Institute for Telecommunication Sciences

Fiscal Year 2017 Technical Progress Report

ITS Organization Chart

Office of the Director

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Amy Weich, *Administrative Specialist*

Executive Offices

Brian D. Lane, *Executive Officer*
Joanne Krumel, *Administrative Specialist*
Tracy Hough, *Budget Analyst*
Amanda C. Carroll, *Budget Analyst*
Lilli Segre, *Publications Officer*

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Sarah L. Vasel, *IT Manager*
Jacob Neal, *Information System Security Officer*

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Lisè Matthews, *Administrative Specialist*

Telecommunications Engineering, Analysis, and Modeling Division

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Kathy Mayeda, *Administrative Specialist*

Telecommunications and Information Technology Planning Division

Andrew P. Thiessen, *Chief*
Kathy Mayeda, *Administrative Specialist*

Telecommunications Theory Division

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Institute for Telecommunication Sciences

Technical Progress Report

Fiscal Year 2017

David J. Redl
Assistant Secretary for Communications and Information
National Telecommunications and Information Administration
United States Department of Commerce

May 2018

ITS

Boulder, Colorado

THE INSTITUTE FOR TELECOMMUNICATION SCIENCES IS AN OFFICE 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.

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

The Institute for Telecommunication Sciences performs cutting-edge telecommunications research and engineering with both Federal and private partners.

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Report and cover art prepared by E. A. Daldoss

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Overview: The Institute for Telecommunication Sciences

ITS MISSION

The Institute for Telecommunication Sciences (ITS) is the research and engineering laboratory of the National Telecommunications and Information Administration (NTIA), an agency of the U.S. Department of Commerce (DOC). ITS performs the research and engineering necessary to inform spectrum policy and enable the growth and prosperity of the telecommunications sector of the U.S. economy. ITS is the technical office of NTIA, and supports the Assistant Secretary and other offices with technical data, while remaining an independent testing and development organization.

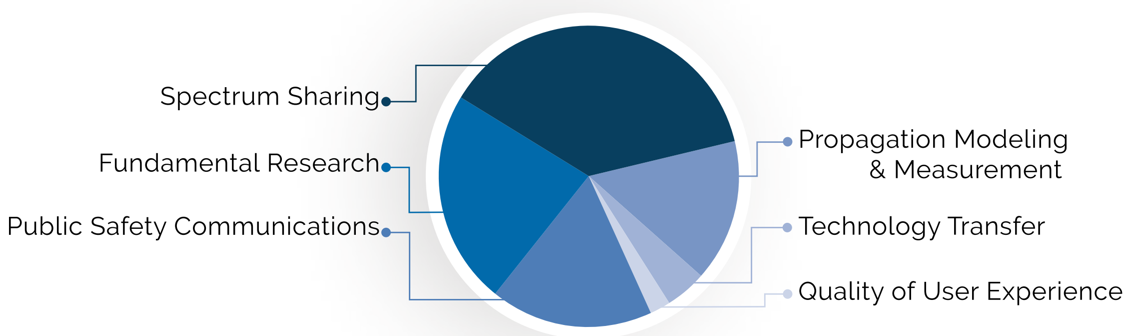
ITS research enhances scientific knowledge and understanding in cutting-edge areas of telecommunications technology. The Institute's research capacity and expertise is used to analyze new and emerging technologies, and to contribute to standards creation. Research results are broadly disseminated through peer-reviewed publications, as well as through technical contributions and recommendations to standards bodies. ITS staff represent U.S. interests in many national and international telecommunication conferences and standards organizations. Through leadership roles in various working groups, ITS helps to drive innovation and contributes to the development of communications and broadband policies that enable a robust telecommunication infrastructure, ensure system integrity, support e-commerce, and protect an open global Internet.

ITS also serves as a principal Federal resource for solving the telecommunications concerns of other Federal agencies, state and local Governments, private corporations and associations, and international organizations. Through cooperative research and development agreements authorized by the Federal Technology Transfer Act of 1986, ITS also performs collaborative research with industry and academia. This Act provides the legal basis for and encourages shared use of Government facilities and resources with the private sector. These partnerships aid in the commercialization of new advanced telecommunications technologies and services. ■

FISCAL YEAR 2017 AT A GLANCE

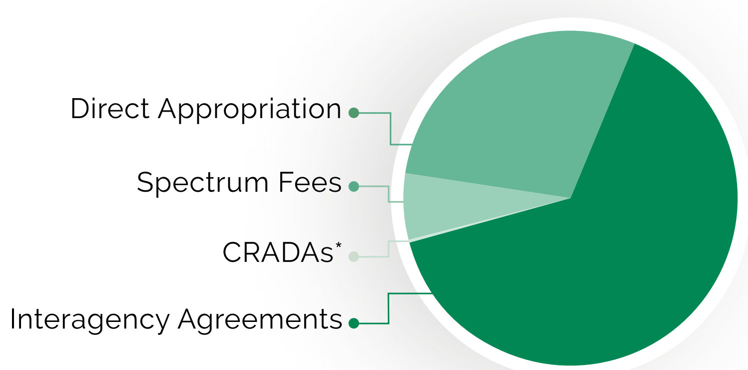
The Institute for Telecommunication Sciences (ITS) is the research laboratory of the National Telecommunication and Information Administration, an agency of the United States Department of Commerce. ***The Institute provides research and engineering that is critical to continued U.S. leadership in communication and connectivity.*** The Institute serves as a U.S. science and technology asset, a Federal resource providing solutions and support to public sector telecommunications concerns, and an objective intermediary between government and industry.

Research Areas



Data represent percentages of total research expenditure allocated to projects in each area

Funding Sources

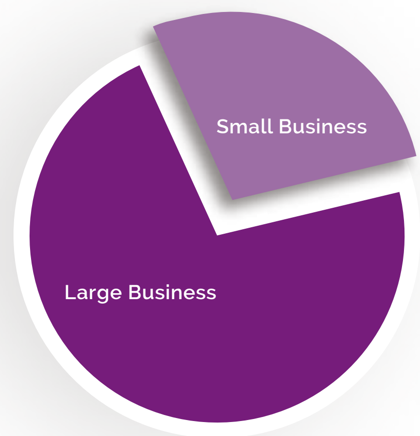


Data represent percentages of total funding allocation from each funding source

* CRADA: Collaborative Research and Development Agreement (with industry or academia)

Collaboration with Small Business

IN FY 2017, 28.3% OF THE INSTITUTE'S COLLABORATIVE RESEARCH AND DEVELOPMENT AGREEMENTS SUPPORTED SMALL BUSINESS



Technology Transfer

93
Research and Engineering Projects

20
Federal Agencies Supported

30+
Positions Held in Standards Organizations

60
Active Industry Collaborations

10
Technical Publications Released

6.2k
Technical Publications Downloaded

2.7k
Data and Software Downloads

https://www.its.bldrdoc.gov

INTRODUCTION

Spectrum research in an era of network densification

The ability for individuals, groups, objects, and systems to communicate across distance shapes daily life. We use ***radio-spectrum telecommunication*** when we conduct daily mobile phone conversations, we rely on its use in critical military operations like radar detection, we trust in its power to alert us of potentially hazardous weather events.

IN THE NEXT 20–30 YEARS, IT IS REASONABLE TO EXPECT THAT ALMOST EVERY OBJECT THAT USES ELECTRICITY, FROM HEAVY AGRICULTURAL EQUIPMENT TO HOME LIGHTING FIXTURES, WILL BE A NETWORKED DEVICE. IT WILL NO LONGER BE A LITERARY EXAGGERATION TO SAY THAT WE LIVE IN A CONNECTED WORLD.

Spectrum is the raw material for wireless communication, and it represents the resource upon which we must draw to realize the connected future.

All wireless telecommunication uses the electromagnetic spectrum to transmit messages. Unlike other natural resources, spectrum is both finite and renewable. Spectrum is finite in the sense that, within a particular geographic area, given frequencies being used to transmit messages by one device are not available for use by any other device. However, the electromagnetic energy that we call radio spectrum can never be exhausted. Spectrum is thus renewable in the sense that, when a frequency is no longer actively in use, it is available for signal transmission once again.

When the Internet was in its ascendency in the 1990s, the term *information superhighway* served as a useful metaphor to understand what is at stake in the expansion of telecommunications. We still use the term *traffic* to describe the volume of data transmission, for example, on wireless mobile networks. We are in the midst of an explosion in the volume of information traffic. As a phenomenon of nature, the electromagnetic spectrum—the “highway”—requires no maintenance and cannot be expanded. It is left to us to devise new telecommunication technologies and spectrum management strategies that will somehow accommodate the incredible growth in demand for connectivity.

Today, the biggest challenge in telecommunication is making spectrum available to meet the demand. New and legacy radio services of all kinds vie for interference-free access to the finite electromagnetic spectrum. Allocation of sufficient spectrum to meet the needs of both government and industry, at one time a foregone conclusion, has now become a pressing economic, regulatory, technical, and physical challenge. Figure 1 represents the current frequency allocations in the radio frequencies of the electromagnetic spectrum. A simple glance at this chart gives a visual indication of what is meant by spectrum crowding.

Meeting the connectivity demands of the future means finding ways to accommodate new systems in the already crowded spectrum. Future smart devices may not be subject to centralized control (as is the case, for example, with mobile phone networks). The number of devices in use will increase by orders of magnitude, and we have no experience to tell us what impact will be created by billions of non-networked smart devices all trying to use the radio spectrum simultaneously. Enabling efficient and effective spectrum use has been a key concern at the Institute for Telecommunications Sciences (ITS) and its predecessor labs for over a century.

Figure 1 Chart of United States radio spectrum frequency allocations, visually demonstrating the concept of spectrum crowding. The horizontal bands below the allocations show whether frequency bands are reserved for Federal use (red), non-Federal use (green), or shared between Federal and non-Federal users.

FEDERAL AGENCIES SUPPORTED IN FY 2017

In FY 2017, the Institute for Telecommunication Sciences entered into or continued Interagency Agreements with the following agencies (for full ***FY 2017 Project List***, see page 112):

Department of Commerce

National Institute of Science and Technology

- Communications Technology Laboratory

National Oceanic and Atmospheric Administration

- National Environmental Satellite, Data, and Information Service
- National Weather Service

National Telecommunications and Information Administration

- Office of Spectrum Management

First Responder Network Authority of the United States

Department of Defense

U.S. Air Force

U.S. Army

U.S. Navy

Joint Warfare Analysis Center

Defense Information Systems Agency

- Defense Spectrum Organization

Defense Advanced Research Projects Agency

Department of Energy

Sandia National Laboratories

Department of the Interior

Department of Homeland Security

Office for Interoperability and Compatibility

Office of Emergency Communications

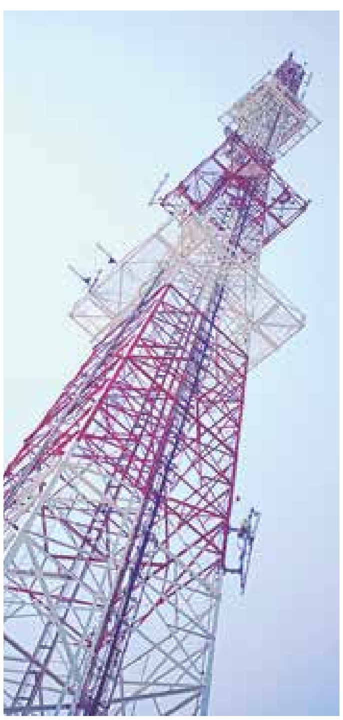
U.S. Coast Guard

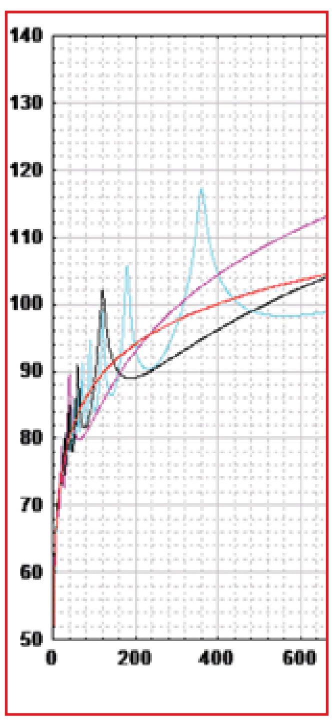
Department of the Interior

Department of Transportation

Federal Highway Administration

Federal Communications Commission





THE INSTITUTE'S RESEARCH CYCLE

As a Federal research and engineering laboratory, the Institute has two separate operational commitments:

1. **Internal research and development: Conducting research on the electromagnetic spectrum, especially the radio spectrum, to maintain the laboratory as a United States science and engineering asset.**
2. **External research and engineering support: To serve as a Federal resource for informing data-driven regulation and for solving problems and supporting advancement in the realm of telecommunications, in government, the private sector, and the international community.**

These two facets of our dual role are equally important, because they form a beneficial feedback loop that enables us to leverage our fundamental research portfolio (represented by item 1, above, and funded by Congressional appropriation) to respond quickly and effectively to the needs of our stakeholders (represented by item 2, above, and funded by reimbursable research agreements). In turn, our work with external stakeholders generates insights and empirical data that we can incorporate into our fundamental research and development (R&D) efforts, further increasing our value as a national science and engineering asset. Figure 2 illustrates this cycle.

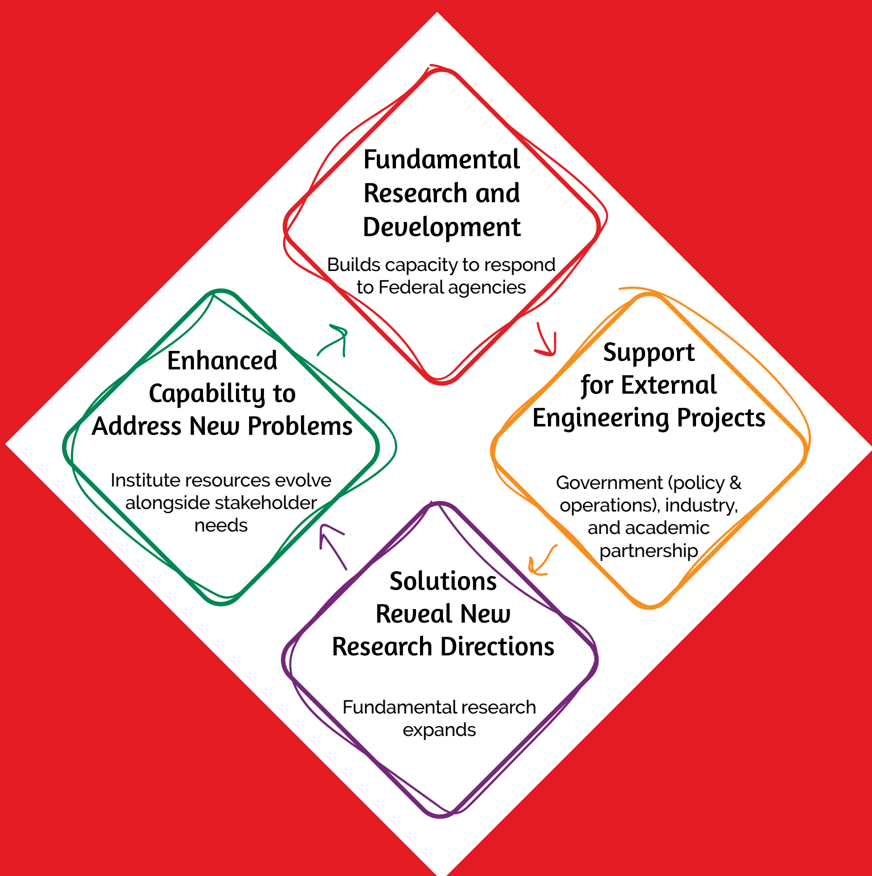


Figure 2 The Institute's Research Cycle

A CENTURY OF TELECOM RESEARCH

The Radio Act of 1912 established the first spectrum allocation regulations. It included interference protection provisions, such as exclusion zones around government installations, and it assigned the task of managing spectrum usage to the Department of Commerce. ***The Institute traces its lineage to 1915***, when the Radio Section of the National Bureau of Standards was first funded by Congress, with a primary goal of ensuring reliable military communications during the two World Wars. Later, it became the Central Radio Propagation Laboratory. Over the next decades, several reorganizations took place, through which the Institute's work persisted. Finally, ***in 1978, the Institute took its present shape*** as the research and engineering laboratory of NTIA.

HISTORY OF LEADERSHIP IN COMMUNICATION TECHNOLOGY

Through its history, the Institute has been a leader in efficient use of spectrum resources. Indeed, the first chapter of the FY 1978 Technical Progress Report is entitled "Efficient use of the Spectrum" and begins with the following text:

> *Since [World War II], American industry, government, and private citizens have put the spectrum to work in such profusion that now saturation appears imminent and, in some cases, has already occurred.* ***To provide for new and expanded use, two major alternatives exist. One is to exploit new regions of the spectrum at progressively higher frequencies. The second is to provide for a better understanding of the basic physical principles upon which spectrum use depends*** *and, complementing this understanding, provide for more effective means of managing spectrum use.*[1]

The first approach listed in the 1978 report continues to be a primary research objective. In 1978, frequencies above 10 GHz were largely unused, owing in part to a limited understanding of their propagation characteristics. Today, frequencies in the 30–300 GHz millimeter band are important to military radar, satellite communication, wireless Internet, emerging 5G mobile communications, and other applications. The Institute's work contributed significantly to this expansion of spectrum use.

The second task, that of gaining "a better understanding of the basic physical principles upon which spectrum use depends," grows in scope with every advance in radio technology and computing power. More accurate, more granular, and more nuanced propagation prediction is essential to this task. Through endeavors to build more accurate propagation models beginning with first principles and basic measurements, strategies for incorporating ever-more-detailed environmental parameters into software modeling applications, and a robust program of testing the new tools that make use of enhanced propagation models, we at the Institute are expanding upon our long tradition of leadership to enable more robust, more efficient, more reliable, and higher quality communication technologies.

Figure 3 highlights some of the Institute's key contributions over its 100 year history.

1 Institute for Telecommunication Sciences of the National Telecommunications and Information Administration, *Annual Technical Progress Report 1978*. https://www.its.bldrdoc.gov/publications/2702.aspx [Emphasis added.]

1910s	DOC radio research begins	Developed "bible for radio engineers" and comprehensive guide for WWI military radio operators.
1920s	Commercial radio standards	Broadcasted standard frequency signals weekly so operators could tune transmitters to stay on assigned frequencies.
1930s	Ionospheric research	Published ionospheric maps to help radio users adjust power and frequency for farther transmission and reduced interference.
1940s	Intensive military research	Developed reliable radio navigation, military radar, and proximity fuzes for bombs to support the war effort.
1950s	Propagation modeling	Provided calculations to inform FCC licensing of commercial TV stations based on predicted coverage.
1960s	Computerized modeling	Implemented Irregular Terrain Model in FORTRAN, allowing faster, more complex propagation modeling. ITM is still in wide use.
1970s	Air-to-ground modeling	Developed, with the FAA, IF-77 propagation model (still in use) to predict space-to-Earth and Earth-to-space communications.
1980s	Packet switched networks	Contributed to network performance standards for optimal user experience of data communication systems and services (including the ARPANET).
1990s	Analog to digital	Contributed to standards for software-controlled radios and interference avoidance technology.
2000s	Spectrum sharing	Conducted electromagnetic compatibility studies and interference protection criteria estimations, paving the way for spectrum sharing.

Figure 3 Highlights of the Institute's 100 year history.

The "grasshopper" automated weather station built by the National Bureau of Standards during World War II.

Photo courtesy National Archives and Record Administration, Broomfield, CO.

THE CHALLENGE OF SPECTRUM RESOURCE USE AND THE SHAPE OF SOLUTIONS TO COME

The Institute's priority is to work for progress at all levels of inquiry—from the open theoretical questions of electromagnetism to just-in-time solutions to exigent technological requirements. By engaging in research, engineering, and spectrum management, we develop an expertise that surrounds the multiple sciences of telecommunication. With the quickening pace and deepening complexity of signal transmission, such a holistic viewpoint is becoming essential to adequately rise to the challenges that face us today.

Among these challenges are network densification and the expansion of ***spectrum sharing***, which defines our current decade. Meanwhile, new and evolving telecommunication introduces questions at a level of complexity that requires world-class expertise to address (see inset box, page 12).

Today, as in FY 1978, two major directions shape solutions to come. The first and most essential direction is that of fundamental science. We must continue to deepen our understanding of radio wave propagation in complex environments, and we must enhance our ability to predict what will occur when multiple systems operate together in complex radio frequency environments. Protecting crucial Federal systems from interference and preserving wireless communication for the general public depend absolutely on this research.

The second direction, and one whose importance has become evident more recently, is that of collaboration. Answering the questions raised by new telecommunication trends will require close coordination among government, industry, and academia, as well as the international community. In this arena, the Institute is uniquely positioned to facilitate progress, poised as we are at the intersection of the developments in 21st century communication.

WHAT IS SPECTRUM SHARING?

As spectrum becomes more crowded, wireless services must increasingly share frequencies. Many services already share spectrum; to prevent interference, they are separated in time, space, or frequency. Bands where new sharing techniques are being developed or deployed include:

- ***AWS-3 bands***: 1695–1710 MHz, 1755–1780 MHz, and 2155–2180 MHz
- ***3.5 GHz band***: 3550–3700 MHz
- ***5 GHz band***: 5250–5350 MHz, 5470–5725 MHz

New technologies (e.g., dynamic frequency selection) in these bands can help optimize spectrum resource use by minimizing separations between systems.

FISCAL YEAR 2017 AWARDS

In FY 2017, ITS researchers received three prestigious NTIA Bronze Medals for their outstanding scientific and engineering achievements. This award is a Department of Commerce Honor Award granted by the head of an operating unit or Secretarial Officer for superior performance.

- (Pictured) For engineering analysis allowing NOAA to refine specifications for a system to protect weather satellite earth stations and associated data products from interference while maximizing commercial access to spectrum:

  John Carroll, Ken Tilley, Eric Nelson, Geoffrey Sanders, Robert Stafford, Chris Redding, Ken Calahan, Irena Stange, Robert Achatz, Joel Dumke

NTIA Bronze Medal award recipients pictured with ITS Director Keith Gremban.

- For improving potential return on the government's $7 billion in FirstNet by ensuring that features essential to public safety users are included in international standards for commercial-off-the-shelf LTE devices:

  Bruce Ward, Randall Bloomfield, Andrew Thiessen, Al Vincent (NTIA/OPCM), Ihab Guirguis (FirstNet), Dean Prochaska (FirstNet)

- For improving critical security capabilities at NTIA and meeting a significant goal for Information System Continuous Monitoring and Mitigation, as Federally mandated:

  Arthur Robinson (NTIA/ITD), Jacob Neal, Michael Miller (NTIA/ITD), Patrick Poell (NTIA/ITD), Ted Mullen

PRESSING QUESTIONS IN TELECOMMUNICATIONS RESEARCH

- **New and emerging military technologies such as unmanned aircraft, new radar systems, and LIDAR imaging applications all require more and different spectrum resources. Can defense organizations maintain interference-free access to the spectrum they need in an increasingly crowded and shared spectrum environment?**
- **The economic, political, and social value of video and audio continue to skyrocket, with special potential in law enforcement. Can multimedia communications technologies deliver adequate end-user quality of experience while balancing the trade-off between bandwidth demand and spectrum crowding?**
- **Public safety organizations are in the midst of migrating to shared LTE infrastructure. Can LTE networks deliver the quality, robustness, and reliability essential to mission critical communications?**

EMERGING ROLES FOR THE INSTITUTE

As a Federal research laboratory, the Institute provides a neutral scientific environment for conducting research and conversation, enabling us to act as a trusted intermediary across Federal agencies, and between government and industry—a role that we expect will become increasingly important in years to come. A major goal will be to enhance our ability to respond to the needs of Federal and other stakeholders by focusing our fundamental research portfolio on key research directions in the field. Such efficient focus is itself enabled by our collaborative work, wherein our research partners help alert us to their most pressing telecommunications needs.

The Institute maintains a portfolio of fundamental research and technology development, which we leverage to support problem solving in government, industry, and academia

The Institute's time-honored role in contributing to international standards, specifications, and recommendations continues as we work with organizations like the International Telecommunication Union, the 3rd Generation Partnership Project, and the Video Quality Experts Group. Through this work, we contribute to providing a technological framework for evolving information infrastructures and enhancing international trade opportunities for U.S. telecommunications firms.

Finally, as network connectivity accelerates, small businesses look to contribute to the U.S. telecommunications economy by developing novel wired and wireless technologies. To do so, they need advanced research and development facilities. By entering into collaborative research and development agreements with businesses, the Institute can permit growth that might otherwise be out of reach of small business.

THE TECHNICAL PROGRESS REPORT

Each year, the Institute publishes the Technical Progress Report, summarizing the technical contributions made by ITS researchers during the prior Fiscal Year. This report covers our appropriations-funded fundamental research (Section 1), our reimbursable engineering research for Federal agencies and other stakeholders (Sections 2-4), and our technology transfer efforts, including international cooperation (Section 5). In addition, Section 6 provides an overview of our key tools and facilities, which are available for use by government, industry, and academia through cooperative research agreements. A glossary of abbreviations and acronyms can be found at the end of this report. ■

FOCUS ON 3.5 GHZ

Emerging 5G wireless technologies promise dramatic increases in wireless broadband speeds. In the scramble for bandwidth to accommodate the demands of these technologies, attention has been focused on the millimeter wave (mmWave) bands, which are considered under-utilized. However, commercial mmWave technologies are still developing.

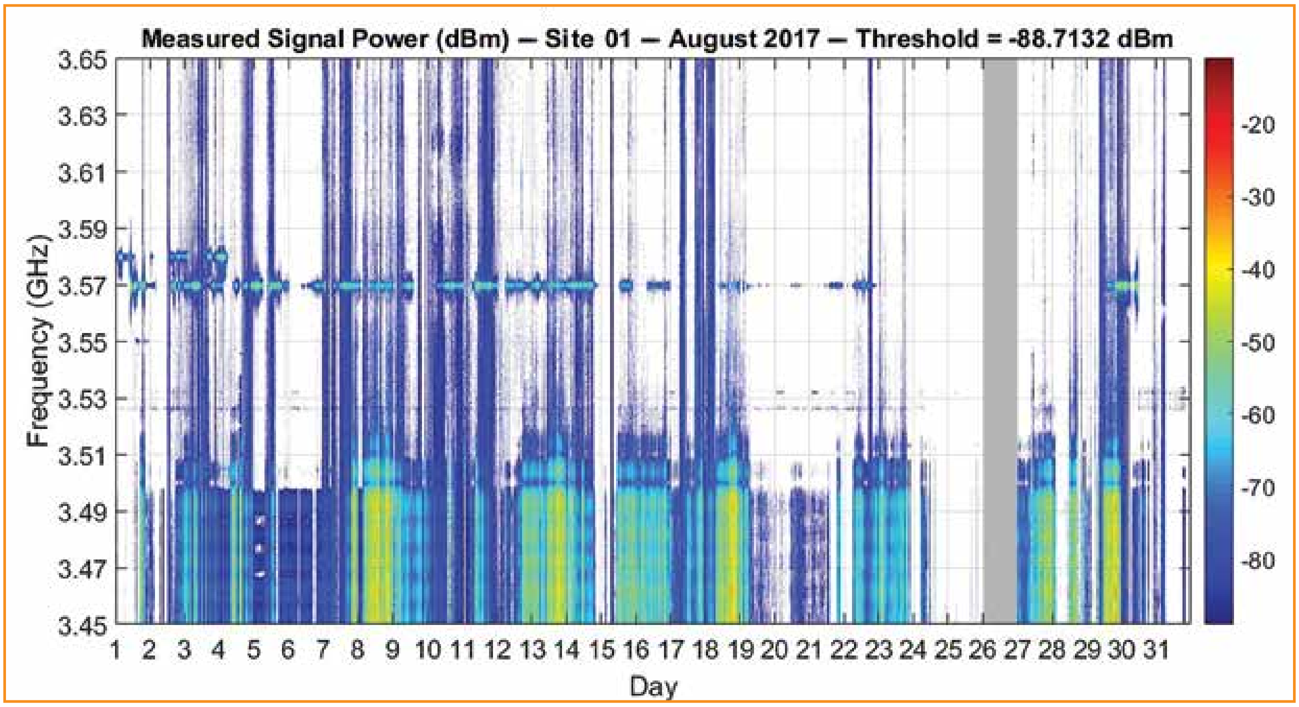
By contrast, technologies that use mid-band spectrum (1–6 GHz) for commercial services like fixed wireless are already on the market. Mid-bands like the ***3.5 GHz band (3550–3700 MHz)*** thus present an attractive alternative for immediate 5G exploitation. However, a variety of Federal radar and satellite systems already use the 3.5 GHz band. Since such systems cannot feasibly be relocated, there is a need to devise new ways for commercial services to share spectrum with incumbent Federal services.

The FCC order that opened the way for commercial use of the 3.5 GHz band proposed a novel framework for spectrum sharing that relies on innovative technologies to dynamically allocate and manage shared spectrum resources in real time.

The Institute's research in the 3.5 GHz band supports this revolutionary new approach to spectrum sharing. The following articles describe related FY 2017 research projects:

- ***Aggregate Emissions Modeling Project*** on page 22
- ***Radio Spectrum Measurement Sciences Program*** on page 26
- ***Spectrum Monitoring*** on page 34
- ***Terrain and Clutter Modeling*** on page 52
- ***Test and Certification Frameworks*** on page 60

Our 3.5 GHz work intensified in FY 2017 in anticipation of expected deployment in late 2018 or early 2019.



