band 66 and for the mmWave 5G n260 band. To obtain an experimental license to operate in LTE band 66, approval from the spectrum licensee was required. ITS performed an extensive set of propagation analyses looking at signal propagation in this band using various transmitter power levels and antenna heights. These propagation analyses were used in negotiating an acceptable maximum transmitter power level and antenna height with the spectrum licensee. Full operational deployment of the mmWave test cell site is expected to complete in 2024.

For development of the AAC measurement system, hardware and control software modifications were made to the ITS 37-40 GHz CW propagation measurement system receiver (see NTIA Technical Report TR-22-561). These modifications included the addition of a low-noise amplifier bypass switch in the receiver preselector and software to control this switch. The bypass switch increases the measurement system dynamic range by adding the capability to easily measure high power signals in addition to low power signals. Development of the OOBE measurement system and conducting AAC and OOBE measurements on the mmWave 5G gNodeB are planned for FY 2024.



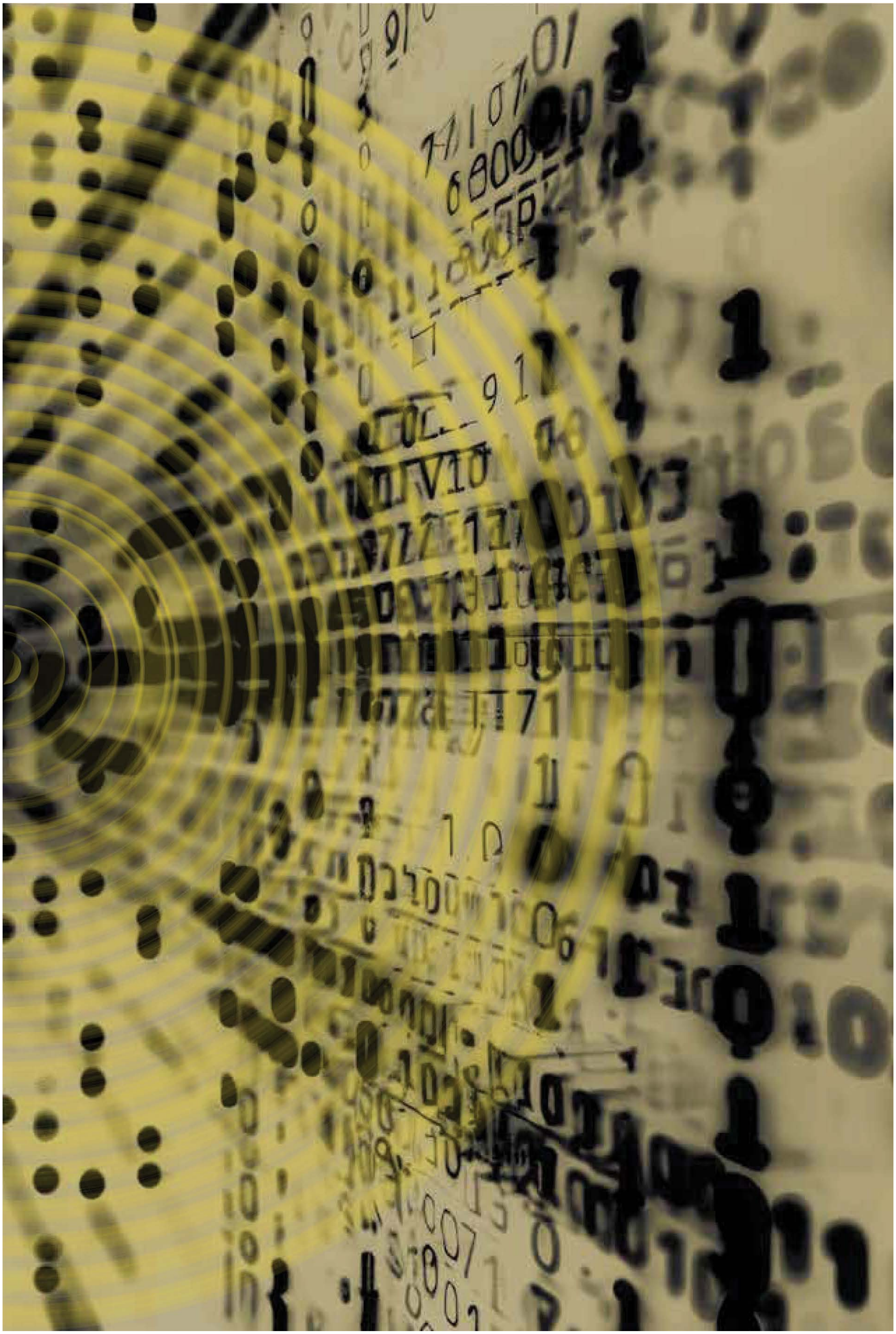
Advanced Measurement Techniques

To address complicated theoretical concerns raised by the theory and modeling division, a cross-divisional project was launched in FY 2023 to develop advanced measurement techniques. These techniques required specialized systems to be developed, measurements to be conducted for comparison to theory, and procurement of systems to support the expansion of ITS's capabilities into the future.

Two decades ago, ITS developed a pseudo-noise (PN) channel probe and successfully conducted mobile impulse response measurements in the 1850–1990 MHz band. These measurements were analyzed statistically to provide a qualitative understanding of multipath propagation within the measurement environment. Multipath characteristics can be useful in categorizing complex environments, such as urban centers, and in developing statistical models for wide-area predictions. Work has been done to generate the necessary PN sequences and the new, 21st century system has completed calibration on the bench. ITS plans to validate this system in the field in early FY 2024.

A proof-of-concept measurement campaign was specifically designed to isolate the effects of location and time-based variability within a measured environment. This measurement was conducted in March 2023, using a mobile and a static system. The mobile system repeatedly drove a set route around the static system at different times of day for two weeks. The distribution of data from the mobile system was then compared to that of the static system and the differences noted. In FY 2024, ITS plans to use the results to influence the design of future measurements where static systems are easier to deploy and, if possible, repeat the measurement in a more complex environment and for a longer duration of time.

To further expand ITS measurement capabilities for future investigations, ITS began the development of an improved mobile clutter system intended to measure frequencies up to 20 GHz. ITS plans to deploy this system for validation in the summer of FY 2024.

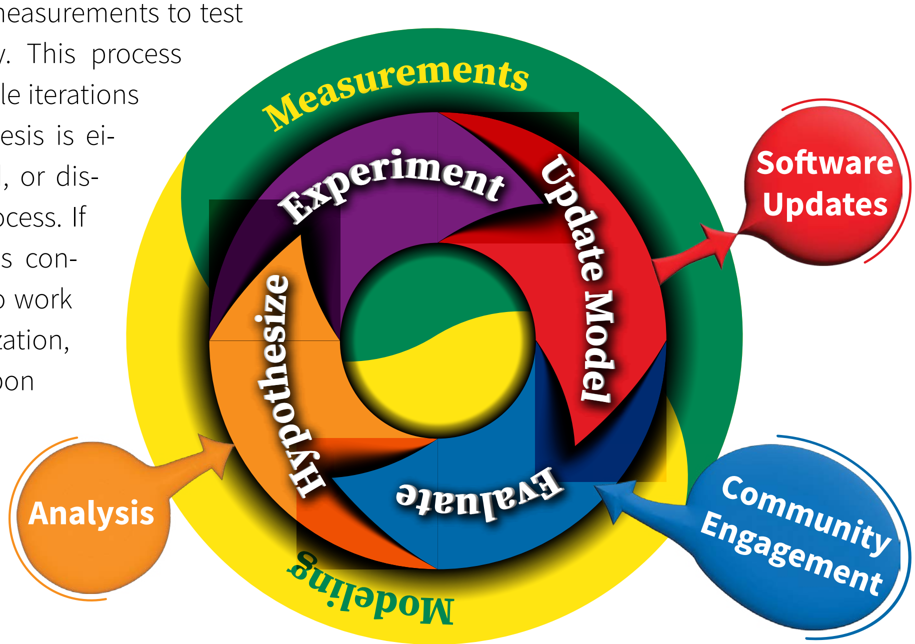


Propagation Modeling

Propagation models are mathematical algorithms that predict the real-world effective coverage area of a transmitter and its potential overlap with other transmitters by characterizing radio wave propagation as a function of frequency, distance, and other conditions. Models drive decisions about how and where to deploy cell towers, which rules to establish for sharing spectrum, and what kind of spectrum dependent equipment to build. Many propagation models—each optimized for a specific scenario—have been developed since Maxwell's equations first described the basics of radio wave behavior in 1861. Trusted models are foundational to spectrum sharing: it can succeed for all stakeholders only if all can agree on the optimal model for each scenario, trust the implementation used, and accept the results as sound.

To continuously improve propagation models, ITS researchers add new parameters or refine algorithms based on insights into refraction, reflection, and absorption of RF signals gleaned from propagation measurement data. The revised model is then validated against the measured data. For more than half a century ITS, has applied this iterative lifecycle—measurements, modeling, standardization, repeat—to support fundamental research and improvements in modeling and analysis. With constant reference to first principles, this rigorous approach has produced models that are highly regarded as objective, accurate, and authoritative. As a result, ITS research remains in the forefront of propagation theory, producing cutting-edge system and modeling design that is considered a national resource by other agencies, and ITS researchers are sought out as propagation subject matter experts. ITS models have been incorporated into NTIA and FCC rulemakings and national and international standards.

As both increased computing power and increasingly granular data (measurements, weather, terrain, and even profiles of the built environment) have become available, software implementations have become more complex, incorporating ever more parameters and granularity of conditions. Following the scientific process, ITS engineers generate a hypothesis based on technical theory regarding how either new propagation models can be formed or existing models updated. These hypotheses then motivate carefully designed field measurements to test and evaluate the theory. This process usually undergoes multiple iterations until the original hypothesis is either confirmed, modified, or discarded, restarting the process. If the original hypothesis is confirmed, the final step is to work towards model standardization, as community agreed upon propagation models support greater spectrum management goals of collective agreement among multiple stakeholders.

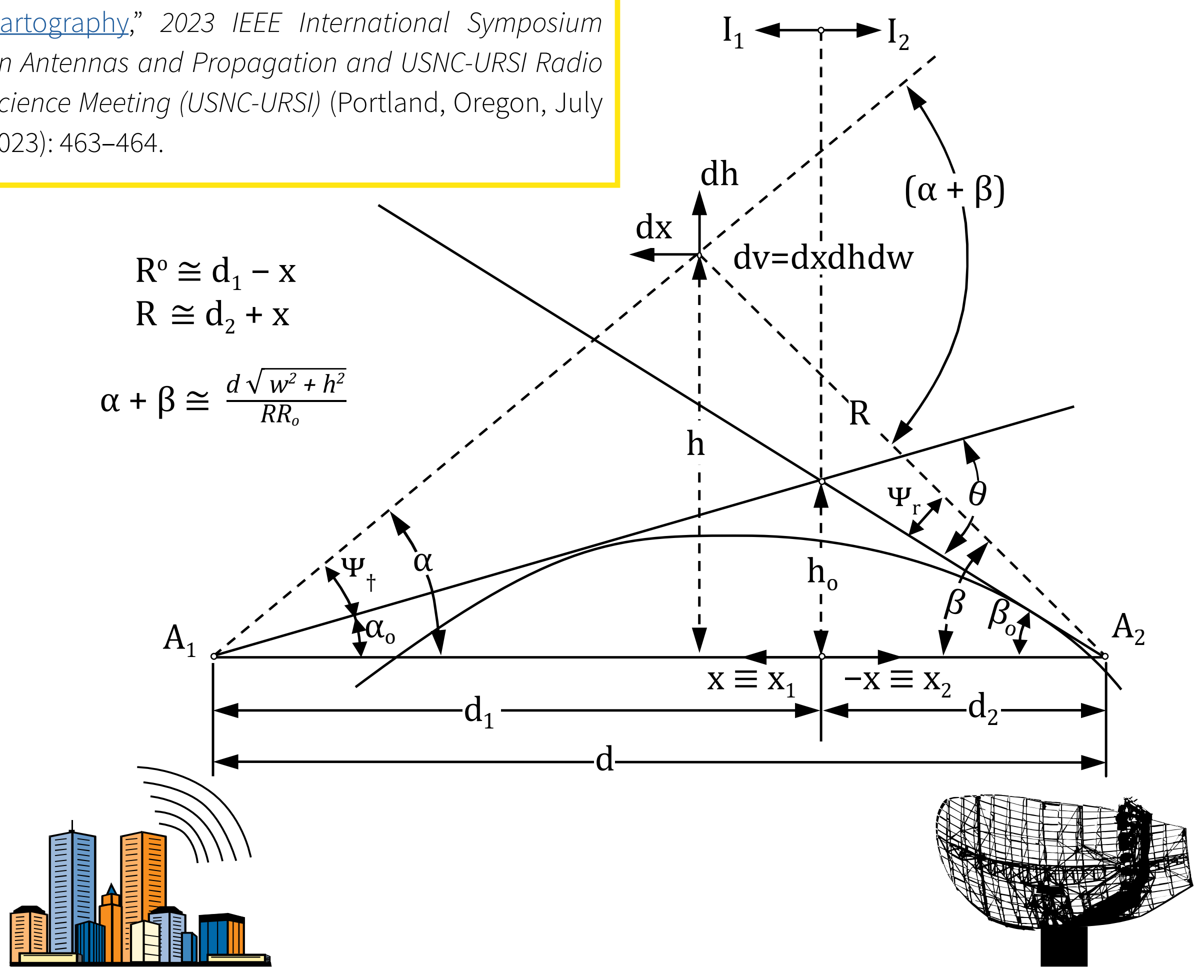


FY 2023 Propagation Modeling Efforts

ITS propagation modeling efforts focus on solving real-world issues through community-accepted modeling. Working closely with OSM, ITS develops models that can be applied to spectrum management and sharing analyses. In FY 2023, theoretical research from first principles was largely directed towards mid-band (3.1–4.2 GHz) propagation models. These bands are of intense interest for expansion of commercial 5G cellular services, and are also heavily occupied by a variety of DoD spectrum dependent systems vital to national security, from radars to radios. The office of the DoD Chief Information Officer (DoD-CIO) is supporting a multiyear ITS research program in this area in search of solutions for interference-free mid-band sharing. Also in FY 2023, ITS continued its leadership in International Telecommunication Union Radiocommunication Sector (ITU-R) Study Group 3 (SG3), which deals with radio wave propagation and issues international recommendations for propagation modeling. (See related article on page 62.) ITS technical leadership in ITU-R SG3 supported U.S. positions in international deliberations during the November 2023 World Radiocommunication Conference (WRC-23) and contributed to successfully advancing U.S. policy priorities with respect to international harmonization of spectrum allocations in the 3.3–3.4 GHz and 3.6–3.8 GHz bands.

Related Publications

- William Kozma Jr. and Michael G. Cotton, "A Proposed Mid-band Statistical Clutter Propagation Model Utilizing Lidar Data," *Proceedings of the 2023 17th European Conference on Antennas and Propagation (EuCAP)* (Florence, Italy, March 2023): 1–5.
- Charles R Dietlein, "Wide-Area Spectrum Cartography," *2023 IEEE International Symposium on Antennas and Propagation and USNC-URSI Radio Science Meeting (USNC-URSI)* (Portland, Oregon, July 2023): 463–464.



DoD-CIO Mid-Band Propagation Project

The DoD-CIO Mid-Band Propagation Project (DoD-Prop) is a multiyear project in support of the Department of Defense Chief Information Officer (DoD-CIO), with the goal of establishing an improved and community-accepted mid-band (3.1-4.2 GHz) RF propagation model framework to predict basic transmission loss for a diverse range of link geometries. The model must be suitable to support sharing and interference analysis. It must also contain such propagation phenomena as clutter (statistical and site-specific), troposcatter, and a complete model of signal variability. Funded by DoD from the proceeds of the AMBIT spectrum auction, the model is to be developed with a combination of theoretical, empirical, and data-driven methodologies.

The focus in FY 2022 was to bootstrap the project and establish goals and capabilities, such as measurement system development. Springboarding from that preparatory work, engineering, analysis, and modeling activities to execute the project plans began in earnest in FY 2023, the first of five project years towards the end goal of model development.

Measurements

It was agreed that the primary focus of FY 2023 activities would be the collection of measurement data, and in particular clutter measurement data. The propagation model development would need a large amount of empirical measurement data to perform model verification and validation. In addition, application of the scientific process required measurement data to validate modeling concepts and methodologies.

In December, the measurement team deployed to the field for the first time a newly developed triple-transmitter mobile measurement system. This system allowed for placement of up to three transmitters at remote locations to simultaneously transmit a signal (with a 3 kHz offset between them). The receiver captured all three transmitted signals and, during post-processing, separated the signals into the individual sources. This measurement system was developed and tested during FY 2022 and provides the project with significant new capabilities by allowing for the design of more complicated measurement campaigns around specific modeling questions. In nearly all mobile clutter measurements in FY 2023, to support modeling goals measurements were designed to avoid the impact of terrain diffraction on the clutter measurements.

This initial measurement campaign occurred in Boulder, Colorado and was split between two different seasons, taking place in December and June. Measurements in the Martin Acres and Drexel suburban neighborhoods collected information on the impact of elevation angle, bearing, and how seasonal changes in foliage impact clutter loss.

Two additional measurement campaigns took place in FY 2023. In spring 2023, a Denver, Colorado, measurement campaign occurred in which the mobile measurement system was used to collect clutter data in various urban and suburban environments. The campaign included geometric configurations to support urban canyon effects. The measurements were also designed to overlay previous 1.7 GHz measurement data to leverage prior modeling work at ITS and assess the impact of broader generalization. In summer 2023, a Salt Lake City, Utah, measurement campaign was executed. This was the largest of the three primary clutter measurement campaigns. It focused on multiple different clutter environments (dense urban, urban, industrial, suburban) and enabled researchers to leverage the nearby mountains by placing a transmitter in such a way that higher elevation angles (up to 10 degrees) could be achieved.

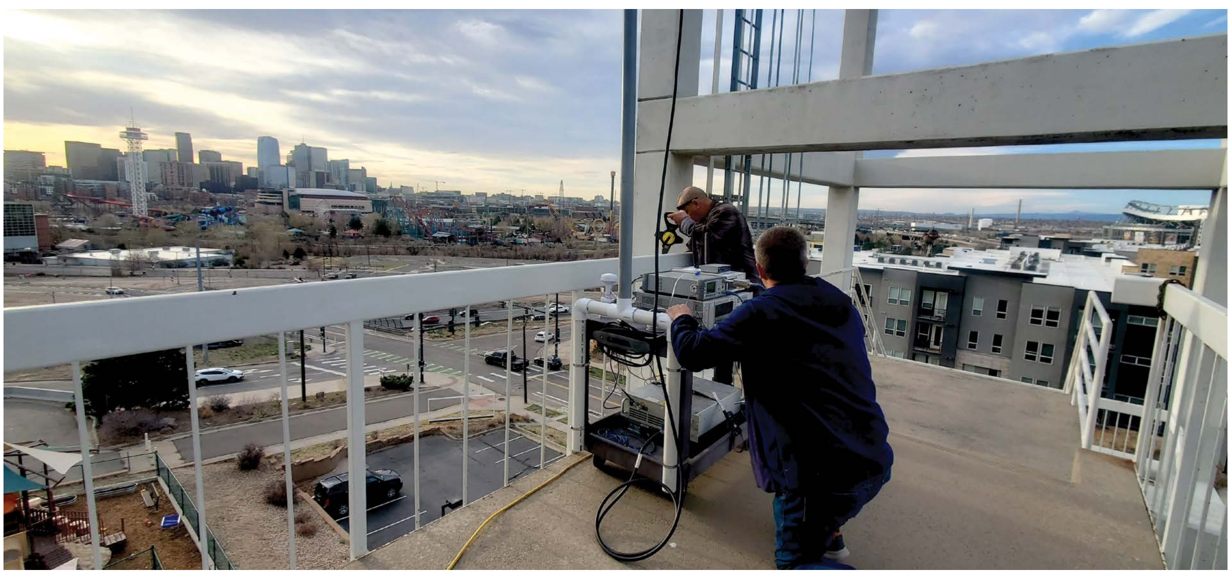
In addition to taking mobile clutter measurements, the measurement team worked towards deployment of the newly developed troposcatter measurement system. The team planned for an approximately 180 km link from the Table Mountain Radio Quiet Zone to Sterling, Colorado. The measurement was planned to run continuously for at least six months, with possible extensions, depending on the results of initial measurement data collection. Initial spot measurements at the end of FY 2022 had validated design of this measurement system. Although an initial deployment plan fell through, a new collaborator was identified to support the measurement. Northeastern Junior College collaborated with ITS to allow placement of the troposcatter measurement system transmitter on its campus. Deployment of the system is expected in winter of FY 2024.

Lastly, initial plans for terrain diffraction measurements were developed in the last quarter of FY 2023. Terrain diffraction measurements will use the same triple-transmitter mobile measurement system that the clutter campaigns did. However, whereas the clutter campaigns specifically avoided terrain effects during their data acquisition, the diffraction measurements will focus on terrain effects while avoiding clutter to the greatest extent possible. This allows the measurement datasets to isolate specific propagation phenomena for modeling. This will lay the groundwork for development of more complex links in future project years.

Software and Data

Because of the significant amount of planned measurement activities and the amount of environmental data required for modeling and analysis, a dedicated sub-project team was established to focus exclusively on software development and data management. This team's initial focus was on making major improvements to the measurement system software. Software quality and robustness were addressed to improve the overall reliability of the system. Remote operational support was added, allowing transmitters to be operated and configured from a remote location via cellular links.

Data management strategies were established, including naming, storing, and processing of the raw measurement data. Discussions were held to establish what constituted different data products. Additionally, a documented data format was created to store the final measured basic transmission loss values for the modeling activities.



ITS engineers James McLean (foreground) and Kenneth Brewster prepare a transmitter for a clutter measurement campaign in support of the 3.5 GHz Propagation Modeling Project. The urban canyons of downtown Denver, Colorado, can be seen in the background. (Photo credit: Adam Hicks)

Modeling

Modeling efforts in FY 2023 primarily focused on formulating the initial questions and developing measurement plans to gather data to evaluate the hypotheses developed from these questions. Within the clutter modeling space, in order to reduce the number of confounding parameters the modeling team focused on the impact of clutter in the absence of terrain effects. This drove the design of the initial measurement drive routes to minimize terrain losses. Modeling topics that motivated measurement activities were: line-of-sight propagation effects, including urban canyons; impacts of elevation angle; impacts of bearing; and acquisition of clutter measurements in diverse environments – from dense urban areas to low-density suburban neighborhoods.

Left to right: ITS engineers James McLean, Kenneth Brewster, and Mike Chang prepare to raise the mast on a CoW to transmit towards downtown Salt Lake City, Utah, in July 2023. This clutter measurement campaign targeting the 3.1–4.2 GHz frequency band supported the 3.5 GHz Propagation Modeling Project. (Photo credit: William Kozma, Jr.)

Propagation Library (PropLib)

Standardized methods for solving various radio propagation problems support spectrum sharing both nationally and internationally. Realistically, however, it is the heretofore unstandardized software implementations of models and methods that are applied to produce propagation predictions. This results in situations where, although various parties may agree on a particular approach, due to differences in the software implementations being used by different parties, disagreements can still occur even at the most basic level of radio wave propagation prediction.

ITS's decades-long leadership in propagation modeling, the Administration's strengthening commitment to Open Science, ITS's obligation as a federally funded laboratory to engage in technology transfer, and the fact that software prepared by government employees in the furtherance of their official duties is not copyrightable in the United States (17 U.S.C. 105) and is therefore in the public domain—all these position ITS as a natural leader in addressing the issue of standardized propagation modeling software implementations. Thus, several years ago, the Institute launched the ITS Propagation Library (PropLib)—a collection of code-signed, formally citable, open-source software implementations of radio wave propagation models and tools that will be made available to the community one model at a time.

This systematic multiyear effort is ongoing, but by the end of FY 2022 five important propagation models had been migrated from the original FORTRAN code to modern languages, open-sourced in NTIA's GitHub repositories, and were beginning to be used by the wider community:

- ITM — The Irregular Terrain Model (also known as the Longley-Rice model after two of the ITS researchers who first published the model in 1967 and the FORTRAN implementation in 1968) predicts terrestrial radio wave propagation for frequencies between 20 MHz and 20 GHz based on electromagnetic theory and empirical models. It has been widely used for over half a century and is frequently called out in spectrum sharing rules.
- eHata — A 2015 FCC rulemaking, years in development, opened up the CBRS band for sharing between federal and non-federal users. Initial 2010 feasibility studies proposed extensive exclusion zones to protect federal shipborne and ground-based radar systems. By 2015, the technology had evolved and NTIA, working in collaboration with the FCC and the DoD, reevaluated the exclusion zone distances. Working with OSM, ITS researchers referenced both ITM and the 1980s Hata model (limited to frequencies from 150 to 1500 MHz) to produce a new model that extended Hata in both frequency and distance (dubbed extended Hata, or eHata). Applying this model to the evolved CBRS sharing scenario reduced exclusion zones to much smaller coordination zones. The Wireless Innovation Forum (WInnForum) Spectrum Sharing Committee, which developed the technical standards to enable commercial operations in the CBRS band, used eHata to calculate coverage and protection areas.
- P.528 — Recommendation ITU-R P.528 *A propagation prediction method for aeronautical mobile and radionavigation services using the VHF, UHF and SHF bands* is the international technical standard for computing propagation loss for air-to-ground paths at 100–30,000 MHz. Working within the community of International Telecommunication Union Radiocommunication Sector (ITU-R) Study Group 3 Radiowave Propagation (SG3), ITS developed the U.S. Reference Software Implementation for this model. Companion software (p528-gui) provides a Graphical User Interface (GUI) that can be used with this software implementation.
- P.2108 — ITU-R Recommendation P.2108 *Prediction of clutter loss* provides statistical methods for estimating loss through clutter at frequencies between 30 MHz and 100 GHz for a number of different envi-

ronments. P.2108 defines clutter as "objects, such as buildings or vegetation, which are on the surface of the Earth but not actually terrain." Working within the community of ITU-R SG3, ITS developed the U.S. Reference Software Implementation for this model.

- LFMF — The NTIA/ITS implementation of the Low Frequency/Medium Frequency (LF/MF) Propagation Model. LF/MF predicts basic transmission loss in the frequency range 0.01–30 MHz for propagation paths over a smooth Earth and antenna heights less than 50 meters.

An important aspect of implementing PropLib through GitHub is the opportunity for bidirectional interaction with the user community. Widespread dissemination of such tools to users was part of ITS's mission when Longley and Rice published the FORTRAN code for ITM in a technical report and continues to be a focus of ITS's Technology Transfer effort. The GitHub developer platform encourages open-source collaboration among developers, but the propagation model user community is vaster than the developer community.

Thus, efforts in FY 2023 focused on disseminating awareness of these models to the wider community through peer-reviewed publications, presentations, and participation in appropriate symposia. While the results of ongoing ITS research frequently lead to model improvements, feedback and comments from the broader community also contribute significantly to continuous improvement in the overall quality and behavior of individual model implementations. For example, ITS is in on-going conversation with the International Civil Aviation Organization (ICAO) on supporting incorporation of ITS's P.528 software implementation into ICAO's frequency planning tools.