This visualization, created from spectrum monitoring data at a West Coast site, represents actual spectrum usage in the 3.5 GHz band in August, 2017. ITS delivers visualizations like this one to spectrum management offices on a monthly basis to provide RF awareness. See page 34.

Section 1: Fundamental Research Portfolio

The Institute for Telecommunication Sciences pursues a diverse program of fundamental research funded by Congressional appropriations. Our goal is to maintain the Institute as a national science and technology asset, safeguarding United States leadership in telecommunications. In working independently to advance the knowledge and technology in the field, we simultaneously build a portfolio of capabilities for responding to the needs of other agencies and of industry.

IN THIS SECTION:

Historically the science of radio wave propagation has been the primary focus of the Institute's research. The other areas of emphasis in our research portfolio are more dynamic, shifting over time to respond to the most pressing needs in government and industry.

In FY 2017, our fundamental research fell under three broad categories:

1. The Institute is recognized for our expertise in the prediction and measurement of radio frequency wave propagation, as well as interference analysis. This expertise serves our research into the ***electromagnetic compatibility*** of telecommunication systems operating in the same or adjacent frequencies or geographies. Within these areas, we are currently pursuing several avenues of research, including multiple efforts to improve our ability to understand and model, in minute detail, how radio waves propagate in complex environments. We are also engaged in monitoring the radio spectrum and developing new tools to understand and visualize spectrum use in real time.
2. We have dedicated resources to the investigation of video and audio quality. Our focus is on ***quality of experience***, or understanding the technical conditions that contribute to user-perceived quality in video and audio streams. Not only is such work important economically, it also has an important public safety function, because national preparedness and first response rely on adequate transmissions of sound and images.
3. The Institute is also pursuing a strategic goal of excellence in ***software development***. Software is essential to enabling timely analyses that incorporate the multiple, complex parameters of today's telecommunication environment. Open publication of ITS software also allows other researchers to take advantage of the outcomes of our diverse portfolio.

The following sections detail the Institute's FY 2017 developments and achievements in each of these three areas. ■

ELECTROMAGNETIC COMPATIBILITY ANALYSIS

Researching the harmonious coexistence of telecommunication systems in the radio spectrum

All wireless telecommunication uses the electromagnetic spectrum to transmit information. Because the spectrum is a finite (but renewable) resource, disparate communications systems must increasingly share spectrum frequencies. The need for spectrum sharing introduces complex research challenges, because the reliability of communications systems could be compromised if the implications of spectrum sharing scenarios are not thoroughly understood. In order to share spectrum, electromagnetic signals must be compatible.

*THE INSTITUTE IS RECOGNIZED AS A LEADER IN **ELECTROMAGNETIC COMPATIBILITY (EMC)** ANALYSIS. THIS EXPERTISE HAS ENABLED US TO PLAY A SIGNIFICANT ROLE IN EVALUATING SPECTRUM-SHARING SCENARIOS AND IDENTIFYING NEW POSSIBILITIES FOR EFFICIENT SHARED USE OF SPECTRUM.*

__Radio propagation__ is the behavior of transmitted radio waves as they travel (or propagate) from one point to another.

As it pertains to spectrum sharing, EMC analysis involves three broad areas of research:

1. **Propagation modeling and measurement:** *understanding how electromagnetic signals are propagated in various scenarios (e.g., inside buildings, across mountainous terrain) and developing the ability to accurately predict information transmission. Analysis of field measurements is used to create propagation models that can be applied to similar propagation scenarios.*
2. **Spectrum monitoring**: *identifying and characterizing current spectrum usage, understanding spectrum availability. Spectrum monitoring informs policymakers about how spectrum is actually used, so sharing scenarios can be identified. Its goal is to collect radiated emissions from all transmitters that are active in a given area during a given observation period.*
3. **Interference protection criteria (IPC) estimation**: *determining the level of interference allowable before signal degradation becomes unacceptable, and identifying solutions to potentially problematic interference.*

To make spectrum sharing possible, policymakers, product engineers, and users in the public and private sectors must have reliable information about the required distance and frequency separations between transmitters and receivers of unrelated telecommunications systems. These separations are determined by combining the findings of these fundamental research areas.

By pursuing these research areas on an going basis, the Institute develops the expertise required to respond efficiently to the modeling, measurement, and analysis needs of government and industry. For example, ITS expertise and technological capability enable us to obtain the parameters necessary to develop ***link power budgets*** (equations describing the factors that influence the power of a received signal, such as antenna radiation details and environmental man-made and natural noise).

We are thus uniquely poised to advance spectrum sharing by maintaining a portfolio of trusted measurements and developing innovative techniques to address today's most complex telecommunications questions.

The remainder of this section describes our research programs and FY 2017 developments in these three core realms of EMC analysis. ■

Figure 4 The Institute's core areas of electromagnetic compatibility (EMC) analysis. Like the three legs of a stool, each area is essential. EMC analysis helps ensure the reliability of telecommunications systems that share spectrum.

PROPAGATION MODELING AND VALIDATION

Overview The purpose of the ***Propagation Modeling and Validation*** project is twofold:

1. To assess the accuracy of existing models for predicting how radio waves are propagated from one place to another under various conditions
2. To develop new and more precise models for making more precise predictions.

Improving the precision of propagation models has enormous economic potential. Product engineers are tasked with designing transmitting and receiving devices that are safe, effective, and compliant. With less-than-perfect predictions about how those devices will operate, industry has no choice but to manufacture over-engineered products to compensate for uncertainty about the electromagnetic environment.

A more accurate understanding of radio propagation will empower policymakers and product engineers to ensure that communications systems function together in harmony. Precision predictions could therefore lead to the elimination of unnecessary expenditure in both government and the private sector.

Given the importance of precise predictions to government and industry, the Institute's goal is to provide the U.S. telecommunications community with a comprehensive package of validated propagation models. The Propagation Modeling and Validation project addresses this goal using a conceptually unique process.

Theoretical Approach The theoretical approach of the Propagation Modeling and Validation project is to start from first principles, building upon our solutions to simple scenarios as we progress to more complex modeling problems. By taking this approach, we develop a high degree of certainty regarding the basic foundations of our models, in an ongoing effort that will enable us to improve the accuracy of our predictions in real-world environments.

The Propagation Modeling and Validation project consists of three integrated and iterative tasks, each of which is essential to improve our ability to predict how communications systems will operate:

1. Modeling: We begin by modeling short-range propagation scenarios in simple environments, progressing to longer ranges and more complex propagation environments.
2. Measurements: We take field measurements to observe the propagation behavior of electromagnetic waves, generating data that we can compare with our predictions.
3. Computation: We assess the accuracy of both our models and measurements through detailed, large-scale numerical computation. In this step, we quantify the differences between the predictions of existing models and the measurements we obtain in the field.

The Propagation Modeling and Validation project is an ongoing, multi-year project with the ultimate aim of completely renewing our ability to predict electromagnetic wave propagation.

Radiated test setup for channel sounding comparison, located on an open-area test site (OATS) at the U.S. Department of Commerce Boulder Laboratories.

FY 2017 Developments There were two major research outputs of the Propagation Modeling and Validation project during FY 2017: a comparison of existing channel sounding systems and a comparison of existing propagation simulation software. These comparisons (described below) yielded data that will help ITS researchers develop more accurate measurement systems and better propagation models.

Channel sounding comparison. Channel sounding is the process of sending test signals between a transmitting device and a receiving device and then comparing the original signal with the received signal. By analyzing the differences between the two signals, it is possible to understand what happens to the signal as it travels.

Vector network analyzer (VNA) systems are the "gold standard" for channel sounding over short distances (< 200 m), but they are not useful at longer distances, limiting their utility. Therefore, in FY 2017, ITS and NIST researchers continued a comprehensive test of three longer-range channel sounder systems. These new systems will offer enhanced utility by providing higher accuracy and measurement fidelity. We tested the following on an open-area test site (OATS) at Boulder Laboratories:

- An ITS-developed continuous wave (CW) mobile channel measurement system
- A NIST-developed pseudo-noise (PN) channel measurement system
- A NIST-developed oscilloscope channel sounder with a multi-sine pulse generator

The photo above shows the test site setup. The radio channel (the path for signal transmission) consists of a transmitting antenna and a receiving antenna located over a metal ground plane. The antennas are connected to each of the channel sounders through a switched matrix system. We found that the ITS system closely matched the VNA results, indicating that the ITS channel sounder yields excellent accuracy, and that our propagation measurement procedures are effective.

PROPAGATION MODELING AND VALIDATION (continued)

Simulator comparison. In FY 2017, ITS engineers also performed an extensive comparison of existing propagation simulation software packages, or codes, for predicting electromagnetic wave propagation. Using four different simulation tools, we simulated simple, short-range propagation scenarios (free-space and ground-plane environments, various scattering and diffraction scenarios). Then, we compared the accuracy of the results obtained using the following pairs of codes:

1. Full-wave codes (i.e., highly detailed simulations requiring a great deal of processing power)
   a. The method-of-moments code
   b. The finite-difference time-domain code
2. Ray-tracing codes (i.e., less detailed but more useful simulations capable of modeling propagation over broader areas)
   a. The Numerical Electromagnetic Code–Basic Scattering Code developed at Ohio State University
   b. A commercially available wireless ray-tracing code

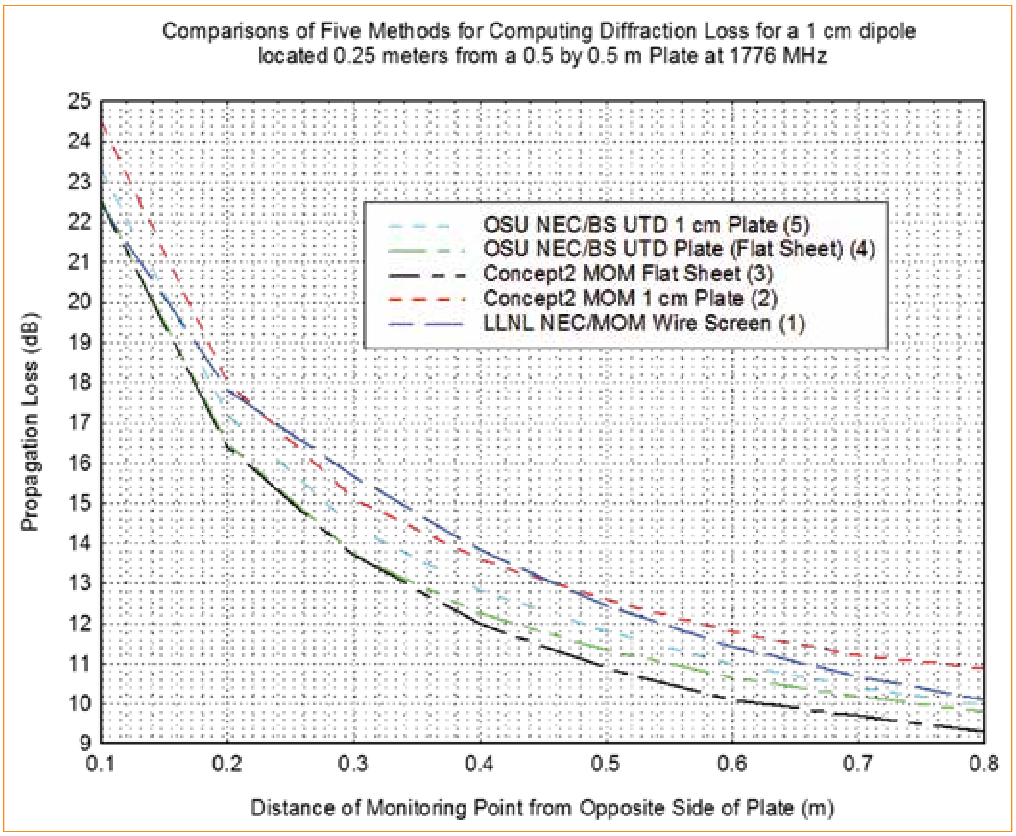


Figure 5 Sample Result: Comparisons of propagation losses predicted by the full-wave Concept-2 method-of-moments code and the ray-tracing Numerical Electromagnetic Code–Basic Scattering for points located at various distances from the opposite side of a square metal plate. Method-of-moments full-wave results are also shown for a wire screen approximation of the plate.

Figures 5 and 6 show examples of the type of comparison results we obtain (see captions for technical detail). We found that the full-wave codes yielded highly accurate predictions, with excellent agreement between them. The ray-tracing codes were, as expected, less accurate, but still provided useful models. Our results revealed some limitations with the commercial code, giving the Institute an opportunity to provide feedback to industry.

By benchmarking codes using simple structures like a metal plate, we develop an excellent understanding of the accuracy of our existing propagation models. This work is expected to inform studies of more complex modeling scenarios in FY 2018, eventually enabling us to develop improved models. Such expertise and capabilities position us to respond to the propagation modeling needs of government and industry with a comprehensive set of validated and precise models. ■

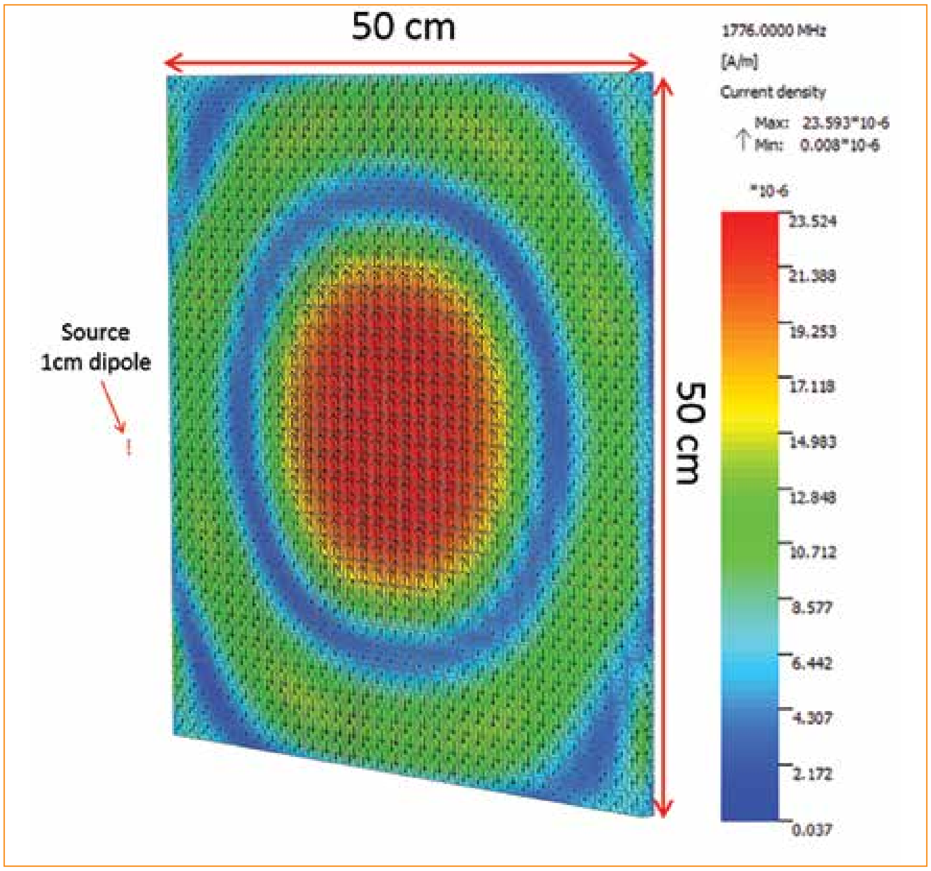


Figure 6 Sample Result: Concept-2 method-of-moments full-wave simulation diffraction model of a short electric current source at a frequency of 1776 MHz in close proximity to a square metal plate. The surface electric current densities are plotted on the surface of the plate.

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AGGREGATE EMISSIONS MODELING PROJECT

Background: Aggregate Radio Frequency Interference

Modeling interference from multiple sources

There are two basic types of radio frequency (RF) interference:

- Interference from a single source: A receiver may pick up part of a strong signal emitted by a single nearby transmitter. This type of interference occurs when, for example, an FM radio is tuned to a particular station, but the listener intermittently hears audio from a different station, making an enjoyable listening experience impossible.
- Aggregate interference from multiple sources (i.e., ***aggregate emissions***): A receiver may pick up parts of many weak signals that, individually, would not cause a problem, but that become problematic when they are all added together. An analogy is useful to understand this problem: it can be very difficult to hear someone sitting across the table in a restaurant if the restaurant is very crowded with many other people talking. No individual speaker is loud enough to disrupt your conversation on their own, but with enough people there can be a great deal of noise.

The purpose of the Institute's ***Aggregate Emissions Project*** is to understand the aggregate interference problem and develop new ways to address it. This problem is important because spectrum-sharing arrangements often involve many devices spread over a large area, as is the case in frequency bands shared with LTE mobile device networks.

ITS Core Competency: The Aggregate Emissions from LTE Model

To facilitate new spectrum-sharing arrangements, the Institute has developed the *Aggregate Emissions from LTE (AELTE)* model to describe and quantify the interference produced by LTE cellular networks. To account for unknowns, like the number of active transmitters and their locations, this model uses a mathematical approach called a Monte Carlo simulation, which enables researchers to assess thousands of likely scenarios without having the exact details available. Analyzing these scenarios allows us to estimate the likelihood that interference will exceed given thresholds. One practical application of the AELTE model is determining how best to deploy telecommunications systems to minimize the likelihood of harmful aggregate interference.

FY 2017 Developments

3.5 GHz spectrum sharing analysis. In FY 2017, important improvements and extensions were made to the AELTE model. The most important of these involved the recent FCC rulemakings that established a mechanism for automated frequency coordination to open the *3.5 GHz band* for shared use between government and commercial services under a three-tiered access prioritization framework (see ***Test and Certification Frameworks*** on page 60 for a more detailed description). This development has introduced new complexity to the aggregate emission problem, and the Institute has been leveraging its competencies and assets, including the AELTE model, to analyze the spectrum-sharing approach that the FCC is taking to the 3.5 GHz band. In this band, different types of transmitters in the LTE system (cellular towers, on the one hand, and mobile devices, on the other) broadcast information over the same frequencies, avoiding interference by taking turns transmitting signals rather than by using different frequencies. This approach is called Time Division Duplex (TDD).

WHAT DOES SPECTRUM SHARING MEAN FOR PROPAGATION MODELING?

1. Spectrum sharing enables us to **simplify** our modeling in the sense that low-power transmitters, such as individual handheld devices, are mathematically eclipsed by high-power transmitters like cell towers.
2. Spectrum sharing requires us to **add complexity** to our model in the sense that we must now account for the fact that the potential victim of interference may be a shipborne radar system (or another mobile system) whose location is unknown in advance and may even be considered secret.

3.5 GHz analysis is a substantially different problem that introduces a new set of engineering challenges for aggregate modeling. Therefore, we developed the AELTE-TDD model to address the 3.5 GHz spectrum-sharing approach. The new model again took a Monte Carlo approach, and it depended on the Irregular Terrain Model (ITM)—a widely used radio propagation model developed at Boulder Labs in the 1960s—to predict terrestrial propagation loss, but now we quantified the aggregate emissions as viewed from multiple, randomly generated locations that a victim transmitter might inhabit. Figure 7

AGGREGATE EMISSIONS MODELING PROJECT (continued)

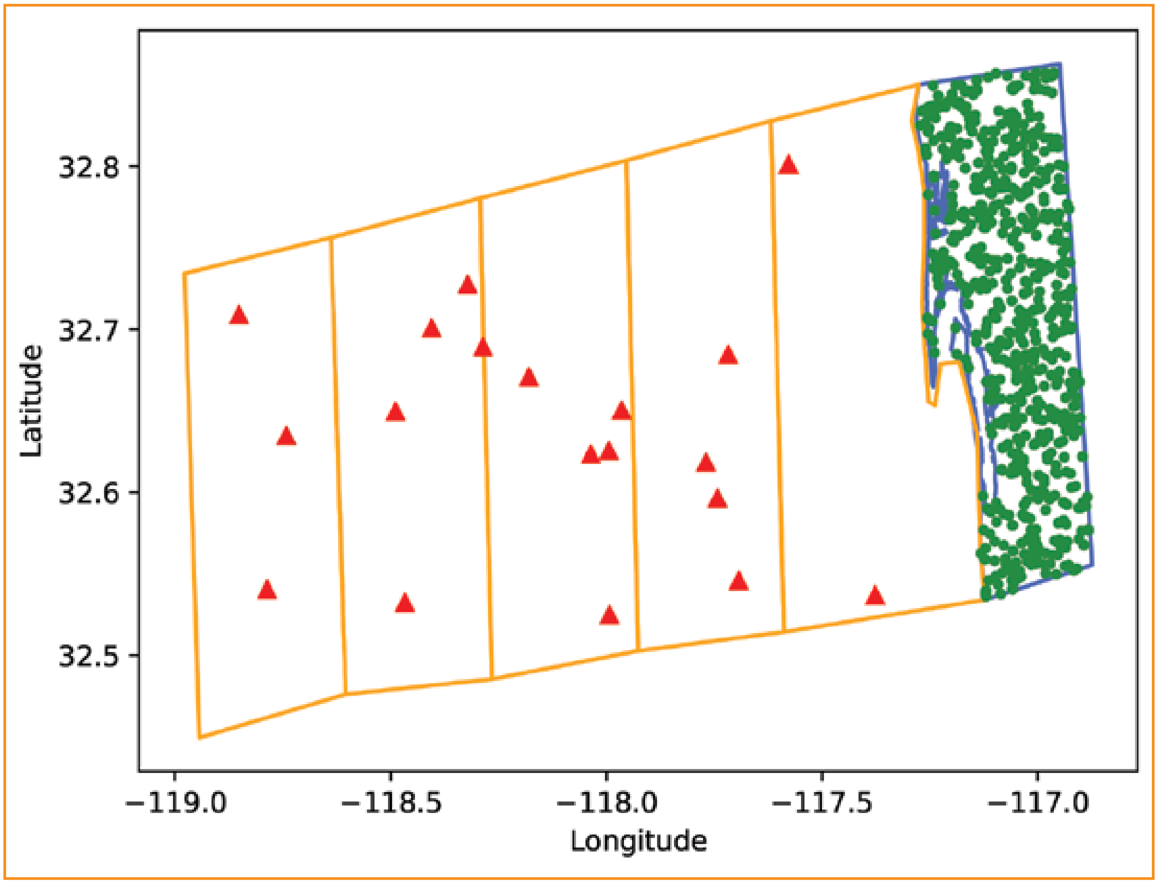

Figure 7
An example of a simulation using the Institute's Aggregate Emissions from LTE–Time Division Duplex (AELTE-TDD) model. The area traversed by orange bands represents the water off the coast of San Diego, California. Red triangles represent the randomly generated possible locations of maritime radar receivers. Green dots represent randomly generated possible locations of LTE base stations in the 3.5 GHz band.

illustrates one of our simulations using AELTE-TDD. These valuable modeling and simulation capabilities should aid government and industry in the deployment of spectrum sharing services within the 3.5 GHz band. In FY 2018, we expect to further validate AELTE-TDD and identify test scenarios that we can use to benchmark our results. An accurate and reliable aggregate model is the essential tool for evaluating whether policy and engineering decisions will be effective in reliably averting harmful interference. The Institute's new AELTE-TDD model readies the Institute to swiftly respond to government and industry needs to understand the requirements for safe and reliable spectrum sharing in multiple bands.

Advanced clutter simulation. In FY 2017, many important improvements and extensions were made to the AELTE model. One of these was to expand the simulation to account for the effects of trees, buildings, and other obstacles—collectively called "clutter." This represents an update to ITM and continues a decades-long tradition of research progress in the area of propagation modeling at the Institute. Adding the ability to account for clutter would substantially improve the accuracy of our results. We also implemented more sophisticated modeling of victim receivers (i.e., the receivers subject to interference), which allows us to account for the fact that such receivers may not be equally sensitive to interference over the entire range of frequencies they receive.

Sensitivity analysis. The Aggregate Emissions Project also undertook a major sensitivity analysis of AELTE in FY 2017. This involved observing how the AELTE's aggregate emissions results vary given the widest possible range of hypothetical conditions. Although it was a theoretical exercise, this analysis was extremely valuable because it profoundly deepened our understanding of how changing network parameters, such as the number of people trying to connect to a cellular network at different times of day, or even atmospheric conditions, do or do not lead to harmful interference. Such knowledge empowers us to focus our efforts on the elements of the model that have the greatest importance. This development has the potential to increase the efficiency of our future research efforts, representing significant added value to our ongoing and future partnerships with industry and government agencies.

As the number and complexity of spectrum-sharing arrangements increase, there is the potential for unexpectedly frequent occurrences of harmful interference. Such interference could have drastic consequences in the form of economic losses and safety concerns, so we must maintain the readiness to respond to such events. The Institute's experience with the AELTE sensitivity analysis will greatly enhance our ability to understand the real-world conditions responsible for unforeseen interference, to identify the source of the interference, and to quickly identify and implement solutions alongside government and industry. ■

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RADIO SPECTRUM MEASUREMENT SCIENCES PROGRAM

The ***Radio Spectrum Measurement Sciences (RSMS) Operations*** and ***Development*** programs support both NTIA and other Federal agencies by maintaining the Institute's capability to take critical, time-sensitive radio frequency (RF) measurements for purposes including

- spectrum and channel usage surveys
- equipment characterization and compliance
- interference resolution and electromagnetic compatibility
- signal coverage and quality

Our Federal agency partners leverage RSMS expertise and capabilities to prevent and, if necessary, resolve interference problems involving Federal systems. To support this broad goal, the Institute has identified four essential directions for the RSMS program:

1. Developing new and improved propagation measurements to support model development in built-up areas with man-made structures and foliage
2. Expanding capabilities for generating characteristic waveforms for evaluating the performance of detect-and-avoid sensors employed in spectrum sharing devices
3. Automating routines for capturing emissions from devices which are being introduced into a band for use in electromagnetic compatibility analysis
4. Tailoring existing capabilities and applying the Institute's body of knowledge to troubleshooting incidents of interference between systems

To date, our work in these areas has been transferred to the broader research community through reimbursable research partnerships with NIST, NOAA, the FCC, the Department of Defense's Defense Spectrum Organization, the U.S. Air Force, and NTIA's Office of Spectrum Management.

FY 2017 Developments: RSMS Operations

3.5 GHz environmental sensing capability tests to enable spectrum sharing. In FY 2017, the RSMS Operations program supported two major spectrum sharing efforts. The first, a continuance of previous years' work, focused on the 3550–3650 MHz segment of the 3.5 GHz band (which extends to 3700 MHz). At present, the 3.5 GHz spectrum is primarily occupied by Federal radar systems, particularly radars deployed on Navy ships. The FCC adopted rules[1] for a new 3.5 GHz terrestrial broadband communication service in April of 2015 to coexist in the same radio spectrum as these radars. In the time since that order, the private sector and Federal agencies have made great strides to enable spectrum sharing in this band. A condition of using this band is that the entrant must deploy an environmental sensing capability (ESC) to detect incumbent radars and then perform mitigation techniques to prevent interference.

Before the ESCs are deployed, enabling industry to offer broadband service in the 3.5 GHz band, the ESC sensors

1 Federal Communications Commission, "Amendment to the Commission's Rules with Regard to Commercial Operations in the Band 3550-3650 MHz," FCC Docket No. 12-354, Report and Order and Second Further Notice of Proposed Rulemaking, April 17, 2015. https://apps.fcc.gov/edocs_public/attachmatch/FCC-15-47A1.pdf

HOW ARE RSMS CAPABILITIES EMPLOYED AND ADAPTED TO MEET THE EMERGENT NEEDS OF OTHER FEDERAL AGENCIES?

A few examples of how our recent work continues to generate value for other agencies:

- The Institute developed simulated terminal Doppler weather radar (TDWR) waveforms and test systems to support the introduction of dynamic frequency selection (DFS) technology for commercial devices sharing spectrum with Federal radar in the 5 GHz band. Subsequently, we transferred the technology to the FCC, which now performs all DFS compliance tests. Drawing on our experience with DFS, in FY 2017 the Institute prepared to test the performance of environmental sensing capability (ESC) in the 3.5 GHz shared spectrum band by developing test waveforms and test procedures. As with DFS, this new testing capability will eventually be transferred to the FCC. See also ***Case Study: 5 GHz Interference*** on page 58.

- To respond to spectrum sharing in the AWS-3 band, U.S. Air Force researchers needed precise measurements of LTE emissions to perform interference analyses. The Institute's modernized RF measurement system, developed through the RSMS program, was expeditiously deployed to meet the Air Force's need.
- ITS engineers' experience provides a unique situational awareness that facilitates the resolution of problematic interference situations. In FY 2017, we drew upon our work spearheading the resolution of interference into TDWR systems from DFS devices when we were called upon to resolve an interference complaint involving wireless Internet devices at Cape Canaveral and Vandenberg Air Force Base.

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themselves must be certified—an action typically performed by the FCC. This is typically done by subjecting a device to a synthesized set of radar waveforms and monitoring the device's outputs for the correct responses. Recognizing the significant subject matter expertise and capabilities that ITS possesses regarding radar systems and our history simulating radar environments, the FCC asked for assistance. In preparation for the eventual ESC sensor tests that will be performed at the ITS laboratory, ITS engineers have worked closely with the incumbent users and the FCC to develop a suite of laboratory tests to assess the detection and avoidance abilities of the sensors. These tests have been publicly released as two NTIA memoranda.[2,3] ITS will eventually test these ESC sensors, write up the results, and send a report to the FCC for each sensor tested. On the bases of the test results, the FCC will decide which ESC sensors to certify. This is expected to take place in FY 2018.

2 Frank Sanders, "Distinction Between Radar Declaration and Pulse Burst Detection in 3.5 GHz Spectrum Sharing Systems," NTIA Technical Memo TM-18-526, 2017. https://www.its.bldrdoc.gov/publications/3182.aspx

3 Frank Sanders, John Carroll, Geoffrey Sanders, Robert Sole, Jeffery Devereux, and Edward Drocella "Procedures for Laboratory Testing of Environmental Sensing Capability Sensor Devices," NTIA Technical Memo TM-18-527, 2017. https://its.bldrdoc.gov/publications/3184.aspx

RSMS PROGRAM (continued)

5 GHz instrumentation radars. The Federal government operates 5 GHz instrumentation radars at test and launch facilities in the United States and abroad. These radars provide range safety officers with rapidly updated data showing launch vehicle velocities, predicted future vehicle positions based on those velocities, and predicted impact points.

The data are used to verify that navigation systems are not guiding launch vehicles into zones where they would have to be destroyed. If vehicles fail during launches, the radars are also used to follow falling debris. The radars also identify and track hazardous aerosolized propellant clouds from destroyed booster tanks so that civilian populations can be alerted and protected as the clouds drift and disperse.

In recent years, the 5 GHz range radars at Cape Canaveral and Vandenberg Air Force Base have been experiencing RF interference from unlicensed national information infrastructure (U-NII) transmitters. Recognizing our significant subject matter expertise, the U.S. Air Force (USAF) reached out to the Institute. ITS engineers traveled to Cape Canaveral in early 2017 to witness the actions that the local FCC field office and the USAF's internal radio teams perform prior to a launch to ensure a clean RF environment. ITS engineers were then able to provide recommendations to the USAF on ways forward to effectively coordinate launches.

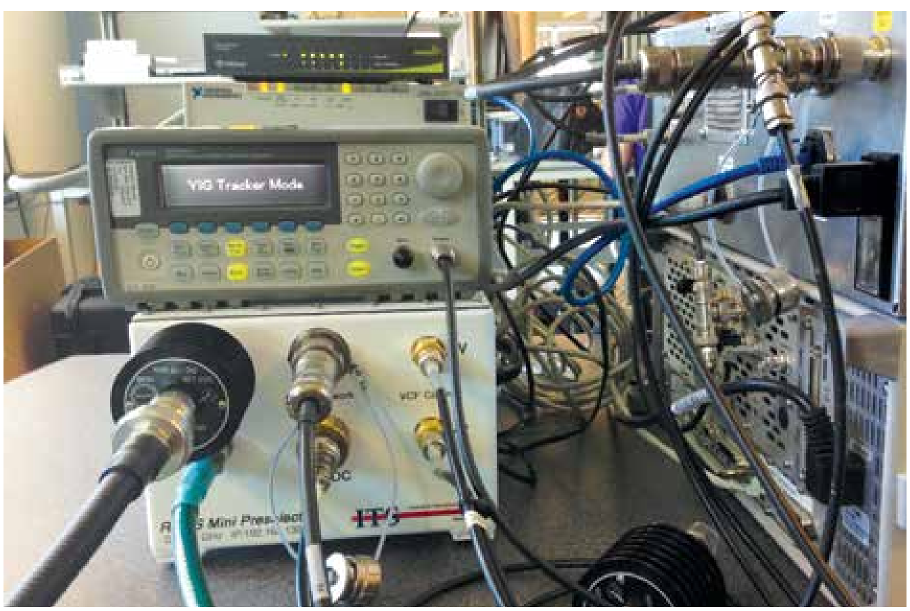

Photo by Frank Sanders

In FY 2017, the Institute's Radio Spectrum Measurement Sciences program supported the National Advanced Spectrum and Communications Test Network in measuring the emissions of LTE equipment

FY 2017 Developments: RSMS Development Program The RSMS Development program provides maintenance and upgrades of existing infrastructure to support RSMS Operations and other ITS programs. This continuous progress is made possible by the modular design of the ITS-developed RSMS software and hardware suite (see description, page 122).

In FY 2017, we acquired new equipment including a state-of-the art spectrum analyzer, instrument controllers, antenna rotator, and waveform generator. Several laboratory and office spaces were upgraded to anti-static tile flooring to protect sensitive electronics from damage from static discharge.

Preselector hardware upgrade. Our primary development activity in FY 2017 was to upgrade our custom-built preselector hardware. Generally, a preselector is a piece of equipment that reduces interference to a radio receiver by allowing only the desired frequency to pass from the antenna to the receiver. The Institute's preselectors are more complex, incorporating attenuators and amplifiers. Depending on the scenario, we can use the amplifier to reduce overall noise (for low-power signals), or we can use the attenuator to prevent high-power signals from overloading our measurement system. Our preselectors enable RF measurement between 10 MHz and 40 GHz, setting the Institute apart in RF measurement capability.

The Institute's preselectors contain an yttrium-iron-garnet (YIG) filter that blocks interference by acting as a voltage-controlled, tunable bandpass filter. The YIG filter needs to be electrically tuned in sync with a commercial spectrum analyzer's frequency sweeps. In FY 2017, we upgraded the hardware and software required to tune to the latest line of spectrum analyzers. This work was essential to maintain our ability to perform high-dynamic range measurements, vital to testing electromagnetic compatibility and compliance in spectrum-sharing scenarios.

Improved measurement capabilities. Our secondary development activity in FY 2017 focused on creating instrument drivers to interface with equipment supporting an automated general purpose I/Q measurement application. Raw I/Q data are important because they capture all the information available for a given frequency band. Our I/Q measurement application, which we expect to complete in FY 2018, will therefore have strategic importance for the Institute, because the utility of less precise data is increasingly limited.

The Institute is also responding to increasing demands for vector signal analysis of device or system emissions by procuring an RF recorder to expand our capabilities. The device consists of a hard drive array customized to save dual-channel data streamed from a vector signal analyzer at up to 600 MB/s. Accompanying software facilitates the identification and retrieval of transmissions of interest for later analysis. Future applications include monitoring for infrequent or intermittent noise transmissions at remote sites. ■

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INTERFERENCE PROTECTION CRITERIA ESTIMATION

Interference protection criteria (IPC) estimation predicts the interference power that a receiver can tolerate given a specific offset between the spectrum frequencies used by the interfering transmitter and those used by the receiver subject to interference (the "victim" system). IPC estimation requires a profound knowledge of the characteristics of both the interfering and the victim systems, including how they process signals. It also requires a wealth of data characterizing the systems' real-world performance. IPC estimates are obtained from measurements in the laboratory and field, as well as by computer simulation.

Background: Methods of Protecting Telecommunication Systems from Interference Telecommunications systems must be able to deliver clear signals. If receiving systems experience enough interference, their performance can significantly degrade, potentially resulting in lost information and failed telecommunication. To minimize the probability of interference, spectrum managers separate systems in distance and frequency. The amount of separation is determined by *interference protection criteria* (IPC), which specify the allowed interference power at a specific center frequency offset. The purpose of the Institute's *IPC Program* is to improve existing and develop new methods for estimating IPC. This work yields results that can be used to maximize the value of spectrum resources without compromising the quality and reliability of telecommunications.

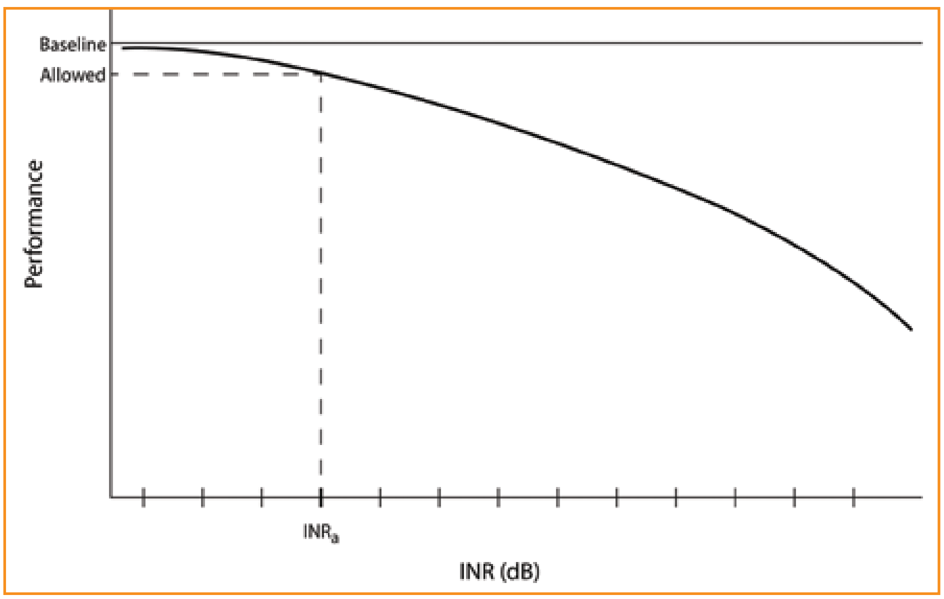

Figure 8 Graph showing how results of an IPC measurement at a specific frequency offset are typically presented. Baseline performance is evaluated without interference. The IPC is the allowed INR, INR$_a$.

Figure 8 shows how results of an IPC estimation are typically presented, and how the results can be translated into policy. The top of the graph represents nominal "baseline" performance in the absence of interference. The solid line represents the actual measurement results—as the power of the interfering signal (INR, plotted on the x axis) increases, the performance of the victim signal (plotted on the y axis) decreases. The point at which the horizontal and vertical dashed lines meet represents the most powerful allowed interference signal (INR_a), or the IPC. The victim system operators and spectrum managers determine the amount of allowed degradation from baseline performance.

IPC are estimated using three methods. The aim of all three methods is to determine the amount of interference power the victim receiver can tolerate over a range of frequency offsets. The three methods of determining frequency-dependent rejection are as follows:

- ***Analytic methods.*** This process involves positing an interfering transmitter and a receiver subject to interference, assuming that they have identical center frequencies (i.e., zero frequency offset), and calculating how the victim system will perform given the interference from the transmitter. From the results of this calculation, we can estimate how the victim system's performance would change given greater offsets between the center frequencies. Although analytic methods are useful for certain types of systems, including LTE networks, they may yield inaccurate results for other types of systems, like wideband pulsed radar.
- ***Measurement methods.*** Spectrum engineers often turn to measurement when they need IPC estimates more precise than those available from analysis. ITS engineers typically estimate IPC by taking measurements from working equipment in the laboratory or in the field. Figure 9 shows a schematic of how IPC measurement systems are arranged. The basic method for measuring IPC involves the following steps:
  1. Set the power of the victim system's transmitter to a baseline signal-to-noise ratio corresponding to typical interference-free performance
  2. Set the power of the interfering system's transmitter to a low power
  3. Measure performance of the victim system by analyzing what the receiver "hears"
  4. Incrementally increase the power of the interfering signal, taking additional measurements to quantify the performance of the victim system at various interference signal strengths

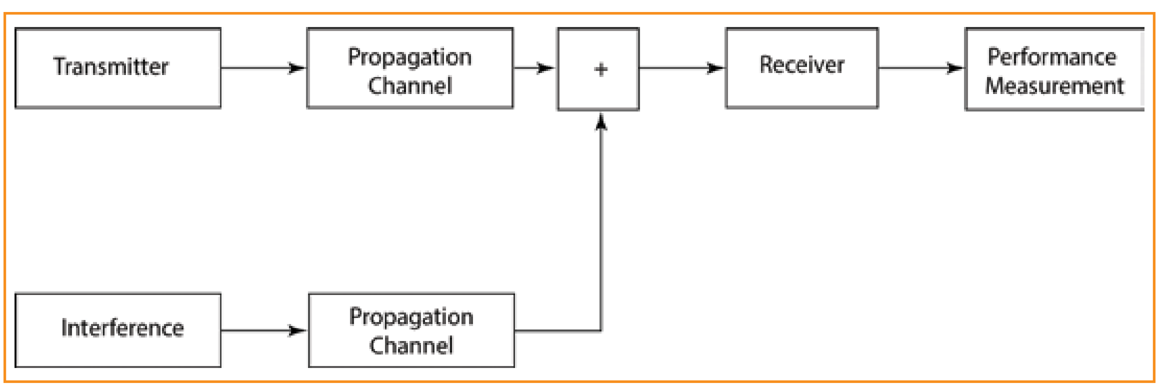

Figure 9 General IPC measurement setup. Desired and interfering signals go through independent propagation channels since their transmitters are generally not co-located.

IPC ESTIMATION METHODS (continued)

- ***Simulation methods.*** IPC measurements are often hindered by restrictions on equipment availability. In some cases, spectrum managers need estimates for systems that have not even been built yet, so measurements are not possible. In other cases, the systems can only be tested for a brief period of time to avoid service interruptions. These and other factors can make accurate and repeatable measurements difficult to obtain. With recent advances in radio system simulation software, IPC simulation has drawn considerable interest. IPC simulation uses software to emulate the same IPC measurement setup shown in Figure 9. ITS engineers' recent work has shown that these simulations can be executed quickly and at low cost.

Of these three methods, simulation is currently the most promising, because, owing to increased spectrum sharing, spectrum managers need more IPC data than is practical to generate using the other two methods.

> ***THE INSTITUTE'S IPC LABORATORY HAS MADE SIGNIFICANT INVESTMENTS INTO SIMULATION CAPABILITIES, IN ADDITION TO MAINTAINING EXPERTISE IN ALL THREE IPC ESTIMATION METHODS.***

An ongoing IPC estimation research program is essential to prepare the Institute to respond efficiently to spectrum sharing analysis challenges. In the past few years, this research has been primarily devoted to developing IPC simulation methods and models. Notably, we have developed IPC simulation models for maritime surveillance radars, SPN-43C shipborne radar, and LTE eNodeB and UE. Our work has also focused on developing procedures for determining simulation uncertainty, which is essential for minimizing simulation execution time.

FY 2017 Developments In FY 2017, our major focus was on publishing our first results comparing IPC simulations to measurements. The purpose of this work was to determine whether laboratory and field measurements can be replaced by software simulations. This research was the result of a joint effort by the Institute and the NTIA's Office of Spectrum Management (OSM).

Currently, there is considerable interest in allowing LTE systems to share spectrum with Federal radars in the 3.5 GHz Citizen Broadband Radio System band. Consequently, we chose to compare IPC simulations to IPC measurements previously taken from LTE devices and SPN-43C radar systems, which operate in that band, to determine the characteristics of interference between these two systems.

The results were surprising. In the case of the SPN-43C radar system, we found that IPC determined through simulation were more applicable than those obtained from measurements. Specifically, the simulation showed that the probability of the SPN-43C detecting a target (P_d) increases as the interference power increases. This result is counterintuitive, because increased interference power is typically associated with a decrease in P_d. The cause of this surprising result was that, previously, we had attempted to measure the probability of detection by visually identifying the number of targets on the radar display. However, the SPN-43C radar system used a manually set detection threshold, so false alarms obscured the targets on the display. The obscuration made it difficult to distinguish between targets and false alarms, yielding inaccurate results about the levels of acceptable interference.

We concluded that IPC for radars with manually set detection thresholds (like the SPN-43C) should use probability of false alarm (P_{fa}) as the performance metric instead of P_d. Since it is not feasible to measure P_{fa} visually, simulation will be required to determine the IPC for such systems.

For the LTE devices, simulated results once again differed dramatically when compared with measured results. In the simulation, the radar system's pulses repeatedly interfered with the LTE signals, resulting in catastrophic signal degradation under conditions that, according to our measurements, should not have been problematic. We are continuing research to determine the applicability of our result and to identify the reason for the discrepancy. One possible explanation is that the LTE devices used some sort of built-in radar pulse mitigation signal processing that our simulation failed to account for. If so, this information will be highly valuable in helping us improve our simulation methods. ■

U.S. Navy photo by Will Tyndall/Released

Sailors perform maintenance on an SPN-43 radar

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SPECTRUM MONITORING

Background: Spectrum Awareness

Optimizing use of spectrum resources in real time

The growth and stability of wireless communications depends on real-time awareness of the radio frequency (RF) environment (generated through *spectrum monitoring*) and coordination of diverse communication services (*spectrum management*). Data generated through spectrum monitoring are used by spectrum managers to enforce spectrum use rules and frequency assignments. Spectrum monitoring is also essential to optimizing the use of spectrum resources, now and in the future. New devices and technologies make new demands on the finite radio spectrum (e.g., smart home devices, self-driving cars). Modern, dynamic spectrum management allows communications systems to use different frequencies at different times, or to share frequencies with other systems, depending on real-time spectrum availability within the ever-changing RF environment.

***SPECTRUM MONITORING** IS LONG-TERM, CONTINUOUS MEASUREMENT OF THE RADIO FREQUENCY ENVIRONMENT FROM MULTIPLE SENSORS, PROVIDING REAL-TIME INFORMATION ABOUT THE USE OF RADIO FREQUENCIES ACROSS BROAD AREAS AND ENABLING OBSERVATION OF HISTORICAL TRENDS AND EVENTS.*

Broadly, spectrum monitoring involves three components:

1. Operating hardware that is capable of sensing radio signals
2. Transmitting data about radio signals from the sensors to a database using networking infrastructure
3. Using the resulting spectrum data in data analytics and visualization to characterize the sources and strengths of radio signals, and to identify potential conflicts among them

The purpose of the Institute's ***Spectrum Monitoring Program*** is to provide spectrum managers with more effective monitoring and advanced data visualization, enabling them to access information on spectrum use at a level of detail that was previously unattainable (see inset box, next page, for examples). The Institute is involved in both monitoring spectrum

MONITORING ENABLES ADVANCED REAL-TIME AWARENESS OF SPECTRUM USE

The Institute's Spectrum Monitoring Program provides spectrum managers with data and visualization enabling advanced awareness of the spectrum environment:

- actual spectrum use compared with assignment and license information
- spectrum maps for visualizing spectrum use and signal strength
- spectrum efficiency data (to compare usage before and after rule changes)
- occupancy statistics for different frequency bands
- potential interference events identified with a specified level of confidence
- statistics on man-made interference sources

use and conducting research to develop improved spectrum monitoring tools and techniques.

FY 2017 Developments

Spectrum monitoring in the 3.5 GHz band. In the 3550–3650 MHz span of the Citizen Broadband Radio Service band (the 3.5 GHz band, which extends to 3700 MHz), Federal maritime radars will soon share spectrum with new commercial wireless systems. This development necessitates a thorough awareness of existing spectrum use in the band, so that new systems can begin operation without endangering radar functionality. To support this transition, the Spectrum Monitoring Program has been continuously collecting monitoring data in the 3.5 GHz band at locations on the coasts of the United States. In FY 2017, we established three radar sensors near San Diego, San Francisco, and Virginia Beach. In FY 2018, we plan to establish three additional radar sensors near Astoria, Boston, and the Florida Keys.

Spectrum characterization and occupancy sensing. Fully characterizing the wireless environment is a monumental task that requires coordinated data collection, organization, and analysis efforts to aggregate spectrum monitoring data for the common good. To date, there is a lack of broad cooperation; existing spectrum monitoring efforts are largely independent and are each constrained to the scope of individual organizations' resources. This is a problem because uncoordinated spectrum monitoring cannot provide the volume of data that regulators need.

SPECTRUM MONITORING (continued)

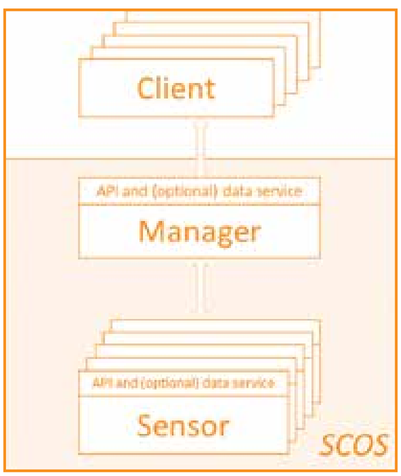

Figure 10 Schematic of the high-level software architecture for the Institute's Spectrum Characterization and Occupancy Sensing application.

To address the problem of uncoordinated spectrum monitoring and to enable the development of a spectrum monitoring software ecosystem, ITS personnel are leading a standardization effort (chartered under IEEE 802.22.3) entitled ***Spectrum Characterization and Occupancy Sensing*** (SCOS). The purpose of this project is to develop a public standard for the control of spectrum sensors and the distribution of spectrum data to authorized clients.

In FY 2017, we finalized the high-level software architecture for SCOS in order to identify needs for application development. This architecture identifies three independent areas of specialization: (a) sensor technology ("sensor"), (b) data acquisition and distribution ("manager"), and (c) data management and visualization ("client"). Each of these specialization areas will have distinct business incentive and evolutionary trajectories, but each will need to communicate and share data with the others. This architecture is illustrated in Figure 10.

With our SCOS architecture in place, we can begin developing applications to support standardized spectrum monitoring. During FY 2017, we began prototyping the first SCOS implementation. In FY 2018, we are scheduled to release both the *data transfer specification for spectrum characterization and occupancy sensing* and the *scos-sensor application*. Both will be open-sourced in GitHub (https://github.com/NTIA) in FY 2018. Scos-sensor is the cornerstone of the SCOS project and establishes a RESTful API enabling others to interface with sensor data. Ultimately, our SCOS work will yield the capability to conduct networked spectrum monitoring according to standardized protocols—a fundamental step in establishing spectrum sharing that leverages real-time data.

Boulder wireless test bed. In FY 2017, the Institute continued its work with University of Colorado at Boulder (CU) faculty members who share our interests in spectrum monitoring and automated spectrum enforcement. Together, we are developing the

Boulder Test Bed—a planned network of RF sensors that will eventually encompass the City of Boulder and surrounding communities.

The Boulder Test Bed project represents a significant development in the field of spectrum monitoring, and it is expected to have wide-ranging impact on government, industry, and the scientific community. This city-wide test bed will enable the efficient testing of both sensors and sensor networking applications under real-world conditions, both for spectrum monitoring and for the broader field of wireless technology. The Boulder Test Bed will also provide a glimpse of what will be required to build and maintain a nationwide spectrum monitoring network.

Development of the Boulder Test Bed is currently in its early stages. We will begin by placing sensors and associated network infrastructure around the CU campus, which is larger and has a richer radio propagation environment than the Boulder Labs campus. In FY 2017, the Institute developed a programmable and relatively low-cost ($2,500–$3,500 per unit) RF sensor. The sensors are built in-house at the Institute, based on commercially available software-defined radio technology. Our sensors will enable the rapid development and trial of sensing algorithms for monitoring and protecting mission-critical government systems. In FY 2018, we will build and install 10 sensors in and around Boulder, Colorado. ■

Google Earth™ map data ©2017 Google; image Landsat Copernicus.

In FY 2018, the Institute will create a wireless test bed by building and installing 10 radio frequency sensors around the University of Colorado campus in Boulder, CO

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AUDIOVISUAL QUALITY OF EXPERIENCE

Quality of user experience is important to telecommunications for economic and public safety reasons. The primary goal of both audio and video communications is to transmit information in a way that is understandable to the receiver. As a signal's quality increases, so does the bandwidth needed to transmit that signal. For optimal spectrum use and economic audiovisual data transmission, telecommunication systems must use the minimum bandwidth necessary to provide the required level of quality. Since the 1980s, the Institute has played an important role in defining objective measures of quality of experience and providing technical parameters that can describe quality. Such measures and parameters are of use to both the public and private sectors. In FY 2017, the Institute's quality of experience research programs focused on developing metrics for speech intelligibility and video quality characterization. ■

AUDIO QUALITY AND SPEECH INTELLIGIBILITY

Background: Speech Intelligibility

Measuring whether speech signals can be understood

Transmitting speech sounds is a foundational telecommunications application. Speech intelligibility is therefore key to the success of many telecommunication systems, and has remained so despite fundamental shifts in the dominant technologies.

An important telecommunications challenge is the efficient measurement of speech intelligibility. Hundreds of factors can harm or improve the intelligibly of speech, such as background noise, speech codec parameters, and network transmission conditions. Characterizing how these factors interact to affect speech intelligibility requires *speech intelligibility measurements*. Speech intelligibility can be measured by asking individual listeners to report what they have heard under various conditions, but this process is costly and time consuming.

Automating speech intelligibility measurements using digital signal processing (DSP) would eliminate the need for human listeners and enable rapid, low-cost acquisition of large datasets. These datasets directly support the design, development, deployment, and optimization of telecommunications technologies and devices. DSP-based speech intelligibility measurement was thus a focus of the ITS *Audio Quality Program* during FY 2017.

FY 2017 Developments

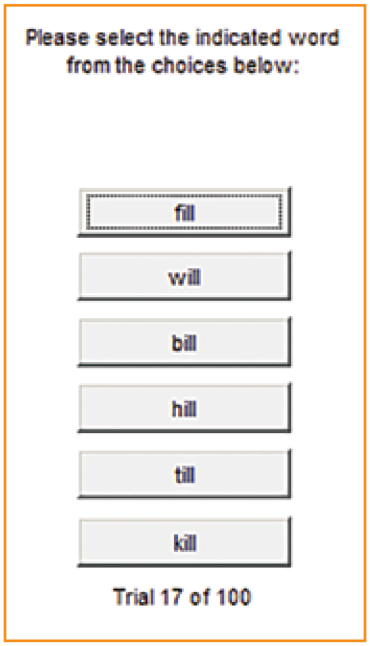
ABC-MRT16: a new algorithm for measuring speech intelligibly. In response to the challenge of automated speech intelligibility measurement, the Institute developed a DSP-based speech intelligibility measurement algorithm called *Articulation Band Correlation Modified Rhyme Test (ABC-MRT16)*. The algorithm is based on the Modified Rhyme Test (MRT), a well-known test that asks human listeners to listen to a recorded sound and then identify which of six rhyming words (e.g., not, tot, got, pot, hot, lot) they have heard. If many people can make accurate identifications, the audio signal is highly intelligible. The ABC-MRT16 analyzes the same MRT recordings to produce estimates of speech intelligibility without human listeners.

In FY 2017, the Institute published a technical paper[1] describing the ABC-MRT16 algorithm, and the Institute released the software platform to make it available to industry. The paper describes the results of ABC-MRT16 testing, revealing that this DSP-based measurement is very highly correlated with MRT test results using human listeners. The success of the ABC-MRT16 is attributable to several factors; it

- uses a mathematical model that very closely mimics how humans distinguish between similar-sounding words
- takes individual variation into account, producing results that are applicable to whole populations of listeners rather than a single listener
- automatically determines, without requiring user input, the most relevant frequency bands to include and thus can measure narrowband, wideband, super-wideband, or fullband systems

Owing to these success factors, the ABC-MRT16 has generated industry interest, and ITS researchers have had the opportunity to support external organizations seeking to use ABC-MRT16 measurements in new intelligibility testing systems.

Crowdsourced Modified Rhyme Testing. In parallel with the automated ABC-MRT16 (described above), the Institute has developed an Internet-based



A Modified Rhyme Test question like those used in the Institute's online crowdsourced version of the test

1 Stephen Voran, "A Multiple Bandwidth Objective Speech Intelligibility Estimator Based on Articulation Index Band Correlations and Attention," Proceedings of the 42nd International Conference on Acoustics, Speech and Signal Processing (ICASSP2017), New Orleans, LA, March 5-9, 2017. https://www.its.bldrdoc.gov/publications/3169.aspx

AUDIO QUALITY AND SPEECH INTELLIGIBILITY (continued)

platform enabling us to expand our subjective speech intelligibility measurements with human listeners. This platform "crowdsources" the MRT by enabling self-selecting, anonymous listeners to complete the test online. Our crowdsourced MRT (CMRT) enables us to obtain large sample sizes at very low cost; this efficiency compensates for our lack of control over the test conditions. In FY 2017, we published the details of the CMRT in a technical memorandum,[2] explaining how to achieve laboratory-grade MRT results using CMRT. This approach provides excellent value for those requiring quick, low-cost, speech intelligibility measurements with human listeners.

Decision Framework. Owing to their technical and conceptual complexity, it can be challenging to determine which speech intelligibility testing tools are best suited to particular applications. Thus, industry needs a clear guideline for effectively employing the various tests that the Institute has made available. To address this industry need, in FY 2017, we began developing a statistics-based decision framework that can guide industry users toward the most efficient and effective applications of ABC-MRT16 and CMRT, depending on their specific needs. In most cases, it is most efficient to first employ the ABC-MRT16 to generate a large set of estimates, then to analyze its results to determine the cases that will benefit from additional testing using the CMRT. We expect to finalize the documentation and release the framework in FY 2018.

Separating speech from background noise. In FY 2017, we made considerable progress on open research questions related to statistical models of speech and background sounds. This research direction addresses the problem that, in transmitted audio signals, speech and background sound are indiscriminately blended together, making it difficult to transmit clearly intelligible speech when the speech originates in noisy environments. Existing strategies to separate speech from background noise are not yet fail safe and, under certain conditions, they may even harm audio quality. Therefore, considerable resources are being devoted to this problem across government, industry, and academia.