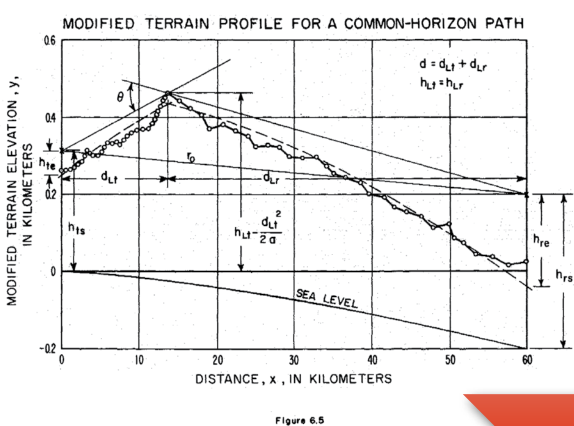
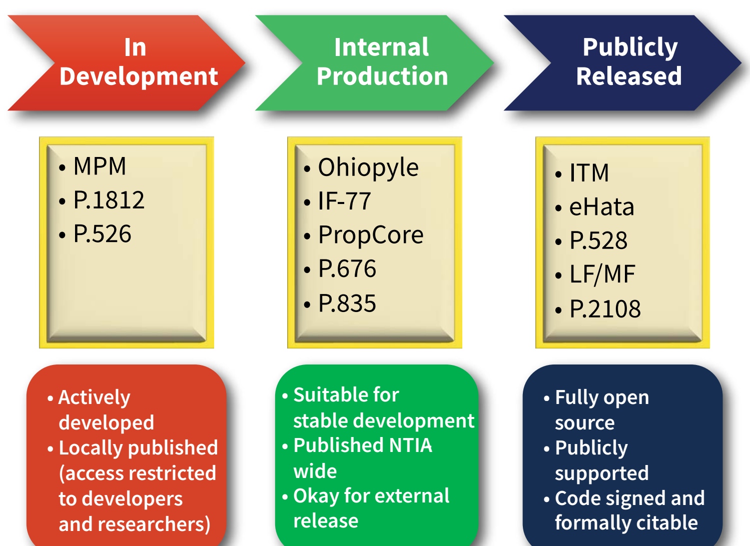


Figure 6.5 from Philip L. Rice, Anita G. Longley, Kenneth A. Norton, and Albrecht P. Barsis, "Transmission Loss Predictions for Tropospheric Communication Circuits: Volumes I and II," Technical Note NBS TN-101 Vol. I and II, U.S. Department of Commerce, Environmental Science Services Administration, Institute for Telecommunication Sciences and Aeronomy, January 1967, vol. I, p. 6-12. NBS TN-101 described the propagation model now known as ITM.



ITS Propagation Library (PropLib) development status as of FY 2023 year end.

Propagation Modeling Website

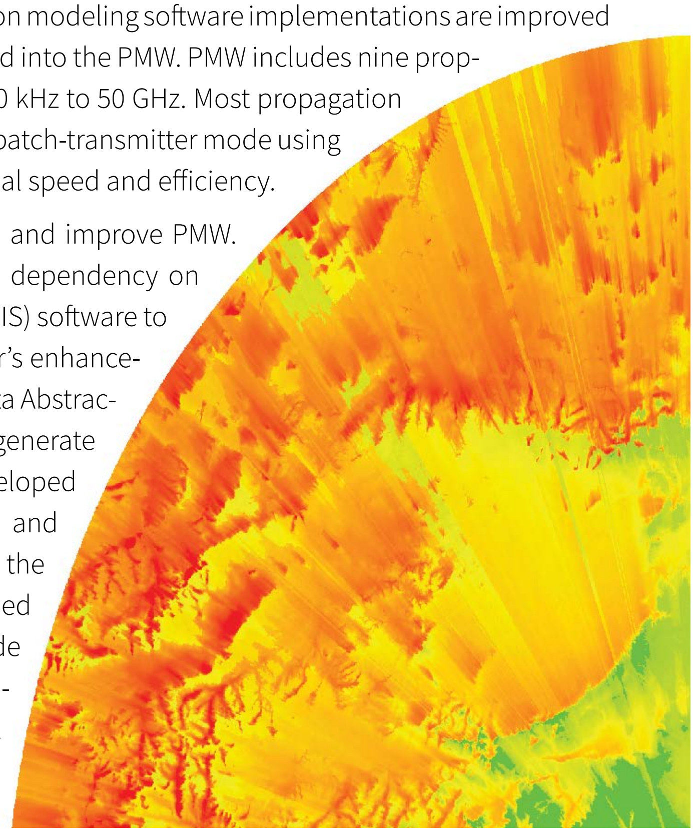
Many government agencies depend critically on the ability to successfully and rapidly predict propagation in a variety of environments and conditions in order to execute their missions. Immediately after the first propagation models were successfully computerized, ITS began working to provide a computer-based tool for propagation prediction that non-specialists could access and use for operational and planning purposes. The objectives included the ability to successfully integrate geographic data and display coverage predictions describing the performance of communication systems that would be easily accessible to non specialists and also detailed and accurate enough for specialists to use in deployment.

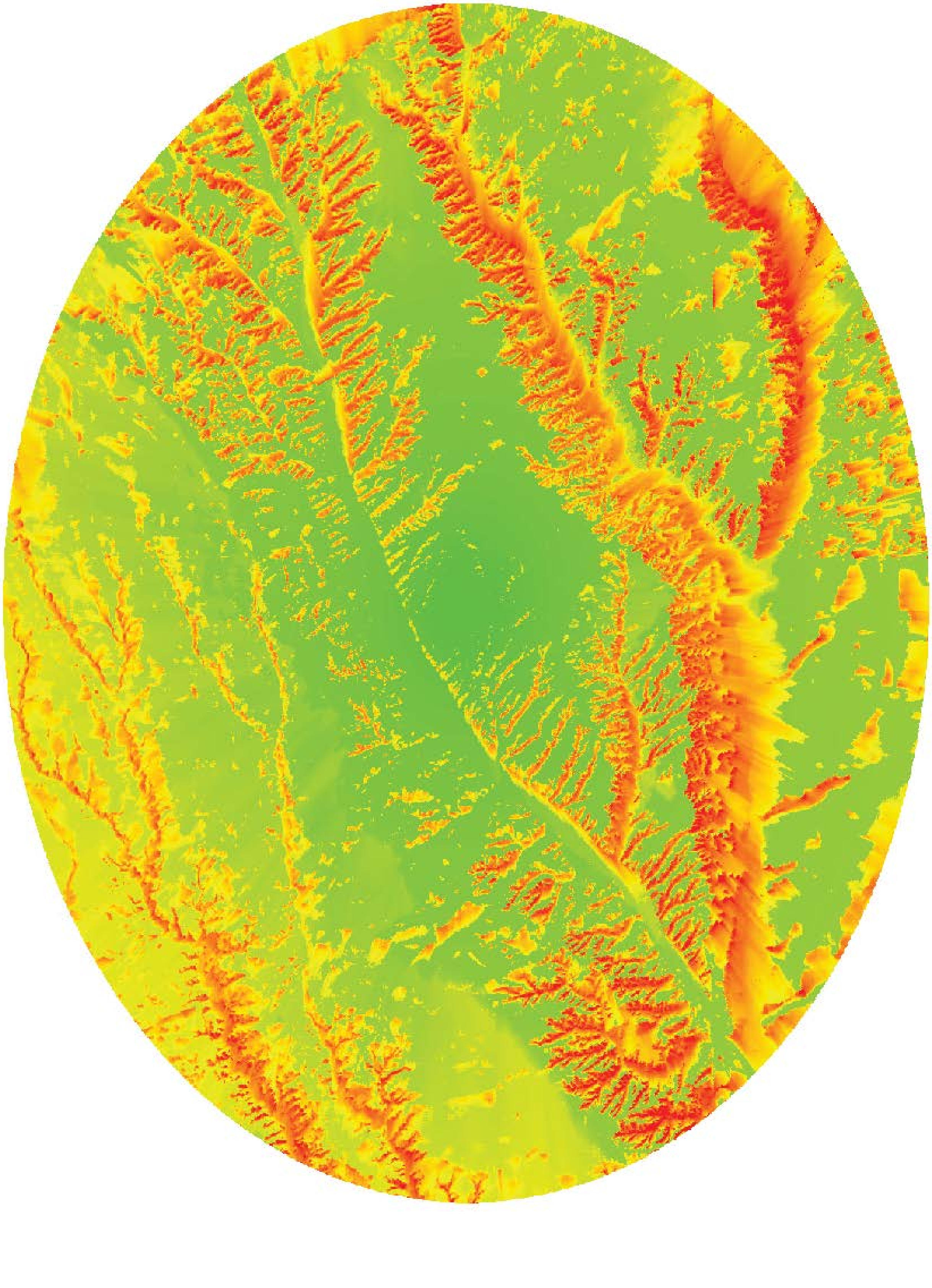
The Propagation Modeling Website (PMW) is the third and most current generation of software tools developed for government agencies over the last 30 years. It allows government users to perform RF propagation analyses for different frequencies and geospatial scenarios using a broad variety of propagation models through a web-based interface. This approach is consistent with the Administration's Open Science goals of making existing high-value data and content available through web APIs and using a shared platform approach to developing and delivering digital services to lower costs and reduce duplication.

PMW was jointly funded through IAAs with several agencies and is currently available only to U.S. Government users. It is used by the DoD through distribution and installation at secure sites or through servers hosted at the ITS Boulder Laboratory. For example, The National Weather Service (NWS) uses PMW to plan and optimize the location and characteristics of new transmitters on the NOAA Weather Radio (NWR) All Hazards nationwide network, which broadcasts continuously on specified frequencies. NWS must provide access to the potentially lifesaving NWR broadcasts to at least 95 percent of the U.S. population and uses the PMW to verify population coverage for selected transmitters by incorporating U.S. Census population data into the propagation analysis output.

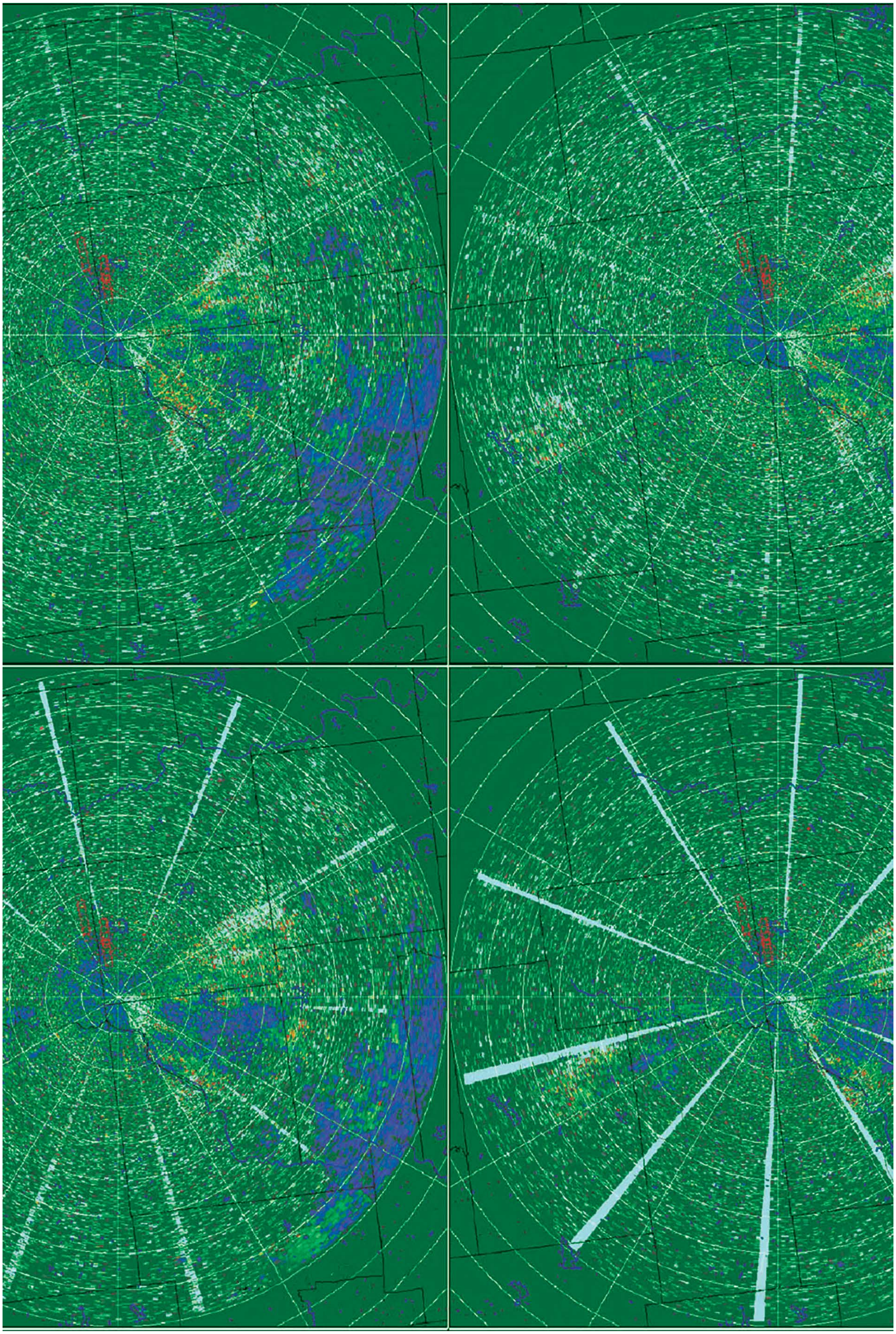
As ITS's publicly disseminated propagation modeling software implementations are improved and validated, improved models are integrated into the PMW. PMW includes nine propagation models spanning frequencies from 10 kHz to 50 GHz. Most propagation analyses can be performed in either single or batch-transmitter mode using a separate process for each analysis for optimal speed and efficiency.

In FY 2023, ITS continued to modernize and improve PMW. Work this year focused on migrating from a dependency on proprietary geographic information system (GIS) software to the use of open-source GIS libraries. This year's enhancements allowed PMW to use the Geospatial Data Abstraction Library (GDAL) to read terrain data and generate propagation results. The PMW team also developed functions with GDAL to generate shapefiles and merge propagation rasters. In addition to the GIS migration, PMW developers also upgraded the system to use 2020 census data to provide population coverage estimates and began implementing web services to support internal inter-process communication and integrations with external applications.





Left and above, examples of PMW coverage visualizations. Green areas indicate good connectivity and red areas indicate no connectivity, with the color ramp from green to red indicating decreasing connectivity. Precise calculations are also provided for specialists performing the deployment; for example, in the figure above, green represents excellent signal power (52.15 dBm path loss) and red represents no signal at all, for all practical purposes (-195.577 dBm path loss).



Electromagnetic Compatibility

Electromagnetic compatibility (EMC) analysis is multidisciplinary, in-depth, scientific and engineering investigation that yields a prediction of the probability that two or more services will be able to operate as intended in the same RF environment without interfering with each other. Spectrum is a finite resource: to accommodate expanded use of the spectrum, disparate wireless systems must share the radio waves. The goal of EMC studies is to find ways to protect spectrum dependent systems already operating in a frequency band (labeled “incumbent victims”) from natural or man-made sources (labeled “interferers”) of extraneous energy that degrades their performance and impedes the reception of desired signals.

Demand for access to spectrum appears insatiable. Every week, it seems, a new type of spectrum dependent system is commercialized, and every year Congress directs NTIA to lead feasibility assessments of sharing between federal and non-federal users at some particular frequencies and to identify some vast amount of spectrum the federal government can reallocate for non-federal or shared use. NTIA’s task is to protect the vital federal government operations that use spectrum while also supporting the growth of commercial wireless broadband and technologies in the U.S.

Analysis models developed by OSM are used to perform deterministic and statistical analysis for spectrum sharing studies. In addition, OSM funds complementary research tasks that are performed by ITS in Boulder to advance scientific understanding in support of policy decisions and spectrum management processes. ITS provides planned R&D (i.e., science, models, data, analyses, and software) and quick-reaction subject matter expertise to OSM. Within this collaborative framework, the goal of ITS EMC research is to standardize, validate, and advance NTIA interference analysis (IA) practices with a focus on establishing community-accepted and validated interference protection criteria.

ITS’s EMC program studies the generation, propagation, and reception of intentional and unintentional electromagnetic energy transmissions that may cause unwanted effects between similar or disparate systems. ITS expert staff perform detailed engineering analyses to assess the feasibility of sharing between these disparate systems. Each key element in the path from one receiver to another is intensely analyzed: the transmitter emission characteristics, the radio propagation channel, the directionality of the receive antenna, amplification and filtering incorporated in the front end of the receiver, the response of the receiver to a transmitted waveform, and the associated interference protection criteria (IPC). Measurements, modeling, simulation, and analysis are combined to support comprehensive EMC studies that tie all the pieces together. EMC studies provide the data that regulators and users need to implement sharing that works as intended, in the form of IPC that determine the level of interference allowable before signal degradation becomes unacceptable and point the way to effective mitigation of harmful interference. OSM develops engineering algorithms for wireless system compatibility analyses that involve radio wave propagation models; transmitter, receiver, and antenna models; and IPC.

Work performed under NTIA’s leadership in collaboration with other federal agencies and industry has resulted in the development of innovative analysis methods and engineering algorithms used to facilitate sharing between federal and commercial systems. These engineering capabilities are used to support national and international spectrum management processes.

A Difficult Use Case: Spectrum Sharing with Radars

Spectrum coexistence between radars and non-radar systems presents challenges that are neither trivial nor easy to resolve. Radar systems of different kinds operate in bands from 5 MHz to 142 GHz. There are long and short range air traffic control radars; maritime navigation and surface search radars; over-the-horizon surveillance radars and long and short range line-of-sight air surveillance radars; naval surveillance radars, FAA microburst warning radars and other wind profiler radars; ground-based and airborne weather surveillance radars; tactical and short-range surveillance, warning, and fire control radars; land and maritime collision avoidance radars; long-range space search, surveillance, and early warning radars; and airborne radio altimeter radars, just to name a few.

Radar design and engineering is a specialized and niche part of engineering and science curricula. Because many mission critical radars are federal radars, over the course of five decades of working with other agencies ITS has acquired unique expertise in assessing coexistence scenarios involving radars, as well as a unique library of generalized radar waveforms that can be used for initial benchtop feasibility studies. These resources are critical to understanding how it can even be possible for radars to share spectrum with other spectrum dependent systems.

Engineering solutions for spectrum sharing with radars—whether in-band or adjacent band—must take into account the unique physical characteristics of radar. In a sense, the laws of physics "hardwire" the transmit and receive characteristics of radars. Radars emit massively high radiated transmitter power and receive echoes through super-sensitive receiver circuits that must operate with the lowest possible amount of ambient noise. For this reason, until the end of the twentieth century it was considered impractical to allow other services into frequency bands allocated to radar. With the increasing sophistication of all radiocommunication technologies, however, coexistence between radar and telecommunications services has become more feasible.

Since the first radars were invented just prior to World War II, radar design has become increasingly complex. Many salient characteristics that make every sharing scenario unique must be taken into account to come up with the rules that will allow all services using a given band (or near-adjacent band) to operate without harmful interference. Among the signal characteristics that need to be taken into account are pulse width, pulse repetition rate, radar antenna beam width, radar antenna beam-scanning rate, radar receiver intermediate frequency (IF) (or processing) bandwidth.

Sharing in the Mid-band

In the U.S., frequency bands between 8.3 kHz and 275 GHz are allocated, designated for use by one or more terrestrial or space radiocommunication services or the radio astronomy service under rules promulgated by the FCC. Physics and available technologies dictate which frequencies are best suited for which use. As a general rule, lower frequencies travel farther but carry less data—and as the technology currently stands, all users want to carry as much data as they can squeeze out of the spectrum. Mid-band spectrum, between 1 and 6 GHz, has been called the current "beachfront property" in spectrum, hitting a sweet spot between transmission range and data carrying capacity. Its other advantage is that equipment to utilize the mid-band is already in commercial use. This physical and economic reality has made the mid-band particularly useful for many safety-of-life radar systems, and it also made the band particularly attractive to emerging 5G commercial applications demanded by a public increasingly addicted to wireless video and data.

Since the turn of this century, NTIA and the FCC have been working together to make more spectrum available to more services, with particular emphasis on the mid-band. A major portion of ITS EMC studies in the past several decades have correspondingly addressed coexistence in the mid-band. A detect-and-avoid technology called dynamic frequency selection (DFS) is a technology dependent sharing regimen first conceived in 1995 and for which rulemaking was initiated in 2003. The history of ITS's research in support of DFS has been recapitulated in NTIA Technical Report TR-20-544, "Lessons Learned from the Development and Deployment of 5 GHz Unlicensed National Information Infrastructure (U-NII) Dynamic Frequency Selection (DFS) Devices" published at the end of 2019.[1] DFS relies on computerization of radio transmitters and receivers to manage a protocol whereby wireless access systems classified as U-NII devices operating in the 5.47–5.725 GHz band listen before transmitting to detect the presence of radar signals and then avoid those radar frequencies. Thus U-NII devices transmit in the time, frequency, or geographical interstices not occupied by radar.

A major concern for sharing in the 5 GHz band was protection of FAA Terminal Doppler Weather Radars (TDWRs) operating at 5.60–5.65 GHz to provide detection and alerts for wind shears at airports. Subsequently, and relevant to the research reported in the following pages, the FCC began investigating the possibility of developing an automated frequency coordinator system to enable interference-free spectrum sharing at 3.5 GHz between new 5G telecommunication systems and maritime navigation, surface search, and short- and long-range air surveillance radars operating at 3600 MHz. The first rules for commercial access to what the FCC dubbed the Citizens Broadband Radio Service (CBRS) band were adopted in 2015. Standardization of the technology required for coordination took a number of years and full commercial deployment began in 2020.

More recently, the FCC proposed to open access to the 3.7 GHz portion of the C-band (variously defined as 3.7 or 4 GHz to 8 GHz) to commercial 5G use. Although there are no radar allocations in the specific segment of the C-band proposed for auction for 5G services, there are radar allocations all around it. Of particular concern was the possibility of adjacent band interference into safety of life radar altimeters operating at 4.2–4.4 GHz. ITS has been deeply involved in EMC studies for sharing involving both CBRS and C-band.

1 Frank H. Sanders, Edward F. Drocella Jr., Robert L. Sole, and John E. Carroll, "Lessons Learned from the Development and Deployment of 5 GHz Unlicensed National Information Infrastructure (U–NII) Dynamic Frequency Selection (DFS) Devices," Technical Report NTIA TR-20-544, U.S. Department of Commerce, National Telecommunications and Information Administration, Institute for Telecommunication Sciences, December 2019

CBRS Dynamic Spectrum Sharing

In 2015, based on initial spectrum occupancy data collected by ITS and on theoretical EMC engineering studies directed by NTIA and the FCC, the FCC adopted rules for laying out IPC for shared commercial use of the 150 MHz-wide CBRS band (3.55 to 3.7 GHz). The rules created a novel three-tiered access and authorization framework to allow shared federal and non-federal use of the band.

- Tier 1 (Incumbent Access) users at 3.55 to 3.7 GHz receive protection against harmful interference from other users. Permanent incumbent users include all authorized federal users and fixed satellite service earth stations.
- Tier 2 (Priority Access) established 10 MHz channel, 10-year renewable Priority Access Licenses (PALs) to be licensed at 3.55 to 3.65 GHz on a county-by-county basis through competitive bidding. Devices operating with a PAL must protect and accept interference from Incumbent Access users but receive protection from Tier 3 users. The 2020 PAL license auction raised $4.6B for the Treasury.
- Tier 3 (General Authorized Access (GAA)) is licensed-by-rule ("unlicensed") to permit open, flexible access to the entire 3.55 to 3.7 GHz band for the widest possible group of potential users. GAA users must not cause harmful interference to Incumbent Access users or Priority Access Licensees, must accept interference from these users, and have no expectation of interference protection from other GAA users.

A unique aspect of the CBRS framework was the introduction of Dynamic Protection Areas (DPAs) in which commercial entrants dynamically share spectrum with protected incumbents. DPAs define areas or points with frequency ranges where incumbent users are protected from interference. Multiple types of DPAs exist, with different rules for activation. Dynamic sharing for PAL and GAA users is enabled by automated Spectrum Access Systems (SASs), which manage the operation of commercial entrants in order to protect incumbent users when and where they operate. To manage access, SASs may incorporate information from an Environmental Sensing Capability (ESC), a sensor network that detects transmissions from incumbent radar systems and transmits that information to the SAS. SASs and ESCs must be approved by the FCC through conformance testing.

Beginning in 2016, ITS worked with the Wireless Innovation Forum (WInnForum, which created the CBRS specifications), the FCC, OSM, and DoD to build the requirements and test code to ensure protection for different tiers of users in accordance with FCC rules. Conformance testing ensures that systems created by different vendors are able to implement interference-free dynamic frequency coordination amongst themselves and between the tiers of CBRS users, especially protection of incumbents from CBSDs such as cell towers. ITS technical contributions helped ensure that incumbent federal detection and protection requirements were incorporated into the technical standards. ITS also made publicly available on GitHub the authoritative implementation of the ITS-developed Irregular Terrain Model (ITM) to be integrated into the SAS software for propagation prediction.

Related Publications

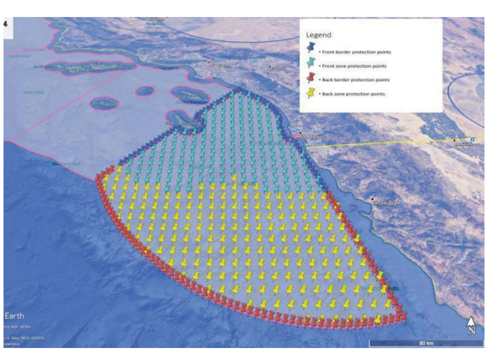
- Frank H. Sanders, "Distinction Between Radar Declaration and Pulse Burst Detection in 3.5 GHz Spectrum Sharing Systems," NTIA Technical Memorandum TM-18-526, October 2017.
- Frank H. Sanders, John E. Carroll, Geoffrey A. Sanders, Robert L. Sole, Jeffery S. Devereux, and Edward F. Drocella Jr., "Procedures for Laboratory Testing of Environmental Sensing Capability Sensor Devices," NTIA Technical Memorandum TM-18-527, November 2017.
- Frank H. Sanders, Robert L. Sole, Geoffrey A. Sanders, John E. Carroll, "Further Procedures for Laboratory Testing of Environmental Sensing Capability Sensor Devices," NTIA Technical Memorandum TM-18-534, June 2018.

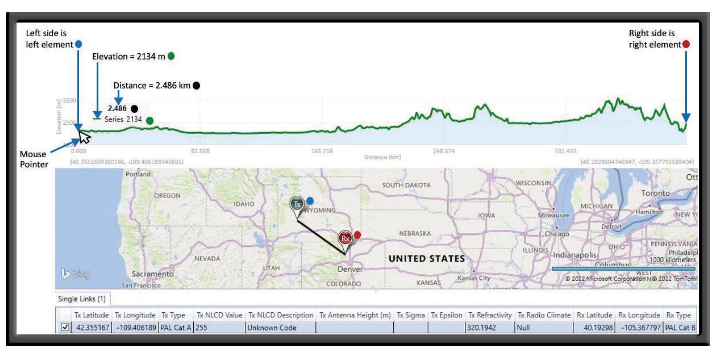
ITS developed, refined, and documented test configurations used to determine whether an ESC sensor system accurately detects pulsed and chirped radar and then signals that detection as required. In this work, ITS's radar expertise and waveform libraries were invaluable. These procedures ensured the ESC could detect radar waveforms with 1000 different parameters without disclosing any classified information, and share information with a SAS without implicating DoD operational security. The first ESCs were certified in 2019 under CRADAs and the test harness was then transferred to the FCC.