The ITS Audio Quality Program is contributing to this multisector research effort by developing novel statistical methods that could contribute to our ability to dynamically predict which parts of an audio signal are likely to be relevant for intelligibility, and which merely represent noise. With more research into signal statistics, we hope to uncover opportunities to optimize transmitted audio quality. Although this research is in its early phases, we hope to begin publishing our results in FY 2018. ■

2 Stephen Voran and Andrew Catellier, "A Crowdsourced Speech Intelligibility Test that Agrees with, Has Higher Repeatability than, Lab Tests," NTIA Technical Memo TM-17-523, 2017. https://www.its.bldrdoc.gov/publications/3168.aspx

Learn more online: https://www.its.bldrdoc.gov/audio

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VIDEO QUALITY CHARACTERIZATION

Background: Optimizing networked video streams

The purpose of the Institute's **Video Quality Characterization** project is to enable the public and private sectors to optimize networked video transmission.

> ***TO DELIVER HIGH-QUALITY VIDEO TO USERS, WHETHER COMMERCIALLY OR IN PUBLIC SAFETY AND SURVEILLANCE USES, VIDEO STREAMING APPLICATIONS NEED TO DYNAMICALLY BALANCE AVAILABLE STREAMING BANDWIDTH WITH VIDEO RESOLUTION, PROVIDING THE BEST QUALITY VIDEO POSSIBLE WITHOUT REQUIRING EXCESS TIME FOR VIDEO BUFFERING.***

Achieving a dynamic balance between quality and bandwidth optimization requires a metric capable of estimating how users will perceive the quality of video files that have been re-encoded using lower bitrates. With this knowledge, networks can optimize video delivery. Existing video quality metrics are either inaccurate or require difficult-to-obtain information about the encoder and the network. Thus, the Institute supports the development of objective and trusted metrics that can be used to optimize video delivery and promote a level playing field.

FY 2017 Developments

its4s study to enable no-reference metrics

Study background. 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. We believe that all prior work on NR metrics was hindered by flaws in the video sequences used to "train" these metrics.

Research design. In FY 2017, we created new training data using an experiment, called its4s, designed specifically for NR metric development. We conducted a subjective experiment that spanned 813 different video scenes, emphasizing the unexpected video content that NR metrics are likely to encounter. The goal of this subjective test was to characterize human perception of quality problems that stem from the original filming and

VIDEO QUALITY CHARACTERIZATION (continued)

editing. Factors that degrade quality can include issues with the camera, lighting, videography, editing, and reformatting—in short, everything that occurs prior to video encoding for final distribution. Typically, subjective video quality experiments exclude such problems, so our data represent an important contribution to the available data on how viewers perceive video quality.

To understand whether our new dataset, along with data generated using similar experiments, can be used to address the gap in NR metrics, we evaluated the advantages and disadvantages of our experiment design. We reasoned that, if our research design is valid, the resulting data should agree with our theoretical understanding of the factors that make viewers perceive video as high quality. Over three decades, ITS researchers have developed (both internally and as part of international validation efforts that led to ITU Recommendations), an understanding of the wide variety of parameters that influence video quality perceptions. One such parameter is the amount of the color red in a video. Therefore, we tested whether the viewers' ratings in our dataset were correlated with the amount of red in each of the test videos.

Munsell Red is a simple calculation that tracks the amount of red in a video frame. Because compression, recompression, and network distribution do not change the amount of red in a video sequence, the Munsell Red calculation tells us something about the original video as it was shot and edited.

Research findings. Figure 11 shows a scatter plot of the correlation between *Munsell Red* and the subjective data from the its4s study. The *Munsell Red* score ranges from zero (no red) to one (100% shades of red). The viewers' opinions of the video quality (mean opinion score; MOS) range from 1 (bad) to 5 (excellent). This scatter plot indicates that very few participants gave low ratings to videos that contained high amounts of red. Such a low-level correlation is what we would expect, because the amount of red in a video is one factor among many others.

To determine whether our its4s data yielded better results than previous NR metric training data, we also calculated the correlation between a previous dataset, *CCRIQ*, and the *Munsell Red* parameter. The CCRIQ dataset was not designed for NR metric development. As the scatter plot in Figure 12 demonstrates, the correlation was more random and did not conform with theoretical expectations (i.e., several low-quality ratings were given to scenes with large amounts of red). From the perspective of validating our experiment design, this is an encouraging result. The new dataset contains information that better matches our knowledge of filming quality and video editing quality, without requiring comparison "benchmark" images, thereby enabling the development of NR metrics. We expect to make the its4s dataset freely available for research and development purposes in FY 2018. ■

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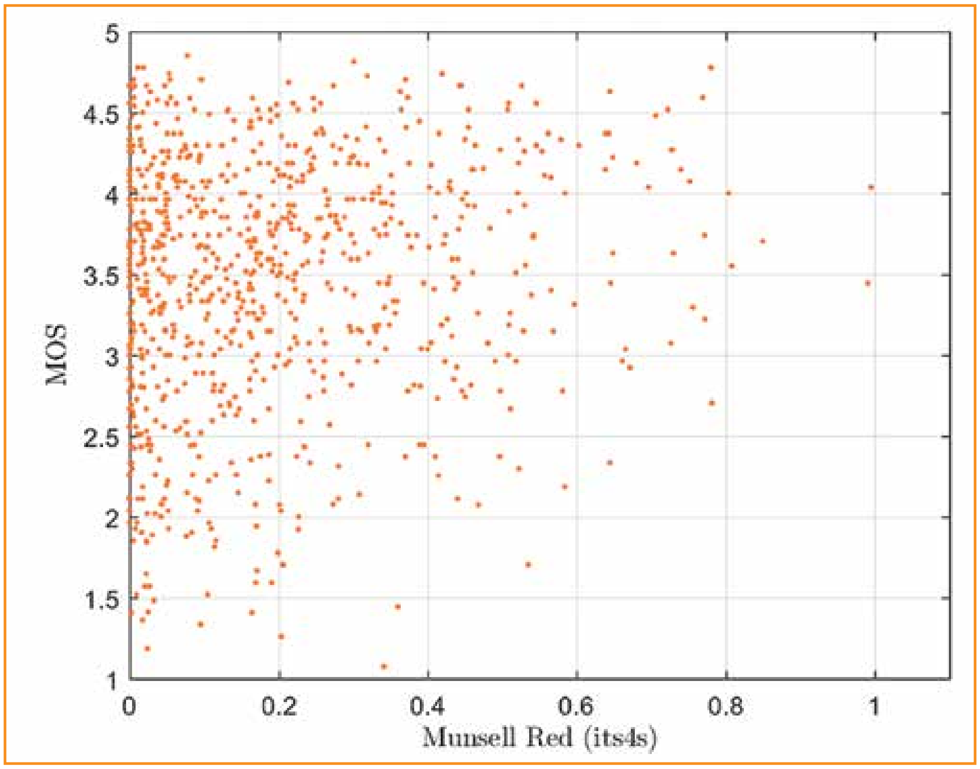


Figure 11 Correlation between Munsell Red scores and viewers' ratings of video quality generated through a novel experimental design for no-reference metric development.

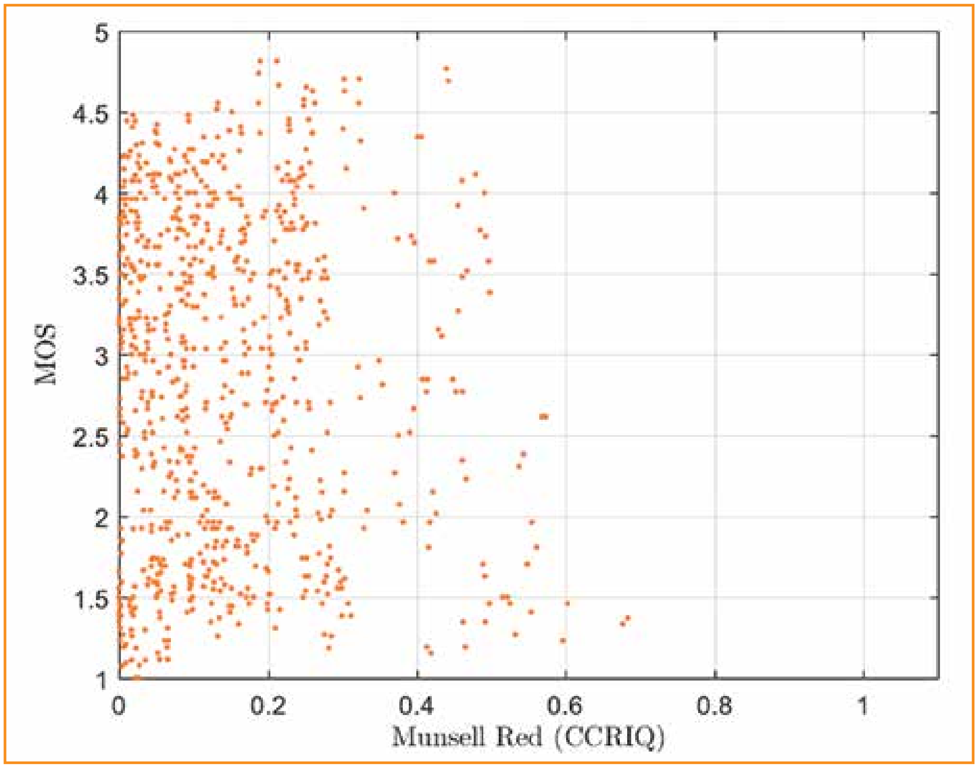


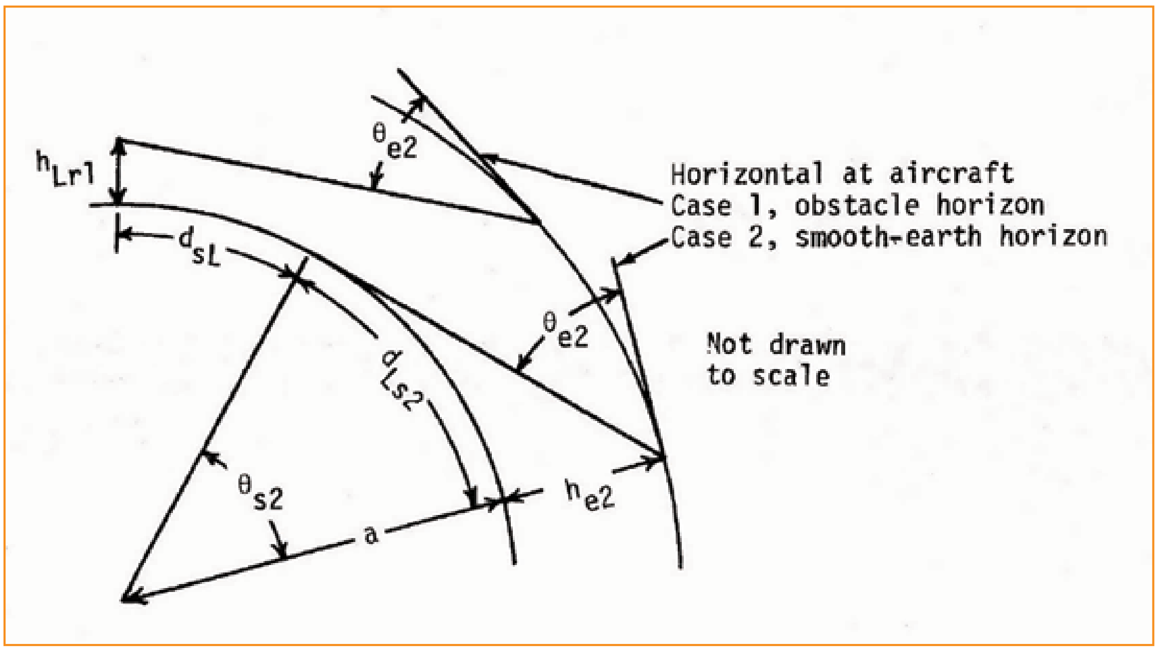
Figure 12 Correlation between Munsell Red scores and viewers' ratings of video quality on a "traditional" experiment not designed for no-reference metric development.

SOFTWARE DEVELOPMENT AND PROCESS IMPROVEMENT

The Institute is pursuing a major strategic initiative to further develop our leadership in telecommunications software development. Software development is integral to the Institute's research and engineering work. The analyses, measurements, and modeling needed to understand today's complex RF environment require extensive computational resources. Additionally, the vast majority of devices using the radio spectrum, and those used to measure their emissions, are controlled by internal computer hardware and software. We develop open-source software for release to the public, and are constantly engaged in creating and modifying software for our own use and for the benefit of our Federal agency partners.

To elevate our software aptitude and vouchsafe the trustworthiness of our software portfolio, we are working to establish a coherent and uniform approach to software development processes. Key goals are to implement more structured procedures and to enhance transparency, both across ITS divisions and with the public. We are also devoting resources to shifting our existing software capabilities to a more modular, cross-compatible framework.

During FY 2017, our appropriations-funded achievements included work on specific software projects such as the IF-77 propagation model, as well as broader work toward realizing our strategic goals of modular software architecture and process improvement. The following sections describe our progress. ■



G. D. Gierhart and M. E. Johnson, "The IF-77 Electromagnetic Wave Propagation Model," Fig. 6. https://www.its.bldrdoc.gov/publications/2524.aspx

A diagram from the 1983 publication of the IF-77 electromagnetic propagation model

IF-77 PROPAGATION MODEL UPGRADE

In 1977, ITS released the IF-77, a radio wave propagation model developed for the Federal Aviation Administration. Today, IF-77 remains the standard model for predicting high-altitude propagation, as is required for radio communication to and from aircraft. A version of the ITS model is incorporated into the International Telecommunication Union recommendation (ITU-R P.528 "Propagation curves for aeronautical mobile and radionavigation services using the VHF, UHF, and SHF band") concerning air–ground radio communication modeling. The IF-77 is the only internationally standardized air–ground propagation model.

Few propagation models are appropriate for modeling propagation at high altitudes above 1,000 m. The IF-77 fills this gap, because it is the only mathematical model to account for ray-bending and other phenomena unique to high-altitude conditions. It is therefore especially useful for predicting the transmission losses and interference levels over air-to-ground communication links.

Air-to-ground propagation modeling has entered the research spotlight, owing to a newly emerged need to protect Federal air assets from interference by commercial broadband services. In FY 2017, ITS begin an extensive analysis of the fundamental derivation of the IF-77 model, with the long-term goal of ensuring that IF-77 remains ready to meet the technological needs of the future. Thanks to our diverse expertise in radio wave theory, measurement, and mathematical modeling, ITS has the capacity to re-derive the underlying physics of the model from first principles (i.e., Maxwell's equations). Using the ongoing updates to our theoretical models, we have begun the process of comparing the existing IF-77 software code base with the latest theory. One specific application of these updates will be to expand the IF-77 to apply to higher frequency ranges, such as the millimeter wave range. Ultimately, this process will enable us to identify the best theoretical approaches to robustly model propagation, and will reveal opportunities to improve the accuracy and efficiency of IF-77. ■

Learn more online: https://www.its.bldrdoc.gov/resources/radio-propagation-software/if77/if-77-electromagnetic-wave-propagation-model-gierhart-johnson.aspx

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PROPAGATION MODELING ARCHITECTURE WORKING GROUP

The underlying physics of radio wave propagation is well understood, but many variables affect how waves will propagate in the real world (e.g., terrain, distance, interference). Therefore, in practice, predictive propagation models are scenario-specific, but often use the same "building blocks" to model recurring elements (e.g., the natural loss in the power of a signal as it travels through free space). These building blocks can be applied via software implementations of propagation models.

As telecommunication advances, we must update propagation modeling software to incorporate new information and to improve the accuracy of our predictions.

Because the pace at which we improve our models has accelerated, there is a need for a new approach to the development of propagation modeling software. The Institute is researching a modular approach to software design that will enable us to readily update our existing models and create new software implementations that use the most current and appropriate technology.

The goal is to create modules that can be used with various programming languages and software platforms. Currently, we are in the early stages of propagation modeling architecture development. We have created a working group to discuss methods for creating common propagation modeling components that can be incorporated as modules into propagation software models. ■

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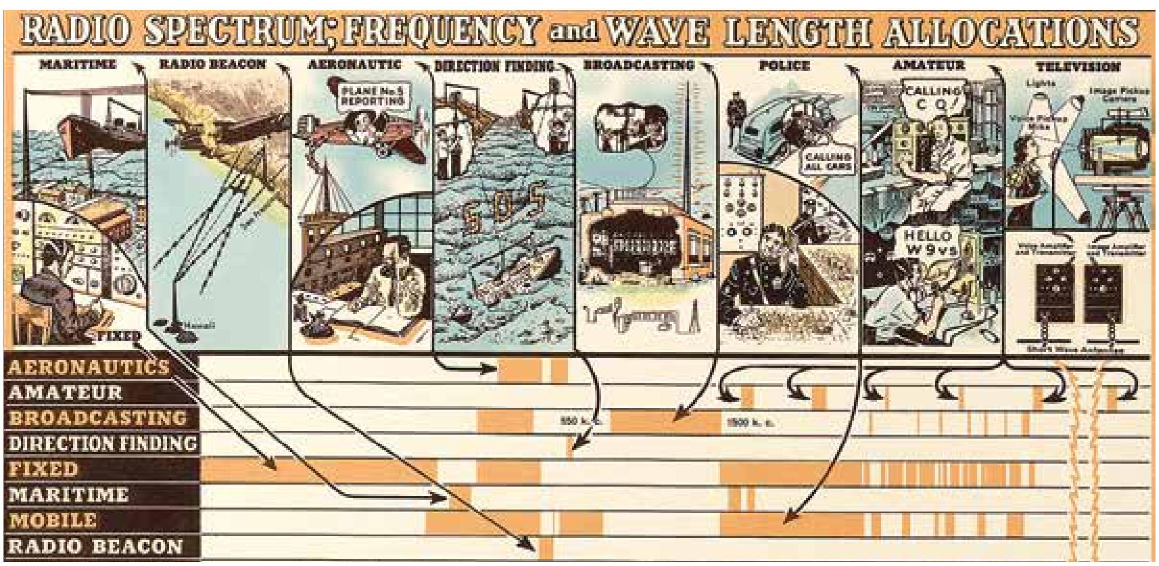
CAPABILITY MATURITY MODEL INTEGRATION TRAINING

In FY 2017, the Institute continued its process improvement journey toward reaching maturity Level 2 in the Capability Maturity Model Integration (CMMI) training and development program. CMMI is an international standard of excellence applicable to both software development and other development efforts at the Institute. We maintain our commitment to adopting Agile software management practices to cultivate healthy teams, streamline development efforts, and gather essential feedback from stakeholders through minimum viable product releases. The Institute is already recognized as a quality leader in software implementations of our radio wave propagation modeling algorithms. We have set a strategic goal to claim a similar leadership position in project management and software development, and we have chosen the CMMI process model to assist us in reaching that goal.



Excerpted from the W. M. Welch Scientific Company's "Chart of Electromagnetic Radiations," 1944.

Jesse Varner

Section 2: Engineering Analysis to Inform Spectrum Policy

Telecommunication systems coexist in the radio spectrum, so considerable coordination and enforcement are required to preserve and protect the operations of those systems. As wireless systems proliferate and networks grow denser with more users and devices, there is a need for a ***balanced and responsive approach to spectrum policy***. Such an approach would be impossible without research, which provides the technical and theoretical basis for sound policy decisions. The box below describes spectrum policy's foundational research needs.

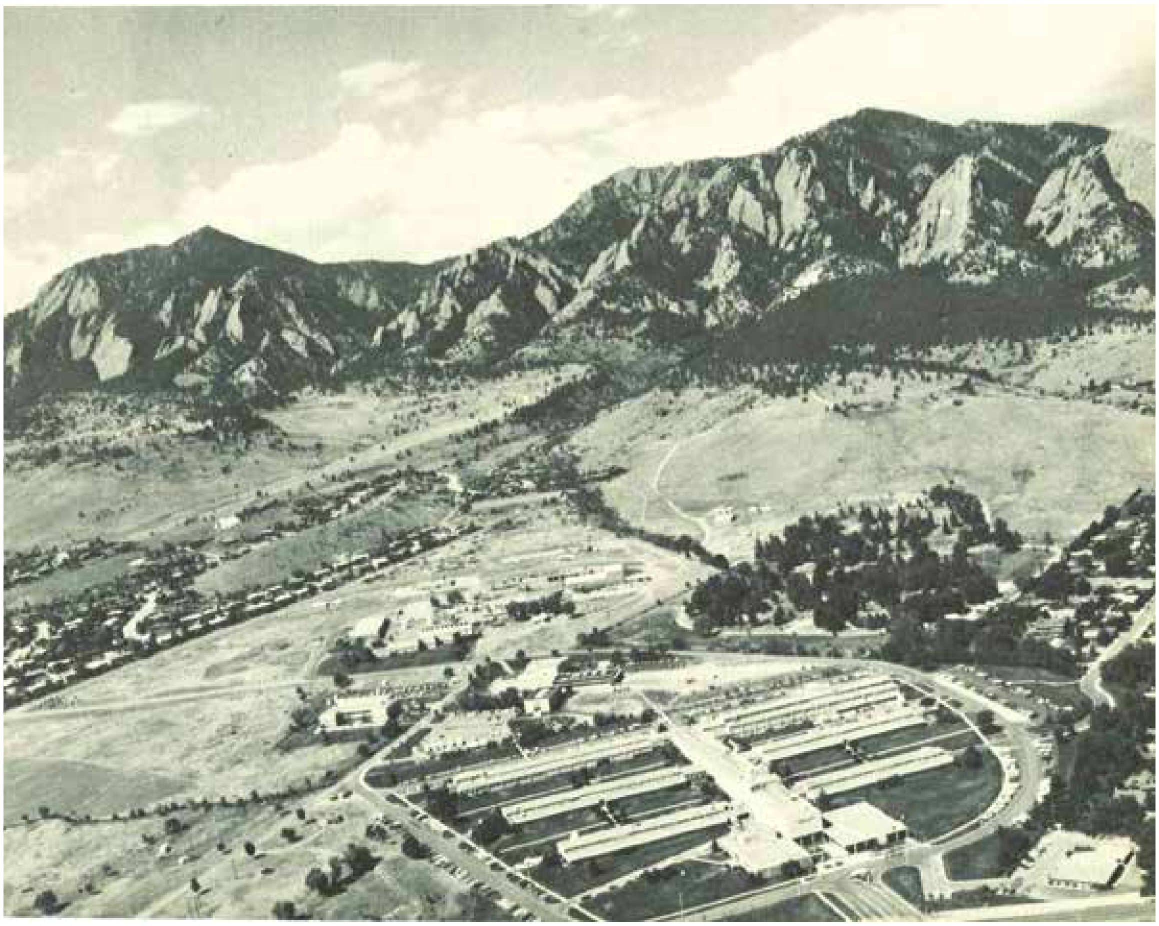
Policy Information Need		Function
▪ Profound technical knowledge of how devices use spectrum	→	facilitates analysis of proposed technologies to ensure telecommunication reliability.
▪ Theoretical expertise in electro-magnetic signal transmission, including interference	→	makes possible thorough analysis of historical trends and strategic directions for spectrum policy.
▪ Research skills and facilities relevant to propagation modeling and measurement	→	enables responsive redress of acute interference and other unexpected exigencies.

The Institute for Telecommunication Sciences is a Federal resource providing these services to spectrum management organizations within NTIA and the FCC. In this capacity, we serve as both an ongoing source of daily support and a laboratory available to investigate specific issues.

During Fiscal Year 2017, we had the opportunity to provide value to NTIA's Office of Spectrum Management, as well as the U.S. Coast Guard, by investigating several current issues in spectrum resource use. We also supported the FCC in developing methods for testing and certifying two new spectrum sharing technologies. This section describes these and other FY 2017 achievements in our work supporting other Federal agencies' missions to effectively manage spectrum use. ■

IN THIS SECTION:

SPECTRUM EFFICIENCY RESEARCH REVIEW



Cover image of the Institute for Telecommunication Science's FY 1983 Technical Progress Report

Every new innovation in connected devices promises exciting possibilities for the future, but it also means greater demand for spectrum, a critical and limited resource used both by the public and private sectors. NTIA is committed to ensuring that the government's use of this valuable resource is as efficient and effective as possible. But what does it mean to be an efficient user of spectrum? And how can future systems make better use of spectrum? In FY 2017, the Institute's researchers worked to address these conceptual questions; we will publish our findings and recommendations in an FY 2018 report.

To provide stakeholders with a thorough understanding of the context in which we must ask questions about spectrum efficiency, we dedicated considerable time to reviewing the history of the topic. The report includes a detailed technical review of more than 50 years of research examining domestic and international spectrum efficiency. Such a review of past research is important, not only to policymakers, but also for the next generation spectrum efficiency researchers to better understand what has been done in the field. With detailed background knowledge, researchers

FUTURE SPECTRUM EFFICIENCY RESEARCH NEEDS

Following our review of 50 years of spectrum efficiency studies, the Institute's key recommendations for future spectrum efficiency research are:

- Meaningful comparisons can be made only between telecommunications systems that share similar characteristics.
- There is a significant lack of research into the efficiency of new communications technologies, including "smart" antennas and the ability for systems to dynamically change frequencies based on real-time information about the radio frequency environment.
- Existing research has reflected an unbalanced focus on transmitters; future research should incorporate an equal emphasis on both receivers and transmitters.

can work to extend spectrum efficiency studies and technologies by building on past successes and overcoming existing limitations.

We conclude from our review that there is broad consensus among spectrum efficiency researchers regarding the fundamental metrics we use to measure spectrum efficiency. The global research community agrees that the efficiency of any spectrum-using system (either a transmitter or a receiver) is a quotient. The numerator in that expression is the radio system's useful throughput. The denominator is the product of the amount of bandwidth, time, and spatial volume that are blocked from use for other radio systems by the transmitter or receiver under examination. The report also finds universal consensus that a telecommunication system's spectrum efficiency can only be usefully compared with systems that are very similar in function and architecture.

In our report, we carefully review many of the major spectrum efficiency studies performed domestically and internationally during the last half century. We also assess the extent to which recommendations and software developed in these studies have been implemented. Such developments include novel methods of examining the spectrum efficiency of new Federal radio systems. The Institute and the NTIA's Office of Spectrum Management have been leaders in implementing such methods to ensure that radio frequencies assigned to new radio systems preserve or improve the efficiency of spectrum use.

Finally, we use our assessment of the past 50 years of spectrum efficiency research to make a number of recommendations for future research addressing spectrum efficiency. These include a need to extend work more than ever on new approaches for spectrum sharing between new and existing systems. ▪

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TERRAIN AND CLUTTER MODELING

Measuring and modeling signal strength variation in complex propagation paths

BACKGROUND

Protecting Federal radar from interference using novel propagation models

In response to a 2012 report of the President's Council of Advisors on Science and Technology,[1] the FCC identified the possibility of sharing the 3550–3650 MHz band (collectively referred to as the 3.5 GHz band). A prominent issue with spectrum sharing in the 3.5 GHz band is the incumbent use of the band by Federal maritime radars. Therefore, in 2015, the Institute and NTIA's Office of Spectrum Management (OSM) developed an extended version of the well known Hata radio propagation model (eHata) to identify the necessary characteristics of *coastal exclusion zones*—areas near the coasts where nongovernment signals should be forbidden in the 3.5 GHz band.[2]

Our results indicated that, in order to protect Federal maritime radars from harmful interference from commercial wireless networks, the exclusion zones would need to be geographically very large, precluding access to new services for nearly 60% of the U.S. population. In 2017, the Wireless Innovation Forum (WInnForum) nevertheless incorporated our modeling methods into its reference propagation model for use in WInnForum-compliant servers.[3] However, owing to the conservative predictions yielded by the models we used, this reference standard could overestimate aggregate interference, thereby limiting consumer use of the 3.5 GHz band

We conducted further measurements and analysis to investigate the possibility of reducing the size of the exclusion zones, but many questions remain. Therefore, in FY 2017, the OSM funded a multifaceted project aimed at improving our ability to accurately predict propagation in the 3.5 GHz band.

1 President's Council of Advisors on Science and Technology, "Report to the President: Realizing the Full Potential of Government-held Spectrum to Spur Economic Growth," Washington DC, 2012, Accession Number : ADA565091, https://www.dtic.mil/docs/citations/ADA565091.

2 Edward Drocella Jr., James Richards, Robert Sole, Fred Najmy, April Lundy, and Paul McKenna, "3.5 GHz Exclusion Zone Analyses and Methodology," NTIA Technical Report TR-15-517, 2015, https://www.its.bldrdoc.gov/publications/2805.aspx

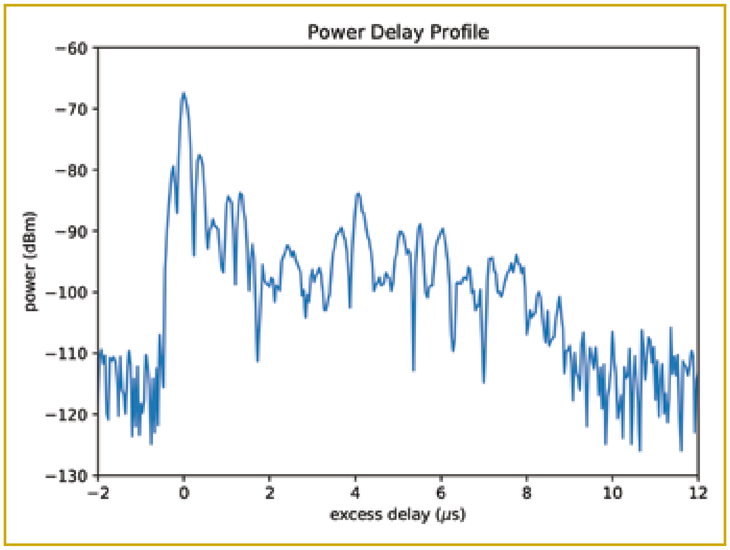
3 WINNF-TS-0122-V1.0.0.