In 2018, ITS began a six-month verification and validation process for the first generation WInnForum-developed SAS Certification Test Harness code. Near weekly modifications and 26 code releases took place before the first production-level commercial SAS began testing. Over the next five years, ITS continued working with government and industry stakeholders to develop the thresholds, requirements, and mechanisms to test regulatory compliance of this brand new innovative cloud-based spectrum management system. The first wave of testing, administered under CRADAs in a sequence of five tranches and leading to FCC certification of five SASs, was completed in FY 2020 and a second wave in FY 2022.

In FY 2023, ITS focused on final software updates, code fixes, and usability improvements to the test harness in preparation for transferring the SAS Certification Test System to the FCC. This included developing software to create test configuration files to fill gaps in the existing configuration library, tools to automate configuration file creation, two additional test tranches, and software tools to automate log parsing and results analysis. Function integration into the ITS-developed METS (Map Enabled Tool for SAS) software package now supports creating configurations that test the ability of SAS units under test to protect the tiered levels of federal and commercial protected entities from interference from emissions from the CBRS devices. ITS created a new tranche of 387 tests unknown to any of the SAS Administrators covering all the tests in the WInnForum test suite for the FCC to use in the future. The complete library provided to the FCC included more than 2,100 tests.

Along with all the components of the test harness, ITS provided an as-is overview of the SAS Certification Test System architecture and assistance in planning and setting up the required server infrastructure and software applications in the FCC environment. ITS also created more than 300 pages of documentation in a user guide that explains how to use all software test system components, including the METS, test harness, and log parsers. Following successful transfer of the SAS Certification Test System to the FCC, ITS conducted seven virtual training sessions for FCC engineers.





Right, top: map overlays show CBRS DPA boundaries. Right, bottom: close-up of one DPA; pin markers indicate points where different rules for activation are applied. Red and blue pins mark the boundary, where SASs must coordinate among neighboring DPAs; teal and yellow pins mark different IPC within those boundaries. Above,the METS tool display of one path's parameters. The top half of the screen shows the terrain profile between two devices. The middle plots their location on a map, with a table of exact values for different parameters used to calculate coordination on the bottom.

Radio Frequency Coordination Portal

After the Advanced Wireless Services 3 (AWS-3) auction concluded in 2015, NTIA was asked—urgently—to stand up a website to receive and process requests for coordination between federal incumbent agencies and commercial entrants in the 1695–1710 MHz segment of the band,[1] where meteorological-satellite earth stations were operating. With funding from a coalition of five DoD sponsors, ITS led development and deployment of the Radio Frequency Coordination Portal (RFCP) under punishing time constraints—a beta version was deployed after only five months of requirements identification, development, and testing, including a two-week window for incumbent testing and feedback. A team of nine ITS and two OSM engineers shared a group NTIA Bronze Medal Award for this outstanding effort.

As an alternative to technology dependent automated sharing, which would have taken far too long to implement, the RFCP provides users a central location to input and validate data, store proposed deployment information, store output of analyses, manage workflows, provide automatic e-mail notifications, and generate reports. Using the RFCP, frequency managers and federal meteorological-satellite earth station operators can assess the risk of interference to incumbent systems and provide risk-informed decisions on and parameters for sharing. Five federal agencies and numerous AWS-3 licensees use the RFCP to exchange information and formally communicate about engineering issues related to successfully sharing in the band. The RFCP also allows federal incumbents operating in the same geographic area to coordinate with each other and serves as a reliable archive of requests. Notifications are automated and customized to alert users to activity that affects their respective organizations. Tools like the RFCP could become increasingly necessary as wireless technologies grow in importance, necessitating centralized efforts to facilitate coordination in the service of effective spectrum sharing.

Spectrum Quantification, Validation, and Characterization

With funding from OSM, ITS has been executing a multiyear project to develop a repeatable means to quantify, validate, and characterize spectrum utilization of frequency bands prioritized for sharing. Spectrum Quantification, Validation, and Characterization (SQVC) studies provide data useful for the full life cycle of a sharing scheme, from assessing initial feasibility to post-deployment utilization monitoring. The initial priority band identified for SQVC analysis was the CBRS band (3.55–3.7 GHz).

OSM identified commercial use of CBRS as a priority band for study and ITS began coordinating with the SAS Administrators and the FCC to obtain aggregate SAS data. In FY 2022, ITS, the SAS Administrators, and the FCC identified aggregate data that was appropriate to release. ITS began developing software to allow the SAS Administrators to transform SAS Full Activity Dump (FAD) data into the agreed upon aggregate data. In addition, ITS developed software to analyze and visualize the aggregate SAS data. In FY 2023, ITS published the first in a planned series of annual longitudinal reports. “An Analysis of Aggregate CBRS SAS Data from April 2021 to January 2023” presents an analysis of aggregate CBRS Spectrum Access System (SAS) data reported quarterly from April 1, 2021, to January 1, 2023. This first-of-its-kind study provided important information about how the dynamic CBRS sharing framework had increased access to spectrum by January 1, 2023. Five key findings:

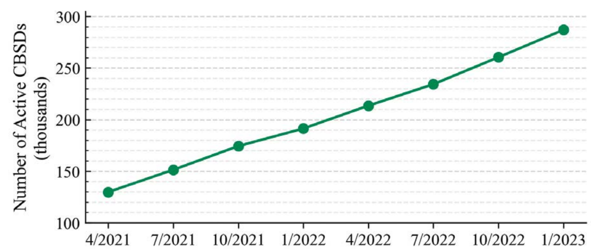
Related Publication

Douglas Boulware, Anthony Romaniello, Rebecca L. Dorch, and Michael G. Cotton, “An Analysis of Aggregate CBRS SAS Data from April 2021 to January 2023," NTIA Technical Report TR-23-567, May 2023.

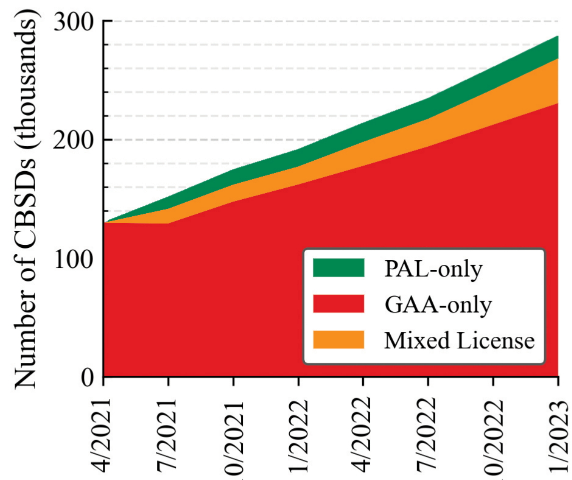
1 1695–1710, 1755–1780, and 2155–2180 MHz are collectively called the AWS-3 band.

- CBRS deployments grew at a steady rate with a mean quarterly increase of 12.0% and a total increase of 121% over the 21 month analysis period. Both indoor and outdoor deployments grew steadily, but over 95% were outdoors.
- The number of Citizens Broadband Service Devices (CBSDs) with PAL grants grew consistently over the study period, with a mean increase of 17% per quarter, but GAA CBSDs dominated deployments. At the start of 2023, four out of five active CBSDs were GAA-only, 85% of active grants were GAA, and two-thirds of active CBSDs with a PAL grant had at least one active GAA grant.
- More than 70% of all active CBSDs were deployed in rural census blocks. Rural CBSDs experienced approximately double the growth of urban CBSDs. Rural areas added 102,340 CBSDs (14,623 per quarter, on average), compared to 54,893 new CBSDs in urban areas over the same period.
- While demonstrating significant growth, data on mean band utilization by county suggested there was still room to grow.
- At the start of 2023 there were 128,351 active CBSDs in DPA-impacted counties with a total population of 232,348,897 residents. Had DPA neighborhoods been designated exclusion zones, those CBSDs could not have been deployed.

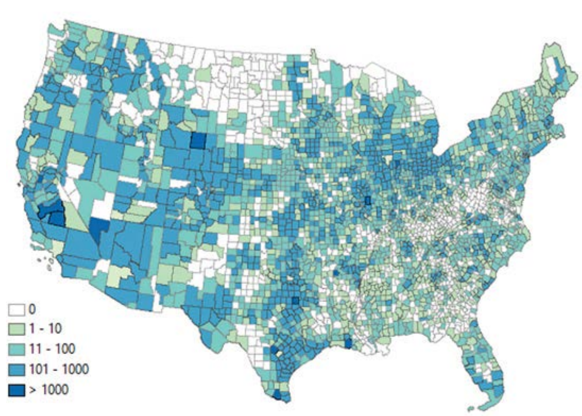
SQVC and SEA *(see Sharing Ecosystem Assessment on page 14)*, which measures how much spectrum CBRS emissions near DPAs occupy over time, are complementary companion studies designed in collaboration with stakeholders to analyze spectrum utilization from multiple angles. The objective data from these studies provide valuable insights into the growth of CBRS, the impact of dynamic spectrum sharing, the role of unlicensed GAA spectrum usage, and CBRS's role in rural wireless connectivity. This data will inform the evolution of sharing in the CBRS band and development of future dynamic spectrum sharing proposals in other bands.



NTIA Technical Report TR-23-567, "An Analysis of Aggregate CBRS SAS Data from April 2021 to January 2023," Figure 2. Nationwide number of active CBSDs from 4/1/2021 to 1/1/2023.



NTIA Technical Report TR-23-567, "An Analysis of Aggregate CBRS SAS Data from April 2021 to January 2023," Figure 5(a). Nationwide number of active CBSDs with PAL-only, GAA only, and mixed license from 4/1/2021 to 1/1/2023.



NTIA Technical Report TR-23-567, "An Analysis of Aggregate CBRS SAS Data from April 2021 to January 2023," Figure 39. Number of active CBSDs by county for Continental United States on 1/1/2023.

The Institute
Propagation Measurement
Propagation Modeling
Electromagnetic Compatibility
Networks & Quality of Experience
Technology Transfer
Research Capabilities

5G Coexistence with Radars in C-band

In February 2021, the FCC completed the auction of commercial 5G licenses in the 3.7–3.98 GHz band, commonly referred to as the C-band, which is surrounded by radar allocations. The introduction of 5G systems in this frequency range and planned spectrum sharing between 5G and incumbent U.S. government radar systems operating at 3.1 to 3.55 GHz and 4.2 to 4.4 GHz raised concerns. The most urgent concern was whether 5G transmitters might cause harmful radio interference to integrated safety-of-flight radar altimeter (radalt) receivers in the near-adjacent 4.2 to 4.4 GHz range.

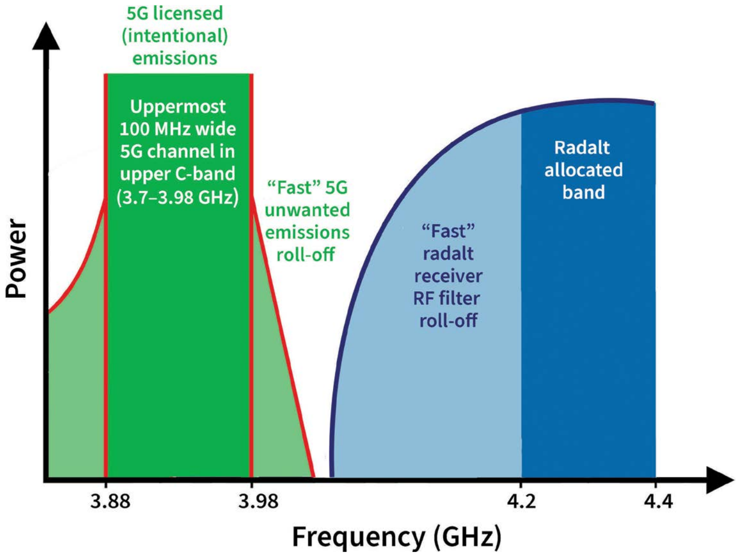
As cellular carriers began deploying 5G base stations, the FAA became increasingly concerned about potential interference with radalts and issued airworthiness directives that effectively delayed full 5G commercial deployment near airports. Around the same time, Hill Air Force Base (AFB) deployed a private 5G cellular network and began experiments around spectrum sharing between commercial networks and highly sensitive DoD assets, including radalts as well as several other types of radars. In support of this project, DoD had an agreement in place with ITS to obtain subject matter expertise to design appropriate coexistence testing. To speed resolution of the disagreement between the FAA and cellular operators on how to reach interference-free coexistence, Hill AFB agreed to re-scope the existing agreement with ITS to focus on radalts.

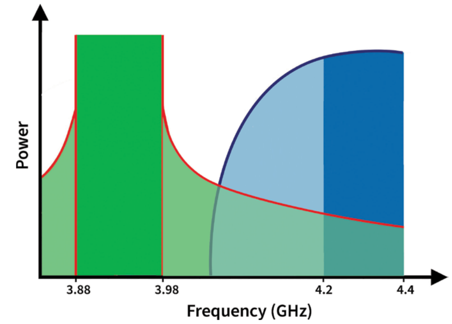
DoD organized a Joint Interagency Fifth Generation Radar Altimeter Interference (JI-FRAI) multi-stakeholder group to agree on a test design that would provide trusted ground truth data to guide the negotiations. ITS was put in charge of the testing. The NTIA, FCC, and FAA; eight other federal agencies; three cellular carriers; three airlines; and four aircraft and radalt manufacturers were among those who substantively participated in the program, which spanned FY 2022 and 2023.

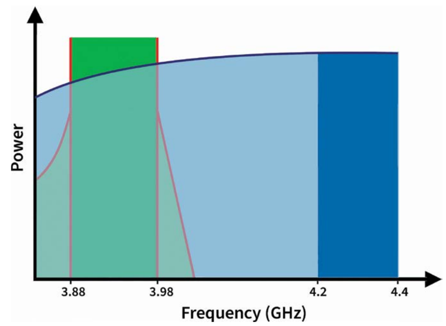
ITS established a 5G testbed at Table Mountain that included the highest-power (56,000 watts) 5G base stations that existed at the time, from every manufacturer then deploying 5G gear in the U.S., along with a new capability to measure and analyze 5G emissions on the ground and in the sky. The novel airborne 5G radiation measurement system designed, built, tested, and flown for this effort was deliberately engineered for use by future spectrum coexistence studies, potentially implemented with uncrewed drones rather than helicopters. Using these new capabilities, ITS researchers planned and implemented first-of-their-kind quick-reaction over-the-air 5G transmitter measurements and analyses, working in collaboration and in parallel with other researchers to ensure full transparency and the most efficient use of resources.

The four-phase test design encompassed bench testing of 5G equipment (to be performed by a contractor already engaged in similar testing at Hill AFB); in-flight radalt performance testing in the presence of 5G radiated signals; measurements of on-the-ground radalt emissions from taxiing aircraft at civilian and military airfields; and controlled, calibrated measurements of emission spectra and three-dimensional radiated field strength patterns around 5G base station transmitters. Over 100 JI-FRAI participants previewed the test plans and results, which ITS also shared internationally with other spectrum regulators. This full transparency inspired trust in the results and led to consensus on a technical solution to coexistence that was accepted by all parties.

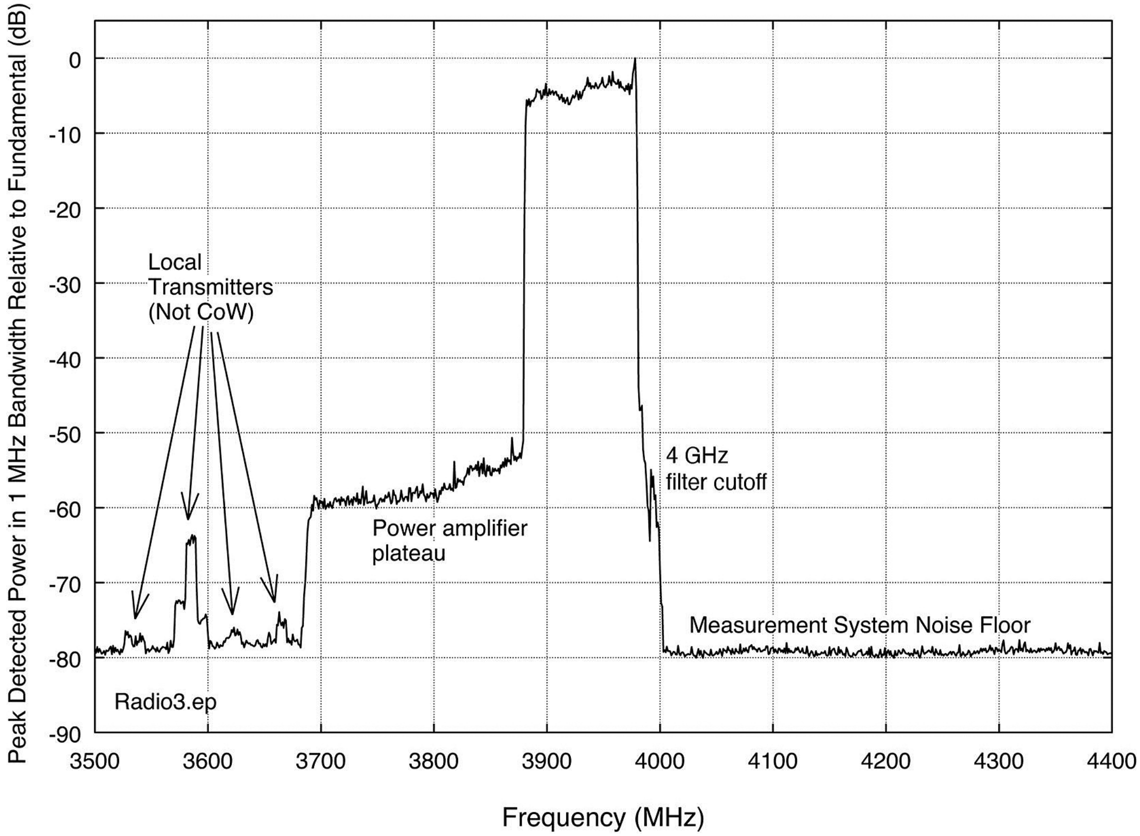
Building on the results of the benchtop work and on ITS's decades-long expertise in EMC studies involving radars, ITS then led the remaining three phases involving over-the-air testing in realistic conditions. ITS designed in-flight Joint Test and Evaluation (JT&E) of radalt performance in the presence of radiated 5G base station signals under controlled conditions. Selected aircraft carrying representative examples of a wide variety of radalts (mostly military but some civilian and some dual-use) were used for







These notional schematic drawings illustrate the nature of the concern being investigated. Above left, the ideal scenario would have both spectrum dependent services operating in their allocated band, with roll-off of out-of-band emissions "fast" enough that the two services do not overlap. The two notional drawings on the right show the possible concerns: top, unwanted out-of-band and spurious 5G emissions might trespass into the radalt receivers' band; bottom, 5G desired (intentional) emissions might produce harmful interference to radalt receivers because the receivers lack sufficient RF filtering and are "looking" into the 5G band. Below, a representative tracing of an actual measurement shows the 5G transmitter is well-filtered to minimize out of band emissions. The collected data revealed that all three models of 5G base station being deployed in the U.S. in the frequency bands of interest were fitted with effective RF bandpass filtering. This indicates that installation or retrofitting of more-effective RF power-rejection filters on radalt receivers for frequencies below 4200 MHz could be an effective technical solution to EMC problems in this scenario—and that is what the FAA ultimately required of aircraft operators.



NTIA TR-22-562, Figure 47. Measured emission spectrum of 5G base station transmitter Radio 3.

JT&E at Hill AFB in Utah (near Salt Lake City) and at Majors Airfield at Greenville, Texas (near Dallas). In these flight tests, aircraft with radalts were repetitively flown in closed-loop routes, such as traffic patterns. Each route was first flown while nearby 5G base station transmitters were turned on and then again with them turned off, and radalt performance was assessed in 5G base station transmitter on off conditions.

For comparison to previous predictions, the third phase of the JI-FRAI test design measured on-the-ground emissions radiated from civilian and military aircraft on the ground while sitting in gate areas and taxiing. ITS researchers measured on-the-ground emissions from airliners at Denver International Airport (DIA) and from F-16 jet fighters at Buckley Space Force Base (SFB). The raw data taken in those environments were converted to EIRP levels radiating from underneath the on-the-ground aircraft bellies. The fourth phase of testing was the characterization, via carefully calibrated radiated measurements, of the three-dimensional aerial radiation patterns and emission spectra of 5G base station transmitters built and sold by the three known manufacturers of 5G band equipment then deployed in the U.S.

This detailed engineering analysis of both systems provided objective and quantifiable characteristics of out-of-band and in-band signals. The collected data and an in-depth report showing that 5G can coexist safely with radalt receivers were published in early FY 2023, laying to rest fears of imminent 5G-to-radalt interference. The results showed that 5G base stations are well-filtered against emissions in the spectrum band used by radalt receivers; that 5G base stations transmit between 10 to 1,000 times less power into the sky than they do to UEs on the ground; and that the only remaining technical coexistence issue would be how well radalt receivers are filtered to reject 5G transmissions on the 5G's own frequencies. That question was shown to be resolvable by retrofitting selected radalt receivers with better filters.

EMC analysis yielded interference protection criteria of radalts, submitted to the FCC in March 2023. ITS also collaborated with the FAA to document mitigation methods so 5G base stations and radalts could safely coexist. As a result, the FAA issued a new airworthiness directive mandating that all planes used in scheduled passenger or cargo flight operations have 5G C-band-tolerant radio altimeters, or otherwise install an acceptable radio frequency filter. The collaboration between the FAA, the FCC, ITS, wireless companies, aviation stakeholders, and other federal agencies, in which ITS played a central role, produced the data required to resolve concerns about coexistence between 5G and radio altimeters. On July 1, 2023, cellular operators were able to complete full-power deployments across the C-Band and take full advantage of their multi-billion dollar investment in spectrum licenses.

As demonstrated by the many Awards *(see Awards on page 4)* this project won at the conclusion of FY 2023, the project had substantive scientific and economic impact. Test design, execution, and analysis of the results took place under conditions of unprecedented transparency, with open peer review by over 100 stakeholders. ITS researchers designed, built, tested, and flew a novel airborne 5G radiation measurement system that exhaustively explored, through calibrated radiated

Related Publication

Frank H. Sanders, Kenneth R. Calahan, Geoffrey A. Sanders, and Savio Tran, "Measurements of 5G New Radio Spectral and Spatial Power Emissions for Radar Altimeter Interference Analysis," NTIA Technical Report TR-22-562, October 2022.

Related Videos

- Frank H. Sanders and Kenneth R. Tilley, *Further 5G In-Air Field-Strength Measurements for Radar Altimeter Research*, NTIA Special Publication SP-23-570, YouTube video, September 2023, https://youtu.be/QCK26X-U678
- Frank H. Sanders and Kenneth R. Tilley, 5G *In-Air Field-Strength CoLT Measurements for Radar Altimeter Research*, NTIA Special Publication SP-22-560, YouTube video, March 2022, https://youtu.be/AVVCxC3JZFY.

measurements, the three-dimensional aerial radiation patterns and emission spectra of 5G base station transmitters. The test design and measurement system created for this study represent an important advancement in the state of the art for effective spectrum coexistence engineering measurements, studies, and analyses.

With increasing pressure to make more spectrum available for disparate systems to be able to fully utilize this limited resource, many more such studies will be required. ITS researchers responded thoughtfully to the urgency of the immediate problem by designing a method and test harness that is fast, accurate, and easily adaptable to provide reliable and actionable data about similar problems in other frequency bands to inform future rulemaking. A detailed description of the measurement system and its parameters, and the methodology used to collect accurate and repeatable measurements was published in TR-22-562, allowing other researchers to replicate the rigor of this data collection in future.

The transparency of the entire experiment, the thorough analysis, the rapid release of both the description of the method and the collected data, and the assurance of accuracy contributed substantively to allowing cellular carriers to fully realize their collective $80B investment in C-band licenses. Because of this project's unqualified success, plans were made to continue to apply the methodology to measurement, analysis, and resolution of 5G coexistence with other radar systems in FY 2024 and beyond.

Vehicle-to-Everything (V2X) Communications

ITS has been conducting research and analysis into the Vehicle-to-Everything (V2X) communications technology for automotive safety for several years, through the sponsorship of the U.S. Department of Transportation's Intelligent Transportation Systems Joint Program Office (USDOT ITS JPO). The USDOT ITS JPO's mission is to lead innovative research into Intelligent Transportation Systems that will improve transportation safety and, ultimately, save lives.

V2X research advances that lifesaving mission because V2X enables vehicles to share information that can warn drivers of imminent danger and prevent motor vehicle accidents (vehicle-to-vehicle (V2V) communications). The technology also connects vehicles-to-infrastructure (V2I), enabling vehicles to receive important messages to prevent adverse driving events, enhance mobility, and reduce transportation's impact on the environment. Communications from vehicle-to-pedestrians (V2P) creates alerts and warnings for both drivers and vulnerable road users (including bicyclists) about the potential for crashes.

The V2X technology currently being deployed is based on 4G Long Term Evolution (LTE). In future years, 4G-LTE-V2X may be joined by 5G-NR-V2X. Years of research and testing of 4G-LTE-V2X devices, as well as the Institute's 5G expertise, puts ITS in an excellent position to perform testing and analysis activities on the first 5G-NR-V2X devices that become available to ensure the USDOT and transportation industry stakeholders that the devices perform as expected and will improve safety.

In FY 2023, ITS focused largely on the potential for adjacent channel interference from unlicensed broadband devices that may emit energy into the V2X 30 MHz band from U-NII bands both below and above the V2X band, which starts at 5.895 GHz and stops at 5.925 GHz. The U-NII bands are used primarily for wireless local area networks (WLANs) which can include devices such as mobile phones, laptops, wireless routers, or mobile hotspots. The potential for interference to V2X from these types of devices was evaluated both in laboratory conditions and in field testing.

In FY 2023, in addition to performing testing at the Institute's radio interference laboratory, ITS engineers also provided on-site support at three lab and field measurement events to evaluate the interference scenarios of highest concern. This included characterization and configuration of the radios prior to testing, scenario development that provides the most informative results within the limited field testing time, lab experiments that match the field results and guide the future of the field testing, and development work on the command and control system used for testing that makes it possible to conduct large scale field testing with many devices.

After the field tests were completed, ITS engineers provided support in analyzing and interpreting the resulting data, including refinement of a simulation tool that is calibrated with the test site data, so that it may be a source of supporting evidence for upcoming regulatory decisions and deployer guidance. ITS also contributed to evaluating 4G-LTE-V2X readiness for deployment by providing laboratory and on-site support for testing of security enabled 4G-LTE-V2X in field conditions. The goal is to replicate real-world conditions to help mature the 4G-LTE-V2X technology. In addition, throughout the year, ITS participated in standards meetings and conducted analyses where needed, for 4G-LTE-V2X as they are being refined and for 5G-NR-V2X as they are being developed. While 5G-NR-V2X devices were not yet available for testing, ITS has developed the capability to perform valuable simulations where testing is not possible, such as simulating the performance of 5G-NR-V2X devices. This work was also completed in FY 2023, building on the simulation environment that was developed and validated against field data in the previous year.

While the transportation safety upgrades brought about by V2X communications are highly anticipated, it is also important to identify potential security vulnerabilities in the technology, so that security vulnerabilities may be mitigated. ITS engaged in a parallel effort to its V2X testing work that considered this security aspect. Ongoing research focuses mainly on the vulnerabilities at the radio layer that may

An ITS engineer working at a field test site checks a hand-held spectrum analyzer in order to verify that no other RF signals are present in the band prior to testing to ensure valid results. (Photo courtesy Federal Highway Administration) be present in 4G-LTE-V2X or 5G-NR-V2X. In FY 2023, ITS built on previous years' identification and testing of LTE-V2X vulnerabilities, and made headway on the development of a testbed that will enable laboratory experiments that evaluate the feasibility of more sophisticated attacks against multiple forms of V2X devices. Standards analysis had a role as well, as ITS continued to participate in standards working group meetings that decide on the security features of 5G-NR-V2X.

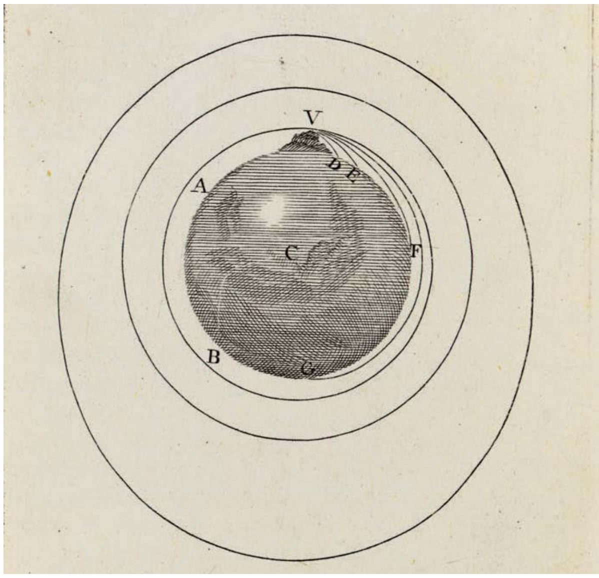
In FY 2024, ITS is continuing test and evaluation of V2X devices for interference scenarios as needed, and will work to understand and evaluate the evolution of cellular-based V2X technology as new and updated radio devices become available. ITS will also continue to focus on security and continue to investigate potential vulnerabilities. Further field and lab testing, as well as analytical work, will support the USDOT ITS JPO in its mission to thoroughly research and enable this important new technology that could save many lives in future.

Non-terrestrial Networks

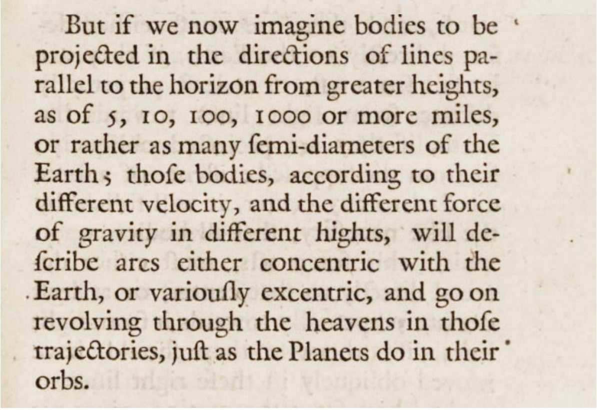
The successful launch of Sputnik 1 in 1957 launched the space age predicted by Sir Isaac Newton in 1687. Since then, society has come to depend on the data sent back to Earth by satellites such as weather satellites (first launched in 1960) and space has become much more crowded as the technology has evolved to enable more and more applications of space-based communications and to drive down the cost of satellites and launches.

By the end of 2023, the European Space Agency calculated there were 9,000 functioning satellites in orbit around the earth. Many of these satellites must communicate with each other, and all of them communicate with Earth. Thus, space frequency allocation and coordination have become of paramount importance, as have EMC analyses of air-to-ground and air-to-air communications.

Satellites communicate through non-terrestrial networks (NTNs)—networks or segments of networks that use airborne or spaceborne platforms to carry a transmission equipment relay node or a base station. NTNs offer connectivity anywhere, any time. This promise of coverage anywhere in the world has captured the interest of many industry and government entities. The market potential and social benefit to be gained from global coverage that can bring services such as internet to everyone has led a growing number of companies and governments to rapidly launch communication satellite constellations.



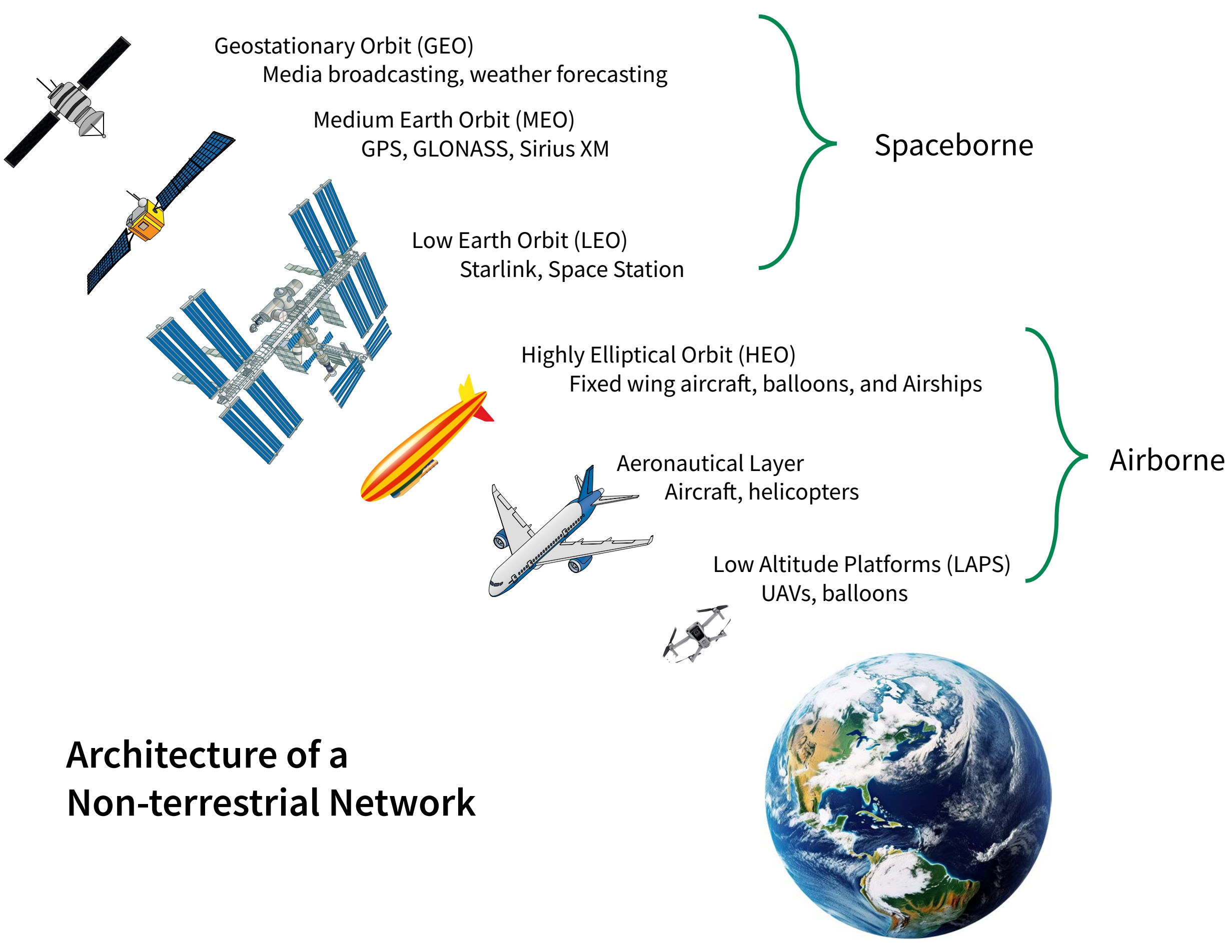
Page 6 of Sir Isaac Newton's A Treatise of the System of the World (2nd Ed., London: for F. Fayram, 1728) illustrates the supposition that a cannonball launched at sufficient velocity from the top of a mountain would completely encircle the Earth, and return to the mountain from which it was projected at the same velocity as when it left. On page 7, Newton continues:



But if we now imagine bodies to be projected in the directions of lines parallel to the horizon from greater heights, as of 5, 10, 100, 1000 or more miles, or rather as many ſemi-diameters of the Earth; thoſe bodies, according to their different velocity, and the different force of gravity in different hights, will deſcribe arcs either concentric with the Earth, or variouſly excentric, and go on revolving through the heavens in thoſe trajectories, juſt as the Planets do in their orbs.

Although NTNs have advantages over terrestrial networks, they also present new technical challenges such as frequent handovers, extremely high Doppler shifts, and difficult beam tracking. Whether an airborne or spaceborne platform has base station capabilities on board or is solely acting as a repeater, the link budget must also take into account the latency inherent to the physical reality of the greater distances to be covered as well as the layers of atmosphere that the signal must pass through. NTN networks also have larger cell sizes than terrestrial networks, which could lead to higher variations in latency and stronger near far effects.

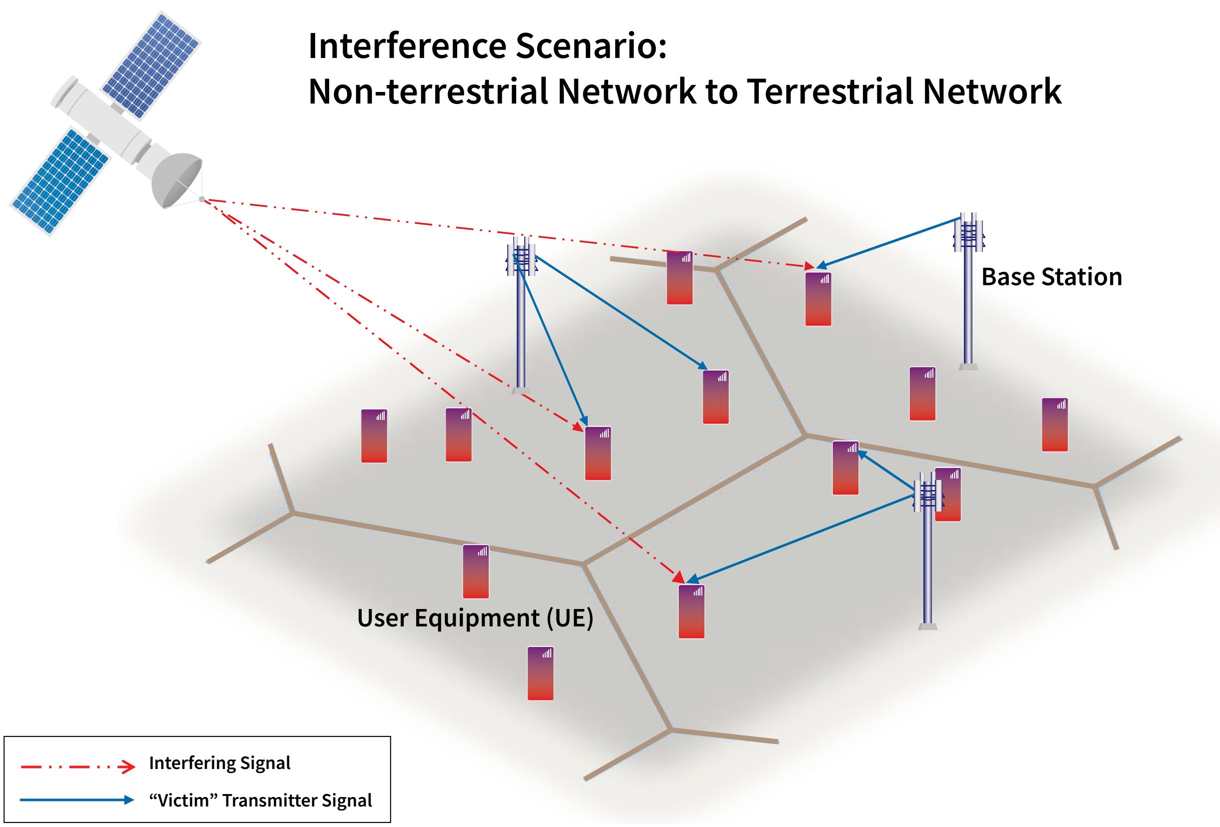
Current 3GPP standards (Releases 17 and 18) for NTNs are based on 5G systems, i.e., next generation base stations (gNodeBs), user equipment (UE), and core networks. Release 17, frozen in 2022, saw the first normative requirements for NTNs in 3GPP specifications. As 3GPP begins to shift its attention to 6G starting with work on Release 19 in 2024, standards for NTNs will be the focus. Driven by use cases for universal and ubiquitous connectivity, such as industrial internet-of-things, holographic communication,



Architecture of a Non-terrestrial Network

and tactile internet for telemedicine, the goals for 6G NTN standardization include greater speed, lower latency, network simplification and interoperability, and energy efficiency. Implicit in the envisioned 6G environment are an increase in distributed edge computing, more sensor networks, and dynamic spectrum coordination that can keep up with the speed of satellites.

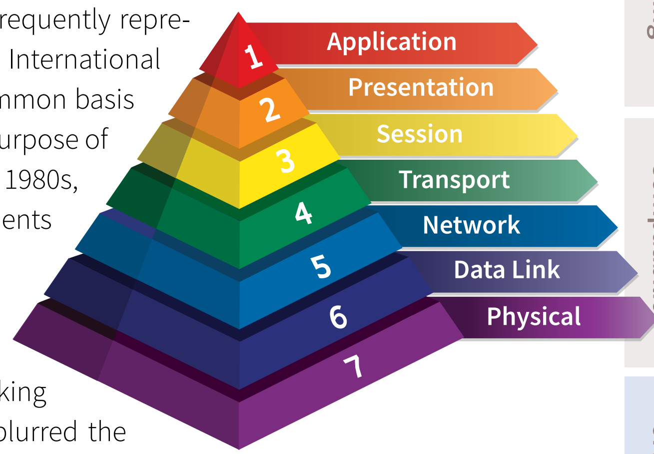
ITS has begun working with OSM and other government agencies on this issue and providing theoretical analyses of potential interference scenarios—like interference from internet service providers at low earth orbit to federal terrestrial satellite receiving stations for weather and national security data. To this end, ITS rigorously follows the literature and standardization efforts pertaining to NTN and is developing the capability to simulate NTN scenarios for future analyses. Conjectural interference analyses are being performed on potential interference scenarios already identified as likely to occur involving non-federal NTNs and federal systems. The goal is to be proactively prepared to promote interference-free coexistence between legacy spaceborne federal transmitters and systems yet to be developed.



Networks and Quality of Experience

Modern spectrum dependent devices and systems use complex digital signal processing techniques to fully exploit the physical RF spectrum by controlling how transmissions occupy spectrum in frequency, time, and space. Miniaturization of components such as antennas, amplifiers, and filters, as well as the circuit boards that control how they operate, has packed a plethora of increasingly sophisticated technologies into modern spectrum dependent systems, all relying on software controls. What has added even greater complexity is softwarization—the use of software to perform a function previously performed by hardware—and network virtualization, which replaces physical networking equipment with software-based resources that can combine multiple physical networks to one virtual, software-based network or divide one physical network into multiple independent virtual networks.

The Open Systems Interconnection (OSI) model, frequently represented as a seven-layer pyramid, was developed by the International Organization for Standardization (ISO) to provide "a common basis for the coordination of standards development for the purpose of systems interconnection." When it was developed in the 1980s, it was a convenient way to visualize the different components and functions of a wired network, end to end.



The evolution of wireless radiocommunication networks, the increasing computerization of wireless devices, and now the advent of software defined networking (SDN) and network function virtualization (NFV) have blurred the lines of demarcation between OSI layers. As spectrum dependent devices and systems proliferate at an unrelenting rate, so too do the research questions posed by new technologies, increasingly sophisticated digital signal processing, and rapidly evolving networking paradigms.

ITS's approach to radio science must encompass all the disciplines required to answer these questions holistically by measuring and modeling telecommunications systems end-to-end, from the physics of radio wave propagation to the end user experience. Understanding the scope and limits of all of these technological advances has become essential to understanding how increasing numbers of both similar and disparate spectrum dependent systems might effectively coexist in a sharing scenario.

The litmus test for determining whether any spectrum dependent system is useful and effective is the experience of the end user. Engineers use metrics such as bit error rate or compression ratio to evaluate system performance and make adjustments that optimize the trade-off between bandwidth and quality. End users, on the other hand, judge a system in terms of the perceived quality of experience (QoE)—for example, the visibility of targets on a radar display, the intelligibility of an audio stream, or the number of individually identifiable objects in a video stream. Objective measures that can provide useful indications of the quality the user experiences independent of the underlying transmission medium provide critical feedback for system design and provisioning so that users' expectations can be met in the most spectrally efficient way.

*

5G, the fifth generation of mobile networks, was defined by 3GPP Release 15, functionally frozen in June 2018. With Release 15, 3GPP defined the first phase of a completely new radio transmission technique targeting key concepts such as industry-grade reliability, extended modularity, and faster response times. From day one, 3GPP 5G networks were designed to operate in an inter-vendor and inter-operator context for use by all industry sectors and for time-critical applications such as autonomous driving and telemedicine. This approach to radically expand the versatility of cellular network protocols included new technologies like network function virtualization (NFV), slicing, and edge computing, and also began incorporating NTNs and satellite communications for ubiquitous coverage.

The new capabilities promised by 5G network protocols opened the door to new services such as enhanced mobile broadband (eMBB), ultra reliable and low latency communications (URLLC), and massive internet of things (mIoT). By design, 5G networks can be customized to support niche applications that meet the specific needs of myriad industries. To take advantage of these capabilities, many different spectrum dependent devices have been and will be designed to connect to specialized 5G networks. In this environment, open and interoperable multi-vendor networks are essential to the future of wireless technologies, including 5G and its successors.

2023 5G Challenge

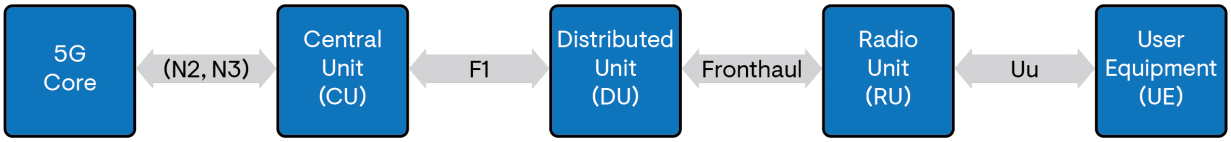
In collaboration with the U.S. Department of Defense (DoD) Office of the Under Secretary of Defense for Research and Engineering (OUSD(R&E)), in FY 2023 ITS carried out the second of two prize challenges aimed at accelerating the adoption of open 5G interfaces, interoperable subsystems, and modular, secure, multi-vendor solutions. The 5G Challenge was devised to accelerate adoption of interoperable 5G Open Radio Access Network (RAN) solutions by fostering a vendor community dedicated to advancing 5G interoperability towards true plug-and-play operation. Modular 5G elements ease network operators' ability to reconfigure, update, or replace components. Accessible examination of open interfaces speeds identification and correction of vulnerabilities. An open, modular, interoperable environment offers new vendor opportunities. A diversified marketplace delivers innovation and drives down costs.

Beneficiaries of an Open RAN 5G market include DoD, international allies, partners, network operators, businesses, and consumers. The broad scope of Open RAN beneficiaries resulted in a high-profile 5G Challenge event that attracted the interest of government leadership at both the federal and state level. The closing ceremony, in which contestants received awards for their 5G Challenge success, drew attention from dignitaries who delivered in-person and prerecorded praise during the ceremony, including Deputy National Security Advisor for Cyber and Emerging Technology Anne Neuberger, Colorado U.S. Senator John Hickenlooper, Colorado governor Jared Polis, and Colorado attorney general Phil Weiser.

The 2023 5G Challenge spanned from March through September 2023 in four stages and offered $7,000,000 in cash and prizes to contestants who successfully integrated 5G Open RAN subsystems to demonstrate multi-vendor interoperability and mobility. To allow sufficient time for all stages of the testing, ITS accepted two types of submissions in 2023: Radio Units (RU) or a combination of Central Unit (CU) and Distributed Unit (DU).

2023 5G Challenge keynote speaker Jared Polis, Governor of Colorado. (Photo credit: Kenneth R. Tilley)

*By https://www.3gpp.org/, Fair use, https://en.wikipedia.org/w/index.php?curid=65889789



Functional components of an Open RAN 5G network and the interfaces that connect them.

Stage One — White Paper Application

During Stage One, contestants applied to participate by submitting a white paper which required them to document 3GPP standards and O-RAN Alliance specification compliance and subsystem test reports. The most qualified contestants were accepted into Stage Two, Wrap-around Emulation Testing.

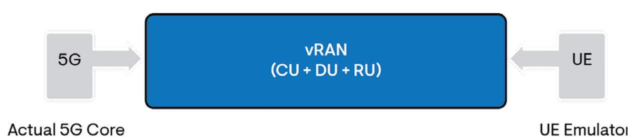
Stage Two — Wrap-around Emulation Testing

In Stage Two, each contestant subsystem was evaluated independently with a wrap-around emulator and test harness. The contestant subsystems underwent testing to evaluate basic functionality and standards conformance. Stage Two challenged the contestants, host lab, and test software because 5G test software and some 5G interface specifications are still emerging. After evaluating Stage Two testing results, all test contestant subsystems received Wrap-around Emulation Prizes of $100,000 each:

CU+DU (Central Unit + Distributed Unit)	*RU (Radio Unit)*
■ Capgemini Engineering	■ Fujitsu/AT&T
■ GXC	■ GXC
■ JMA Wireless	■ Lions USA Technology
■ Mavenir	■ NewEdge
■ Radisys Corporation	■ QCT/Benetel

Stage Three — End-to-End (E2E) Integration Testing

Stage Three prizes rewarded integration of one vendor's CU+DU with another vendor's RU to create a Virtual RAN (vRAN). The goals were to establish a data session across a multi-vendor RAN with emulated user equipment (UE) and a commercial 5G SA core, and to validate the functionality and characterize the performance of the integrated system. In true plug-and-play fashion, multi-vendor contestant pairs approached network integration with no prior experience interoperating with their fellow contestants' subsystems.



The 5G Challenge provided a rigorous schedule for contestants to work through diverse issues, with discrepant 3GPP and O-RAN ALLIANCE software options, interpretations, and configurations being the main roadblock. Five contestant pairs successfully passed Stage Three, which demonstrates the viability of open interfaces and interoperable subsystems to foster multi-vendor 5G networks. After evaluating Stage Three testing results, the 5G Challenge judge awarded the following prizes:

- First prize: Capgemini (CU+DU) and QCT/Benetel (RU)
- Second prize: Radisys (CU+DU) and LIONS (RU)

First prize winners received $750,000 each and three weeks of lab testing time. Second prize winners received $250,000 each.

Stage Four — Mobility Testing

The goal of Stage Four was to test mobility (connected and idle modes across NG and Xn interfaces) across two multi-vendor RAN E2E systems with emulated UEs and a 5G SA core. The 5G Challenge judges selected two teams to participate in mobility testing:

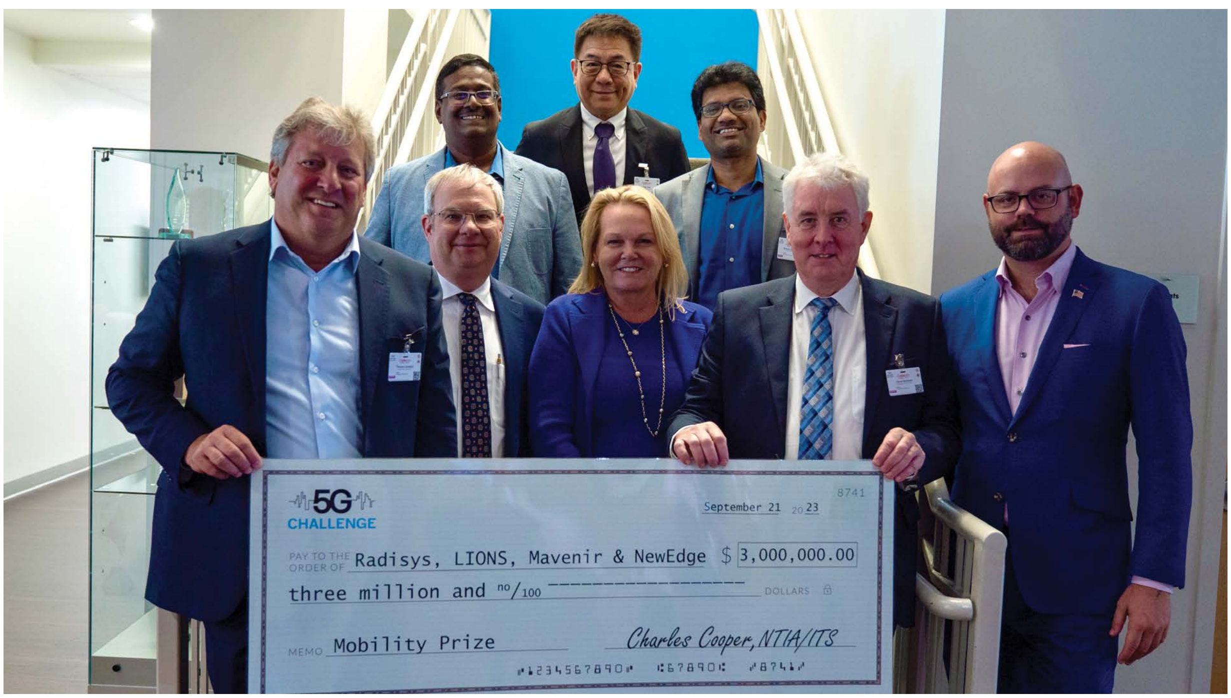
Group	*RAN1 Contestant Names*	*RAN2 Contestant Name*
1	LIONS Technology (RU) Radisys (CU+DU)	NewEdge (RU) Mavenir (CU+DU)
2	QCT/Benetel (RU) Capgemini (CU+DU)	QCT/Benetel (RU) JMA Wireless (CU+DU)

Both contestant groups passed all mandatory and conditional mandatory mobility tests. Stage Four integrations were less time-intensive than Stage Three as most of the alignment issues among the RAN contestants were addressed in Stage Three.

The Stage Four mobility prize was awarded to Group 1: LIONS Technology (RU), Radisys (CU+DU), NewEdge (RU), and Mavenir (CU+DU). Each winner received $750,000.

Best of Show Prize

To address security concerns, each contestant submitted a software bill of materials (SBOM) and vulnerability exploitability exchange (VEX). SBOMs facilitate improved security via vulnerability management by identifying dependencies, patch requirements, license requirements, and risk of cyberattack. The VEX is a machine-readable companion to an SBOM which communicates the status of vulnerabilities in software components itemized in an SBOM.