FY 2017 DEVELOPMENTS

Predicting Signal Strength Variability Caused by Clutter An unresolved issue related to propagation modeling is the question of how to account for what happens when a transmitted signal reflects off objects in the environment, such as terrain features, buildings, or vegetation. Such objects are collectively called *clutter*, and the reflections result in variability in the strength of a received signal. This variability, or *temporal dispersion*, is not satisfactorily captured in existing standard models, including eHata and the Irregular Terrain Model (ITM).

Although the existing models are useful for many applications, their predictions show slight discrepancies when compared with real-world measurements, especially in clutter-rich environments like those involved in 3.5 GHz spectrum sharing. Thus, there is a need for improved models that are based on statistical analysis of real-world measurements.

The first step in developing such models is to gather a robust measurement dataset that can be used to inform new modeling approaches. Therefore, the first component of our project was to develop a broadband measurement system that could not only record the received power of a test signal, but could also produce *power delay profiles* like that shown here to measure temporal dispersion, enhancing our



An example of a power delay profile, showing how signal strength varies over time (temporal dispersion).

THE INSTITUTE
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POLICY RESEARCH
SPECTRUM SHARING
PUBLIC SAFETY
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TERRAIN AND CLUTTER (continued)

ability to incorporate temporal dispersion in predictive models.

In FY 2017, we deployed our measurement system, collecting data in three locations: Boulder, CO, Chapel Hill, NC, and Boone, NC (see sample result, facing page). Thanks to the rich and diverse clutter features in these environments, our ongoing modeling effort can draw on information about real-world signal paths to predict how clutter will contribute to signal degradation in situ.

Although our model is in its infancy, when compared with the ITM, our latest results show a 20 dB improvement in the mean difference between model prediction and measurement result, as well as a 10 dB reduction in prediction variability. We will continue to refine our propagation model for cluttered environments in FY 2018.

Aggregating Geographical Data for Efficient Propagation Modeling Based on Real-World Environments To develop an advanced propagation model for spectrum sharing in the 3.5 GHz band, we are employing a novel approach, which we are calling a *map-based attenuation factor approach*. This approach uses publicly available datasets, such as terrain, building, foliage, and landcover databases, to characterize the propagation path of a radio signal using several distinct categories of clutter. A simple calculation (least-squares optimization) allows us to adjust our predictions by accounting for the signal degradation we expect to observe given the clutter categories involved in a particular propagation path (attenuation factors).

For this map-based approach to work, we need to be able to input geographical information about real-world propagation environments into our model. Therefore, we are developing a terrain and map-feature server that can rapidly supply the map-based inputs to our propagation models. In FY 2017, we focused on collecting terrain and LIDAR data, as well as developing software that can quickly and accurately supply 2D terrain and building profiles.

Because our geographical data server provides functionality that has not previously been available to spectrum engineers and managers, this component of the Terrain and Clutter project has significantly grown in scope. We are now developing a system that can extract and classify map-based features from multiple databases simultaneously, enabling rapid aggregation of data into usable information. Future efforts will emphasize both 3D profile extraction and the ability to extract user-defined map features.

Throughout this effort, the Institute has been able to leverage its fundamental research portfolio and its expertise in propagation measurements and propagation model development. As a result, we have made rapid progress toward a physically motivated propagation model that significantly advances the current state of the art. ■

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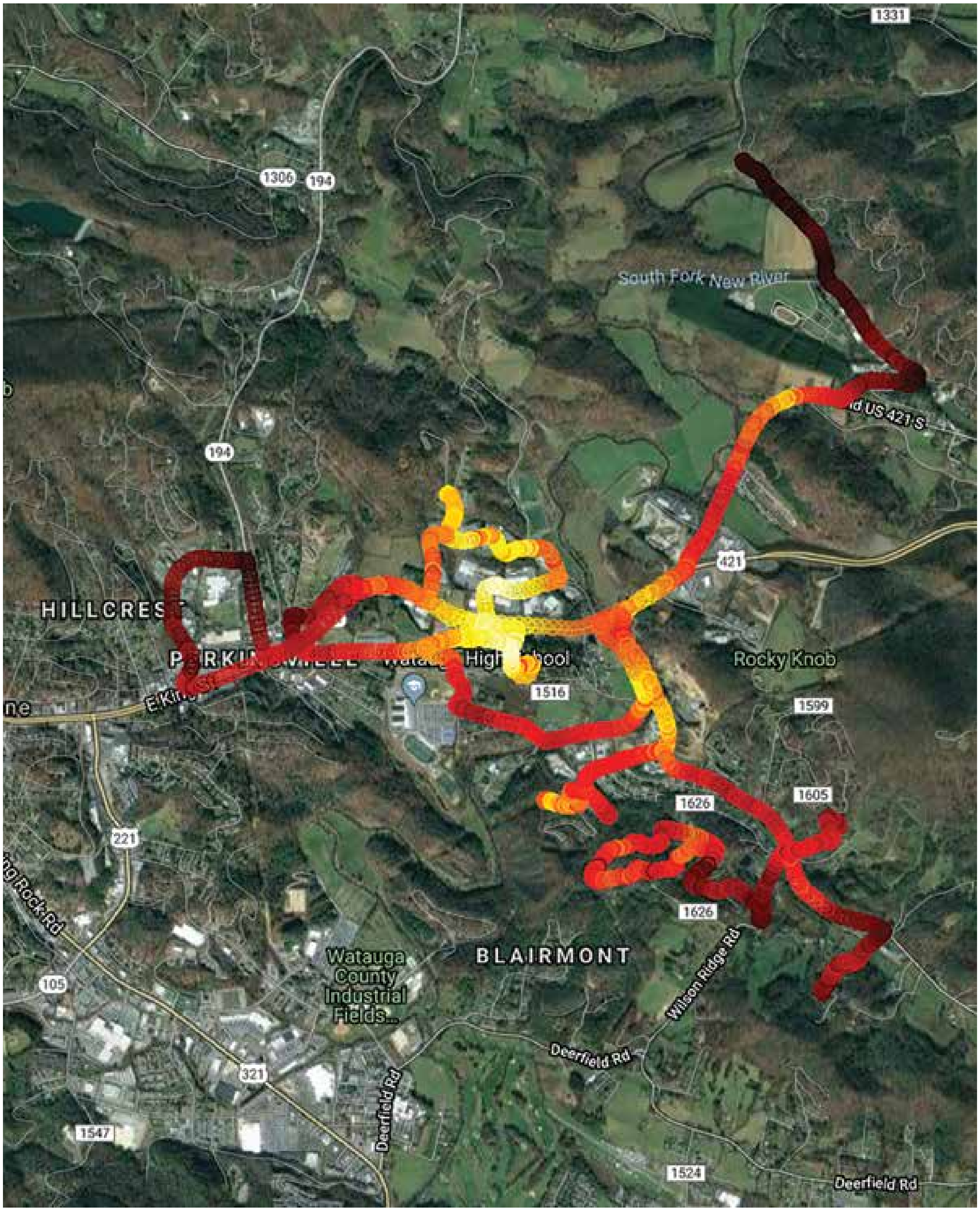

Example heat map from the Institute's FY 2017 measurement efforts in support of an improved propagation model that accounts for terrain and clutter. Lines show the route along which we drove our mobile measurement vehicle to collect data. Dark red areas indicate places where mountainous and heavily forested terrain contributed to weakened signal strength.

MARITIME SURVEILLANCE RADAR INTERFERENCE

BACKGROUND: MARITIME SURVEILLANCE RADAR, MAGNETRON VERSUS SOLID-STATE TECHNOLOGY

In FY 2017, the United States Coast Guard (USCG) engaged the Institute's IPC Laboratory to conduct research related to maritime surveillance radar (MSR). MSR technology transmits pulses whose received reflections determine the locations of various maritime obstacles such as buoys, vessels, icebergs, and shorelines. In the past, MSRs used short, high power continuous-wave pulses generated by a magnetron oscillator. The magnetron oscillator requires relatively frequent maintenance, which increases costs, and it has high frequency instability, making it difficult to develop signal processing algorithms that enable the systems to effectively reject clutter (i.e., environmental interference from terrain and other objects). Modern solid-state MSR transmitters overcome these issues.

An additional advantage of solid-state MSR technology is that it can illuminate targets over multiple ranges simultaneously. This represents an improvement over magnetron MSRs, which require users to manually switch between ranges. Solid-state MSRs accomplish multiple range illumination by transmitting a composite signal made up of pulses that illuminate short-, medium-, and long-range targets.

Although solid-state radar systems have great potential to improve maritime navigation, it is not yet known whether they are compatible with magnetron radar systems operating in the same frequency band. Measurements have shown that magnetron radar systems are able to mitigate interference from other magnetron radar systems, whose signals have low duty cycles (i.e., low ratios of pulse width to pulse repetition interval). However, solid-state radar signals have high duty cycles, and existing magnetron systems are not capable of mitigating interference from

Interference from solid-state maritime surveillance radars to older magnetron radars may be more likely when multiple solid-state radars are present in busy ports.

IT MAY NOT BE FEASIBLE TO MODIFY OLDER TECHNOLOGIES WHEN CONFLICTS WITH NEWER SYSTEMS ARISE, SO EVIDENCE-BASED SPECTRUM MANAGEMENT SOLUTIONS ARE CALLED FOR.

these signals. Field trial results have shown anecdotal evidence that this interference is a potential problem. Other research shows that interference from solid-state MSR is more likely to occur when multiple solid-state radars are present in busy ports. Such interference events can only be expected to increase with the number of solid-state MSRs.

It is not feasible to modify the many magnetron MSRs in operation, so evidence-based spectrum management solutions are called for. The purpose of the Institute's MSR interference project is to determine whether this interference is in fact a potential problem and determine characteristics of the solid state radar waveform that might contribute to the interference. Depending on the outcomes of this work, we may ultimately be able to offer a uniform method of testing for such interference that could be used to perform factory tests, reducing the likelihood that operational magnetron MSR systems will encounter interference.

FY 2017 DEVELOPMENTS

In FY 2017, we reached several milestones in our work, including briefing the Radio Technological Committee Maritime (RTCM; an association of radar manufacturers) on the project. We attended RTCM's annual meeting in Clearwater, Florida, and briefed the organization on the ongoing research project. Additional activities completed as part of the FY 2017 partnership with the USCG included:

- Developing simulations that enable us to input the characteristics of the MSR systems of interest and obtain predicted system performance data given varying levels of interference.
- Constructing methods to mathematically model important features of real-world MSR systems (e.g., composite solid state MSR pulse waveforms with Taylor weighted side-lobe suppression, dual threshold magnetron radar detection, and magnetron radar interference rejection).
- Optimizing the performance of our simulation model, enabling us to run simulated scenarios in a reasonable amount of time.

Continued research into MSR simulation is imperative if we are to understand the risks posed by interference and develop strategies to mitigate those risks. In addition to informing OSM policies, the findings of ITS research into solid-state MSR interference to magnetron MSRs could be of great interest to Federal agencies, who could face similar questions in other frequency bands. ■

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CASE STUDY: 5 GHZ INTERFERENCE

BACKGROUND

Interference to Federal radars from wireless networking devices in the 5 GHz band

In 2010, ITS engineers led an investigation into an interference problem that was hindering the operation of Federal terminal Doppler weather radars (TDWRs). The interference was caused by certain wireless networking devices using dynamic frequency selection (DFS). Both the TDWRs and the interfering devices, called unlicensed national information infrastructure devices (U-NIIs), operate in the 5 GHz band. FCC regulations for U-NIIs state that the devices must employ DFS to detect Federal radar signals and, if necessary, switch frequencies. If devices fail to comply with FCC rules, problematic interference can, and indeed did, occur.

Following the TDWR interference episode, the Commerce Spectrum Management Advisory Committee recommended that NTIA consider a study of mechanisms that could contribute to more effective enforcement of radio spectrum rules and frequency assignments. In FY 2017, the Institute responded by writing a case study on our experience researching the TDWR interference. NTIA's Office of Spectrum Management funded this work.

PREVIEW OF CASE STUDY

Report to be published FY 2018

Our case study examines the historical and technical aspects of the development and deployment of 5 GHz DFS, describing the strengths and weaknesses of DFS as they relate to TDWRs. In the report, we summarize our experience researching DFS and share lessons learned, describing how they could be applied to, and perhaps used to improve, other spectrum-sharing scenarios.

To help stakeholders understand how to prevent similar interference problems, the case study focuses on the process by which DFS was developed and implemented, and on government and industry experience with DFS subsequent to its introduction.

There may be an inherent tradeoff between quickly implementing innovative new technologies and adopting more conservative deployment schedules to reduce uncertainty and unexpected interference.

As our case study shows, DFS is a successful, but not trouble-free, technology. We suggest in our report that, the more innovative a new technology is, the greater the likelihood that it will produce unforeseen interference problems. There may be an inherent tradeoff, therefore, between quickly deploying new technologies to reap their benefits, on the one hand, and adopting more conservative deployment

The Institute is preparing a case study on interference to Federal radar from wireless networking devices using dynamic frequency selection (DFS; called U-NII devices) in the 5 GHz band. Areas of special emphasis in the report include:

- Protocols that were created for dynamic frequency selection (DFS) spectrum-sharing rules,
- Testing methods that were put into place to verify, in advance of DFS deployment, that DFS-equipped U-NII transmitters would adequately avoid frequencies in use by Federal radar systems
- Government and private-sector experiences upon the initial marketing and release of DFS-equipped radio systems
- Initial interference problems that occurred at terminal Doppler weather radar sites after the technology was first deployed
- Eventual solutions to U-NII–TDWR interference

schedules to reduce uncertainty and the potential for interference, on the other.

We conclude our case study with 10 "Lessons Learned" to provide guidance to government and industry in the future development and deployment of dynamic spectrum-sharing technologies. Two of these Lessons Learned are:

- Implement the most robust possible testing of spectrum-sharing systems prior to deployment
- Acknowledge that dynamic spectrum-sharing technologies will never be "fire and forget." They will always require ongoing maintenance and government support to ensure proper functioning, timely upgrades, and efficient redress of problematic interference.

The 5 GHz case study reached an advanced draft stage in FY 2017, and will be published in FY 2018. ■

John Carroll

Engineers Frank Sanders (ITS) and Robert Sole (Office of Spectrum Management) analyze interference to a Federal Aviation Administration terminal Doppler weather radar station at San Juan, Puerto Rico, during the investigation described in the upcoming 5 GHz Case Study report.

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TEST AND CERTIFICATION FRAMEWORKS

Verifying the operation of new spectrum sharing technologies

BACKGROUND

In the 3550–3700 MHz Citizen Broadband Radio Service (CBRS) band (the 3.5 GHz band), new commercial wireless systems will soon share spectrum with the telecommunication systems already operating in the band (the "incumbents"). Incumbents include both commercial operations licensed by the FCC and Federal operations authorized by NTIA, such as radar used on Navy ships.

The novel tiered priority sharing scheme adopted by the FCC has three essential components:

- *Spectrum access systems (SASs),* which will dynamically manage commercial broadband service providers' and users' spectrum use, ensuring that they do not cause interference to incumbent Federal radar systems
- *Environmental sensing capabilities (ESCs),* which detect Federal radar operation and communicate with the SAS, enabling the SAS to make decisions about spectrum use to protect the radar
- *Citizens band service devices (CBSDs),* which provide wireless broadband service to end users and send information about the radio frequency (RF) environment back to the SAS.

These three components must be able to communicate and share the information necessary to protect incumbents and high-priority commercial users. The first two components, SASs and ESCs, represent new concepts that have not previously been tested. Therefore, the FCC developed a strategy whereby both government and industry expertise are to be leveraged in SAS and ESC testing, and in developing standards for these technologies.

Owing to our extensive knowledge of radio propagation, spectrum sensing, and measurement, as well as our expertise in testing pulsed and chirped radar detection equipment, ***the FCC tasked the Institute with developing a testing and certification framework capable of ensuring that SASs and ESCs are compliant with the FCC's rules.*** This agreement is part of an established tradition of collaboration between the Institute and the FCC.

Certification for SASs involves testing the systems to ensure that they are capable of protecting incumbent operations from interference using algorithms and calculations to determine the following:

- How much power can each CBSD emit before its signals become strong enough to cause interference?
- How close can a device be to an incumbent system before interference becomes problematic?
- How quickly can a device be shut off or moved to a non-interfering frequency in the case of predicted or observed interference?

ESCs are equally important to Federal incumbents. The FCC requires ESCs to alert SASs when Federal radars are operating and to provide information about the frequencies the radars are using, so that the SASs can instruct CBSDs to move to another frequency, lower their power, or shut down to prevent harmful interference to Federal incumbents.

FY 2017 DEVELOPMENTS

SAS Certification In FY 2017, the FCC funded the Institute to leverage our work with the WInnForum Spectrum Sharing Committee, a multi-stakeholder standards group, to develop, verify, and validate an SAS testing framework. There were many highlights of our work during this fiscal year. We:

- Shared our experience measuring and monitoring spectrum at 3.5 GHz with WInnForum to facilitate their development of SAS and ESC standards and requirements
- Open sourced the code describing our extended Hata urban propagation model; WInnForum planned to use the code within its reference models for interference protection.
- Began verifying the WInnForum reference models
- Leveraged our own method for calculating aggregate interference to efficiently validate WInnForum's aggregate reference model
- Verified consistency of WInnForum's implementations of the Irregular Terrain Model (ITM) against the Institute's reference implementations (the "gold standard")
- Provided expert guidance on protecting radio quiet zones and international borders
- Applied our prior experience developing standards for other organizations to help WInnForum ensure clear specifications
- Drew upon our existing RF testing expertise to develop SAS testing scenarios pertaining to the systems' core operations, hypothetical limit cases, and scalability
- Interfaced with intergovernmental representatives of the incumbent Federal systems, serving as a trusted intermediary between Federal and industry stakeholders
- Continued developing visualization tools to facilitate test configuration and interpretation

The SAS Certification project is ongoing and is expected to continue through FY 2018. After WInnForum finalizes the SAS testing and certification standards, the Institute will verify and validate the certification framework. Under cooperative research and development agreements (CRADAs) with SAS administrators, we will then test SAS units using the certification test system. This will be an important step toward commercial deployment of new broadband services in the 3.5 GHz band.

ESC Certification The Institute's efforts in FY 2017 to develop the ESC certification test system have included:

- Developing radar waveform parameters for existing and future Federal radars in the 3.5 GHz band, in conjunction with the Office of Spectrum Management (OSM)
- Soliciting approval from DOD and OSM of the parameters for ESC certification testing
- Publishing our radar waveform test parameters
- Programming a vector signal generator with the radar test waveforms and developing test configurations that will generate the waveforms at the RF level

(list continues)

TEST AND CERTIFICATION FRAMEWORKS (continued)

ITS engineers discuss research results with industry representatives.

- Developing and publishing, in conjunction with OMS, draft procedures for laboratory testing of ESC sensor devices[1]
- Creating simulated radar test waveforms to enable efficient analysis of ESCs in the laboratory

The Institute is continuing to work with the FCC and DOD on the ESC test system, developing tests to determine whether an ESC unit can reliably detect our test waveforms, declare the radar's presence, and alert the SAS within the prescribed timeframe. We are also working with ESC developers to share our expertise on how to detect both chirped and pulsed radars.

Work on this project will continue in FY 2018. In addition, we expect to engage in pre-certification engineering work with the ESC operators and to use the ESC certification test system to test individual ESC units. ■

1 Frank Sanders, John Carroll, Geoffrey Sanders, Robert Sole, Jeffery Devereux, and Edward Drocella Jr., "Procedures for Laboratory Testing of Environmental Sensing Capability Sensor Devices," NTIA Technical Memorandum TM-18-527, 2017, https://www.its.bldrdoc.gov/publications/3184.aspx

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Over the past several years, the Institute has conducted extensive appropriations-funded research on radar systems and their electromagnetic compatibility with other spectrum uses, including wireless LTE devices, resulting in numerous publications in the field.[1] As part of that program, we developed versatile radar test waveforms with a view toward being able to test current and future radar systems with a wide range of characteristics and specifications. In an earlier project, ITS researchers also developed a set of radar test waveforms for assessing the dynamic frequency selection capabilities of commercial devices operating in the 5 GHz band. Finally, the Institute has a long history of engaging in certification testing of radar systems under the Radar Spectrum Engineering Criteria program, and we authored a set of best practices for radar spectrum certifications.[2,3]

1 A few notable recent examples:
John Carroll, Geoffrey Sanders, Frank Sanders, Robert Sole, Jeffery Devereux, and Edward Drocella Jr., "Non-Linear Effects Testing of High Power Radar Pulses on 3.5 GHz Low-Noise Amplifiers," NTIA Technical Report TR-17-525, 2017, https://www.its.bldrdoc.gov/publications/3173.aspx.
Frank Sanders, Edward Drocella Jr., and Robert Sole, "Using On-Shore Detected Radar Signal Power for Interference Protection of Off Shore Radar Receivers," NTIA Technical Report TR-16-521, 2016, https://www.its.bldrdoc.gov/publications/2828.aspx.
Edward Drocella Jr., James Richards, Robert Sole, Fred Najmy, April Lundy, and Paul McKenna, "3.5 GHz Exclusion Zone Analyses and Methodology," NTIA Technical Report TR-15-517, 2015, https://www.its.bldrdoc.gov/publications/2805.aspx.
Geoffrey Sanders, John Carroll, Frank Sanders, Robert Sole, Robert Achatz, "Emission Spectrum Measurements of a 3.5 GHz LTE Hotspot," NTIA Technical Report TR-15-512, 2015, https://www.its.bldrdoc.gov/publications/2790.aspx.
Frank Sanders, John Carroll, Geoffrey Sanders, Robert Sole, Robert Achatz, and Lawrence Cohen, "EMC Measurements for Spectrum Sharing Between LTE Signals and Radar Receivers," NTIA Technical Report TR-14-507, 2014, https://www.its.bldrdoc.gov/publications/2760.aspx.

2 Frank Sanders, Robert Hinkle, and Bradley Ramsey, "Measurement Procedures for the Radar Spectrum Engineering Criteria (RSEC)," NTIA Technical Report TR-05-420, 2005. https://www.its.bldrdoc.gov/publications/05-420.aspx

3 ITU-R M.1177

SPECTRUM MANAGEMENT SUPPORT

NTIA's Office of Spectrum Management (OSM) engages the Institute to provide as-needed consultation and assistance for propagation modeling, propagation measurement, and standards activities. The following sections describe the highlights of our FY 2017 support to the OSM.

FY 2017 SPECTRUM MODELING SUPPORT

- We supported the Interdepartment Radio Advisory Committee's (IRAC's) Technical Focus Group (TFG) on GPS, which performed a meta-analysis of existing measurement studies on the susceptibilities of a wide variety of GPS receivers to interference. The meta-analysis went to great lengths to ensure that all of the comparisons across different measurement campaigns were faithful. In addition, the TFG undertook theoretical studies of the propagation losses that would be incurred by terrestrial adjacent-band-signal transmitters in order to estimate the ranges at which the GPS receivers might be expected to experience interference.
- We applied the Walfisch-Ikegami propagation models to GPS. The two Walfisch-Ikegami (WI) models predict propagation in scenarios where there is a direct line-of-sight (LoS) between a transmitter and a receiver, and in non-LoS (nLoS) scenarios.
- We reviewed the Department of Transportation's (DOT's) GPS Adjacent Band Compatibility Report, providing numerous comments on the models utilized by the DOT in their compatibility analyses.
- We supported the 3.5 GHz Joint Working Group and the Dynamic Protection Area Working Group. These Working Groups focused on providing dynamic protections for Federal incumbents (principally radars) in and adjacent to the 3550–3650 MHz band. The Working Groups settled on the concept of Dynamic Protection Areas (DPAs), to be activated (and deactivated) by Environmental Sensing Capabilities (ESCs). See ***Test and Certification Frameworks*** on page 60 for more detail on ESCs and associated concepts.
- We supported NTIA/FCC modeling activities related to Spectrum Frontiers/37 GHz band studies. We evaluated the 3GPP above 6 GHz urban macro-cell propagation model for LoS and nLoS situations. The model accounts for the two situations by assigning a (principally) distance-dependent probability, p, that the path

is LoS, with the complementary probability, $q = 1 - p$, that the path is nLoS. This type of combined model has interesting implications for power aggregation of multiple independent sources.

- We supported Government Master File Contour Verification/Validation Studies by assisting in propagation modeling to identify locations useful for long distance measurements of the signal strengths of two radars located in Platteville and Parker, Colorado.

UPDATES TO THE MILLIMETER WAVE PROPAGATION MODEL

The Millimeter Wave Propagation Model (MPM-93) can be utilized to predict the complex refraction (and, therefore, absorption) by atmospheric gases of radio waves in the frequency range 1–1000 GHz. The model accounts for the molecular resonance lines of O_2 and H_2O, as well as continuum terms for N_2 and H_2O. An extensive survey was performed of relevant published literature produced since the model was developed in 1993. Based on the survey, the following updates were deemed useful:

- Update of the gaseous O_2 60 GHz–line complex spectroscopic (i.e., mixing) coefficients; we utilized the Tretyakov et al.[1] spectroscopic coefficients to perform this update.
- Update of the H_2O continuum coefficients; we utilized the Rosenkranz[2] continuum form for this update.

ITU-R STUDY GROUP 3 AND INTERNATIONAL CONSULTATIVE COMMITTEE SUPPORT

See also ***International Telecommunication Union, Radiocommunication Sector Study Group 3*** on page 103.

- March, 2017 (Geneva): notable accomplishments were the Liaison Statement (Document 5-1/38) from ITU-R Working Parties 3J, 3K and 3M to ITU-R Task Group 5/1, Recommendations ITU-R P.1411-9 ("Propagation data and prediction methods for the planning of short-range outdoor radiocommunication systems and radio local area networks in the frequency range 300 MHz to 100 GHz"), P.1238-9 ("Propagation data and prediction methods for the planning of indoor radiocommunication systems and radio local area networks in the frequency range 300 MHz to 100 GHz"), P.2108-0 ("Prediction of clutter loss") and P.2109-0 ("Prediction of building entry loss").
- August, 2017 (Geneva): notable accomplishments were the completion and approval of Report ITU-R P.2406 ("Studies for short-path propagation data and models for terrestrial radiocommunication systems in the frequency range 6 GHz to 100 GHz") and the Liaison Statement (Document 1A/215) from ITU-R Working Parties 3J, 3K and 3M to ITU-R Working Party 1A concerning propagation characteristics for sharing and compatibility studies being undertaken with regard to WRC-19 agenda item 1.15. ■

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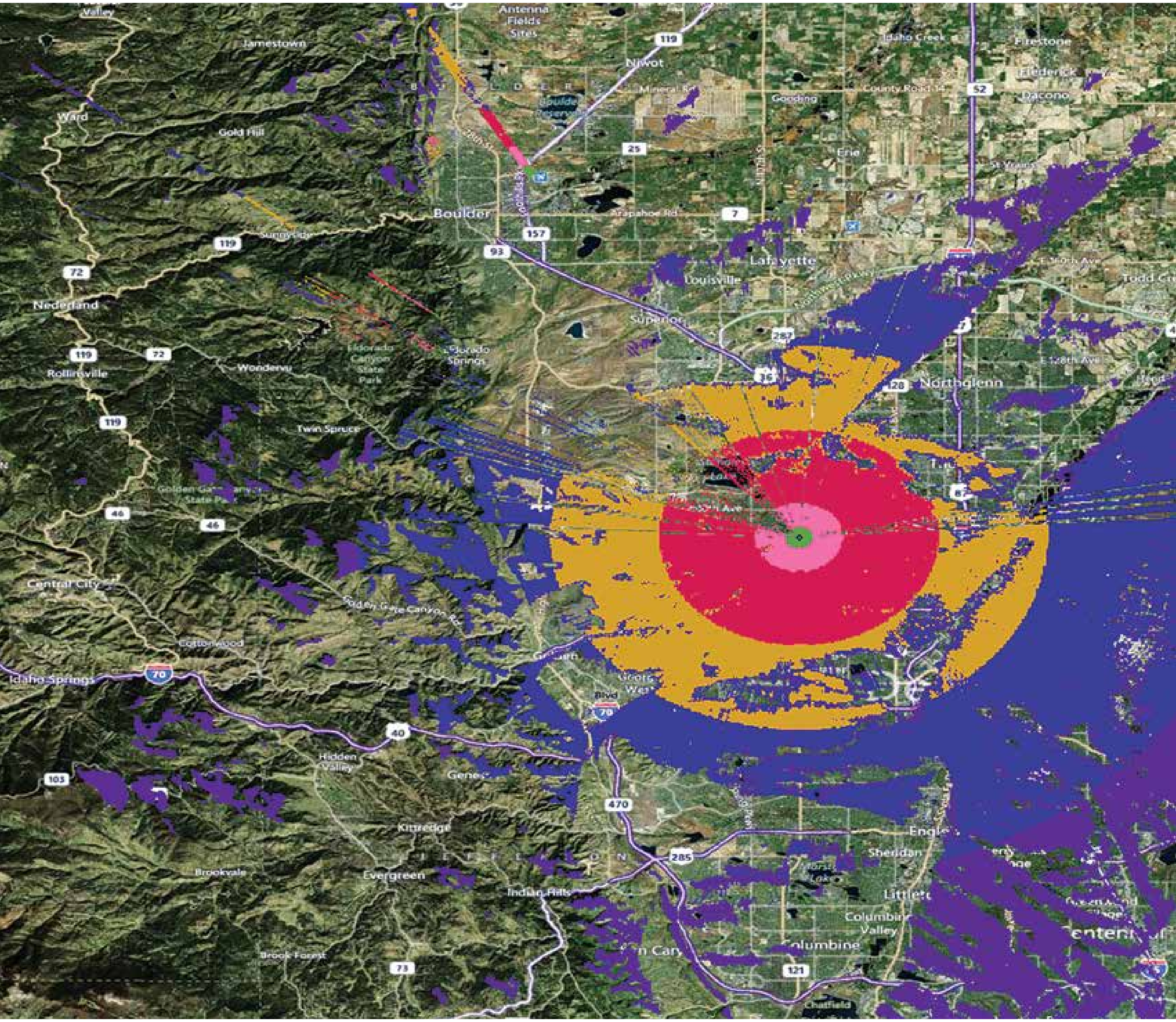
1 M. Tretyakov, M. Koshelev, V. Dorovskikh, D. Makarov, and P. Rosenkranz, "60-GHz Oxygen Band: Precise Broadening and Central Frequencies of Fine-structure Lines, Absolute Absorption Profile at Atmospheric Pressure, and Revision of Mixing Coefficients," *Journal of Molecular Spectroscopy* 231, no. 1 (2005): 1-14.

2 Philip Rosenkranz, "Water Vapor Microwave Continuum Absorption: A Comparison of Measurements and Models," *Radio Science* 33, no. 4 (1998): 919-928.

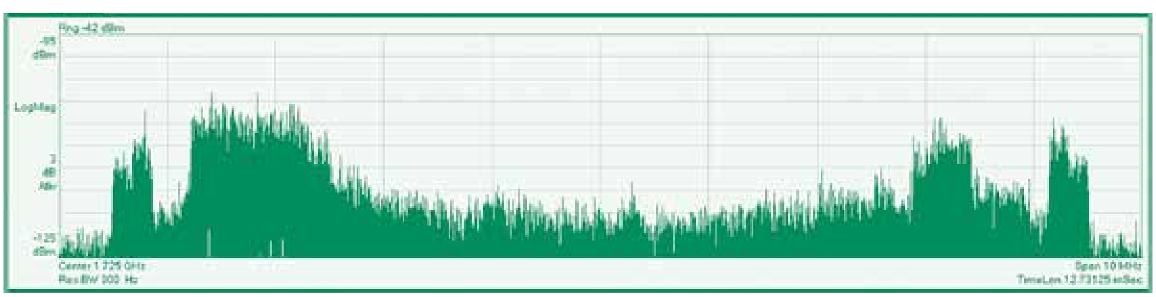


The Propagation Modeling Website enables users to model transmitter field strength. See page 78.

Section 3: Engineering Analysis to Enable Spectrum Sharing

The electromagnetic spectrum is a finite but renewable resource enabling the transmission of meaningful signals at specified frequencies. As telecommunication, particularly wireless communication, grows in scope, there is a pressing need to identify ways of using spectrum resources more efficiently. One key strategy for improving spectrum use is spectrum sharing, whereby regulators assign disparate telecommunications systems to operate over the same frequency ranges, employing techniques to prevent the systems from interfering with one another (e.g., frequency offsetting and exclusion zones). In Fiscal Year 2017, a large part of the Institute's work dealt with the issue of spectrum sharing.

Alongside our appropriations-funded work on spectrum sharing (see Section 1), we engaged in several significant projects for other Federal agencies to support their emergent needs to share spectrum with commercial wireless systems. This year, notable efforts involved supporting the Department of Defense in its Spectrum Sharing Test & Demonstration Program, and supporting NOAA in its acquisition of a new system to monitor spectrum use around its satellite downlink receiving stations and prevent interruption of the data stream. The remainder of this section describes these and other FY 2017 interagency agreement projects to enable spectrum sharing. ■



Radio frequency measurement output from a vector spectrum analyzer.

CLUTTER MEASUREMENTS

Investigating variations in radio wave propagation to support the Department of Defense

BACKGROUND: MEASURING RADIO SIGNAL PROPAGATION LOSSES FROM ENVIRONMENTAL CLUTTER

Taking radio propagation measurements from a mobile measurement vehicle along a suburban, heavily forested route in Boone, North Carolina.

The Department of Defense (DOD) is funding a major, multiyear research and engineering effort called the ***Spectrum Sharing Test & Demonstration (SST&D) Program***. A key component of the SST&D Program is the development of improved real-world measurements and predictive models of how DOD radio signals will propagate in radio frequency (RF) environments shared with commercial wireless systems. The Institute's established expertise in propagation modeling and measurement has enabled us to undertake this work on behalf of the DOD.

An important step in our goal of improving propagation modeling is to incorporate estimates of how physical objects in the environment, like buildings and vegetation, contribute to radio signal degradation. Such objects are collectively called *clutter*. Although existing predictive models like the Irregular Terrain Model (ITM) can predict

FEDERAL PROVISION FOR RESEARCH TO ASSESS SPECTRUM SHARING

Through a series of auctions, the FCC has recently released spectrum in the Advanced Wireless Service-3 (AWS-3) bands (1695–1710 MHz, 1755–1780 MHz, and 2155–2180 MHz) to make 500 MHz of additional spectrum available for commercial use, principally through spectrum sharing. Before commercial wireless service can be deployed in these shared bands, there is a need for research and testing to determine the feasibility, in terms of safeguarding critical Federal communications systems already operating in bands proposed for sharing, of various spectrum sharing scenarios. Therefore, the Commercial Spectrum Enhancement Act,[1] as amended by the Middle Class Tax Relief and Job Creation Act of 2012,[2] allows Federal agencies to recover costs associated with engineering studies to assess spectrum sharing possibilities.

1 Public Law 108-494

2 Public Law 112-96

terrain-dependent path loss, they do not sufficiently account for clutter losses. Therefore, the purpose of the Institute's ***SST&D Clutter Measurements Project*** is to advance the inclusion of clutter loss predictions in propagation models.

In the first two years of the Institute's involvement with the SST&D Program (FY 2015–2016, "Phase 1"), ITS engineers made propagation measurements in and around Denver, CO; Washington, DC; and Los Angeles, CA, to enable preliminary estimation of clutter losses. Clutter loss estimates are added as end-point corrections to terrain-dependent path loss predictions to assess possible interference into critical Federal systems. As we have moved to Phase 2 of the project, we have continued taking measurements in a diverse range of environments to further improve our understanding of and our ability to model the effect of clutter on radio signal propagation in spectrum sharing scenarios.

FY 2017 DEVELOPMENTS

In FY 2017, we travelled to Phoenix, AZ, to take measurements in the downtown and suburban environments of Phoenix, and at the rural Pima Indian Reservation. We selected this location for its comparatively flat and featureless geography, which implies that any signal degradation in the area is likely to result from clutter, rather than from the terrain.

We measured signal strength in radio signals received by a mobile measurement system driving on preset routes through each of the measurement areas. We used several different transmitting locations to better understand how the terrain and

CLUTTER MEASUREMENTS (continued)

environmental features influence radio signal propagation. Most transmitting locations were located near the downtown area and were not elevated above the immediate terrain. We also measured clutter loss given a transmission location of approximately 12 km from the downtown area at an elevation of approximately 80 m above the other locations.

Our measurement results indicated that, as we expected, the propagation paths were relatively devoid of terrain interactions. The measurements thus provided good estimates of how clutter itself contributed to path losses. Figure 13 exemplifies the type of results we obtain during this work. The figure shows the strength of our measured signal (in black) and the ITM-predicted signal strength (in red). The gap between the red line and the black measurement points indicates a level of signal degradation not accounted for in the ITM—this gap is attributable to clutter loss.

The final measurement locations for FY 2017 were in Chapel Hill and Boone, NC. This area was chosen due to its dense foliage and rural locations. During this measurement effort, we also incorporated a sliding correlator channel sounder in the measurements. We chose several transmitting locations in close proximity to one another to understand how the ITM's location variability analysis corresponds to real-world location variation measurements. We also compared measurements obtained on the same routes with three different antenna heights, and we took repeated measurements to understand how differences in the propagation channel (e.g., changes in atmospheric conditions) contribute to variability in the received signal. Figure 14 presents a repeated measurement for one of our mobile measurement routes. We drove the same route two times, indicated in the figure as Pass 1 and Pass 2. The gap between the two passes represents the time it took to drive back to the starting point. As Figure 14 shows, both the measurements (indicated by black x marks) and ITM model (red circles) show good repeatability from Pass 1 to Pass 2, suggesting that the propagation channel does not change significantly from run to run.

These data are being used to improve propagation models, understand propagation channel variability, and understand the impacts of terrain versus clutter in the received signal characteristics. ■

In FY 2017, the Department of Defense funded radio propagation measurements in suburban Phoenix, Arizona, in support of their Spectrum Sharing Test & Demonstration Program.

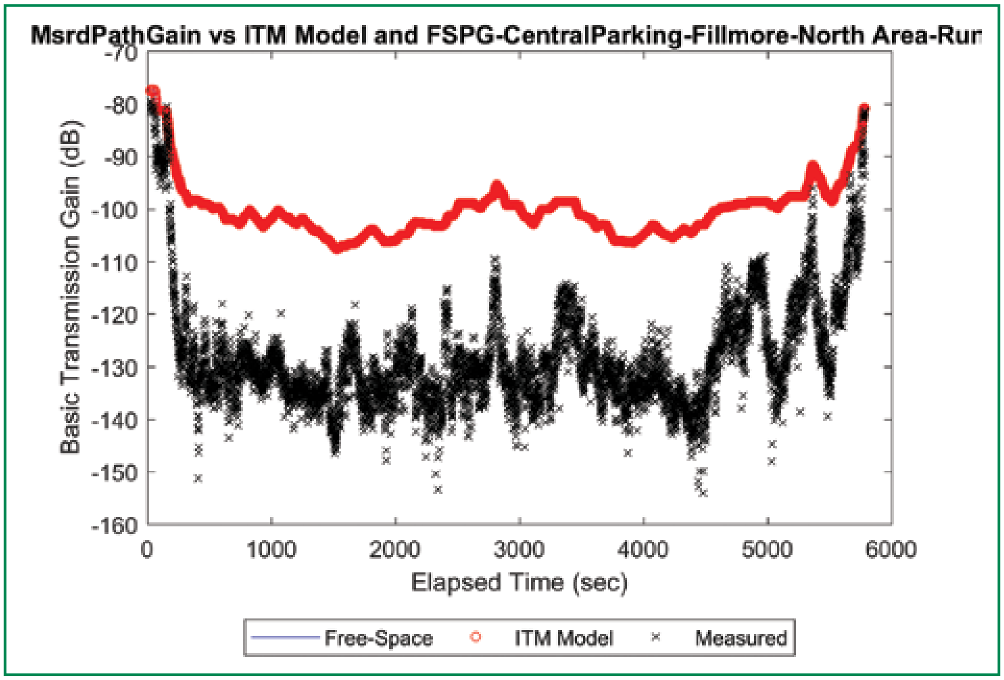


Figure 13 Basic transmission gain measurements taken from a parking lot near the downtown area into the northern suburban area of Phoenix, AZ.

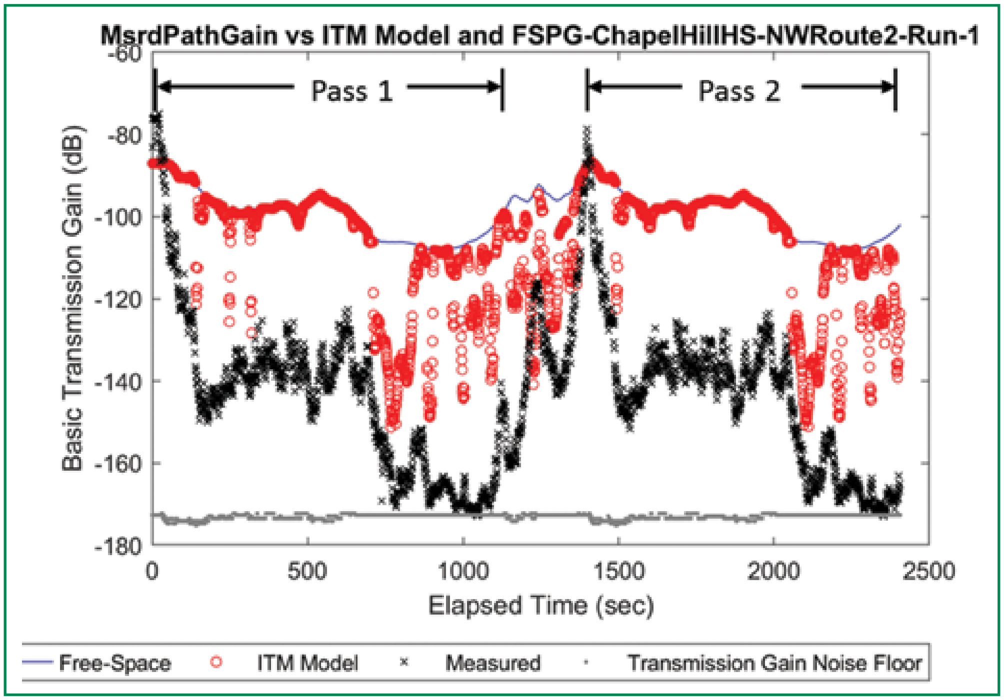


Figure 14 Basic transmission gain graph showing measured data (black x's), ITM model (red circles, free space (blue line), and noise floor (gray dots), for a repeated measurement of the same measurement route in North Carolina.

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SPECTRUM SHARING FEASIBILITY

Subject Matter Expertise in Support of Department of Defense Spectrum Sharing Research

BACKGROUND

The ***Spectrum Sharing Test and Demonstration Program (SST&D) Subject Matter Expert (SME) Support Project*** is supported by spectrum relocation funds from the FCC's Advanced Wireless Service-3 (AWS-3) auction proceeds. The project is funded by the Defense Information Systems Agency's Defense Spectrum Organization (DSO).

In the AWS-3 band, commercial wireless user equipment (UEs; e.g., smart phones) transmits over 1755–1780 MHz, frequencies shared with systems operated by the Department of Defense (DOD), including aeronautical mobile telemetry used for flight testing, the air combat training system, and unmanned aerial vehicle systems.

Engineering studies performed prior to the AWS-3 auction established guidelines for protecting existing Federal telecommunications operations from aggregate interference from the commercial UEs. The purpose of the SST&D SME Support Project is to perform additional engineering studies to improve the accuracy of these analyses and permit greater commercial access to the band.

FY 2017 DEVELOPMENTS

Data Collection and Best Practices in Support of Federal Research In FY 2017, the Institute collected samples of UE transmissions at a number of Boulder-area base stations. Statistical analysis of these data provides key insights into the dynamics of LTE uplink power control, frequency assignments, and temporal characteristics. The data are used by other research teams supporting DSO, including representatives from the private sector and academia. Additionally, the Institute's *Aggregate Emissions for LTE* project team uses characteristic data from these empirical datasets in its Monte Carlo simulator (see page 22).

The Institute's SST&D Clutter Measurements team also provides subject matter expertise to improve the quality of propagation measurements. In FY 2017, the team developed a best practices handbook, expected to be published in FY 2018, which details means of calibrating, documenting, verifying, and validating mobile propagation measurements. These best practices have already been adopted by other parties supporting the SST&D Program.

Related Projects

There are two other Defense Spectrum Organization–sponsored SST&D projects at the Institute, namely, the ***SST&D Clutter Measurements Project*** (see page 68) and the ***IF-77 Propagation Model Project*** (see page 76).

Investigating the Upper Limits of Telecommunication System Usage Measurement efforts in FY 2017 focused on expanding the prior year's dataset, which showed surprisingly low levels of channel occupancy (around 15%) during busy hours on some of the Boulder area's busiest base stations. Another key parameter of interest, the number of UEs assigned during any given 1 ms timeslot, was shown to be on the order of 1 to 3 devices, rather than the 6 that were previously assumed.

To better understand the upper bound for system usage, the Institute collected data at a University of Colorado football game with an attendance of 46,600 people. The data derived from one wireless carrier's heavily loaded base station, installed within the stadium, showed channel occupancy of approximately 50%. Despite the heavy loading, our data showed an average of only 4.2 UEs in use per timeslot—still below the 6 UE assumption.

Gathering Reference Data on LTE Communications Across Wide Geographic Areas To achieve its broad SST&D Program goals, the DSO requires reference data on over-the-air transmissions in LTE uplink bands across wide geographic areas. In FY 2017, we worked to identify suitable sites for collection of such data, as well as to refine the measurement system.

Preliminary measurements demonstrated a need for greater antenna gain and a preselector capable of rejecting signals from nearby cellular base station transmitters. Therefore, we procured a cellular cross-polarized, 20.5 dBi panel antenna and constructed a preselector to the necessary specifications. Finally, we identified an optimum measurement location at the south end of Boulder (see photo, this page). The hilltop location is more than 1.6 km from the nearest UEs and has a panoramic view of the city, making it ideal for taking meaningful aggregate UE measurements in FY 2018.

These data will be used by other SST&D research teams to develop theoretical models of aggregate LTE UE transmissions. Within the Institute, they will also be used as a means of calibrating the AELTE model. In FY 2018, we expect to apply this model to the aggregate estimation problem on behalf of DSO. ■

Measurement vehicle with a mast mounted cellular panel antenna collecting aggregate LTE user equipment measurements at a hilltop location near Boulder, CO.

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SATELLITE COMMUNICATION MONITORING SYSTEM

BACKGROUND

Spectrum Sharing in the L Band NOAA operates the nation's environmental satellites through its National Environmental Satellite, Data, and Information Service (NESDIS). NESDIS provides access to valuable global environmental data from both polar-orbiting and geostationary satellites using L-Band (1–2 GHz), S-Band (2–4 GHz), and X-Band (8–12 GHz) frequencies.

In January, 2015, the FCC held the Advanced Wireless Service-3 (AWS-3) auction to sell licenses to spectrum in the 1695–1710 MHz frequency band, where commercial wireless carriers can now deploy technologies such as LTE. NESDIS already uses these frequencies to transmit signals from satellites to 16 Earth stations across the United States. Thus, wireless carriers licensed to operate in the same geographic locations as these 16 stations will have to share spectrum with the NOAA systems.

Testing the Radio Frequency and Interference Monitoring System There is a need for analysis and planning to ensure that Federal satellite communications are not disrupted by interference from LTE signals. The Institute was ready to respond to this need, thanks to its expertise in electromagnetic compatibility studies, interference resolution, complex radio frequency (RF) measurements, and sophisticated simulations and models. The Institute has accordingly worked with NOAA on L Band spectrum sharing analysis, via interagency agreement, since FY 2015.

The Institute's role is to provide support in the acquisition of a Radio Frequency and Interference Monitoring System (RFIMS). These systems will be deployed at each of the 16 NOAA Earth stations to allow spectrum sharing with commercial LTE networks in the 1695–1710 MHz band while protecting NOAA weather satellites from interference. When the RFIMS components are ready for testing, the Institute will serve as NOAA's test and evaluation agent. We have been working to prepare the capabilities necessary for efficient and reliable testing.

ABOUT THE RFIMS PROJECT

NOAA describes the RFIMS project as follows:

Objective: Design, develop, test and deploy a system for 16 NOAA ground stations (and potentially DoD and DoI ground stations), as well as a centralized station, to monitor, identify and mitigate harmful radio frequency interference from wireless carriers' LTE services where the 1695 MHz –1710 MHz band is shared between the U.S. government and wireless carriers.

Result: The RFIMS system, once deployed, will allow commercial carriers to expand their wireless LTE systems into new territories and allow them to operate in the 1695-1710MHz frequency band without interfering with critical NOAA weather satellite operation, thereby increasing the effectiveness and efficiency of the frequency spectrum.

Source: *https://www.nesdis.noaa.gov/OSGS/assets/rfimsinfosheet.pdf*


NOAA National Environmental Satellite, Data, and Information Service

NOAA satellite imagery of a powerful nor'easter moving up the U.S. Eastern Seaboard.

FY 2017 DEVELOPMENTS

In FY 2017, the Institute took important steps in preparing to test the RFIMS, continuing our ongoing efforts in three key areas:

- We continued to establish a field-based test and evaluation capability at the Table Mountain Field Site (see page 136). The test site needs to be able to emulate, under controlled conditions, real-world RF environments that the RFIMS is expected to encounter once deployed to the NOAA Earth stations.
- We continued to examine and analyze the link budget of the satellite system, the signal propagation channels, Earth station receive systems, the external RF environment, and aggregate interference from LTE user equipment in both the main-beam and side lobes of the Earth station antennas. This analysis is necessary to determine the sensitivity requirements of the RFIMS.
- We worked to develop a long-term study that deploys ITS-developed spectrum survey systems at two NOAA sites at a time to examine spectrum usage trends in the 1695-1710 MHz band and adjacent bands before and after new commercial wireless systems are deployed.

In addition to preparing for RFIMS testing and analysis, the Institute also assisted NOAA in selecting sources for RFIMS components, following the release of NOAA's request for proposals in April, 2017. Access to the Institute's unbiased expert capabilities will enable NOAA to confidently move forward in acquiring and ultimately deploying the RFIMS. ■

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IF-77 AIR-TO-GROUND PROPAGATION MODEL

BACKGROUND

The Department of Defense Early Entry Portal Analysis Capability

The recent Advanced Wireless Service-3 (AWS-3) auction in the United States released spectrum in the so-called AWS-3 bands to commercial wireless service providers, with the goal of promoting spectrum sharing between Federal communications systems already operating in the bands (the incumbents) and new entrant broadband services. The Department of Defense (DOD) developed its Early Entry Portal Analysis Capability (EEPAC) to enable analysis of potential spectrum sharing scenarios within the 1755–1780 MHz band. A critical task for the EEPAC is to verify, using propagation modeling, that new commercial entrants into the band are not likely to cause problematic interference to the DOD incumbent systems. One incumbent system operating in the band is the Federal Air Combat Training System, an air-to-ground system.

*THE ITS-DEVELOPED **IF-77 PROPAGATION MODEL** IS A WIDELY ATCCEPTED STANDARD FOR AIR-TO-GROUND PROPAGATION MODELING. THEREFORE, THE INSTITUTE WAS TASKED, AS PART OF THE DOD'S **SPECTRUM SHARING TEST & DEMONSTRATION (SST&D) PROGRAM**, TO ASSIST IN INTEGRATING THE IF-77 MODEL INTO THE EEPAC.*

FY 2017 DEVELOPMENTS

Our FY 2017 work with the DOD involved collaboratively defining a common software interface that could support IF-77 modeling alongside other EEPAC functionality. We also made modifications to IF-77 to support the DOD's unique needs. The standard IF-77 yields targeted output values modeling how a radio wave will propagate given the input parameters. However, the DOD expressed a need for additional information on how the output is calculated. To respond to this need, we modified the IF-77 to produce intermediate output values describing characteristics of the propagation scenario, such as the path geometry used in the calculations. The DOD can use these intermediate values to conduct further studies of spectrum sharing scenarios.

Owing to our propagation modeling expertise, the Institute was able to respond to the DOD's need efficiently, establishing initial operational capability for air-to-ground modeling within EEPAC in three months. ■

See also

We built upon our FY 2017 work for the Department of Defense to begin an appropriations-funded IF-77 improvement effort. See **IF-77 Propagation Model Upgrade** on page 45.

To further develop our capability to respond to other Federal agencies' needs, we expect to continue improving the IF-77 model in FY 2018.

RADIO FREQUENCY COORDINATION PORTAL

The **Radio Frequency Coordination Portal (RFCP)** for the 1695–1710 MHz band is a website that allows new users of the frequency band (i.e., *entrants*) to submit network laydown requests for wireless operations, facilitating spectrum sharing with systems already operating in the band (i.e., *incumbents*). The Institute developed the portal in FY 2015 for coordination of sharing requests between commercial entrants and Federal incumbents across five agencies. In the last two years, we have continued to improve and maintain the RFCP in response to the needs of each of the agencies.

Commercial entrants can upload detailed coordination requests to the RFCP; Federal incumbents can then use the information to predict interference to existing operations. The RFCP also allows Federal incumbents operating in the same geographic area to coordinate with each other, and it serves as a reliable archive of requests. Notifications are automated and customized to alert users to activity that affects their respective organizations. Innovative 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. ■

In FY 2016, the Institute received a Department of Commerce bronze medal for our work on the Radio Frequency Coordination Portal

Screenshot of the Institute's Radio Frequency Coordination Portal

See also

The Radio Frequency Coordination Portal was one of the first projects to benefit from an ongoing strategic initiative at the Institute to build leadership in high quality telecommunication software development. See **Software Development and Process Improvement** on page 44.

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PROPAGATION MODELING WEBSITE

BACKGROUND

The Institute's Propagation Modeling Website (PMW) is a web-based software tool that allows users to perform radio frequency propagation analysis for different frequencies and geospatial scenarios using a broad variety of propagation models. PMW is widely used by other Federal agencies. It can be installed at users' secure locations or hosted on the Institute's own servers. We host a PMW installation for the NOAA's National Weather Service (NWS).

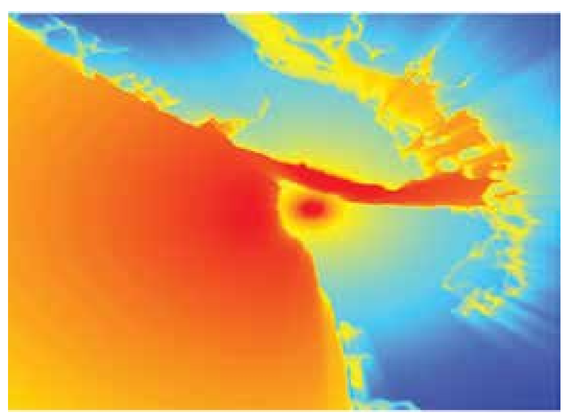
The NWS uses the PMW to plan and optimize the location of new transmitters on the NOAA Weather Radio All Hazards nationwide network, which broadcasts continuously. The potentially life-saving NWS broadcasts are required to reach at least 95% of the U.S. population. To facilitate this mission, the NWS uses PMW to verify the coverage of selected transmitters, incorporating U.S. Census 2010 population data, mapped with a granularity of 90 m^2.

FY 2017 DEVELOPMENTS

Eightfold Increase in Processing Speed In FY 2017, ITS engineers improved the PMW's broadcast coverage analysis by exploiting today's multicore computing power. We developed a solution that made the PMW population analysis at least eight times faster. When our improvements are combined with future hardware upgrades, even greater performance improvements are anticipated. The Institute also enhanced the PMW's user account controls to improve data security.

Improved Map Displays We also enhanced the PMW's map displays and modeling capabilities for the Department of Defense. Notably, we added automatic grouping/clustering of transmitters, color coding based on transmitter frequency, and advanced filtering. Further, we developed web services to support integrating the PMW with other systems and to provide greater automation capabilities. FY 2017 improvements, coupled with prior years' investments, have reduced the average processing time by 60%.

Expanded Modeling Capabilities Finally, we extended the lower end of the PMW's modeling capabilities by incorporating the ITS-developed low frequency/medium frequency (LF/MF) model. The LF/MF model supports groundwave modeling from 10 kHz–30 MHz and skywave modeling from 150 kHz–3 MHz. The software also features groundwave models that allow it to account for variation in the characteristics of soil and terrain throughout the propagation path. ■



The Institute's Propagation Modeling Website newly supports propagation modeling using the ITS-develop low frequency/medium frequency model.

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DEDICATED SHORT-RANGE COMMUNICATIONS ANALYSIS

The Dedicated Short-Range Communications (DSRC) service is a two-way short- to medium-range intelligent (or "smart") transportation communication service intended to improve roadway safety for both public safety and private operations. It uses short-range wireless links to enable data transmission between appropriately equipped vehicles ("*vehicle to vehicle*" or "*V2V*") and between vehicles and roadside systems ("*vehicle to infrastructure*" or "*V2I*"). A proposed National Highway Traffic Safety Administration (NHTSA) rule published in the Federal Register in January, 2017, would require automakers to include V2V technologies in all new light-duty vehicles. NHTSA estimated that, once fully deployed, the technology could prevent hundreds of thousands of crashes and prevent over one thousand fatalities annually.

In 1999, the FCC allocated 75 MHz of spectrum at 5850–5925 MHz (also known as the 5.9 GHz band) for DSRC. The band has also been identified as a prime candidate for sharing with Unlicensed National Information Infrastructure (U-NII) devices. U-NII devices provide short-range, high-speed unlicensed wireless connections in the 5 GHz band for, among other applications, Wi-Fi–enabled local area networks and cordless telephones. The FCC has also suggested moving the three most heavily used DSRC safety channels (V2V, control, and high-power V2I) to the upper 30 MHz of the DSRC band.

The Federal Highway Administration asked the Institute to perform several electromagnetic compatibility analyses of different scenarios under both the current and proposed band occupancy. The initial goal was to determine, via both analysis and interference testing of actual devices, whether DSRC and U-NII devices can coexist. ITS engineers conducted a survey of potential interference sources operating in and adjacent to the 5.9 GHz band. 802.11ac devices were selected for the analysis because they have characteristics typical to the type of U-NII devices that would be operating in that band if it were opened for unlicensed use.