2023 5G Challenge Mobility Prize winners. Front from left: Thomas Lambalot, Chief Executive Officer, NewEdge Signal Solutions; Charles Cooper, Associate Administrator Office of Spectrum Management, NTIA; April McClain Delaney, Deputy Assistant Secretary, NTIA; Dr. David McIntosh, Chief Technical Officer, NewEdge Signal Solutions; Dr. Thomas Rondeau, FutureG & 5G Office, DoD. Back from left: Ganesh Shenbagaraman, Head of Standards, Regulatory Affairs, Radisys; Anju Day, Chief Executive Officer, LIONS Technology; Shravan Gaddam, Chief Technology Officer, Strategic Accounts, Mavenir. (Photo credit: Kenneth R. Tilley)

Contestant SBOMs and VEX's were evaluated for completeness, intelligibility, depth of dependencies listed, disclosure of known unknowns, and compliance to SBOM format standards. Best SBOM prizes were awarded to Fujitsu/AT&T and JMA Wireless in recognition of their comprehensive, informative, and high-quality SBOM, which went beyond minimum requirements to report vulnerability and risk. The Best SBOM prize winners received $100,000 each and security testing.

The Best Collaborator prize was awarded by fellow contestants and the host lab to LIONS, in recognition of their superior collaboration. LIONS received $20,000 and security testing.

Conclusion and Lessons Learned

The 5G challenge was a truly incredible feat. ITS partnered with DoD to bring together companies and academics from across the country to collaborate on innovation. The 5G Challenge showed how we can advance and facilitate open, interoperable, trusted networks in the 5G ecosystem.

Contestants worked through a rigorous testing schedule for end-to-end integration and testing tackling diverse issues, from inconsistent software option choices to discrepant hardware. Successful solutions demonstrated end-to-end data communication sessions using multiple protocols across a multi-vendor, interoperable Open RAN architecture.

> *The 5G challenge was an incredible industry event. It put together partners that typically don't meet in the marketplace. In a normal course of action when you show up to O-RAN challenges you typically come with partners you've worked with in the past. In this challenge, it's a cold play. You are actually mixing and matching industry leaders that never worked together. That was an incredible challenge. Pressure, as we say, always makes diamonds, and this was an incredible event.*
>
> *Joe Constantine, Chief Technology and Strategy Officer, JMA Wireless*

This 2023 Winners video captures contestants' excitement and satisfaction with the 5G Challenge:

https://youtu.be/cV-mwltChDc

Summarized lessons learned:

- Industry standards compliance ≠ out-of-the-box interoperability. Contestants used different versions of O-RAN ALLIANCE and 3GPP Release 15 specifications, resulting in broad interoperability issues
- Challenges upend industry interactions. The 2023 5G Challenge created new vendor partnerships and integrations that would not have happened otherwise. Integration with software from a different company is normally a long process for many companies but the 5G Challenge 'challenged' the normally slow interoperability process, for the good.
- More options = more risk of incompatibility. Interoperability would be facilitated by specifying a standard configuration of 3GPP and O-RAN ALLIANCE software options that all vendors agree to support. This would provide a starting point for interoperability while leaving plenty of opportunities for vendors to develop unique capabilities and specialties.
- While the Open RAN ecosystem is in the early stages of true "plug-and-play" interoperability and industry standard compliance, the 5G Challenge showed what can be achieved with close collaboration, system integration, and component-level developer expertise.

Video Quality Assessment

The purpose of the Institute's Video Quality Characterization project is to develop open source tools to enable the public and private sectors to optimize networked video transmission. To meet consumer expectations for high-quality video, whether as a part of commercial services or in public safety and surveillance uses, video streaming applications need to dynamically optimize their service.

Current solutions rely on Quality of Service (QoS) measurements—engineering calculations like bandwidth, network delay, packet loss, and monitor resolution. These solutions are suboptimal, because QoS metrics ignore the consumer's Quality of Experience (QoE). QoS metrics misconstrue subject matter, use case, and human perception.

Industry could make more efficient use of wireless bandwidth by bridging the gap between the network's QoS and the consumer's QoE—metrics that estimate how users perceive the quality of video files. With this information, intelligent video systems can identify and mitigate specific impairments, optimizing video delivery. Existing solutions are too inaccurate to be trusted, fail to provide root cause analysis (RCA), or are not suited to real-time workflows. Industry lacks incentive to provide open source metrics, since having better ones than the competition provides a market advantage. Thus, it is left to federal labs and standards organizations to develop objective and trusted metrics that can be used to promote a level playing field.

Successful QoE metric development requires various resources, methods, and capabilities—from experiment designs for evaluating new technologies to new methods for assessing the impact of camera impairments on computer vision. Communication among industry, academia, government, and standards development organizations is critical to ensure industry adoption of new metrics and methods.

No-Reference Metric Development

Although it has long been possible to statistically compare the quality of a video to another reference video, it remains challenging to measure the quality of a single video with no reference. Hence, the term no-reference (NR) metric is used to describe the type of model we are seeking to develop. Since 2016, ITS has sought to develop new techniques for NR metric development that will enable NR metrics to progress from academic research to industrial deployment. ITS efforts apply a multipronged approach:

- Collecting industry requirements
- Assessing the accuracy of previously published NR metrics
- Analyzing why prior NR metric development efforts fail
- Creating new training datasets for image and video quality assessment
- Publishing a GitHub repository of software tools
- Developing new statistical methods that measure the performance of NR metrics
- Developing Sawatch, a baseline NR metric for international cooperation
- Researching use cases, like public safety, medicine, gaming, and computer vision

Related Publications

- Margaret H. Pinson, "The Precision and Repeatability of Media Quality Comparisons: Measurements and New Statistical Methods," *IEEE Transactions on Broadcasting* 69, no. 2 (June 2023): 378–395
- Margaret H. Pinson, "Why No Reference Metrics for Image and Video Quality Lack Accuracy and Reproducibility," in *IEEE Transactions on Broadcasting* 69, no. 1, (March 2023): 97–117

In FY 2023, Margaret H. Pinson, Principal Investigator for Video Quality Assessment, published two important papers in the quarterly journal *IEEE Transactions on Broadcasting* that presented the results of several years of work. Both papers support the development of NR metrics that are accurate enough for commercial applications by describing and evaluating open source tools and sound methodologies that can be applied to assess the performance of metrics under development. The hope is that this information will help users make better decisions in applying and developing NR metrics.

"The Precision and Repeatability of Media Quality Comparisons: Measurements and New Statistical Methods" analyzes 89 datasets that use the 5-level Absolute Category Rating (ACR) method to evaluate the quality of speech, video, images, and video with audio. This figure shows the relationship between the number of subjects and the subjective test's confidence interval (ΔSCI), presented as a 2-D histogram. The right side enlarges the region outlined in a blue box on the left. The relationship established in this figure, in combination with analyses of 88 lab-to-lab comparisons, enabled the development of six new statistical methods.

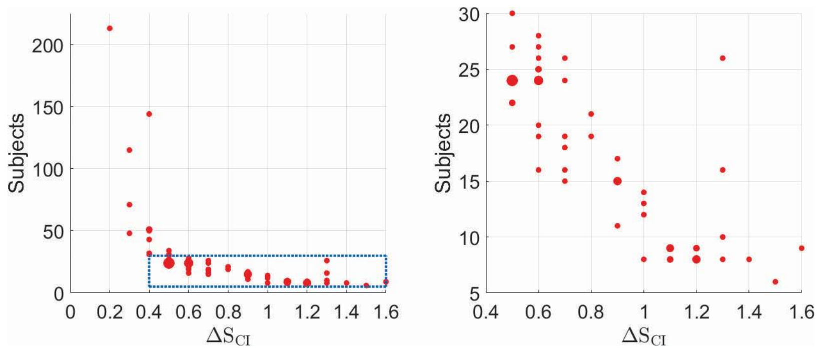
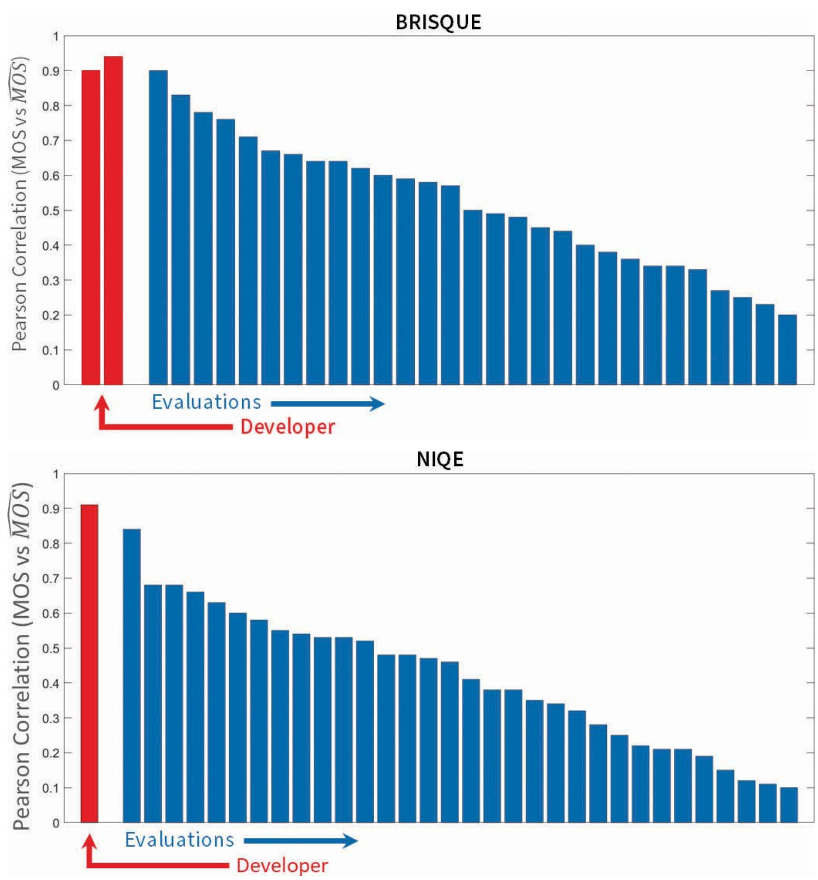


Figure "Precision_of_ACR" from Margaret H. Pinson, "The Precision and Repeatability of Media Quality Comparisons: Measurements and New Statistical Methods."

Some of these statistical methods will help researchers who need to modify subjective tests to accommodate new video services. The remaining statistical methods answer previously unanswerable questions about objective metrics, such understanding whether the metric is "good enough" to be trusted by US industry.

"Why No Reference Metrics for Image and Video Quality Lack Accuracy and Reproducibility" provides a comprehensive overview of no reference (NR) metrics for image quality analysis (IQA) and video quality analysis (VQA). These charts compare performance statistics reported by the developers of two widely reference NR IQA metrics with performance statistics from independent evaluators.



Above, Tables 4 and 5 of "Why No Reference Metrics for Image and Video Quality Lack Accuracy and Reproducibility" are summarized graphically.

Private communications with industry anecdotally support the conclusion that NR metrics lack accuracy and reproducibility. The journal article analyzes the cause of these performance problems and concludes that NR metrics must be developed and evaluated with much more data.

Computer Vision

Also in FY 2023, ITS conducted preliminary investigations into strategies for training NR metrics to assess the quality of images or videos for computer vision applications. Nearly all prior NR metric research was based on human perception. Entirely new research strategies are needed to establish truth data for this innovative new field of research. The first hurdle is the need for new statistical methods that calculate truth data: the measured success rate of a specific computer vision (CV) application for a specific video. Different computer vision applications will require very different statistical methods, because the truth data must isolate failures associated with low video quality from failures associated with imperfect CV algorithms. Robust and repeatable statistical methods will be needed before researchers can create massive datasets for machine learning (ML).

To that end, ITS began expanding the GitHub repository to include an ML workflow for the NR Metric Framework GitHub tool repository. ML algorithms seem to have no upper limit on the worst possible inaccuracy, which could cause unacceptable errors during dynamic optimization of video services. In response, ITS began development of an NR metric workflow that will allow industry to make informed decisions about the likelihood and magnitude of NR metric assessment errors. The initial version of this workflow will be published in FY 2024.

Open Science, Information Sharing, and Standardization

In this as in all its work, the video quality research project is committed to the open sharing of information, data, and software. All ITS video quality assessment metrics and tools are made available on GitHub for any purpose, commercial or non-commercial. ITS facilitates video quality assessments research in the U.S. and worldwide by publishing in high-readership scholarly journals, hosting the Consumer Digital Video Library (CDVL), sponsoring the Video Quality Experts Group (VQEG), and supporting ITU standardization activities.

The CDVL (www.cdvl.org) fills a critical academic and industry need for high-quality royalty-free test material for research and development by providing a digital video library intended for researchers and developers in the fields of video processing and visual quality (both objective and subjective assessment). CDVL hosts many video quality experiments, including, as of FY 2023, 18 datasets from ITS, 12 datasets from VQEG, and 12 datasets from various universities. Each dataset is a published study with hundreds of media files and ratings from a panel of subjects.

The VQEG (www.vqeg.org) is a pre-standardization venue where international experts from industry, academia, government, international organizations, and industry share their expertise with the goal of developing improved methods to assess human perception of video quality. The ITS Video Quality Assessment team has provided substantial leadership to this collaborative effort for 20 years and continues to sponsor VQEG by, for example, maintaining an e-mail distribution list and web presence.

Audio Quality Research Program

Wireless devices and services continue to proliferate and compete for a fixed amount of usable radio spectrum, as dictated by the laws of physics. This means that spectrum must be shared and interference must be tolerated to the maximal extent. But how do we best define those limits? The most relevant definitions are related to users' experiences—sharing and interference can be tolerated up to the level where they start to degrade users' experiences. ITS continues to develop and evaluate novel tools supporting the assessment of user experience for the original and still highly relevant telecommunications application—real-time, two-way voice communications, or "voice telephony."

From the perspective of a voice telephony user, spectrum sharing and radio interference become issues when they have a negative influence on speech quality or speech intelligibility. Low speech intelligibility harms the reliable and efficient transfer of information between users. Low speech quality is less pleasing to the ear, requires more listening effort, and causes greater listener fatigue. When intelligibility or quality drops, user satisfaction naturally drops as well.

So, tools that can quickly and reliably track speech quality and speech intelligibility are the most meaningful ways to identify successful and unsuccessful spectrum sharing. The ITS Audio Quality Research Program continues to make significant contributions in this area. These contributions include applying signal processing and machine learning to produce automated alternatives to subjective tests; novel evaluations and processing of subjective test results; and applying and evaluating a wide range of new tools proposed for quantifying speech quality or speech intelligibility in a range of environments.

User experience in voice telephony can be measured through subjective tests. Such tests can be configured to determine how intelligible speech is, how pleasing it sounds, how useful a connection is in the context of accomplishing a defined task, how much listening effort is required, or other qualities of interest. In every case, results are limited by the population of users included in the test. Tests are complex and time-consuming, and we often seek to impose specific and precise controls. Due to practical limitations, "large" laboratory tests may use several dozen subjects, yet it is hard to imagine that such a small number could be a representative sample of any user community.

ITS has conducted numerous laboratory subjective tests over the years and has more recently conducted multiple large-scale crowdsourced tests, where laboratory control is relinquished in exchange for much larger numbers of subjects (often many hundreds or even thousands) who participate remotely using a custom-built web application. Project engineers have compared the lab and crowdsourced tests and found that the large amount of data gathered via crowdsourcing easily compensates for the loss of laboratory controls—crowdsourced test results agree quite well with laboratory results.

ITS has also contributed significantly to the advance of efficient automated alternatives to subjective tests. These use signal processing models of human hearing and judgment or machine learning to produce estimated values of speech quality, speech intelligibility, or other quantities of interest without involving human subjects. ITS has developed, evaluated, and disseminated the family of no-reference speech tools called wideband audio waveform evaluation networks (WAWEnets).

This work builds on the lab's significant history of laboratory and crowd-sourced subjective testing and our expertise with speech coding and transmission, noise suppression, and modeling of human hearing and judgment inside objective estimators. It also builds on the large ITS collection of digital speech data and digital speech processing tools. But it is unique in that it combines all of these with powerful new machine learning tools to arrive at WAWEnets. These networks accept wideband speech signals and return estimates of speech quality or speech intelligibility, depending on the mode selected.

ITS development work used 334 hours of speech recordings in 13 languages from more than 1000 different talkers. This speech was processed by over 250 different actual or simulated telecommunications systems. Engineers used an iterative training process so that the WAWEnet responses to these signals would agree closely with target values. These targets included over 93,000 subjective ratings along with quality and intelligibility values produced by relatively intricate full-reference algorithms that invoke models of human hearing and judgment.

Next engineers applied WAWEnets to signals that were unseen during the training process. The excellent response to these signals confirmed that WAWEnets are robust and suitable for measuring a wide variety of speech signals across a plethora of telecommunication environments. ITS was awarded the 2020 U.S. Department of Commerce Gold Medal in recognition of this breakthrough.

In 2023, ITS continued to develop ML techniques to build connections between the subjective speech quality scores in multiple diverse speech databases. This allows ITS to combine multiple databases to create a larger and even more powerful database to support our speech quality research activities. Engineers have recently developed a fixed-size modulation spectrum representation for telecommunication speech signals and are evaluating the potential advantages this novel representation may offer for speech quality measurement and related tasks.

Additional FY 2023 ITS work focused on modeling errors and losses in wireless packetized telecommunications systems. This work supports the development of transmission schemes that are more robust to these inevitable challenges, and was made available to stakeholders through a technical memorandum and a software repository.

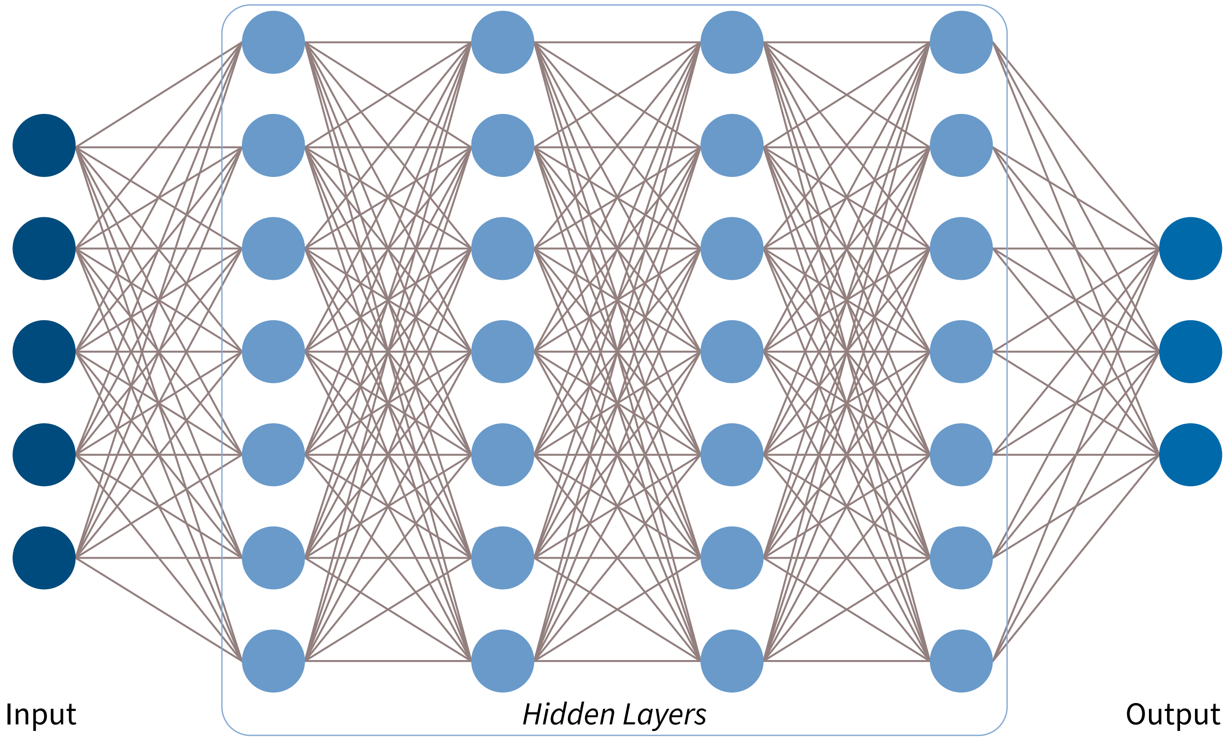
Project engineers have also leveraged machine learning to show that in many common cases, the speech quality at the input to a telecommunications system can be estimated using only the output from that system. They have investigated important issues surrounding the evaluation of speech that has been produced by deep neural networks. Their investigation of speech processing frame sizes reveals that the best frame size is determined by a fundamental trade-off between two very different types of distortions.

Engineers have also conducted analyses of the phase distributions of audio signal transform coefficients and variations in audio processing results due to frame temporal alignments. The connections between these more targeted efforts are fairly technical and perhaps even somewhat opaque, but together, these individual contributions and advances ultimately coalesce into major new telecommunications tools, such as WAWEnets and the ITS developed Articulation Band Correlation Modified Rhyme Test (ABC-MRT16) algorithm.

Looking forward to FY 2024, ITS will continue to develop machine learning techniques to build connections between the subjective speech quality scores in multiple diverse speech databases. s. The project team has recently developed a fixed-size modulation spectrum representation for telecommunication speech signals and will continue with evaluating the potential advantages that this novel representation may offer for speech quality measurement and related tasks.

Related Publications

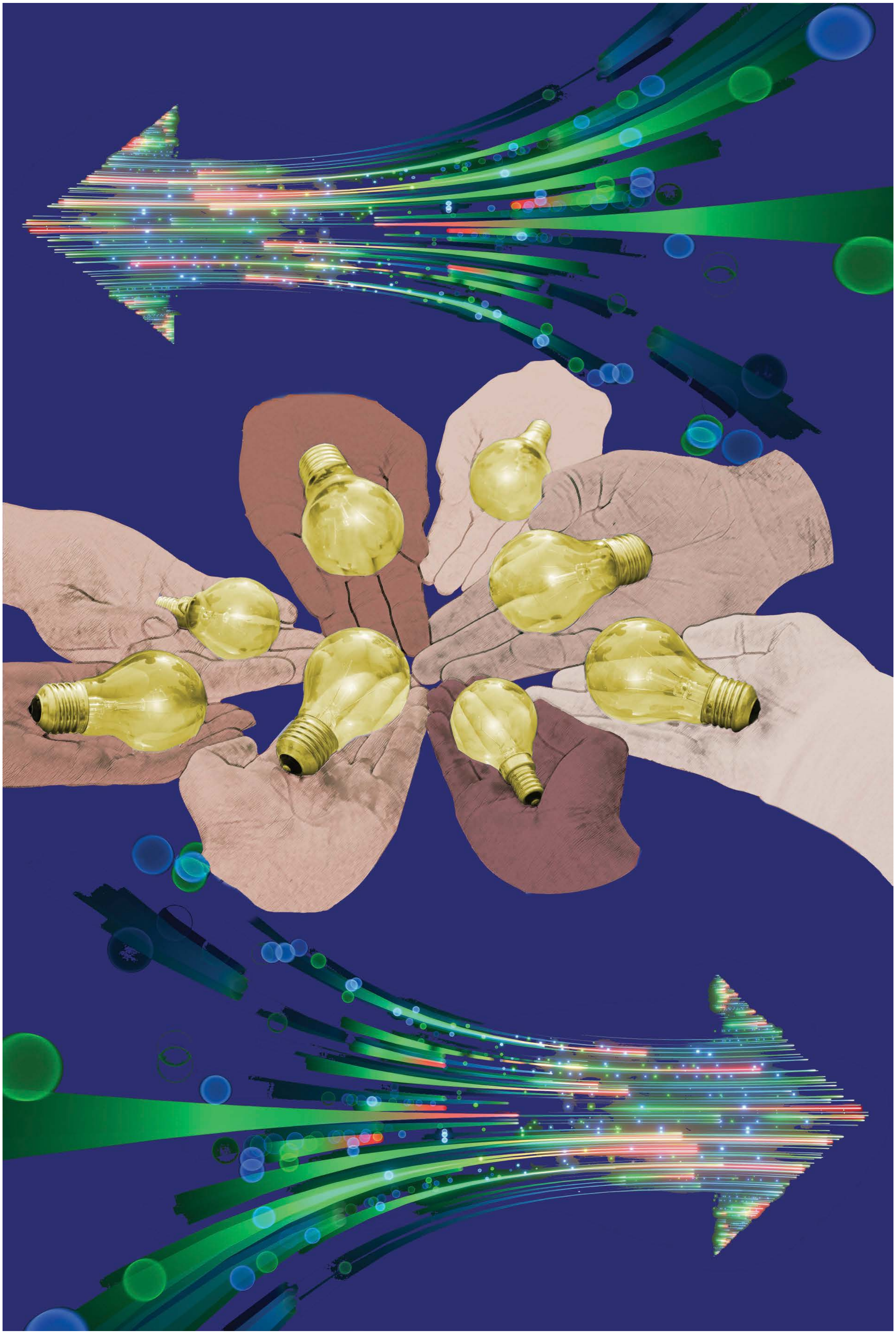
- Jaden Pieper and Stephen D. Voran, "Relationships between Gilbert-Elliot Burst Error Model Parameters and Error Statistics", NTIA Technical Memorandum TM-23-565, January 2023.
- Jaden Pieper and Stephen D. Voran, "Gilbert-Elliot Model Software Tools," NTIA Software, December 2022, https://doi.org/10.5281/zenodo.7438482



Conceptual representation of a neural network.

An important aspect of all ITS work is technology transfer. The Audio Quality Research Program has produced numerous technical publications that thoroughly document the work and results mentioned above. ITS engineers have provided the telecommunications community with software implementations of WAWEnets, ABC-MRT16, and supporting data files in multiple formats. In addition, engineers continue to maintain and upgrade laboratory facilities and perform peer reviews for technical publications both inside and outside of ITS and support other ITS projects when audio, speech, or signal processing expertise is needed.

Taken together, the contributions of the ITS Audio Quality Research Program enable practical real-time field measurements of speech signals produced by wireless mobile devices, thus enabling real-time evaluation of successful spectrum sharing, and detection of cases where interference rises to a level that a voice telephony user will notice, or even to a level that will impair intelligibility.



Technology Transfer

Modern directives for technology transfer begin with the Stevenson-Wydler Act of 1980. The Act and its amendments establish the principal that all federally funded laboratories have a responsibility to "strive where appropriate" to engage in technology transfer to ensure nation-wide return on the government's investment in research and development. The vehicle for formal technology transfer with private industry is the cooperative research and development agreement (CRADA), which leverages federal resources to speed industry research and development efforts in areas consistent with the federal partner's mission while protecting the intellectual property of both parties.

Technology transfer from most other federal agencies takes place through CRADAs and licensing agreements. Current ITS research outputs are typically abstract ideas—e.g., mathematical algorithms and scientific methods—not patentable and therefore not licensable. At the turn of the 21st century, ITS researchers did obtain a handful of patents for inventions developed by the QoE research group, and those were briefly licensed. After the decision to stop licensing the software in FY 2008 and make it available open source, downloads increased dramatically, expanding the benefit to the telecommunications economy. To support spectrum efficiency during the rapid expansion of the wireless industry, ITS no longer licenses any technology but makes all research outputs openly available for any purpose.

Cooperative research with private industry through CRADAs has helped ITS accomplish its mission to support industry's productivity and competitiveness by providing insight into industry needs. For 20 years, ITS Telecommunications Analysis Services (TA Services) provided web-based propagation modeling support on a cost-reimbursable basis for wireless system design/evaluation and site selection to private industry and public agencies through on-demand electronic CRADAs. TA Services was discontinued in FY 2012. Today, the PMW program *(see Propagation Modeling Website on page 28)* maintains a public facing demo server that can be freely used by any federal agency by simply accepting ITS Rules of Behavior for network access, and PropLib *(see Propagation Library (PropLib) on page 26)* makes available the updated propagation model implementations at the root of TA Services as open source downloads.