In previous years, ITS researchers found three propagation models to be suitable to this type of analysis: the ITS-developed Undisturbed-Field Model, the ITS-developed Short Range (ITSSR) Model, and the model described in Recommendation ITU-R P.1411. All three had been previously verified and validated with measured data.

In FY 2017, ITS researchers completed baseline and interference testing of both prototype DSRC devices and the 802.11ac U-NII devices. These results were used to model the interactions of the two types of devices and develop interference protection criteria (see ***Interference Protection Criteria Estimation*** on page 30). Models were validated against measurements in an iterative process to build confidence in the accuracy of the models. Alongside the simulation capabilities that the Institute has been developing, these data will allow us to simulate proposed and existing spectrum sharing scenarios to understand the compatibility of these and future devices. ■

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Section 4: Research & Development for Public Safety

The Institute investigates emerging technologies to ensure that telecommunication systems continue to meet the specialized needs of mission-critical communication. The public safety community, including first response and national security, require reliable network coverage to enable emergency and incident response. Compared with commercial wireless networks, public safety networks have several unique characteristics:

1. Development in commercial wireless communications is often driven by the need to add capacity to networks in areas of high demand. By contrast, reliable public safety network coverage is necessary to enable emergency and incident response everywhere, including in sparsely populated areas not well covered by commercial carriers.
2. In commercial wireless networks, signal degradation caused by interference or other network problems is a nuisance and can be economically costly. By contrast, signal degradation in a public safety network may be life-threatening if it occurs during an emergency.
3. During a large-scale emergency, public safety networks must allow first responders from multiple services and jurisdictions to communicate, while giving the incident commander control over resource prioritization.

Given these differences, the Institute's Public Safety Communications Research (PSCR) Program explores the ways in which both public safety and commercial networks and equipment can be optimized for public safety users. Our research supports the inclusion of public safety requirements in standards for commercial technology. With such standards in place, public safety agencies can cost-effectively acquire communications equipment from the commercial marketplace.

We work with NIST's Communications Technology Laboratory through collaborative research projects to leverage the complementary capabilities of the two laboratories. We also work in close and constant coordination with public safety practitioners and other Federal stakeholders, like the First Responder Network Authority of the United States (FirstNet) and the Department of Homeland Security (DHS). ■

IN THIS SECTION:

IMAGE QUALITY STUDY

BACKGROUND

Public safety practitioners regularly use the Internet and mobile technologies to support their work; such technologies provide an enhanced ability to take photos and receive photos from the public. However, over half of these photos have quality problems that prevent their use in law enforcement. Therefore, there is a need for technology innovation to improve the quality of security surveillance images and other photos that could be of use in promoting public safety.

In FY 2015, the Institute conducted interviews with over 100 first responders from a range of departments across the United States to better understand the magnitude and characteristics of image quality issues. We asked respondents how their departments use cameras and what quality problems they encounter. We have engaged in an ongoing process of categorizing and describing these survey responses to enable us to understand image quality problems in measurable ways.

> ***OUR AIM IS TO ENCOURAGE THE DEVELOPMENT OF NEW CAMERA TECHNOLOGIES TO ENSURE THAT PHOTOS TAKEN BY MOBILE DEVICES AT CRITICAL MOMENTS MEET FIRST RESPONDER NEEDS.***

FY 2017 DEVELOPMENTS:

Our goal in FY 2017 was to leverage ITS expertise in video quality and camera technologies to identify how gaps in existing technology result in the image quality problems that first responders identified in our interview study. We therefore compiled and published a list of 48 technology gaps that impact first responders,[1] with the aim of fostering discussion around research and product innovation. The publication identifies desirable camera attributes, describes how first responders use cameras, and quotes specific problems that were mentioned during our interviews.

One problem discussed in the FY 2017 report is the presence of *obscurants* like rain and deep shadows, which obscure objects in digital images (see photos, facing page). Such environmental obscurants make it difficult for first responders to use photos and videos to observe vehicles, people, and other targets of interest. Digital compression algorithms struggle with some obscurants, introducing artifacts that confound the already difficult viewing situation—even in cases where a human viewing the same scene in person could easily discern the objects of interest.

Future research at the Institute will thus focus on devising solutions, along with ways of implementing them, that are relevant to the variety of imaging applications within the public safety community. ■

1 Margaret Pinson, "Technology Gaps in First Responder Cameras," NTIA Technical Memo TM-17-524, 2017, https://www.its.bldrdoc.gov/publications/3171.aspx.

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Consumer Digital Video Library

Over half of photos taken by mobile devices do not meet the quality needs of public safety, including law enforcement. In the photos above, similar scenes are shown with (top) and without (bottom) dust obscuring the image. The Institute works closely with first responders and Federal public safety agencies to define and prioritize future research projects that might contribute to mitigating or resolving these problems.

PUBLIC SAFETY INDOOR BROADBAND COVERAGE APP

BACKGROUND

The First Responder Network Authority of the United States (FirstNet) will soon deploy a national public safety wireless network, the Band 14 network, within the 700 MHz band. Band 14 was chosen for the FirstNet Long-Term Evolution (LTE) network in part because it provides relatively good propagation into buildings. This is especially important because first responders are often required to enter buildings, and their safety depends on reliable communications with incident commanders and others outside the buildings.

The Institute's ***Public Safety Communications Research (PSCR) Program*** is exploring practical, low-cost ways to empower public safety stakeholders to perform their own LTE coverage measurements inside buildings. With the ability to collect robust data on in-building LTE coverage, public safety stakeholders can identify coverage problems and collaborate with LTE network operators to expedite solutions to those problems.

In order to enable public safety practitioners to college LTE coverage data we need to develop:

- An affordable LTE radio receiver that can provide access to relevant information about received signals
- Measurement methods that are both accurate and reliable
- An app interface that is simple to operate and accessible to public safety practitioners
- A simple and meaningful scoring system to quantify in-building LTE coverage and relate it to the performance of video, audio, and data apps

We are investigating the use of existing Public Safety Band 14 phones, along with a PSCR-developed app, to perform in-building measurements of the LTE reference signal received power (RSRP; a measure of signal strength). We have developed a scoring algorithm that maps the measured RSRP levels to a single score in the range of 1-10. We can relate this score directly to the performance of the Band 14 LTE network. The scale is as follows:

The Institute's scoring algorithm maps measured signal strength to a single, user-friendly score in the range of 1-10:

- **7-10: Excellent network performance**
- **4-10: "Ok" network performance**
- **1-4: Severely degraded network performance**

Using our app, public safety officers can easily identify how the Band 14 LTE network will perform in indoor areas.

- 7-10: Excellent network performance; expect high performance from installed video, audio, and data apps
- 4-10: "Ok" network performance; expect some degradation in high-definition video and high-speed data apps.
- 1-4: Severely degraded network performance; expect that video apps will not function at all and data speeds will be significantly reduced; below a score of 2, expect tenuous network connectivity with possible connectivity loss.

Using the app's simple scoring system (see inset box, facing page), public safety practitioners can quickly determine whether their devices will perform well enough to conduct important operations.

In-Building Coverage App Tests in Boulder and Houston In FY 2017, our progress toward developing the LTE RSRP app continued. Our emphasis was on testing the app in real-world environments where potential first-responder scenarios could take place. Thus, we performed an extensive series of measurements on the campus of the University of Colorado at Boulder (CU) and in Houston, Texas. The buildings that we measured are:

- Coors Events Center (CEC), located on the CU campus
- Champions Center, located on the CU campus
- George R. Brown Convention Center, located in downtown Houston
- NRG Stadium in Houston
- Galleria Mall in Houston

At the Galleria Mall, we connected a Band 14 LTE phone with the app installed to the Harris County Band 14 network, and we performed a series of measurements on three different levels of the main east–west corridor of the building. We captured network performance data for 500 meter long paths on each level. To minimize the potential for the measurer's body to influence the results, we used a plastic selfie stick to distance the phone from the measurer (see photo, page 85).

Figure 15 shows the results that we obtained. On the top level, we obtained a coverage score of 4.7, indicating "ok" coverage. As we progressed to the

FY 2017 DEVELOPMENTS

A public safety officer uses the Institute's indoor network coverage app at the Galleria Mall, Houston, TX. The officer uses the app with a selfie stick to ensure an accurate result.

INDOOR BROADBAND COVERAGE APP (continued)

lower levels, the score decreased. On the middle level, we obtained a score of 3.8, and, at the lowest level of the mall, we obtained a score of coverage score of only 1, indicating very poor coverage.

This work was funded by the Department of Homeland Security's (DHS's) Office for Interoperability and Compatibility (OIC), which leads the DHS effort to enable interoperable emergency communications among 60,000 Federal, state and local public safety agencies.

App Demonstration The DHS's Science and Technology Directorate sponsored the Institute in a demonstration of the public safety app at the 83rd International Conference of the Association of Public-Safety Communications Officials (APCO) on August 14-15, 2017, in Denver, CO. The public safety community and representatives of the commercial wireless industry provided excellent feedback, and there was significant interest in low-cost Band 14 coverage measurement. ■

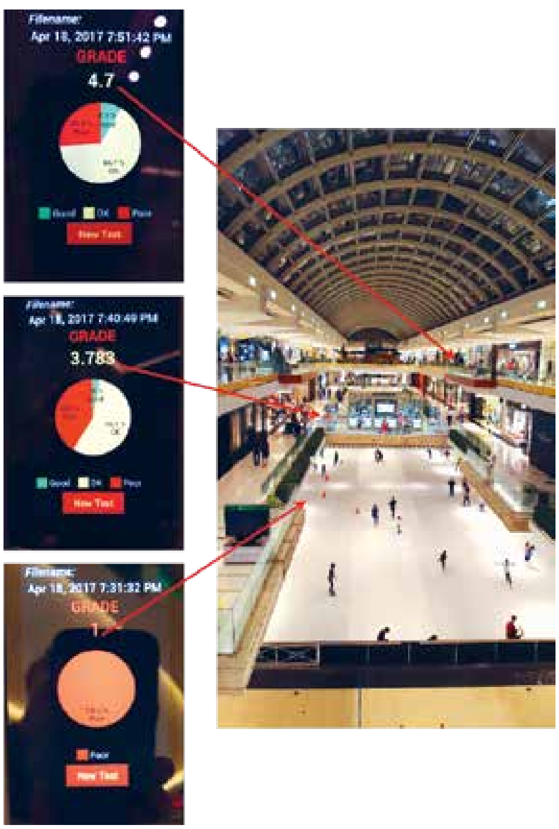

Figure 15 Broadband coverage scores obtained using the Institute's in-building coverage app in the main east-west corridor in the Galleria Mall in Houston.

Sample result showing variation in signal strength in different areas of a hallway in the Champions Center, University of Colorado at Boulder.

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SPEECH CODEC COMPARISON

During FY 2017, the Department of Homeland Security (DHS) sponsored a comprehensive set of speech intelligibly measurements in support of mission-critical voice communications for public safety users. As police officers, fire fighters, and emergency medical providers migrate their communications from land mobile radio (LMR) systems (such as two-way radios) to shared LTE infrastructure (such as mobile phones), there is a need to test the intelligibility of signals in a wide range of potential environments and scenarios.

In FY 2017, we tested speech intelligibility in 120 different scenarios (using 5 different speech codec modes in a total of 24 different environments) in order to precisely quantify the relationships among radio channel conditions, background noise levels, and the intelligibility of the received speech.

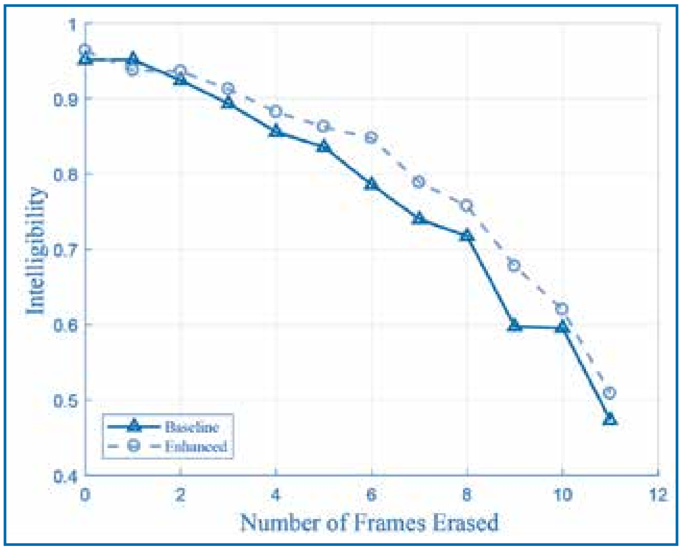

Figure 16 The upper line represents a class of codec modes with enhanced robustness to radio channel degradations. ITS results show the extent to which the enhanced class offers speech intelligibility advantages over the baseline class of codecs represented by the lower line.

An example result is shown in Figure 16 (see figure caption for technical detail). Results like this allow the Institute to identify how much a radio signal can deteriorate before it becomes too difficult to understand. This is important because some of the situations associated with radio channel degradations are also situations where speech intelligibility has an elevated importance. For example, communication may be especially critical at severe incidents that require a large number of emergency responders, but the presence of multiple radio communication systems at the site of such an event increases the likelihood that the systems will come into conflict, degrading signal quality.

Data on speech codec performance in various environments can therefore guide development, deployment, and tuning of mission-critical voice applications. The full results of the DHS-funded speech codec intelligibility study will be published in FY 2018. ■

Learn More Online: The full results of the Institute's speech codec comparison (NTIA TR-18-529) are available online at https://www.its.bldrdoc.gov/publications/3190.aspx

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LTE PRIORITY MECHANISMS FOR EMERGENCY PREPAREDNESS

BACKGROUND

Giving Priority to Critical Communications in LTE Networks Under certain circumstances, commercial wireless networks may experience high network congestion, reducing the probability that a normal call can be completed without interruption. Therefore, there is a need for a system that identifies and gives network priority to critical calls made for public safety, national security, or emergency response. The Wireless Priority Service (WPS), administered by the Department of Homeland Security's Office of Emergency Communication (OEC), provides such a system. To access WPS, users dial a special access code before their destination phone number on a registered wireless device. Commercial networks then give priority to the call, safeguarding critical communications.

The Institute's expertise in national security and emergency preparedness (NS/EP) telecommunications enables us to support the development of emergency communications infrastructure programs like the WPS. The next step in the development of WPS is its implementation in LTE networks. Mobile network operators (MNOs) have proposed various priority mechanisms to deliver the WPS functionality upon which public safety users of 2G and 3G wireless have come to rely. These mechanisms are collectively referred to as Next Generation Networks Priority Services (NGN-PS).

Evaluating LTE Priority Mechanisms

The OEC has engaged ITS researchers as technical consultants in a multi-year project supporting the rollout of LTE WPS. Our recent work has involved exploring the technical parameters of LTE WPS to validate priority mechanisms proposed by MNOs before they are implemented. Such work is essential to ensure that LTE WPS communications will, when deployed, receive priority over less critical calls.

The ITS NGN-PS test bed (see schematic, Figure 17) enables us to analyze proposed priority mechanisms using commercial and public safety equipment. We conduct LTE attach procedure tests derived from OEC's Government Industry Requirements (GIRs) for priority services. The GIRs specify OEC's network expectations regarding number of users, service type (voice, video, data), priority levels, priority access authorization processes, and performance and cost metrics. Our test bed allows us to focus on both the end-user experience and the higher-level protocol traffic that goes with it when NS/EP users send and receive voice, video, and data.

FY 2017 DEVELOPMENTS

In FY 2017, the ITS NGN-PS project team performed a functional evaluation of a number of NGN-PS mechanisms by tracking call data through a typical LTE call flow. Of particular importance were tests performed on two priority mechanisms proposed for LTE wireless network hardware (eNodeBs): the Automatic Access Class Barring (AACB) and High Priority Access mechanisms. The AACB is an algorithm that controls which mobile devices (user equipment [UEs]) are allowed to connect to the network, based on their assigned access class. The goal is to ensure that NS/EP users can communicate during emergency situations by granting network resources to UEs identified as

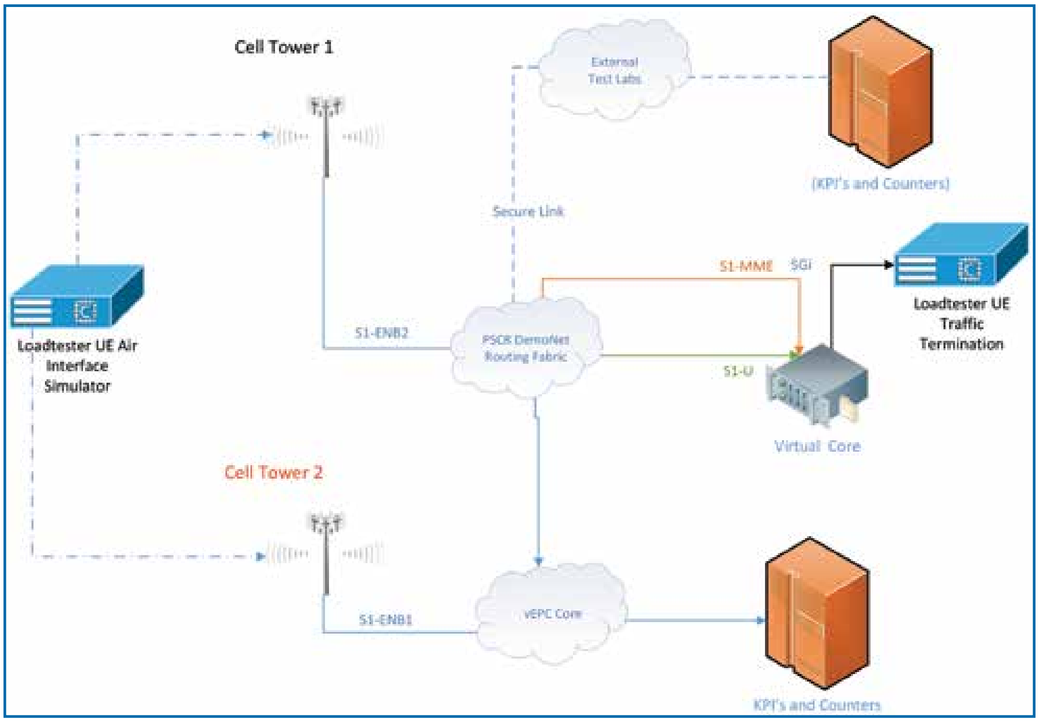

Figure 17 Schematic illustration of the Institute's Next Generation Networks Priority Services (NGN-PS) test bed. This test bed is used to analyze mechanisms that assign network priority to national security and emergency preparedness users, safeguarding critical communications under congested network conditions.

belonging to the NS/EP access class, while temporarily preventing other UEs from connecting.

The Institute acquired the capability to test mechanisms that depend on voice over LTE (VoLTE) technology. During FY 2017, we tested VoLTE-based priority mechanisms for call completion and quality. Results provided the OEC with data showing the effectiveness of the mechanisms on one vendor's eNodeB.

We expect to continue our priority mechanism testing in FY 2018, focusing on how other models of equipment deployed in the network handle data transmission at the level of user data (the user plane) and at the level of network control (the control plane) in NS/EP scenarios. We will also generate and evaluate models of network traffic to be used for emergency simulations.

Although each of these tasks will be essential to deploying LTE WPS, control plane testing is a top priority. It is important that we focus on control plane testing first, since the majority of resource allocation and network access decisions are performed and implemented at the control plane level. ITS researchers can use control plane test results to advise the OEC regarding whether MNOs' proposed solution will satisfy the WPS GIRs. Our work will ultimately provide data that the OEC can use to release a technology road map for priority services. ■

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Researchers from NIST test an unmanned aerial vehicle at the Table Mountain Field Site. See page 98.

Section 5: Technology Transfer

One of the Institute's most important roles is to transfer technology to the private sector and to other government agencies. The White House Memorandum on FY 2019 Administration Research and Development Budget Priorities emphasizes the importance of both maximizing interagency coordination in R&D and leveraging federal R&D investments to drive economic growth.[1]

In accordance with the President's Management Agenda[2] goal to "improve the transfer of technology from federally funded research and development to the private sector," we aim to foster innovation by rapidly integrating our research outcomes into the U.S. economy through technology transfer, with the following objectives:

- multiply the economic and social impact of the Institute's own research and development investments
- aid other public- and private-sector researchers by releasing into the public domain the results of our work with Federal partners under interagency agreements (IAAs)
- promote U.S. leadership in telecommunications technology by advocating for strong unbiased national and international standards that support a globally competitive marketplace.

We accomplish these goals through:

1. cooperative research and development agreements (CRADAs) with industry and state/local governments,
2. IAAs with Federal agencies,
3. technical publications,
4. participation in the development of requirements and standards,
5. conferences, workshops, and symposia, and
6. open source software releases.

The following sections detail our FY 2017 efforts in each of these areas. ■

"BY PROVIDING THE FUNDAMENTAL BUILDING BLOCKS OF NEW TECHNOLOGICAL ADVANCES, THE GOVERNMENT CAN EMPOWER THE PRIVATE SECTOR TO ACCELERATE RESEARCH DISCOVERIES FROM THE LABORATORY TO THE MARKETPLACE."[1]

IN THIS SECTION:

1 https://www.whitehouse.gov/sites/whitehouse.gov/files/ostp/fy2019-administration-research-development-budget-priorities.pdf

2 https://www.whitehouse.gov/wp-content/uploads/2018/04/ThePresidentsManagementAgenda.pdf

CONFERENCES, WORKSHOPS, AND SYMPOSIA

INTERNATIONAL SYMPOSIUM ON ADVANCED RADIO TECHNOLOGIES 2017

August 15–17, 2017
Broomfield, Colorado

The annual International Symposium on Advanced Radio Technologies (ISART) is cosponsored by the Institute and NIST's Communications Technology Laboratory. ISART 2017 was a great success; the results of the post-symposium survey showed that 89% of attendees were completely or very satisfied! ISART 2017 explored millimeter waves (30–300 GHz), also known as mmWaves or extremely high frequency waves. The symposium focused on five different perspectives on the challenges of exploiting mmWaves for new communications technologies: regulation, defense, standards, measurement and modeling, and systems.

The mmWave frequencies are currently less utilized than other frequencies, making their increased utilization a promising way to meet the growing demand for spectrum. However, exploiting the mmWave frequency bands presents significant challenges. Although these bands could increase the speed of cellular service more than ten times, their small size also means that they are more prone to attenuation. Manufacturing the equipment to exploit mmWave frequencies also presents challenges, owing to the bands' short wavelength and high speed.

One of the goals of ISART 2017 was to convene the world's experts on advanced radio systems development, exploring new ideas, brainstorming, and perhaps even solving some of the obstacles to exploiting the mmWave bands. Researchers, business leaders, policymakers, telecommunication regulators, and technology forecasters shared both ground-breaking developments and open questions with respect to mmWave technologies and their applications.

International Symposium on Advanced Radio Technologies 2017 attendees.

ISART 2017 HIGHLIGHTS

- The ISART 2017 keynote address was delivered by Tom Power of CTIA, in a "Power Hour" with Jennifer Manner of EchoStar and Alan Norman of Facebook. The address opened the first full day of the symposium and was titled ***Millimeter Waves: What's at Stake?***
- During the first panel discussion, titled ***Millimeter Wave High-Speed Data Links: a Mobile Backhaul Perspective***, panelists discussed innovative technologies under development to overcome the challenge of the very short range of mmWaves.
- Jean-Aicard Fabien of ITS moderated a panel on ***The Standards Perspective*** that laid out the path being followed by standards bodies to advance from LTE (4G) to New Radio (5G).
- Paul Tilghman of the Defense Advanced Research Projects Agency (DARPA) introduced the ***Spectrum Collaboration Challenge***, a collaborative machine-learning competition to overcome scarcity in the radio frequency spectrum. DARPA challenges competitors to reimagine a new, more efficient wireless paradigm in which radio networks autonomously collaborate to dynamically determine how the spectrum should be used moment to moment.
- The symposium wrapped up with a panel entitled ***5G/mmWave Capacity Improvements: A Systems Perspective***. Speakers looked across the entire protocol stack at potential architectures for the ultra-dense networks demanded by mmWave propagation characteristics. The panel was moderated by Chris Anderson, U.S. Naval Academy and visiting researcher at the Institute.

TACTICAL ENCRYPTION AND KEY MANAGEMENT WORKSHOP

On February 15-16, 2017, the Institute hosted a two-day workshop on Tactical Encryption and Key Management (EK&M) at the Boulder Labs to look into the future to see what E&KM may look like, and at the present to see what technologies can be leveraged to take us there. The workshop was sponsored by the Defense Advanced Research Projects Agency and organized and hosted as a joint effort between the Institute and the RAND Corporation.

CROSS-AGENCY TERRAIN WORKSHOP

George Lukes and Frank Rotondo, experts in geospatial representation from the Institute for Defense Analysis, visited the Institute in Boulder to lead an in-house workshop April 19-20, 2017 to jointly explore the impact of different terrain data sources on prediction results and the associated computational burden. The workshop provided valuable insight into the characteristics and potential applications of the various terrain databases and their origin. ■

Learn more about ISART 2017 online:
https://www.its.bldrdoc.gov/isart/past-programs/2017-isart.aspx
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COOPERATIVE RESEARCH & DEVELOPMENT AGREEMENTS

Cooperative research and development agreements (CRADAs) facilitate the transfer of commercially useful technologies from Federal laboratories to state and local governments and to the private sector. In addition to allowing private-sector entities, including small businesses, to leverage Federal resources and undertake larger research projects than would otherwise be feasible, CRADAs provide the Institute with insight into industry's needs, enabling us to adjust the focus and direction of our programs as needed to provide value to the U.S. economy. In FY 2017, the Institute participated in several CRADAs involving the design, development, testing, and evaluation of advanced telecommunication concepts.

Through recent CRADAs, the Institute has contributed to the development of new products and services in the areas of high-resolution laser radar (LIDAR), autonomous networks for unmanned aerial vehicles (UAVs), and broadband air-interface and core network capabilities for LTE mobile communications.

PUBLIC SAFETY 700 MHZ BROADBAND DEMONSTRATION AGREEMENTS

The Institute maintains a test bed and an over-the-air (OTA) network, which enable evaluation of public safety telecommunications technology. Over the past five years, the majority of the Institute's CRADAs have enabled our partners to leverage this Public Safety 700 MHz Broadband Demonstration Network. Commercial equipment manufacturers and wireless carriers can use these capabilities to test interoperability of 700 MHz LTE public safety communications equipment under simulated field conditions, with the participation of public safety practitioners.

At the close of FY 2017, 53 CRADAs were in place under the Public Safety Communications Research (PSCR) program. Because CRADAs protect our partners' intellectual property, they encourage industry participation in testing, enabling the simulation of real-world multivendor environments. The PSCR test bed is the first non-private facility in the United States with the capabilities necessary to ensure that public-safety-specific LTE requirements are effectively implemented.

SEE ALSO

In FY 2017, the Institute researched mechanisms for ensuring that urgent public safety communications can receive LTE network priority, even in crowded network conditions. See ***LTE Priority Mechanisms for Emergency Preparedness*** on page 88.

COOPERATIVE RESEARCH AGREEMENTS FOR THE USE OF TABLE MOUNTAIN

The Institute manages the Table Mountain Field Site and Radio Quiet Zone, a unique research facility north of Boulder. The site enables radio research and experimentation in a controlled outdoor environment. Because Table Mountain is one of only two Federally mandated radio quiet zones in the United States, partnerships are encouraged to maximize the site's utility. CRADAs enable industry and academia to make use of Table Mountain facilities. Access to Table Mountain particularly benefits small businesses by enabling them to conduct advanced research that would otherwise be out of reach. In FY 2017, the Institute participated in seven CRADAs at Table Mountain, three of which were with small businesses.

The University of Colorado: Communication Networks for Unmanned Aircraft "Flocks" The University of Colorado is researching wireless communication between low-cost, small unmanned aircraft (UA) and ground-based radios. The goal is to develop a system for autonomous "flocking", whereby multiple UAs can collectively and autonomously complete sensing and communication tasks, following ground-control coordination. Work in FY 2017 included continued development of unmanned aircraft systems including cooperative control flight experiments and aircraft launch system testing. Research under this CRADA is targeting atmospheric science applications, including wind sensing. The Table Mountain site also facilitates ongoing work to model the radio frequency environment between unmanned aircraft and ground nodes.

FIRST RF Corporation: Small Business Testing of Radio Antenna Prototypes FIRST RF Corporation is a small business that designs and manufactures radio antennas and systems. Under a CRADA with the Institute, FIRST RF uses Table Mountain as a field location to test the functionality of new antenna designs during product development. In FY 2017, FIRST RF used the large turntable to test antennas of various formats and sizes, from body wearable to aircraft mounted, over a range of frequencies.

Unmanned aircraft research takes place at the Table Mountain Field Site through cooperative research and development agreements with the Institute.

COLLABORATIVE RESEARCH AGREEMENTS (continued)

Areté Associates: Testing Remote Sensing Technologies Areté Associates is a small business that develops and produces remote sensing technologies. Areté is currently developing new airborne and portable advanced LIDAR technologies for the U.S. Department of Defense. By partnering with the Institute, the company can safely conduct field tests to support its LIDAR work. In FY 2017, Areté used the Table Mesa site to evaluate the relative viability of multiple active and passive sensing methodologies (see photo, below). Such testing provides information about how sensing methodologies perform in natural atmospheric conditions, allowing Areté to progress its technologies from laboratory testing to field testing and identify directions for further development work.