More recently, ITS has entered into CRADAs for collaborative research on newly emerging technologies related to spectrum sharing *(see CBRS Dynamic Spectrum Sharing on page 34).* ITS also enters into a handful of CRADAs for research to be conducted in the Table Mountain Radio Quiet Zone each year (see page 82). These CRADAs allow industry to benefit from the only radio quiet zone in the U.S. currently available for research, development, testing, and evaluation of new radio-dependent technology prototypes and gives ITS insight into these new technologies under development.

Of particular benefit to advancing spectrum sharing are CRADAs for the characterization of emissions from new radar systems under development. For many decades, ITS has developed and published the Radar Spectrum Engineering Criteria (RSEC) that are intended to ensure an acceptable degree of electromagnetic compatibility among radar systems, and between radars and other radio services sharing the spectrum and are the basis for U.S. radar regulations and for a number of ITU Recommendations. With OSM, over the past several years, ITS has been working on revisions to the RSEC, originally developed for measuring the emission spectra of tube-type radars, to account for modern digital radars.[1]

1 *See* Frank H. Sanders, Robert L. Hinkle, and Bradley J. Ramsey, "Measurement procedures for the radar spectrum engineering criteria (RSEC)," NTIA Technical Report TR-05-420, March 2005.

Interagency Agreements

To obtain economies of scale and eliminate overlapping activities of the federal government, with the Economy Act of 1932 Congress established the Interagency Agreement (IAA), under which ITS is reimbursed for the cost of research conducted at the request of other agencies. ITS's unique position as the primary radio science laboratory for the executive branch of the federal government means that many IAAs, not usually considered technology transfer, ultimately result in technology transfer to the private sector.

For example, several IAAs with DHS, NIST, NOAA, and the FCC in recent years tasked ITS to develop test methodologies for compliance certification of new technologies. The methodologies are transferred to private industry and commercial laboratory facilities perform the actual certifications. The test harness transferred to the FCC in FY 2023 for certification of CBRS SASs *(see CBRS Dynamic Spectrum Sharing on page 34)* will eventually be turned over to the private sector for routine ongoing certification activities.

ITS has traditionally transferred research results to other researchers, the commercial sector, and government agencies through peer-reviewed publications. Many of these publications—both NTIA reports or monographs and externally published scientific journal articles—have become standard references in several telecommunications areas. In the past decade, the scope of "publications" has expanded to include open source software and datasets. The rigorous peer review process that has assured the scientific integrity of ITS manuscripts since the early twentieth century has served as a blueprint for developing parallel processes for documented peer review of software and datasets.

Open Science

Open Science: "The principle and practice of making research products and processes available to all, while respecting diverse cultures, maintaining security and privacy, and fostering collaborations, reproducibility, and equity." — OSTP August 2022 memorandum

In August 2022, the White House Office of Science and Technology Policy (OSTP) published a memorandum on *Ensuring Free, Immediate, and Equitable Access to Federally Funded Research.*[1] This memorandum extended to all federally funded laboratories specific directives for making results of government-funded research freely and publicly accessible, for the purpose of democratizing knowledge and building public trust in science and decisions based on science.

Of critical importance to ITS, the memorandum imposed on laboratories with less than $100 million in annual research and development expenditures the same requirements f that had been imposed on larger laboratories a decade before—namely, *how* research results are to be made publicly accessible, and for documentation and reporting, that had been imposed on larger laboratories a decade before.

At the beginning of calendar year 2023, OSTP launched the Year of Open Science, featuring actions across the federal government throughout 2023 to advance national open science policy, provide access to the results of the nation's taxpayer-supported research, accelerate discovery and innovation, promote public trust, and drive more equitable outcomes. OSTP's first action was to release the official definition of Open Science, shown in the above quotation, for use by all government agencies.

1 Executive Office of the President, Office of Science and Technology Policy, *Ensuring Free, Immediate, and Equitable Access to Federally Funded Research*, August 25, 2022 https://www.whitehouse.gov/wp-content/uploads/2022/08/08-2022-OSTP-Public-Access-Memo.pdf

ITS and its predecessor laboratories within the National Bureau of Standards (NBS, the ancestor of ITS, NIST, and NOAA) have been committed to making research products and processes available to all since the earliest days of the twentieth century. The NBS laboratories were among the first federal laboratories to use computers for science and engineering research. In 1950, NBS boasted the fastest computer of its day, and during the International Geophysical Year in 1957 the Central Radio Propagation Laboratory (CRPL, which later became ITS) acted as an national data center, jump-starting computer research at NBS. Anita Longley and Phil Rice published the FORTRAN code implementing the Irregular Terrain Model as an appendix to ESSA Technical Report ERL 79-ITS 67[1] in 1968, and thereafter for a couple of decades reports that described new computerized algorithms included as an appendix a listing of the FORTRAN code.

its.bldrdoc.gov (now its.ntia.gov), a new means of technology transfer, was one of the first federal websites on the internet. ITS had participated in development of the Advanced Research Projects Agency Network (ARPANET) and by 1992 was eager to launch its own website. From the beginning, the website was envisioned as a research resource to the public; publications, data, and software were all seen as fulfilling the mandate for technology transfer. Among the first publications to be posted to the web were FORTRAN code implementations of propagation models and RF measurement datasets that could be used to validate the models.

An ITS Open Science initiative was launched at the beginning of FY 2023 to solidify standard operating procedures to enable open, equitable distribution and management of ITS research results. This complements both the large body of manuscript publications ITS digitized and made publicly available at the beginning of the twenty-first century, and the ITS peer review process that protects the scientific integrity of written reports and articles and which has been in place for more than 50 years.

Guided by key presidential memoranda and laws on the management of scientific data, this initiative therefore focused primarily on implementing new ways to mature how ITS manages and distributes its high-quality data and software. Throughout FY 2023, a small team of ITS staff labored to produce the required public access plan and policy, to review procedures already in place to ensure they met the requirements of the memorandum or to revise them appropriately, and to research both the infrastructure required to comply and the costs thereof.

ITS completed the first milestone toward compliance by submitting an initial Public Access Plan draft to NTIA's Office of Chief Counsel for submission to OSTP by the end of FY 2023. This Plan outlines the deliverables and milestones that NTIA will complete over the next four fiscal years to achieve full compliance, most of which will be delivered by ITS. The team also delivered the first Public Access Plan output: the Data Management Plan template, a new industry-standard project management artifact that will be used by project leaders to define and plan what data they will produce and if/how it will be distributed.

1 Anita G. Longley and Philip L. Rice, "Prediction of Tropospheric Radio Transmission Loss Over Irregular Terrain: A Computer Method - 1968," NTIA Technical Report ERL 79-ITS 67, July 1968.

FY 2023 Standards Engagement

Another very important avenue for technology transfer is participation in standards development organizations (SDOs). Strong, unbiased standards are fundamental for advancing new technologies in a shared spectrum environment and globally competitive marketplace. Leadership and technical contributions to national and international telecommunications fora help influence development of standards and policies to support the full and fair competitiveness of the U.S. communications and information technology sectors in a global marketplace.

Several offices of NTIA work collaboratively with the International Telecommunication Union (ITU), U.S. National Committee for the International Union of Radio Science (USNC-URSI), 3rd Generation Partnership Project (3GPP), Wireless Innovation Forum (WInnForum), Institute of Electrical and Electronics Engineers Standards Association (IEEE), O-RAN ALLIANCE, Telecommunications Industry Association (TIA), Internet Engineering Task Force (IETF), and Inter-American Telecommunications Commission (CITEL), to develop, interpret, analyze, and implement standards, specifications, and regulations.

ITS participates most intensely at the Working Group or Working Party level, both directly providing technical contributions and engaging in collaborative assessment and validation of others' technical contributions. Technical contributions to standards may or may not be credited to the authoring laboratory, depending on the SDO, but the impact is not lessened by their anonymity. ITS's technical inputs, unbiased by commercial interests, are heavily relied upon as technically advanced and sound. For example, many of the technical recommendations of the International Communication Union Radiocommunication Sector (ITU-R), a treaty organization, are based on research conducted at ITS over the past 75 years.

In FY 2023, staff from five separate offices of NTIA held 102 positions in 13 standards bodies, including 21 Chair/Co-Chair/Vice-Chair/Chair-Elect positions. NTIA staff filled key leadership positions in the ITU-R, ITU-T, USNC-URSI, and CITEL. This hard work during FY 2023 contributed to several spectrum policy accomplishments at the ITU World Radiocommunication Conference 2023 (WRC-23) in December 2023. The U.S. delegation advanced spectrum policy for critical federal missions like aviation safety, weather, climate monitoring, and—looking to the future—lunar communication; and for the private sector in support of both licensed and unlicensed services, and in expanding space and satellite services.

International Telecommunication Union (ITU)

ITS has a long history of involvement and leadership at the International Telecommunication Union – Radiocommunication Sector (ITU-R) Study Group 3 (SG3), dating to prior decades when it was known as the International Radio Consultative Committee (CCIR). This treaty level organization, which is part of the United Nations, works to establish voluntary consensus standards (called "ITU-R Recommendations") to manage and harmonize spectrum globally to promote efficient spectrum usage and avoid harmful interference across international borders. As a treaty level organization, ITU membership is limited to nations; industry and academia participate through preparatory meetings at the national level, where technical contributions are prepared as input to new or revised Recommendations. The technical contributions are reviewed at the national Study Group level and then formally submitted for acceptance at the international plenary meeting by, for the U.S., the Department of State.

The scope of SG3 is the "propagation of radiowaves in ionized and non-ionized media and the characteristics of radio noise, for the purpose of improving radiocommunication systems."[1]

1 International Telecommunication Union, *ITU-R Radiocommunication Study Groups 2020. Available* https://www.itu.int/dms_pub/itu-r/opb/gen/R-GEN-SGB-2020-PDF-E.pdf#page=23&pagemode=none.

The activities of Study Group 3 are organized into four Working Parties (WP):

- Working Party 3J: Propagation Fundamentals
- Working Party 3K: Point-to-Area Propagation
- Working Party 3L: Ionospheric Propagation and Radio Noise
- Working Party 3M: Point-to-Point and Earth-Space Propagation

An ITS engineer ITS holds one of the four ITU-R SG3 Working Party international chairmanships—of Working Party 3K. Within U.S. SG3, ITS holds a strong leadership role. ITS acts as Head of U.S. Delegation to Study Group 3. ITS also holds three of the four U.S. SG3 Working Party chairmanships: Working Parties 3J, 3K, 3L. Consensus based improvements of ITU-R P-Series Recommendations promoted by ITS technical contributions have far-reaching effects, from ensuring the technical correctness of propagation models used in WRC-23 decision-making, to supporting international organizations such as the International Civil Aviation Organization (ICAO). Nationally, ITS continues to be looked to by other Federal agencies as a national resource in the field of radio wave propagation.

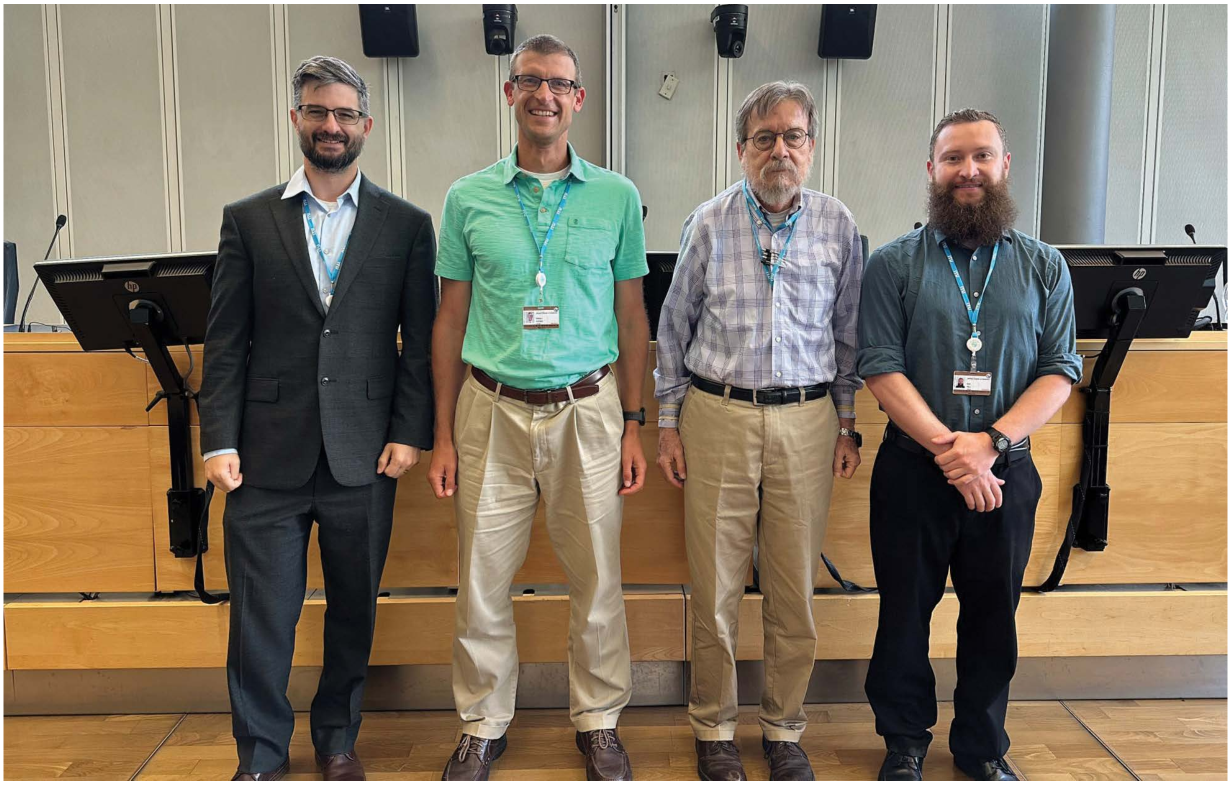
Meeting Preparatory Activities: As Head of U.S. Delegation to Study Group 3, an ITS researcher organizes meeting preparatory activities at the national level. These meetings provide a forum for U.S .persons to propose input contributions to Study Group 3. Inputs undergo a technical review, are presented, discussed, and are approved or disapproved by consensus. Lastly, ITS submits approved U.S. SG3 input contributions to National Committee review—a final review, comment/resolution, and approval process before formal submittal to ITU-R Study Group 3. In FY 2023, ITS organized seven U.S. SG3 Preparatory Meetings, beginning in December 2022 and concluding in April 2023. In total, twenty-three input contributions were approved to be submitted to ITU-R SG3, two of which were authored or coauthored by ITS.

International Meetings: ITU-R Study Group 3 meets once a year for a two-week block. In FY 2023, hybrid meetings of the Working Parties were held from May 22 to June 1, followed by a meeting of the Study Group on June 2. These meetings generated additional responses to new Liaison Statements, as well as updating various SG3 P-series Recommendations. In addition to occupying the previously mentioned leadership roles within ITU-R SG3, ITS employees chaired several Sub-Working Groups and Drafting Groups, on topics from aeronautical propagation to radio noise.

Correspondence Group Activities: Between formal meetings of ITU-R Study Group 3, international activities working towards improved propagation standards—such as updates to SG3 P-Series Recommendations—continue through entities called Correspondence Groups (CG). CG's are non-decisional activities created by one or more SG3 Working Parties that work on addressing outstanding issues and future updates, as defined in the CG's Terms of Reference. Outcomes of CG activities, including formal input documents, are then directly submitted to the corresponding CG's Working Party(ies).

During FY 2023, ITS engineers chaired three separate Correspondence Groups:

- CG-3K-3M-9—Aeronautical Propagation: Correspondence Group 3K-3M-9 focuses on the topic of aeronautical propagation, and specifically, Recommendation ITU-R P.528, *A propagation prediction method for aeronautical mobile and radionavigation services using the VHF, UHF, and SHF bands*. ITS historically has been, and continues to be, a major contributor to this work, including leading the effort to draft a major revision in 2019, as well as contributing an open-source C++ implementation. In FY 2023, CG-3K-3M-9 did not hold any meetings, since it had previously completed updating Recommendation P.528 for discussion during the 2023 World Radiocommunication Conference (WRC-23) sharing studies. The CG attended meetings of another CG that focuses on high altitude platform systems (HAPS), and provided advice on application of air-to-ground modeling related to HAPS sharing scenarios.



ITS ITU-R team members in Geneva, Switzerland on June 2, 2023, at the final day of the ITU-R Study Group 3 meetings. (From left) Adam Hicks, Billy Kozma, Paul McKenna, and Erik Hill. (Photo courtesy ITU-R Study Group 3)

- CG-3L-7—Radio Noise: Correspondence Group 3L-7 focuses on the topic of radio noise and updating Recommendation ITU-R P.372 - Radio Noise, which is cited in the ITU Radio Regulations. Recommendation P.372 provides information on the background levels of radio noise in the frequency range from 0.1 Hz to 100 GHz, taking into account radio noise emitted by lightning, atmospheric gases, clouds, rain, the Earth's surface, the galaxy, and man-made sources. During FY 2023, this group considered the calculation of brightness temperature versus radio noise temperature and submitted a discussion document for wider SG3 members to provide input. It was agreed to calculate brightness temperature in P Series Recommendations and to include this in P.372. The ITU-R-HF software that predicts the performance of HF circuits based on ITU-R Recommendations P.372 and P.533 has been updated with input from global users and is publicly accessible at https://github.com/ITU-R-Study-Group-3/ITU-R-HF .
- CG-3J-11—Reference Standard Atmospheres: Correspondence Group 3J-11 focuses on reference standard atmospheres. It aims to create a model for a single, global reference standard atmosphere to include in Recommendation ITU-R P.835. In 2021, the fifth generation of the European Centre for Medium-Range Weather Forecasts (ECMWF) Reanalysis data (ERA5) became available. This dataset has a spatial resolution of 0.25° in latitude and longitude, a temporal resolution of 1 hour, 37 pressure levels extending to 47 km, and includes global measurement data from 1991 to 2020. From these data, new monthly and annual worldwide digital maps of the mean vertical profiles of pressure, temperature, and water vapor density have been produced and included in a draft revision of Recommendation P.835 that was accepted by ITU-R SG3 in June 2023, along with a draft new fascicle describing the derivation of these data sets and relevant calculations such as the conversion between geometric and geopotential heights.
- CG-3K-3M-12—Clutter Modelling: ITS engineers actively participated in and contributed input materials to meetings of Correspondence Group 3K-3M-12. Mobile clutter measurements and analysis performed

by ITS in previous years at 1.7 GHz was contributed to the CG to support ongoing work on improving the clutter model, Recommendation ITU-R P.2108. In particular, much work was focused on the Section 3.3 model suitable for air-to-ground statistical clutter modeling. The measurements and analysis ITS provided were useful inputs to the deliberations because they were taken with just such link geometries.

Standards for Next Generation Communications

Participation in the 3rd Generation Partnership Project (3GPP), the leading global consortium developing technical specifications for wireless telecommunications networks, allows NTIA to promote strong, unbiased standards that support fair competition in next generation/5G cellular technologies. Member delegates come to 3GPP via organizational membership in a regional SDO. The Alliance for Telecommunications Industry Solutions (ATIS) is the North American founding partner through which NTIA participates with two memberships: one held by the First Responder Network Authority (FirstNet), and one held jointly by the Office of Policy Analysis and Development (OPAD), the Office of International Affairs (OIA), and ITS.

3GPP is organized into three technical specification groups—the Radio Access Network (RAN), Service & System Aspects (SA), and Core Network & Terminals (CT)—each of which is composed of multiple Working Groups (WGs) focused on specific subtopics. ITS participates in RAN Plenary meetings, in SA WG3 for Security and Privacy, and in RAN WG1, focused on the physical layer of radio interfaces for LTE and 5G. Under interagency agreements, ITS briefs other agencies on 3GPP 5G/NR standards development related to agency-specific concerns about spectrum sharing, vehicle-to-everything communication, non-terrestrial networks, unmanned aerial vehicles, and integrated sensing and communication.

NTIA believes that open and interoperable networks are the future of wireless technologies, including 5G and its successors. Such networks will increase the reliability of the U.S. telecommunications supply chain, drive competition, and provide the U.S. and its allies with additional choices for trustworthy equipment. To this end, in FY 2023 ITS also led NTIA's engagement with the O-RAN ALLIANCE, founded by several large mobile broadband network operators to develop technical specifications for Open RAN architecture and focused on RAN disaggregation, automation, and virtualization.

ITS led two Open Testing and Integration Center (OTIC) workshops co-located with O-RAN ALLIANCE meetings in Phoenix, Arizona, and Athens, Greece) to work towards international consistent, repeatable testing and to understand operator concerns about the OTIC badging and certification process. This work follows up the successful 2022–2023 5G Challenge competitions focused on accelerating the adoption of open and interoperable interfaces and multi-vendor solutions *(see 2023 5G Challenge on page 48)*.

WInnForum and IEEE

ITS participates as a member of the Wireless Innovation Forum™ (WInnForum), which is dedicated to advancing technologies supporting the innovative use of spectrum and the development of wireless communications systems, including essential or critical communications systems. The Forum is seen as one of the few entities that successfully crosses defense, civil, and commercial domains, facilitating transfer of ideas to the benefit of all participants. As a result, WInnForum has been a key player in standardizing centralized spectrum sharing systems such as CBRS, for which it continues to issue updated standards *(see CBRS Dynamic Spectrum Sharing on page 34)*. The latest technology standardized through WInnForum is Automated Frequency Coordination (AFC) a database–based spectrum use coordination system used by Wi-Fi access points, especially those operating in the 6 GHz band (5.925–7.125 GHz).

The Institute of Electrical and Electronics Engineers (IEEE) is the world's largest technical professional organization. The IEEE Standards Association (IEEE SA) develops and advances standards by consensus. In 2020, ITS's direct participation in IEEE 802.15.22.3 led to standardization of the SCOS standard to facilitate expanded spectrum monitoring *(see Spectrum Monitoring on page 11).* In FY 2023, ITS staff participated in the IEEE Communications Society/Mobile Communication Networks Standards Committee (COM/MobiNet-SC) Working Group for Project P1944 to develop a new standard for channel models of wireless systems. ITS staff also chaired the subgroup on UAV and V2V channel models.

VQEG

The Video Quality Experts Group (VQEG, vqeg.org) is a group of international experts from industry, academia, government, international organizations, and industry, with a goal to develop improved methods to assess human perception of video quality. VQEG members share their expertise and conduct collaborative research and technical validation tests. The group submits its results to relevant ITU study groups in the Telecommunication Standardization Sector (ITU-T) SG12 and ITU-R SG6, often resulting in new or amended international standards. The ITU-T SG12 and ITU-R SG6 are responsible for Recommendations on video quality metrics, statistical methods, and subjective testing methods. This technical venue for international experts to develop and reach consensus on best practices enables greater participation in ITU activities. VQEG has contributed to more than 28 ITU Recommendations.

ITS has provided substantial leadership to this collaborative effort for 20 years and continues to sponsor VQEG by, for example, maintaining an e-mail distribution list and web presence. Recent VQEG work has focused on emerging video technologies and such applications as immersive media (e.g., virtual reality, augmented reality), high-dynamic-range (HDR) video, ultra–high definition (UHD) video (e.g., 4K, 8K), and Advanced Display Stream Compression (Adv-DSC). VQEG conducts international collaborations on diverse topics, including subjective methods for new video technologies, NR metrics for key industry use cases, and improved analysis methods for subjective experiments.

Workforce Development

Many professional organizations sounded warning bells early in the standardization of 5G about the lack of skilled workers able to deploy these technologies. Congress and the executive branch took note and took action to address this serious concern for industry and government alike. The CHIPS Act of 2022 tasked NTIA with administering the $42.45 billion Broadband Equity, Access, and Deployment (BEAD) Program of grants aimed at expanding high-speed Internet access by funding planning, infrastructure deployment and adoption, and workforce development programs in all U.S. states and territories. NTIA's sister agency NIST administers the $50 billion Creating Helpful Incentives to Produce Semiconductors and Science Act (CHIPS) program, aimed at developing onshore domestic manufacturing of semiconductors critical to U.S. competitiveness and national security through incentives and funding for research and development, workforce development, and technology security and innovation.

ITS researchers maintain informal collaborative correspondence with faculty at a number of universities and ITS has a robust and well disciplined internship program—many interns have converted to full time staff on graduation—but ITS has not previously been directly engaged in workforce development. Workforce development is a key component of the DOC Strategic Plan for 2022–2026[1] and a key objective of the National Science Foundation's (NSF's) Spectrum Innovation Initiative (SII). As a result, ITS is partnering with NSF on several aspects of the SII, including workforce development initiatives focused on transferring the skills and expertise of ITS researchers through expansion of educational curricula at secondary and post-secondary levels.

1 U.S. Department of Commerce Strategic Plan | 2022 –2026, available https://www.commerce.gov/about/strategic-plan

National Science Foundation Collaborations

In 2019, The National Science Foundation (NSF) announced a major investment in a Spectrum Innovation Initiative (SII), with the goal of establishing the following key elements:

- SII-Center: Focal point for sustained R&D expected to develop advanced wireless technologies
- Spectrum Research Activities: Cross-disciplinary R&D leading to more effective and efficient use of spectrum
- Education and Workforce Development: Education and training programs to develop a skilled and diverse spectrum workforce.
- National Radio Dynamic Zone (NRDZ): An area or volume with automatic spectrum management mechanisms that control electromagnetic energy entering, escaping, or occupying the zone that will enable at-scale research and development on advanced dynamic spectrum sharing techniques.
- Polar Program Spectrum Management Support: Apply spectrum subject matter expertise to solve modernization and sharing challenges in Antarctica.

As part of the SII program, NSF and ITS finalized an interagency agreement (IAA) for ITS to provide mission critical subject matter expertise (SME) in spectrum engineering, spectrum management, and radio science. ITS's continued support has played a pivotal role in advancing NSF's mission to foster scientific progress and provide leadership in research and education related to the SII objectives. Anticipating the release of the National Spectrum Strategy in FY 2024, a 2021 Memorandum of Agreement (MOA) among NSF, NTIA, and the FCC strategically leverages NTIA and FCC SME to ensure that NSF SII investments in spectrum research, infrastructure, and workforce development align seamlessly with regulatory and policy objectives, principles, and strategies. Widely acknowledged as an indispensable milestone, this MOA marked a new era of information sharing between NSF, NTIA, and the FCC.

SII-Center

In September 2021, NSF established SpectrumX as the nation's SII-Center. Since then, ITS has played a vital role in providing unwavering support to the center. This includes active participation in SpectrumX quarterly center meetings, the annual NSF SII-Center review meetings, and collaboration on a plan to create a significant and substantial spectrum research, education, and workforce development effort. These efforts have been instrumental in guiding and shaping SpectrumX's initiatives in research, education, workforce development, and community engagement.

In FY 2023 SpectrumX and ITS jointly orchestrated one of only two NTIA National Spectrum Strategy Public Listening Sessions. The listening session, hosted by SpectrumX, had widespread attendance from government, industry, trade associations, and academic researchers, serving as an unparalleled forum for interested organizations and individuals to submit comments and findings crucial to the formation of the National Spectrum Strategy. ITS also actively participated in the inaugural NSF-organized Spectrum Week. This in-person gathering included three related events: Spectrum and Wireless Innovation Enabled by Future Technologies Principal Investigators (SWIFT PI) Meeting, NRDZCOM2, and

SpectrumX Center Meeting. A joint plenary, breakout sessions, poster sessions, and evening gatherings fostered collaboration across the spectrum ecosystem.

Spectrum Education and Workforce Development

NSF has placed significant emphasis within the SII on education and workforce development to facilitate the creation of a technical workforce that is attentive to spectrum technology and policy issues. In FY 2023, ITS and NSF collaborated on spectrum workforce development planning. ITS established an NTIA Visiting Researcher and Intern Program (VRIP) to bridge the gap between university research and national spectrum priorities. The program, first piloted in spring 2022, aspires to foster an environment of continuous learning and discovery built on a foundation of collaboration and support from government and academia. Throughout FY 2023, one academic researcher served in this role to pioneer the program. ITS is evaluating feedback regarding the program and is considering other candidates for additional roles as it expands and grows the program.

NRDZ

ITS has continued to provide crucial subject matter expert support to NSF's SII-NRDZ program, focusing on ensuring at-scale capabilities for next-generation spectrum management techniques to develop dynamic spectrum sharing. Under the MOA and the terms of the NRDZ program solicitation, throughout FY 2023 ITS actively participated in the review process of NRDZ proposals, providing feedback to NSF with an emphasis on aligning potential NRDZ projects with national spectrum management objectives and strategies. ITS has reviewed materials and reports from the NRDZ Engineering and Execution Leads (EELs), offering vital feedback to NSF regarding their efforts to implement the NRDZ vision.

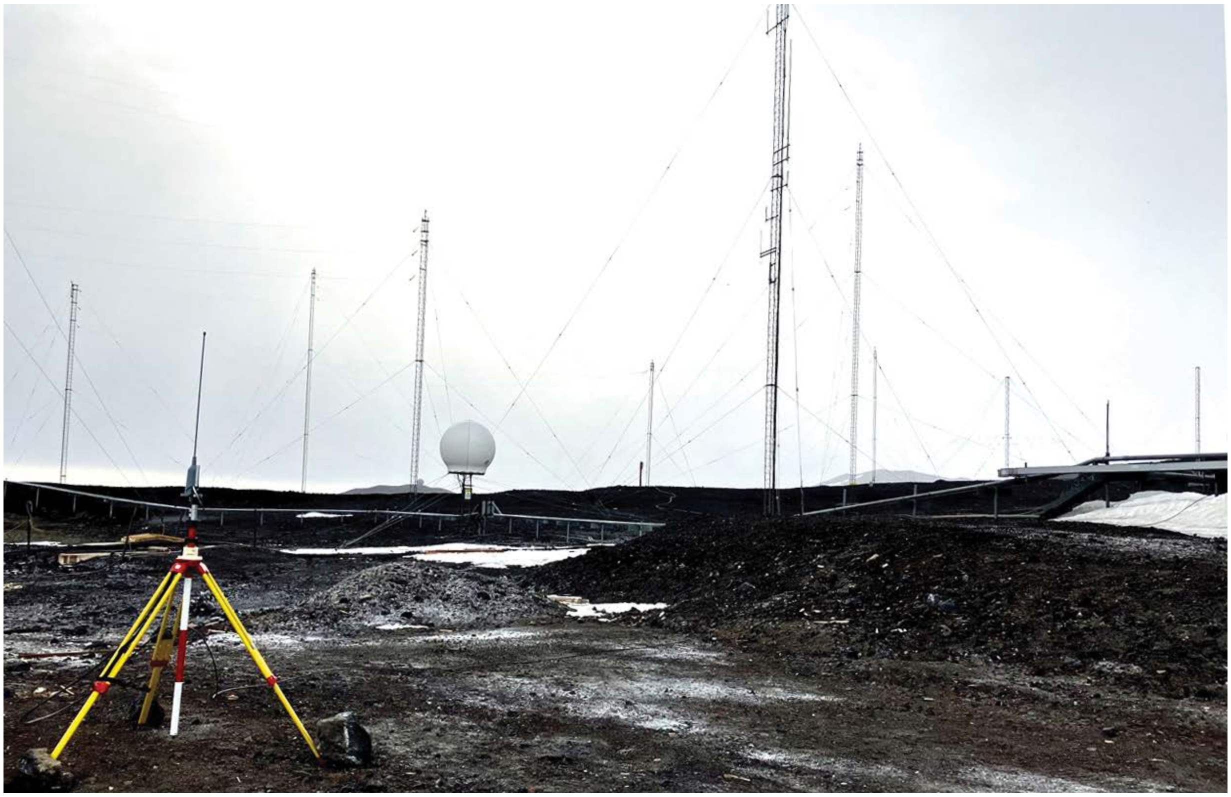
ITS also organized and led two NRDZ Community Open Meetings (NRDZCOMs) that included a review of the state-of-the-art in NRDZ-related research, along with work sessions dedicated to creating a strategy, roadmap, and execution plan for realizing the NRDZ. Additionally, ITS has supported NSF in the evaluation of candidate sites and technologies for an initial NRDZ field trial scheduled for 2025. ITS provided crucial assistance in the development of the NRDZ EEL Phase 2 solicitations, which will fund the implementation of NRDZ field trials. As part of the Phase 2 solicitation development, ITS collaborated with NSF to underscore the alignment of NRDZ with the draft National Spectrum Strategy, identify key components ensuring the success of field trials, and explore pathways that could facilitate the further development of candidate sites into NRDZ experimental facilities.

Polar Spectrum Management Support

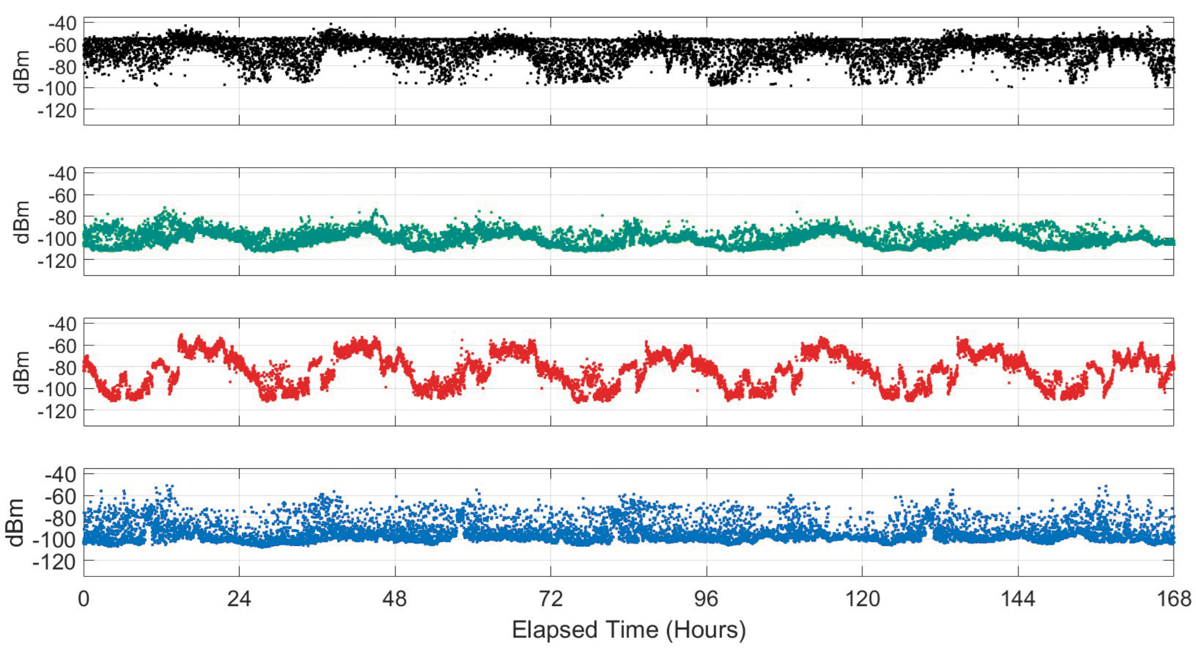
As part of the multifaceted, multiyear collaboration with the NSF, ITS provides indispensable subject matter expert support to the NSF Office of Polar Programs (OPP), with a focus on high-frequency (HF) noise and interference issues in Antarctica. In FY 2023, ITS experts designed, procured, and constructed an HF measurement system engineered to operate flawlessly in the exceedingly challenging conditions of the Antarctic. In January 2023, ITS researchers deployed with the measurement system to McMurdo Station in Antarctica. There, they conducted groundbreaking work to characterize the HF spectrum environment, meticulously examining the specific noise floor of Black Island, located in the Ross Sea 25 miles from McMurdo Station—a pivotal United States Antarctic Program (USAP) HF receive site for over 40 years.

The resulting data analysis has proven to be of paramount importance, guiding recommendations to USAP and its stakeholders for spectrum management improvements. Additionally, the insights derived from the data are influencing critical engineering decisions regarding the modernization of HF to support

McMurdo Station operations, including communications with science parties in the deep field and flight operations. Further, ITS is leveraging its expertise to develop a series of Antarctic-specific spectrum management talks, designed to be made available to the public. These talks will highlight some of the most unique challenges and issues associated with operating wireless systems in the harsh and unforgiving Antarctic environment.



A 1 m high portable rod (PR) antenna collecting spectrum occupancy measurements at McMurdo Station during the austral summer 2023 ITS spectrum measurement campaign. (Photo credit: Sarah Vasel)



Measured power at four HF frequencies over a one week period (168 hours) from a spectrum survey at the Black Island Telecommunication Facility at McMurdo Station.


1925
1939
1950
1980
2023

Research Capabilities

Communications Research and Innovation Network (CRAIN) Laboratory

The Communications Research and Innovation Network (CRAIN) lab 5G test bed is a commercial-grade 5G system consisting of a non-standalone (NSA) core and a standalone (SA) core. ITS began the CRAIN build-out in FY 2021 to allow ITS to perform research and testing of 5G wireless systems and components and determine the efficacy of interoperability between various vendors of Open RAN equipment. The lab was designed with the future in mind, with flexible and upgradable components that will allow it to serve as the ITS test lab for 5G, 6G, and nextG systems as they become available.

The 4G/5G system with SA and NSA cores was deployed and commissioned in FY 2022 after months of intensive testing. The NSA core supports both 4G LTE and 5G NR operation. Many U.S.–based wireless service providers adopted this approach to bridge their existing 4G LTE systems and newly deployed 5G base stations to bring 5G deployments quickly to market. The SA core supports 5G operation with no dependencies on legacy 4G equipment. The CRAIN deployment includes three remote radio heads (RRHs) operating in various frequency bands. These systems will serve as a baseline network using equipment from a traditional RAN provider.

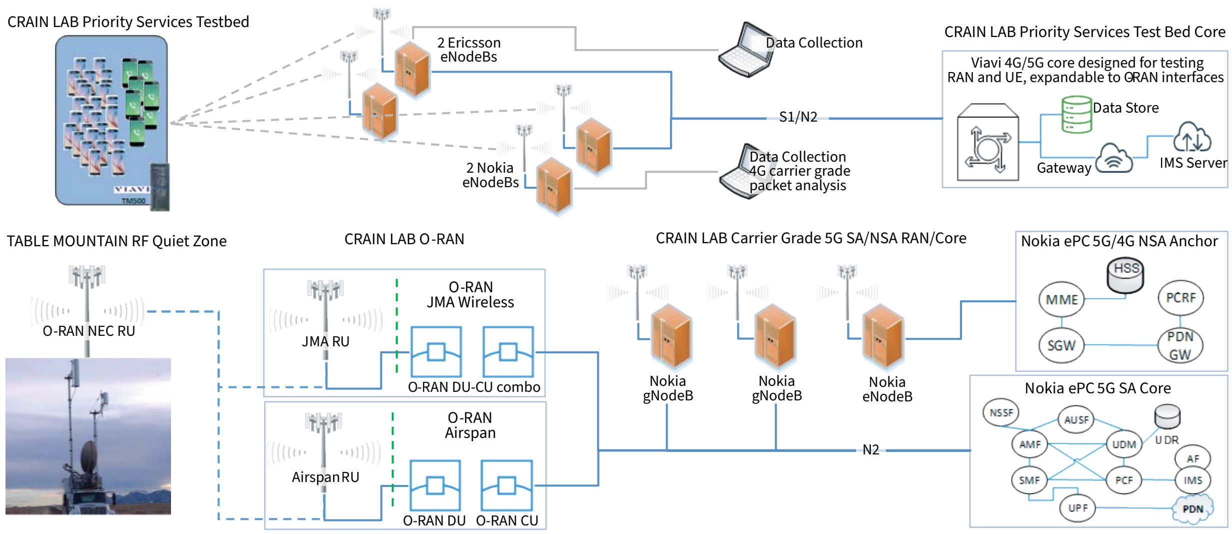
ITS issued a Broad Agency Announcement (BAA) in FY 2021 to gather input for an Open RAN deployment and purchased products from three different Open RAN manufacturers that responded to the BAA. Products were delivered in early FY 2023. Deployment of an Open RAN system in the CRAIN 5G laboratory will allow research and testing of interoperable 5G system components from different vendors. Initial testing objectives include:

- Determining difficulty of integration of Open RAN equipment
- Assessing interoperability of different vendor builds
- Comparing performance of different vendor builds to traditional RAN
- Testing virtualized RAN technology and the intersection with Open RAN
- Developing best practices for integration of NTIA's Software Bill of Materials (SBOM) work with Open RAN softwarization

In FY 2023, CRAIN lab engineers began integrating Open RAN equipment from both Airspan and JMA Wireless. The Central Units (CU) and the Distributed Units (DU) from both Open RAN vendors were installed. Commissioning of these Open RAN systems was halted by renovations to the NIST-owned lab building. In the interim, CRAIN lab engineers began drafting detailed Open RAN test plans. Some of the Open RAN radios operate in the CBRS band and require coordination from a SAS, which will enable CRAIN engineers to collect data from a real-world spectrum sharing scenario.

The CRAIN lab also began deploying a mmWave system at Table Mountain to enable mmWave antenna characterization and out of band emissions field testing. This capability is of great interest to OSM, which is jointly funding initial deployment work. When the mmWave system is operational (expected in mid-FY 2024), it will operate in the n260 band (37–40 GHz).

ITS purchased Nokia's Enterprise Voice Core (EVC) in order to be able to deploy voice services on its 5G systems. Voice services were installed and commissioned FY 2023, but testing and troubleshooting were suspended due to building renovations. Pending tasks that will be taken up in FY 2024 are test plan review, and additional testing and troubleshooting for Domain Name System (DNS) and International Mobile Subscriber Identity (IMSI) provisioning issues. The team continued to pursue lab expansion and future testing capabilities in FY 2023 by integrating additional test equipment, networking equipment, and applications, and researching potential tools to expand capabilities.



CRAIN network architecture and connectivity details.

Radio Frequency Measurement Capabilities

The Institute's Radio Spectrum Measurement System (RSMS) includes a comprehensive suite of test equipment, custom-built hardware and software, specialized measurement and analysis techniques, and the extensive expertise of engineers with years of radio frequency (RF) research experience. ITS engineers design, develop, and maintain a number of mobile and stationary radio frequency measurement systems applicable to frequencies from 10 MHz to 40 GHz. ITS also maintains a library of waveforms that can be used to simulate interference for testing and measurement of receiver responses. In FY 2023, development began of an extremely high frequency (EHF) measurement system for frequencies from 40 to 300 GHz.

RSMS Mobile Laboratory and Software Package

RSMS-4 Mobile Laboratory: In many cases, measurements must be taken on–site; systems being measured may be too large (e.g., radars) to ship to the laboratory, or measurements may be needed of spectrum occupancy in a particular geographic area. An integral part of the RSMS is a measurement vehicle, now in its 4th generation, called the RSMS-4. The vehicle has a highly shielded enclosure (60 dB isolation from the ambient environment) with three full-size equipment racks, three 10 meter telescoping masts, a 20 kW diesel generator with power conditioning, Internet connections, and a climate control system. The RSMS-4 mobile laboratory can be deployed to remote field sites, such as an operational

RSMS-4 taking measurements at the Table Mountain Radio Quiet Zone.

radar installation or satellite dish, and it can operate independently from systems under test. Deploying the RSMS-4 to different locations to take spectrum occupancy measurements ensures that the results are comparable and gives a true picture of geographic variations in spectrum occupancy.

RSMS-5 Software: The RSMS software package is now in its 5th generation (RSMS-5) of development. It is dynamic and flexible, incorporating automated, semi-automated, and manual techniques for radio emission measurement from 10 MHz to 40 GHz, as well as analysis of usage statistics such as spectrum occupancy. Compared with previous versions, RSMS-5 has a simplified, more modular design that makes it easier to implement new measurement algorithms and decreases dependency on third-party software. Compatibility with multiple operating systems has extended the application lifecycle, reduced overall costs, and provided flexibility to continue to keep pace with rapid advances in RF technology.

The RSMS program's objective is to ensure that the Institute has access to the most advanced software and hardware so that accurate and complete RF measurements can be performed on all types of radio systems between 10 MHz and 40 GHz. Dynamic range of up 130 dB can be achieved, extending the nominal 70 dB instantaneous dynamic range of most off-the-shelf precision test equipment.

The modular design of the RSMS measurement platforms allows mobile or stationary measurements, in laboratory settings or at field sites. Deployments can use the 4^{th} generation (RSMS-4) mobile laboratory or be constructed at field sites from individually shipped modules. The RSMS and related ITS engineering expertise are available for use in research collaborations with industry and other government agencies on a cost-reimbursable basis.

Ultrawideband Measurement System

This system takes precision propagation measurements. It has high dynamic range and excellent immunity to RF interference, and it transmits low power levels (typically +5 dBm), minimizing the potential for interference to existing wireless services. These features make it ideal for collecting measurements indoors, outdoors-to-indoors, near operational transmitters, and in densely populated areas. The system consists of a commercial vector network analyzer (VNA), transmit and receive antennas, and an analog optical link. The VNA is configured to perform two-port S-parameter transmission measurements between fixed transmit and receive antennas. The system covers a frequency range of 20 MHz to 18 GHz and measures time- and frequency-domain propagation phenomena at distances of up to 300 meters. It is configured in a stepped-frequency mode, and S21 data (amplitude and phase) are acquired and stored. The resulting data yield propagation parameters such as delay spread and basic path loss. This system also has excellent range resolution capabilities that permit the isolation and evaluation of selected propagation events.

20 MHz–30 GHz Mobile Measurement System

The mobile propagation measurement system has two channel probe modes: narrowband and broadband. The narrowband mode has high accuracy, sensitivity, dynamic range, and immunity to interference. A continuous wave signal is transmitted and received using a spectrum analyzer, vector signal analyzer (VSA), or combined sound card and communications receiver. Broadband channel probe mode is enabled by applying binary phase–shift keying modulation to the transmitted signal using a pseudorandom number code with a user-selectable number of bits. Post-processing yields a channel impulse response from which parameters can be extracted. In both modes, the system is capable of measuring fast- and slow-fading phenomena and path loss.

Microwave Frequency Measurement System

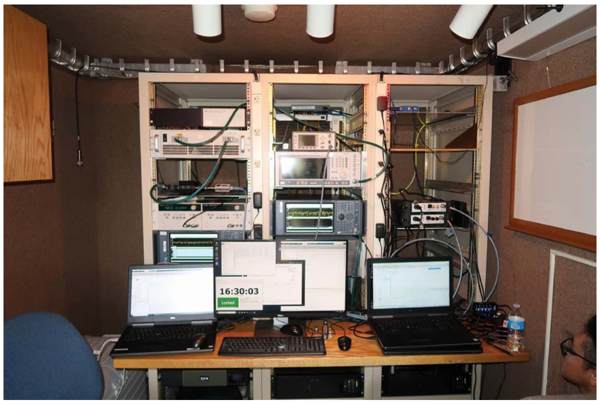
The microwave frequency propagation measurement system consists of a mobile receiver in a modified utility van, which receives signals from a transmitter in the RSMS-4 mobile laboratory parked at a fixed location. The transmitter sends a highly stable (rubidium-standard referenced) carrier wave into space. The receiver, which carries its own onboard matched rubidium oscillator, processes the received signal as the mobile van moves through various locations. The onboard receiver uses a high-speed digital system to record the complex (I/Q) waveform of the propagation signal as a function of environment. The resulting data show the Doppler characteristics and attenuation of the transmitted signal. For outdoor-to-indoor measurements, the receiver system in the van can be removed and converted into a suitcase system, which is then carried into buildings for data collections.

Radiated LTE Measurement System

The ITS Radiated LTE Measurement System consists of a commercial test instrument that can simultaneously receive both uplink and downlink transmissions from three different LTE base stations (eNodeBs), along with the transmissions of their associated mobile phones (UEs). Sampling the radio spectrum at a rate of over 30 million samples per second, this instrument is able to decode command and control information from the eNodeBs to their respective UEs, as well as the replies from the mobile units, in real time. Subsequent analysis of this information, along with correlated information from spectrum analysis traces also provided by the device, allows insight into the network and RF behavior of individual UEs, as well as investigations into the aggregate effects of multiple devices operating simultaneously.

Mobile Measurement Fleet

ITS maintains a small fleet of mobile testbed vehicles, transportable towers, and generators to support field measurements of propagation, radiated emissions, and aggregate interference. The workhorses of the mobile measurement program are the ITS-owned RSMS-4 *(see RSMS Mobile Laboratory and Software Package on page 72)* and two mobile measurement vans. These vehicles have been fitted with antenna masts and equipment racks so that they are easily configurable for different measurement campaigns. Two CoWs supplement the testbed vehicles and a mobile generator allows long-term measurement campaigns. Four GSA leased vehicles used to transport staff and equipment to and from Table Mountain and other measurement sites complete the fleet inventory.



Above top, measurement and data processing equipment racked inside the RSMS-4. Above bottom, measurement van configured as a mobile receiver van for outdoor propagation measurements in the 37–40 GHz band in Boulder, Colorado. Right top, the green van is pictured as configured to transmit a continuous wave 37 GHz signal for the 37–40 GHz band measurement campaign. The fully extended telescoping mast places the transmitting antenna at approximately 10 m above ground level (AGL). Right bottom, CoWs configured for 5G over the air EMC tests at the Table Mountain Radio Quiet Zone.

Table Mountain Radio Quiet Zone

The Table Mountain Field Site and Radio Quiet Zone is located approximately 15 km north of the Department of Commerce campus in Boulder, CO. The site is approximately 4 km (2.5 miles) in a north-south direction by 2.4 km (1.5 miles) east-west and has an area of approximately 680 hectares (1,700 acres). While Table Mountain is owned by the Department of Commerce, ITS has been designated to oversee site management and operations. Table Mountain is expansive enough to support a multitude of radio frequency and non–radio frequency research programs overseen by ITS, NIST, NOAA, and the U.S. Geological Survey.

Due to its location and unique geology, Table Mountain is well suited for conducting radio frequency research and science. The soil is homogeneous and free of inconsistent radio wave scatterers. The topology is that of a flat-top butte with uniform 2% slope. There are no perimeter obstructions, only a few man-made structures, and power lines are buried. To preserve this rare asset, Table Mountain is protected by law as one of only two federally mandated radio quiet zones within the United States where external signals are restricted by state law and federal regulation.

Imagery: Google Earth satellite photo © 2024 Maxar Technologies, imagery date 06/14/2021.

Since 1954, Table Mountain has provided an ideal environment for the sensitive experiments performed by ITS researchers, federal agency partners, academic institutions, and industry. In 2023 Table Mountain hosted multiple C-band 5G base stations which were used to perform national priority research into the potential for 5G interference to radar altimeters on aircraft.

Current ITS research activities at Table Mountain include 3 GHz and mmWave radio wave propagation measurements, precise measurements of radiated emissions of transmitters, and the assessment of the interactions between disparate spectrum-dependent systems such as radars and both commercial and federal telecommunications and telemetry systems.

Facilities available at the Table Mountain site include:

- Spectrum Research Laboratory Space: ITS owns and manages four research buildings spaced at the center and along the perimeter of the site to support various use cases and applications. The Table

Mountain Radio Quiet Zone restrictions ensure that no signal incident on the mesa overpowers any other so the entire radio spectrum is available for study at this location.

- Open Field Radio Test Site: This facilitates studying far field radiation patterns of antennas, the effect on the radiation pattern of antennas due to mounting on such various structures as buildings or vehicles.
- Radar Test Range: This facility provides power and internet for hosting radar systems to support radiated emissions measurements.
- Mobile Test Vehicles: Should existing research buildings be unsuitable for required experiment geometries, there are a number of vehicles available at the mesa. These vary from four-wheel drive trucks to full feature mobile laboratories to support test systems.
- Large Turntable: This is a 10.4 meter (34 foot) diameter rotatable steel table mounted flush with the ground. Laboratory space located directly underneath the table provides a location for test instrumentation as well as the control equipment and motors needed to rotate the turntable.

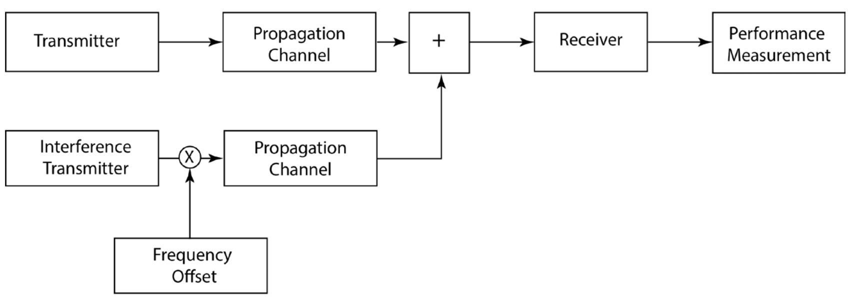
Views of the Table Mountain Radio Quiet Zone

IPC Laboratory

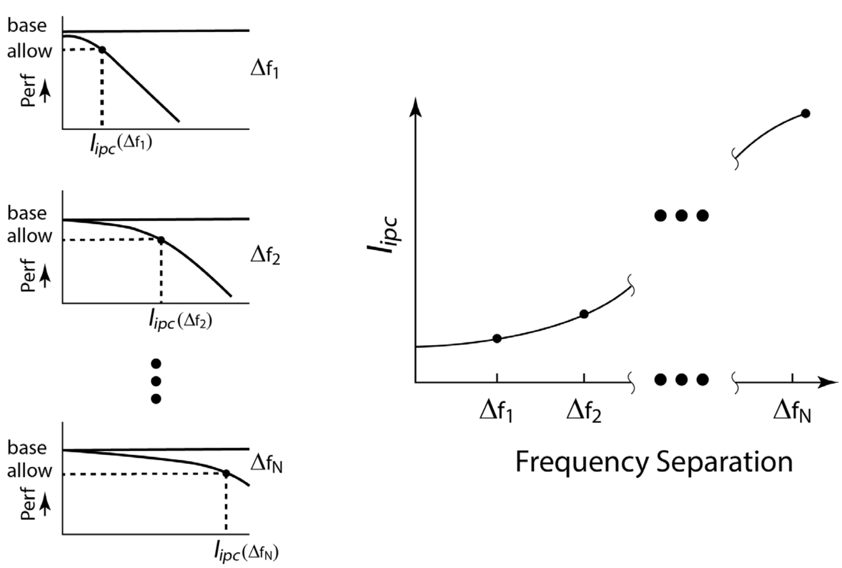
Accurate interference protection criteria (IPC) are critical to sharing feasibility and electromagnetic compatibility EMC studies *(see Electromagnetic Compatibility on page 31)*. IPC are estimated with interference tests that iteratively measure victim system performance over a range of interfering signal powers and frequency separations. The method used to measure performance depends on the victim system. For example, communication system performance is estimated with bit or frame error rate, and radar performance is estimated with probability of detection and false alarm. When these performance metrics are not provided by the receivers, the IPC Laboratory has to “hack” the receiver to obtain them. This is a time-consuming but valuable process that enables engineers to precisely understand how the receiver will perform in the spectrum sharing scenario.

The IPC laboratory is equipped to perform both physical and simulated IPC analyses. As the need to share spectrum increases, it becomes less practical to conduct physical measurements of all of the many IPC spectrum engineers will need. Simulations may be the most practical way to determine scientifically sound IPC that can be replicated by other interested parties. Thus, ITS has invested significantly in computer simulation capabilities. IPC laboratory capabilities include:

- Receiver Characterization: Receivers are characterized by their frequency response and susceptibility to strong interference signals. These characteristics are measured with spectrum analyzers, vector signal analyzers (VSAs), and power meters.
- Interfering Signal Repository: Acquiring interfering signals for IPC tests, by VSA measurement or software simulation, consumes a significant investment of ITS resources. To maximize return on investment, the IPC Laboratory stores these signals in a common format in a signal repository so they can be reused in the future.
- System Simulation: ITS simulators running on desktop computers can emulate interference scenarios involving radar, satellite communications, global navigation satellites, tactical mobile communications, wireless local area networks (WLANs), and cellular communications. ITS's capacity for simulating this broad range of systems is sufficient to address many of today's spectrum sharing questions and continues to be expanded as new systems are introduced into expanded sharing scenarios.



Schematic overview of an IPC measurement test fixture configuration. The principle of the procedure is the same whether the test fixture is physical or virtual.



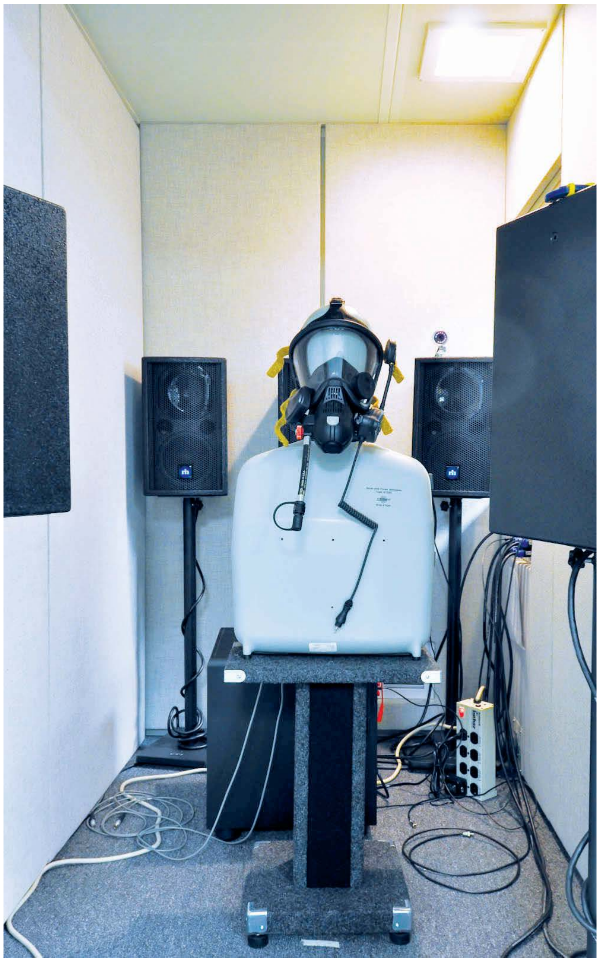
Graphical representation of a series of IPC estimations over a range of frequencies.

Audiovisual Laboratories

The ITS audiovisual laboratories allow ITS researchers, along with government and industry research partners, to conduct a wide range of investigations involving audio and video signals. These investigations are motivated by a need to identify ways to improve both the quality and efficiency of audio and video, encoding, transmission, and decoding.

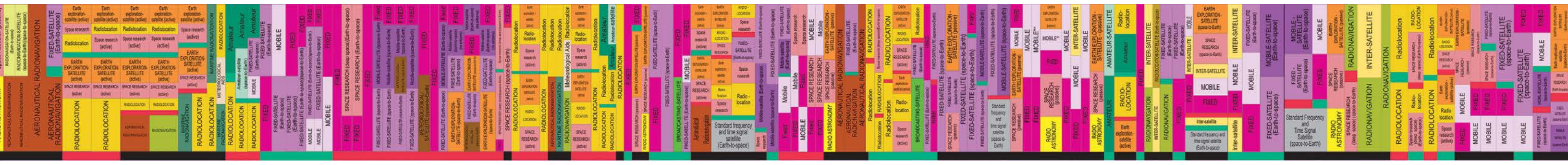
Some of these laboratory studies involve persons who serve as listeners or viewers; these are called subjective tests. Other studies rely solely on hardware– or software–based measurement devices or instruments and these are considered to be objective tests. The two approaches are dramatically different and each comes with fairly pronounced strengths and weaknesses. In some cases ITS researchers leverage both avenues in order to most efficiently and unambiguously pin down new results. Studies may involve hardware, software, or combinations that appropriately represent the relevant aspects of the audio and video signal chains in broadcasting, streaming, multiparty, or two-party wired and wireless communications applications.

Objective tests are faster and less expensive than subjective tests, and they offer exact repeatability. They can identify exact parameter values with great precision to efficiently evaluate devices and systems, and to allow comparisons with subjective test results. But objective test results are always at least one step removed from questions of quality, degradation, intelligibility, and usability. In FY 2023, QoE work focused on narrowing the gap between objective and subjective tests *(see Video Quality Assessment on page 52 and Audio Quality Research Program on page 55).*



An ITU standard Head and Torso Simulator (HATS) set up in a sound-isolated booth for testing. (Photo credit: Andrew Catellier)

The equipment that supports subjective and objective audiovisual testing at ITS includes head and torso simulators with artificial ears and mouths, studio-quality digital and analog video recorders with 2–8 audio channels, and a full range of video monitors, speakers, handsets, and headphones. ITS also has two sound isolation chambers compliant with ITU Recommendations for controlled sound testing (ITU-T Rec. P.800, ITU-R Rec. BT.500, and ITU-T Rec. P.912). These chambers can be interconnected to allow two people to converse using audio, video, or both. To prepare signals for evaluations ITS maintains a wide complement of video editing equipment, audio recording, mixing, filtering, equalization, and conversion equipment, as well as software and hardware that encodes and decodes media signals.



ITS Projects in FY 2023

Other Agency Projects

Federal Communications Commission

Further SAS Testing in Support of Dynamic Spectrum Sharing in the 3.5 GHz CBRS Band followed by SAS Certification Test System Transfer to the FCC

For Spectrum Access System (SAS) administrator conformance testing, develop additional test configuration files, test conformance of SAS to FCC Part 96 rules, and document the processes and procedures during the testing.

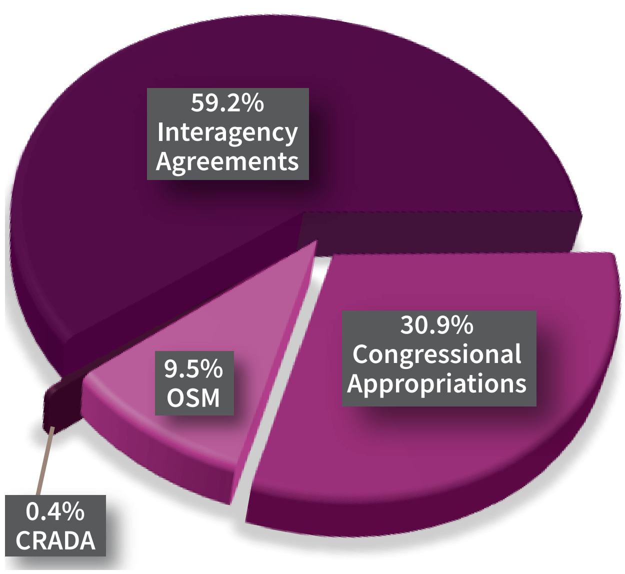
Project Leader: Julie Kub, (303) 503-9639, jkub@ntia.gov

National Science Foundation (NSF)

Spectrum Innovation Initiative (SII) Subject Matter Expertise (SME) and Educational Workforce Development (EWD)

Provide subject matter expertise in spectrum engineering, spectrum management, and radio science to support the NSF's mission to promote the progress of science and to provide leadership in advancing research and education. Tasks include SII-Center support, National Radio Dynamic Zone (NRDZ) planning, Office of Polar Programs (OPP) Spectrum Management Support, and education and workforce development.

Project Leader: Michael G. Cotton, (720) 552-7970, mcotton@ntia.gov



FY 2023 ITS research expenditures by source of funds.

U.S. Department of Commerce

National Oceanic and Atmospheric Administration (NOAA)

Radio Frequency Interference Monitoring System (RFIMS) Support

Provide technical subject matter expertise and engineering support for NOAA in the procurement, maintenance, sustainment and operation of the NOAA interference monitoring system. Activities include SME support, TRL-8 testing/capability assessment, and Earth station maintenance and upgrades.

Project Leader: John E. Carroll, (720) 202-0205, jcarroll@ntia.gov

NOAA National Weather Service (NWS)

National Weather Service Propagation Modeling Website (NWS PMW)

Renew the Authority to Operate (ATO) and operate and maintain a web-based multipurpose GIS propagation modeling tool to predict NOAA Weather Radio coverage and to integrate 2020 Census population data, to verify that the NOAA All Hazards Weather Radio System (NWR) radio transmissions reach 95% of the population of the U.S. as mandated by law.

Project Leader: Douglas Boulware, (720) 552-7610, dboulware@ntia.gov

National Institute of Standards and Technology (NIST) National Advanced Spectrum and Communications Test Network (NASCTN)

National Advanced Spectrum and Communications Test Network (NASCTN) CBRS Sharing Ecosystem Assessment (SEA)

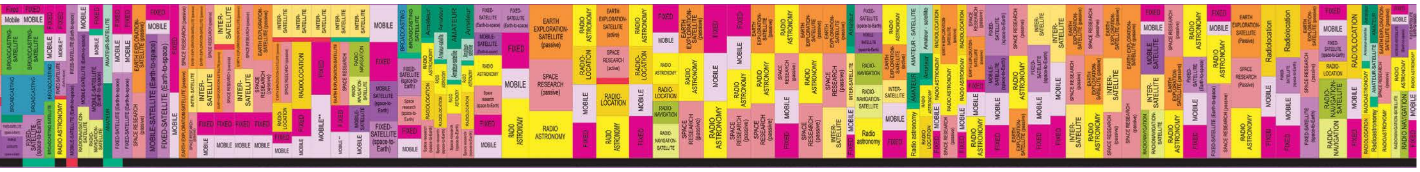
Measure emissions in the CBRS band near "Always On" Dynamic Protection Areas (DPAs) and characterize sharing between federal incumbents and new entrants. Tasks include developing, deploying, and maintaining three prototype sensors. Subteams include hardware, calibration (VBA), software, data pipeline, site survey, and modelling.

Project Leader: Todd Schumann, (720) 552-7613, tschumann@ntia.gov

National Telecommunications and Information Administration, Office of Spectrum Management

OSM Spectrum Management Research and Development

ITS provides planned R&D (i.e., science, models, data, analyses, and software) and quick-reaction subject matter expertise



in support of OSM policy decisions and spectrum management processes.

Project Leader: Charles Dietlein, (202) 355-3801, cdietlein@ntia.gov

Quick-Reaction Subject Matter Expertise

The goal of the QR SME project is to provide SME support to OSM on propagation modeling, policy, and electromagnetic compatibility analyses within the time and schedule constraints intrinsic to each request.

Project Leader: Michael G. Cotton, (720) 552-7970, mcotton@ntia.gov

U.S. Department of Defense (DoD)

Multi-agency Projects

Propagation Modeling Website (PMW)

Update and maintain the IF-77 propagation model to eliminate terminal height constraints and replace remoting communication. Provide information assurance, 5G preparation, GIS migration, and maintenance and support.

Project Leaders: Douglas Boulware, (720) 552-7610, dboulware@ntia.gov and Robert Ballard, (720) 614-4463, rballard@ntia.gov

Radio Frequency Coordination Portal (RFCP) for the 1695–1710 MHz Band

Continue operations and maintenance (O&M), and adhere to security requirements. Tasks include ongoing user support, ATO renewal, PIV/CAC implementation, and migration of the RFCP application to Windows 2019 Server OS.

Project Leader: Kristen Davis, (720) 347-5146, kdavis@ntia.doc.gov

5G Program Office

2023 5G Challenge

ITS carried out the second of two prize challenges to accelerate the adoption of open 5G interfaces, interoperable subsystems, and modular, secure, multi-vendor solutions.

Project Leader: Julie Kub, (303) 503-9639, jkub@ntia.gov

Army Spectrum Management Office (ASMO) Support

Provide quality advisory, engineering, and testing support to the Army Spectrum Management Office via well-engineered spectrum sharing–oriented over-the-air experiments/measurements to resolve spectrum sharing concerns. Tasks include planning, measurements, analysis, and reporting.

Project Leader: John E. Carroll, (720) 202-0205, jcarroll@ntia.gov

DoD Hill Air Force Base Dynamic Spectrum Sharing

Provide quality advisory, engineering, and testing support for the DoD Hill AFB Dynamic Spectrum Sharing (DSS) Project via active participation in DoD groups/meetings and responsive, well-engineered spectrum sharing–oriented bench and over-the-air experiments/measurements to resolve current or projected spectrum sharing concerns.

Project Leader: Frank H. Sanders, (720) 352-2009, fsanders@ntia.doc.gov

Chief Information Officer (CIO)

DoD CIO Mid-Band Propagation Model Study

Establish an improved and community-accepted mid-band (3100–4200 MHz) radio frequency propagation model framework to predict basic transmission loss for a diverse range of link geometries.

Project Leader: William Kozma, Jr., (303) 335-5059, wkozma@ntia.gov

U.S. Department of Transportation (DoT)

Federal Highway Administration (FHWA)

V2X Testing Project and V2X Cybersecurity

Research and analysis that assists the U.S. DoT in understanding the challenges and opportunities associated with the next-generation communications V2X technology. Tasks include laboratory tests and measurements of LTE V2X devices; simulation of LTE V2X and 5G V2X performance, including in complex, hard to test scenarios; standards monitoring and analysis per 3GPP SA1 WG; on-site support and post-test analysis for DOT field testing; and SME support as needed.

Project Leader: Irena Stange, (720) 552-7274, istange@ntia.gov)

Fundamental Research and Engineering Projects

Data Technology and Software Engineering

The ITS Data Technology and Software Engineering (DT&SE) advances and matures ITS's capabilities in data sharing, data science, project management practices, and software quality. DT&SE develops processes and tools to enable adherence to federal open-source requirements.

Project Leader: Robert Ballard, (720) 614-4463, rballard@ntia.gov

ITS Propagation Modeling Project

Provide fundamental research towards the improvement and standardization of radio wave propagation models by designing and prototyping advance propagation measurement techniques and systems, expanding mmWave measurement capabilities, providing U.S. leadership for the ITU-R SG3, and publishing outstanding technical work.

Project Leader: Adam Hicks, (720) 552-7271, ahicks@ntia.gov

Next Generation Communications and Quality of Experience)
Support NTIA on initiatives and standards involving 5G; establish and commission the 5G/Open RAN testbed of the Communications Research and Innovation Network (CRAIN); and contribute to progress in QoE tools (user perspective on whether spectrum is successfully shared).

Project Leader: Angela McCrory, (720) 202-4183, amccrory@ntia.gov

Federal Advanced Communications Test Site (FACTS)
Upgrade the Table Mountain Field Site infrastructure to enable ITS projects to use precision test equipment to perform accurate and actionable over-the-air measurements of techniques, technologies, or systems to promote increased spectrum sharing. .

Project Leader: Eric D. Nelson, (720) 642-3348, enelson@ntia.gov

Table Mountain Engineering Program
Provide adequate and safe resources essential for open-air testing and research by various ITS projects both current and future.

Project Leader: Jason Parks, (720) 836-0535, japarks@ntia.gov

Radio Spectrum Measurement Sciences (RSMS)
Provide NTIA with critical measurement support to determine radio spectrum usage across the U.S., resolve interference problems involving government radio systems, and determine the emission characteristics of radio transmitter systems that may affect government operations. In order to execute these tasks, ensure that ITS continuously maintains state-of-the-art RF measurement systems, technologies, components, infrastructure, and analysis capabilities.

Project Leader: John E. Carroll, (720) 202-0205, jcarroll@ntia.gov

EMC Project
Conduct a literature review about non-terrestrial networks (NTNs) and learn the standards that apply to them. A non-terrestrial network is a network or segment of a network that uses airborne or spaceborne platforms to carry a transmission equipment relay node or base station.

Project Leader: Mustafa Yilmaz, (720) 665-4200, myilmaz@ntia.gov

Technology Transfer
Develop, maintain, and administer processes to protect scientific integrity and ensure that knowledge, facilities, or capabilities developed under federal R&D funding are made freely and openly available to generate Nation-wide return on the government's investment by indexing publications (to include reports/articles, software, and datasets) and making them accessible via its.ntia.gov.

Project leader: Lilli Segre, (303) 497-3572, lsegre@ntia.gov

CRADAs for the Use Of the Table Mountain Radio Quiet Zone

Areté

Areté is a small business that provides multi-domain, multi-discipline expertise and applications supporting the U.S. Navy, the U.S. Army, the U.S. Air Force, the U.S. Marine Corps, the U.S. DoD Missile Defense Agency, the intelligence community, the U.S. Department of Energy, and commercial energy exploration companies. ITS has had a long-standing CRADA relationship with the local Areté R&D group to support development and prototype testing of airborne and portable advanced remote sensing technologies that incorporate lidar, and to evaluate the relative viability of multiple active and passive sensing methodologies. Such testing provides information about how sensing methodologies perform in natural atmospheric conditions, allowing this defense company to progress its technologies from laboratory testing to field testing and identify directions for further development work.

Ball Aerospace

Ball Aerospace Tactical Solutions division has offices in Boulder and manufacturing facilities in nearby Broomfield and has sought the use of the Radio Quiet Zone for testing and characterization of various systems. In 2023, Ball sought a CRADA with ITS to use the Table Mountain site to verify line of sight and noise measurements across an 11 km line-of-sight distance from the north side of the Table Mountain facility to nearby Rabbit Mountain. Ball Aerospace successfully troubleshot and isolated noise sources within several prototype lidar sensing systems under development to establish a baseline for anticipated system performance and modeling. Systems tested included 3D coherent lidar, precision 3D tracking lidar and a counter UAS lidar being developed for the DoD, as well as a methane sensing lidar destined for the open market.

FIRST RF

FIRST RF Corporation is small business in Boulder, Colorado, that applies advanced technologies to the design, development, and production of antennas and RF systems. ITS has had a long-standing CRADA relationship with FIRST RF to support measurement and characterization of installed antenna patterns on various platforms such as models, test fixtures, and ground planes, and to test the integrated performance of antenna systems destined to support telecommunications and electronic warfare. Work in FY 2023 included testing of antenna systems for small to medium UAVs, such as the Shadow; ground-based vehicles, such as Humvees and MRAPs; and antennas that operate at low frequencies.

Lockheed Martin Coherent Technologies

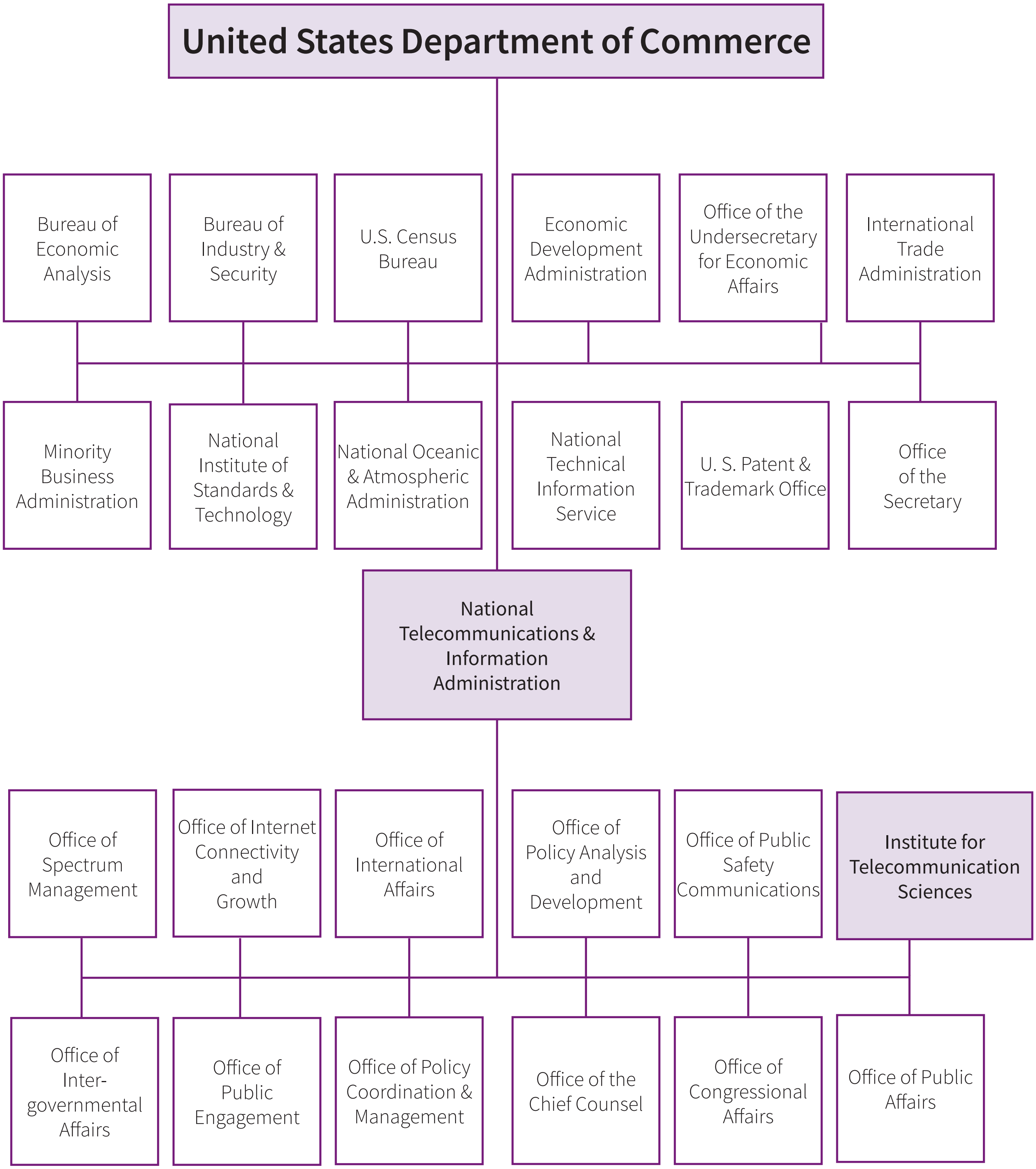
Coherent Technologies originated as a local small business in Louisville, Colorado, and continues to maintain research and development facilities in Colorado after being acquired by Lockheed Martin about 20 years ago. ITS has had a long-standing CRADA relationship with Lockheed Martin Coherent Technologies (LMCT) for testing of prototype systems under development and conducting scaled demonstrations for missions relevant to U.S. government agencies. In FY 2023, LMCT performed field tests for internally funded amplified illumination and active holographic sensing, a government-funded digital holography-based breadboard system, and for the Orion Docking Lidar system in support of NASA's Artemis III mission to the moon.

Nutronics

Nutronics originated as a local small business in Longmont, Colorado, and continues to develop coherently combined lasers and beam control systems (BCS) for high-energy laser (HEL) systems for the defense market in its Colorado facilities after being acquired by nLIGHT, Inc. in 2019. ITS has had a long-standing CRADA relationship with Nutronics to support field testing of prototype systems. The FY 2023 CRADA was for field testing of detection and ranging systems under development for use at sea. Table Mountain provides an ideal test location, as the uniformly distributed turbulence encountered along a horizontal path above the flat terrain at Table Mountain simulates the uniformly distributed turbulence encountered along a horizontal path over the ocean surface.

Abbreviations and Acronyms

AFB	Air Force Base
AMBIT	America's Mid-Band Initiative Team
BAA	Broad Agency Announcement
CBRS	Citizens Broadband Radio Service
CBSD	Citizens Broadband Service Devices
CRADA	Cooperative Research and Development Agreement
CRAIN	Communications Research and Innovation Network
DISA	Defense Information Systems Agency
DOC	U.S. Department of Commerce
DoD	U.S. Department of Defense
DPA	Dynamic Protection Area
E2E	end to end
eHata	extended Hata
EIRP	effective isotropic radiated power
EMC	electromagnetic compatibility
ESC	Environmental Sensing Capability
FAA	Federal Aviation Administration
FCC	Federal Communications Commission
FY	fiscal year
GAA	General Authorized Access
GIS	geographic information system
HAPS	high altitude platform systems
IA	interference analysis
IAA	interagency agreement
ICAO	International Civil Aviation Organization
IF	intermediate frequency
IPC	interference protection criteria
I/Q	in-phase and quadrature
ITM	Irregular Terrain Model
ITS	Institute for Telecommunication Sciences
ITU	International Telecommunication Union
ITU-R	ITU Radiocommunication Sector
ITU-T	ITU Telecommunication Standardization Sector
LF/MF	low frequency/medium frequency
ML	machine learning
mmWave	millimeter wave
NASA	National Aeronautics and Space Administration
NASCTN	National Advanced Spectrum and Communications Test Network
NFV	network function virtualization
NIST	National Institute of Standards and Technology
NOAA	National Oceanic and Atmospheric Administration
NR	no-reference
NRDZ	National Radio Dynamic Zone
NSF	National Science Foundation
NTIA	National Telecommunications and Information Administration
NTN	non-terrestrial network
NWR	NOAA Weather Radio
NWS	National Weather Service
OSM	Office of Spectrum Management
PEO	Program Executive Office
PMW	Propagation Modeling Website
QoE	quality of experience
QoS	quality of service
RAN	radio access network
RF	radio frequency
SAS	Spectrum Access System
SDN	software defined networking
SDR	software defined radio
SDO	standards development organization
SEA	Sharing Ecosystem Assessment
SG	study group
SII	Spectrum Innovation Initiative
U–NII	Unlicensed National Information Infrastructure
USDOT	U.S. Department of Transportation
V2X	Vehicle-to-Everything
WG	working group
WInnForum	Wireless Innovation Forum


United States Department of Commerce
Bureau of Economic Analysis
Bureau of Industry & Security
U.S. Census Bureau
Economic Development Administration
Office of the Undersecretary for Economic Affairs
International Trade Administration
Minority Business Administration
National Institute of Standards & Technology
National Oceanic & Atmospheric Administration
National Technical Information Service
U. S. Patent & Trademark Office
Office of the Secretary
National Telecommunications & Information Administration
Office of Spectrum Management
Office of Internet Connectivity and Growth
Office of International Affairs
Office of Policy Analysis and Development
Office of Public Safety Communications
Institute for Telecommunication Sciences
Office of Inter-governmental Affairs
Office of Public Engagement
Office of Policy Coordination & Management
Office of the Chief Counsel
Office of Congressional Affairs
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