Ball Aerospace: LIDAR Systems Distinguish Kites from Birds of

One of Areté Associates' active sensing experiments at the Table Mesa Field Site used an array of weather stations to collect data for comparison with remotely sensed measurements. Photo courtesy of Areté Associates.

Prey Ball Aerospace's CRADA for the use of Table Mountain enables the company to conduct LIDAR system tests, which require a large, access-restricted open space for safe propagation of laser beams. Systems tested under this CRADA include a wind LIDAR (for NASA), a 3D full-motion video LIDAR (for the Department of Defense), and sensing LIDARs for hazardous liquids and methane (for Federal and commercial applications). In FY 2017, Ball tested its LIDAR systems' ability to distinguish different small targets, such as kites, University of Colorado UAs, and birds of prey.

Lockheed Martin Coherent Technologies: Advanced LIDAR Wind Sensing and 3D Imaging The Institute maintains CRADAs with Lockheed Martin Coherent Technologies (LMCT), through which LMCT conducts research to improve its LIDAR systems, including systems for wind sensing (for the offshore wind energy industry) and 3D imaging. In FY 2017, LMCT began a new round of experiments, testing a photon-counting LIDAR system that uses a low-power pulsed laser to develop 3D images of targets. The new system is one component of a larger research program to develop innovative advanced sensing capabilities. One goal is to develop the ability to determine, in real-time, the range and velocity of targets with low visibility.

Multiple Partners: NOAA Weather Radio Testing The National Oceanic and Atmospheric Administration's Weather Radio (NWR) provides the public with continuous information on weather conditions, natural disasters, environmental catastrophes, and other hazards and emergency conditions. The Institute has developed simulated NWR broadcasts and a series of repeatable measurement methods to test the performance of NWR receivers. We serve as the National Weather Service's (NWS's) independent test laboratory for NWR receivers. In FY 2017, NWR receiver manufacturers Halo Smart Labs and E&S International Enterprises entered into CRADAs with the Institute to have their equipment tested for Consumer Electronics Association compliance using our simulated NWR transmissions. ■

LEARN MORE ABOUT TABLE MOUNTAIN

Table Mountain Field Site and Radio Quiet Zone is available for use through collaborative research agreements with the Institute for Telecommunication Sciences. For more information on the facilities and capabilities at Table Mountain, see ***Table Mountain Field Site and Radio Quiet Zone*** on page 136.

INTERAGENCY AGREEMENTS FOR THE USE OF TABLE MOUNTAIN

Interagency agreements (IAAs) allow one Federal agency to reimburse another for the use of staff or physical resources. Sections 2-5 of this report describe the highlights of the Institute's FY 2017 IAAs leveraging staff expertise. We also have several IAAs specifically for the use of the Table Mountain Field Site and Radio Quiet Zone.

NOAA

Gravity Observatory NOAA's National Geodetic Survey Operations and Analysis Division operates the Table Mountain Gravity Observatory. In addition to having a low, uniform slope and relatively homogeneous underlying ground, Table Mountain is seismically quiet, making it a good location for absolute gravity observation. The observatory has become a major center for performance intercomparisons of absolute gravity meters. NGS also has a Continuously Operating Reference Station on Table Mountain, one of over 2,000 stations that provide Global Navigation Satellite System (or GPS) data to support nationwide three-dimensional positioning, meteorology, metrology, space weather, and geophysical applications.

Surface Radiation Monitoring Station NOAA's Earth System Research Laboratory Global Monitoring Division maintains a Surface Radiation (SURFRAD) Network monitoring station at TMFS. SURFRAD stations perform ground-based measurements of upwelling and downwelling solar and infrared radiation; ancillary observations include direct and diffuse solar radiation, photosynthetically active radiation, UVB, spectral solar, and meteorological parameters. Near-real-time data are available by anonymous FTP and over the Internet. Observations from SURFRAD have been used for evaluating satellite-based estimates of surface radiation and for validating hydrologic, weather prediction, and climate models.

Atmospheric Noise Data Collection NOAA's Solar-Terrestrial Physics (STP) team within the National Centers for Environmental Information takes advantage of the radio quiet at the TMFS to collect data on atmospheric noise. STP is responsible for the archive and access of solar and space environmental data and derived products collected by NOAA observing systems. One application of this data is space weather prediction, which is important to protect high frequency communications, satellite communications, radio navigation systems like GPS, electric power distribution, and many other technologies that are vulnerable to the impact of space weather events such as solar flares.

Cloud cover captured by the Total Sky Imager at NOAA's Surface Radiation observation station at Table Mountain Field Site, near Boulder, Colorado.

RESEARCH AGREEMENTS BENEFIT MULTIPLE AGENCIES

Wherever possible, the Institute leverages funding from interagency agreements to benefit multiple agencies. For example, five different agencies who have frequency assignments in the 1695–1710 MHz band supported the development and deployment of the Radio Frequency Coordination Portal, through which each incumbent user will coordinate use of the band with commercial entrants, reducing the cost for each individual agency. Public safety communications research is also funded by multiple agencies, each of which may bring a specific question to the ITS laboratories for investigation. Addressing each question in the context of all the questions eliminates rework, enhances interoperability, and allows faster dissemination of solutions.

NOAA & NIST: Ultraviolet Monitoring Instrument Calibration The Central UV Calibration Facility, a joint project of NOAA and NIST, provides accurate and repeatable calibrations and characterizations of ultraviolet radiation monitoring instruments. The facility has several UV instruments and is a useful test bed for intercomparisons, including annual spectroradiometer comparisons.

National Oceanic & Atmospheric Administration

The Central UV Calibration Facility at Table Mountain Field Site, near Boulder, Colorado.

U.S. GEOLOGICAL SURVEY

The U.S. Geological Survey's (USGS's) National Geomagnetism Program (Department of the Interior) has operated a magnetic observatory at TMFS since 1963. This observatory is one in a network of 14 that collect magnetometer data. Because of its proximity to the Golden, CO, headquarters, this site also functions as the Program's test bed for ongoing operational developments. Magnetometer data from the USGS observatory network are used to map the main field generated by the Earth's core, to analyze and monitor magnetic variation generated by space weather, and to assess and mitigate magnetic storm interference that poses hazards to technological infrastructure and radio transmission. Regionally, USGS data are used to support aeromagnetic surveys and directional drilling programs for the oil and gas extraction industry. USGS data are also used by the pipeline and electrical power grid industries, and for geophysical sciences research.

DUAL COMB SPECTROSCOPY

In FY 2017, researchers from NIST's Physical Measurement Laboratory, NOAA, and the University of Colorado conducted a Dual Comb Spectroscopy experiment at the TMFS. The goal was to detect and quantify methane leaks in an open field using a portable dual-comb laser spectrometer system and an unmanned aerial vehicle with a mirror retroreflector. Detecting, locating, and quantifying methane leaks in oil fields is vital for economic and environmental reasons, but traditional methods are inefficient and can only cover small areas. The new system could provide a more cost-effective, reliable method to continuously monitor several km^2. ■

NATIONAL AND INTERNATIONAL STANDARDS DEVELOPMENT

For several decades, the Institute has undertaken technical contributions and leadership roles in international standards organizations. These efforts have been vital to support the continuing evolution of more capable, interoperable, and cost-effective communication services. Our principal roles in this regard have been:

1. Advancing development of the Project 25 Standard starting in the early 1990s; this work aims to evolve narrowband Land Mobile Radio technologies, which are widely deployed by public safety organizations, nationally and internationally.
2. Advancing development of 3rd Generation Project Partnership specifications starting in the 2010s; this work aims to evolve broadband technologies involving LTE and 5G.
3. Advancing development of telecommunication standards at the International Telecommunication Union; this work aims to vouchsafe international competitiveness by ensuring international coordination of spectrum assignments and technologies.
4. Advancing video quality standards through the Video Quality Experts Group; our substantial support for this group ensures that stakeholders in government, industry, and academia have a voice in international standards.

The following sections describe our FY 2017 efforts in and contributions to each of these standards organizations. ■

The 3rd Generation Partnership Project is involved in developing specifications for vehicular radio communication. ITS experts advise 3GPP in these specification efforts.

PROJECT 25 COMPLIANCE ASSESSMENT PROGRAM

The Institute has been working closely with practitioners for decades to support continued development of communications systems that meet the unique requirements of public safety communities. One important activity in this area of work is our provision of technical guidance to the ***Project 25 (P25) compliance assessment program (CAP)*** for digital land mobile radio (LMR) systems.

Project 25 is a partnership between the public safety community and the telecommunications industry. Its goal is to develop standards for easy interoperability of radios and other LMR components across agencies and jurisdictions, regardless of manufacturer. In addition to interoperability, P25 standards also address efficient spectrum use at multiple frequencies. The congressionally mandated P25 CAP tests equipment for standards compliance.

The P25 compliance assessment program is a unique partnership whose key members include the Institute for Telecommunication Sciences, the Department of Homeland Security's Office of Interoperability and Compatibility, industry representatives, and public safety practitioners.

The Institute is a key member of the P25 CAP partnership. Alongside the Department of Homeland Security's Office of Interoperability and Compatibility (OIC), industry, and public safety practitioners, the Institute assesses P25 equipment demonstrations to ensure that manufacturers' products comply with P25 standards. The P25 CAP thus provides public safety agencies with evidence that their communications equipment will meet their needs. The program also supports the migration from proprietary telecommunications systems to open, standards-based infrastructure, and it provides a means of verifying that Federal grant and procurement funds are invested in high-performing LMR systems that promote interoperability.

In FY 2017, the Institute assisted the OIC in establishing a laboratory for the test and evaluation of the P25 Inter-RF Sub-System (ISSI) interface. We are also assisting in the validation of a conformance test tool for the same interface. ■

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VIDEO QUALITY EXPERTS GROUP

Background

The Video Quality Experts Group (VQEG) is a group of international experts from academia, government, international organizations, and industry. The group's goal is to develop improved methods to assess human perception of video quality. To this end, VQEG members share their expertise through presentations and conduct collaborative research and technical validation tests. The group submits its results to relevant International Telecommunication Union (ITU) study groups, often resulting in new or amended international standards.

FY 2017 Developments

In FY 2017, VQEG continued to pursue closer collaboration with the ITU Telecommunication Standardization Sector (ITU-T) Study Group 12 (SG12). SG12 is responsible for developing international standards related to performance, quality of service, and quality of experience. Improved collaboration between VQEG and SG12 will allow a wider variety of organizations to contribute to ITU-T standardization efforts on topics related to video quality. Conversely, ITU-T working groups will be able to draw upon the VQEG expertise on a wider range of topics.

During FY 2017, ITS researchers participated in a joint project between VQEG and SG12 to validate and standardize objective quality-of-experience models for adaptive video streaming services. In adaptive streaming, the video provider dynamically changes the video bitrate, resolution, and framerate in response to network conditions such as available bandwidth. Standardized objective models would enable service providers and other stakeholders to understand, in real-time, how changes in the video stream impact the user's experience of video quality. By pursuing such standards through its VQEG participation, the Institute hopes to enable video streaming to make more efficient use of network resources. ■

In recent years, VQEG's work has focused on emerging video technologies and applications like immersive media (e.g., virtual reality, augmented reality), high-dynamic-range video, ultra–high definition video (e.g., 4K, 8K), and Advanced Display Stream Compression.

The Institute has provided substantial leadership to this collaborative effort for 20 years and continues to sponsor VQEG by providing leadership and maintaining an e-mail distribution list and web presence.

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INTERNATIONAL TELECOMMUNICATION UNION, RADIOCOMMUNICATION SECTOR STUDY GROUP 3

The propagation of radio waves does not respect national borders. Coordination among nations is thus required, both to ensure compatibility of nearby systems and to promote investment in radio communication. The International Telecommunication Union, Radiocommunication Sector (ITU-R) facilitates global coordination and management of radio-frequency spectrum resource use.

ITU-R's Study Group 3 (SG3) is the international body responsible for ensuring the technical integrity of the modeling techniques used in predicting and analyzing radio wave propagation. The Institute has a long history of involvement with SG3; we have both contributed our own propagation models and conducted research that has led to the development of alternative models. Additionally, ITS holds two of the four international SG3 Working Party Chairs, as well as the Chair of the U.S. Delegation to SG3.

Background

International management of spectrum resources

As one of the largest financial supporters of the ITU, the United States has a vested interest in ensuring that ITU work supports national priorities.

More information on specific recommendations to which we contributed in FY 2017 can be found in ***Spectrum Management Support*** on page 64.

THE ITS-DEVELOPED IF-77 AIR-TO-GROUND PROPAGATION MODEL AND THE INSTITUTE'S FUNDAMENTAL RESEARCH ON DIFFRACTION INFORMED P-SERIES RECOMMENDATIONS ON TERRESTRIAL PROPAGATION.

In FY 2017, ITU-R began a large-scale international analysis effort to understand the possibilities for spectrum sharing within certain frequency bands. ITU-R SG3 met in a special session to address questions such as how signal power losses from clutter and building entry should be modeled. This fiscal year, ITS researchers made significant research advances in these areas, positioning us to make valuable contributions to the SG3 discussions.

Delegates from the Institute provide SG3 with both theoretical knowledge and practical expertise drawn from our extensive experience with spectrum sharing research. Through our participation, we help ensure that SG3's recommendations are well founded and that its decisions are based in solid research. ■

FY 2017 Developments

ITS delegates provide advice on advanced modeling techniques for spectrum sharing

SEE ALSO

Our FY 2017 research work informed our capacity to provide valuable expertise to ITU-R.

- ***Propagation Modeling and Validation*** on page 18
- ***Terrain and Clutter Modeling*** on page 52

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INTERNATIONAL TELECOMMUNICATION UNION, TELECOMMUNICATION STANDARDIZATION SECTOR

The International Telecommunication Union's Telecommunication Standardization Sector (ITU-T) develops standards for quality assessment in video and multimedia communications. The Institute has contributed to ITU-T standardization activities since 1994. Historically, the Institute participated directly in ITU-T study groups. However, FY 2017 marks an important shift in the structure of ITS participation in ITU-T Rather than participating directly, we will transfer our video quality expertise to the international community through the Video Quality Experts Group (VQEG).

The ITU-T and the ITU Radiocommunication Sector (ITU-R) solicit comments from a small number of organizations, of which VQEG is one. VQEG then submits formal reports to the ITU, influencing the ITU's final Recommendations. Because VQEG has an open participation policy, interested parties who cannot participate in ITU-T directly can have a voice in international standardization through VQEG. Thus, the Institute's VQEG participation allows us to help transfer knowledge from a broad base of government, academic, and industry experts to the sphere of international standardization. ■

From May 8–12, 2017, members of the Video Quality Experts Group met in Los Gatos, CA. The meeting had a record-breaking 94 participants.

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3RD GENERATION PARTNERSHIP PROJECT

Background ***The 3rd Generation Partnership Project (3GPP)*** is an international collaboration among telecommunications stakeholders. The 3GPP develops specifications for mobile communication technologies, including 4G and 5G. Since 2011, the Institute has participated in the 3GPP on behalf of the Department of Commerce (DOC) and the First Responder Network Authority of the United States (FirstNet). We have played a key role in all three of the 3GPP's specification stages for services ("Stage 1"), architectures ("Stage 2"), and protocols ("Stage 3") spanning user equipment, radio access networks, core networks, and external networks. During FY 2017, the Institute expanded its participation in 3GPP to advance the development of specifications for emerging 5G systems, including access to unlicensed spectrum in the 5 GHz band and vehicle-to-vehicle communications (intelligent, or "smart," transportation").

FY 2017 3GPP Participation **802.11p and C-V2X: Working Toward Performance Testing for Smart Transportation.** In 2014, the Department of Transportation (DOT) released its *Intelligent Transportation Systems Strategic Plan (2015 – 2019)* to guide the development and deployment of "smart" vehicles and transportation automation. Similar plans are being implemented in Europe and Asia. Thus, the 3GPP is evaluating interoperable wireless communications solutions such as *802.11p*, a wireless standard governing vehicular communication based on Wi-Fi technology. 3GPP also developed an LTE-based public safety standard called *cellular vehicle–to–everything* (C-V2X). Both technologies support the transmission of basic safety messages without the need for a cellular network subscription. The availability of both of these vehicular radio technologies presents a challenge to car manufacturers, chip manufacturers, and government transportation agencies. Therefore, there is a need to establish reliable methods to test the performance and interoperability of these two technologies.

In our FY 2017 work with the DOT, the Institute has conducted simulations to characterize the performance of 802.11p-compliant devices. This work allows us to establish a benchmark for real-world performance testing of 802.11p prototype products. In addition, ITS experts have been working with DOT to establish the detailed requirements for C-V2X communication, as well as planning performance tests, selecting test equipment, and identifying metrics for the evaluation of C-V2X prototype products.

Preparing for Advanced Research into 5G Technology. During FY 2017, the telecommunications community made great strides in planning for the deployment of 5G New Radio (NR) wireless technology. In June, 2018, 3GPP expects to release specifications for "non-standalone" 5G—an intermediate extension of the LTE 4G cellular networks that will allow operators to accelerate 5G deployment.

5G NR technology can operate in multiple frequency bands, including the extremely high frequency (EHF or millimeter wave) band (24–40 GHz), using an evolved packet switch core. 5G NR devices can also operate in a wide

3GPP (continued)

variety of bandwidth modes (up to 400 MHz). The practical implication of these characteristics is that different types of 5G devices will be able to simultaneously connect to both NR and LTE networks, dynamically switching between operation modes to optimize data transmission over the network. This novel approach will allow for more powerful wireless networking, but it introduces several challenges related to spectrum sharing with incumbent technologies operating in the EHF band (e.g., radar systems and atmospheric monitoring). In FY 2017, ITS experts conducted a thorough evaluation of fundamental 5G NR technology (the physical layer of the networking model) and presented our findings to the 3GPP. The Institute is also preparing to conduct spectrum sharing studies in the EHF band. This ongoing research is supported by the DOC and FirstNet, with the purpose of evaluating how emerging NR-based telecommunications will impact existing use of spectrum resources.

3GPP Release 14: Mission Critical Data and Video Services for Public Safety Communications. ITS involvement has been a key driver in 3GPP's unprecedented establishment of a working group to enable development of application-specific LTE specifications for public safety communications. In FY 2017, the Institute participated in the creation of 3GPP's latest standards by providing expertise in support of specifications for mission-critical data (MCData) and mission-critical video (MCVideo) communications. In addition to mission-critical push-to-talk (MCPTT), established with the Institute's participation), the new MCData and MCVideo services are essential components of FirstNet's Nationwide Public Safety Broadband Network (NPSBN), which enables broadband-based public safety communications. The MCPTT, MCVideo, and MCData work performed by ITS during this fiscal year included technical and leadership roles in contributing to 3GPP's Stage 3 for these technologies. Our work supports the rapid deployment of these LTE-based services, supporting unprecedented capabilities in advanced, interoperable public safety communications throughout the world.

Protecting Public Safety Communications in 5G Networks. As the FirstNet program neared its scheduled delivery of the NPSBN, the Institute also began transitioning to the next stage of our work with 3GPP. During FY 2017, we focused on ensuring that public safety communications requirements will be met in the next evolution of mobile technology, including 5G technologies like NR. We worked to ensure that quality of service, priority, and pre-emption capabilities will be replicated and expanded upon from 4G LTE to 5G NR. We played a strong role this fiscal year in Stage 1 and Stage 2 activities, working to ensure that new network systems will meet public safety needs. For example, we are researching more flexible ways to prioritize access to ensure that high-priority communications (e.g., emergency response and public safety transmissions) are not compromised. ■

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FISCAL YEAR 2017 ACTIVITIES

PUBLICATIONS

Publication abstracts are listed alphabetically by author.

John E. Carroll; Geoffrey A. Sanders; Frank H. Sanders; Robert L. Sole; Jeffery S. Devereux; Edward F. Drocella Jr., **"Non-Linear Effects Testing of High Power Radar Pulses on 3.5 GHz Low-Noise Amplifiers,"** NTIA Technical Report TR-17-525, June 2017. https://www.its.bldrdoc.gov/publications/3173.aspx

Future spectrum sharing between high-power radars and Citizens Broadband Radio Service Device CBSD in the 3550–3650 MHz (3.5 GHz) band could expose radio frequency (RF) receiver front-end low noise amplifiers (LNAs) to high peak power radar pulse signals in the band under certain situations. In this band, radar effective isotropic radiated power peak levels can exceed 1 gigawatt. Previous experience with LNAs exposed to high-power radar pulses in spectrum near 3.7 GHz has shown that non-linear effects can be induced in the LNAs, leading to service interruptions. To assess the level of risk for similar LNA overload at 3.5 GHz, NTIA performed gain overload (e.g., compression) tests on two representative 3.5 GHz LNAs and a small-cell base station receiver. The tests determined the pulsed radar signal power levels that caused overload (1 dB gain compression) for these devices. Approximate distance separations that would be necessary to preclude potential overload interference effects are presented, based on the measurement results and propagation modeling.

Andrew A. Catellier; Stephen D. Voran, ***"Intelligibility of Selected Speech Codecs in Frame-Erasure Conditions,"*** NTIA Technical Report TR-17-522, November 2016. https://www.its.bldrdoc.gov/publications/3165.aspx

We describe the design, implementation, and analysis of a speech intelligibility test. The test included five codec modes, four frame-erasure rates, and two background noise environments, for a total of 40 conditions. The test protocol required twenty listeners to repeat all words that they heard in short messages with median length of seven words. Each condition was tested using approximately 1100 words total. Listeners' responses were scored against the original message transcripts to produce a count of words correctly repeated and thus a measure of speech intelligibility. We present results that show exactly how this measure of speech intelligibility drops as frame-erasure rate increases for three of the five codec modes. The remaining two codec modes did not produce valid results due to defects in the reference software provided to us.

Chriss A. Hammerschmidt; Robert T. Johnk, **"Understanding the Impact of Terrain Databases on the Irregular Terrain Model,"** *Proceedings of the 2017 IEEE International Symposium on Electromagnetic Compatibility & Signal/Power Integrity (EMCSI)*, Washington DC, August 7-11, 2017. https://www.its.bldrdoc.gov/publications/3185.aspx

This paper discusses a mobile propagation measurement in Los Angeles, CA and compares these measurements to the output from the

PUBLICATIONS (continued)

Irregular Terrain Model (ITM). Propagation measurements are currently being used at the Institute for Telecommunication Sciences (ITS) to improve and validate the ITM propagation model. In this paper, these measurements are compared to the predicted terrain attenuation losses from ITM as a function of four different terrain databases. We began using ITM to calculate clutter losses (i.e. attenuation due to vegetation and man-made structures) by subtracting the ITM prediction from the measured data. As with any model, the estimation of clutter losses changes as the prediction from ITM changes based on the terrain database; therefore, it is important to understand why these changes occur. This paper briefly discusses the measurement system, the results from this campaign, and the output from ITM as a function of four different terrain databases of various horizontal resolutions.

Robert T. Johnk; Chriss A. Hammerschmidt; Irena Stange, **"A High-Performance CW Mobile Channel Sounder,"** ***Proceedings of the 2017 IEEE International Symposium on Electromagnetic Compatibility & Signal/Power Integrity (EMCSI)***, Washington DC, August 7-11, 2017. https://www.its.bldrdoc.gov/publications/3186.aspx

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We describe an advanced mobile channel sounder system that has been under development by engineers at NTIA's Institute for Telecommunication Sciences since 2010. We provide a description of the channel sounder and the key system components. We then highlight the flexibility and power of this system by showing a variety of measured and processed radio propagation results obtained using this system. This system has been deployed in numerous outdoor and indoor propagation measurement campaigns. This system has also been used for both in-building and building penetration measurements.

Margaret H. Pinson, **"Technology Gaps in First Responder Cameras,"** NTIA Technical Memo TM-17-524, May 2017. https://www.its.bldrdoc.gov/publications/3171.aspx

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This report identifies camera technology gaps that impact first responders. These technology gaps were identified by interviewing first responders about images, video, and camera systems in general. This is a working document that is intended to foster discussion around research and product innovation.

Margaret H. Pinson, **"Gaps in Public-Safety Cameras: How dust, rain, snow, and shadows impact public safety video,"** ***MissionCritical Communications***, August 2017.

A video is not always an accurate representation of what a first responder sees at an incident. New research suggests that first responders would benefit from a camera that removes airborne obscurants and shadows before the video is compressed. Current public-safety cameras' faithful reproduction of rain, falling snow, dust, and shadows hinders our understanding of the situation. First responders need new technologies better serve them by better reproducing the subjects of interest.

Stephen D. Voran, **"A Multiple Bandwidth Objective Speech Intelligibility Estimator Based on Articulation Index Band Correlations and Attention,"** *Proceedings of the 42nd International Conference on Acoustics, Speech and Signal Processing (ICASSP2017)*, New Orleans, LA, March 5-9, 2017. https://www.its.bldrdoc.gov/publications/3169.aspx

We present ABC-MRT16—a new algorithm for objective estimation of speech intelligibility following the Modified Rhyme Test (MRT) paradigm. ABC-MRT16 is simple, effective and robust. When compared to subjective MRT data from 367 diverse conditions that include coding, noise, frame erasures, and much more, ABC-MRT16 (containing just one optimized parameter) yields a very high Pearson correlation (above 0.95) and a remarkably low RMS estimation error (below 7% of full scale.) We attribute these successes to concise modeling of core human processes in audition and forced-choice word selection. On each trial, ABC-MRT16 gathers word selection evidence in the form of articulation index band correlations and then uses a simple attention model to perform word selection using the best available evidence. Attending to best evidence allows ABC-MRT16 to work well for narrowband, wideband, super-wideband, and fullband speech and noise without any bandwidth detection algorithm or side information.

Stephen D. Voran; Andrew A. Catellier, **"A Crowdsourced Speech Intelligibility Test that Agrees with, Has Higher Repeatability than, Lab Tests,"** NTIA Technical Memo TM-17-523, February 2017. https://www.its.bldrdoc.gov/publications/3168.aspx

Crowdsourcing of subjective speech, audio, and video quality of experience (QoE) tests has received much interest and study, but crowdsourcing of speech intelligibility testing has not. We hypothesize that speech intelligibility tests offer a unique crowdsourcing opportunity because, unlike QoE testing, each trial has a correct answer. That allows us to motivate and evaluate listeners. We describe the design, implementation, and analysis of a Crowdsourced Modified Rhyme Test (CMRT) that replicates our recent Laboratory MRT (LMRT) work. Our results show that CMRT results are more repeatable than LMRT results, CMRT repeats LMRT better than LMRT repeats itself, and application of a simple listener selection rule produces per-condition CMRT results that almost exactly agree with reference LMRT results. ■

PRESENTATIONS

Presentations are listed alphabetically by presenter, then chronologically.

- Michael Cotton, "NTIA/ITS R&D in Propagation and Monitoring," U.S./ECC/Canada Spectrum Management Consultation Meeting, Washington DC, June 7-9, 2017.
- Michael Cotton, "Innovations in Sustainable Spectrum Management for 5G and Beyond," IEEE Vehicular Technology Conference, Toronto, Canada, September 24–27, 2017.
- Kristen Davis, Earl Dean, Dylan Hicks, Billy Kozma, and Julie Kub presented on ITS propagation models and their software implementations to the Defense Information Systems Agency Defense Spectrum Organization Spectrum Sharing Test and Demonstration program Mid-Far Term Propagation Working Group, Washington DC, March 6-9, 2017.

PRESENTATIONS (continued)

- Nick DeMinco, "A Statistical Short-Range, Low-Antenna Height Propagation Model Based on Electromagnetic Theory and Measurements", U.S. National Committee–International Union of Radio Science Meeting, Boulder, CO, January 4, 2017.
- Rebecca Dorch was a Guest Lecturer at the University of Colorado Spectrum Management Maymester class, Boulder, CO, May 22, 2017.
- Keith Gremban participated at MILCOM2016, chairing a Technical Paper Session on MIMO and Directional Networking and moderating a Technical Panel on Spectrum Sharing - Issues and Approaches, Baltimore, MD, November 2, 2016.
- Keith Gremban and Fellow Frank Sanders presented at the 2017 Federal Spectrum Management Training Course, Washington, DC, January 23-27, 2017.
- Keith Gremban gave a talk on spectrum sharing at the 10th Annual Military Radar Summit, Arlington, VA, March 1, 2017.
- Keith Gremban, with Paige Atkins of OSM, "Spectrum 101" briefing to Congressional staffers, Washington DC, April 10-11, 2017.
- Keith Gremban participated as a panelist on the "Emerging Technologies Panel" and the "IoT Performance, Quality, Reliability" panel at the IEEE ComSoc International Communications Quality and Reliability Workshop, Naples, FL, May 16-18, 2017.
- Keith Gremban presented an introduction to ITS research at the spring meeting of the National Academies of Sciences' Committee on Radio Frequencies (CORF), Washington DC, May 24, 2017.
- Keith Gremban attended the 2017 IEEE International Conference on Prognostics and Health Management, where he participated in the Internet of Things (IoT) workshop and presented an overview of spectrum considerations with regard to IoT, June 18-20, 2017.
- Keith Gremban participated in the 2017 IEEE International Symposium on Electromagnetic Compatibility, Signal and Power Integrity as a panelist on "Spectrum Challenges In The Next 10 Years – How The EMC Community Can Help," Washington DC, August 9, 2017.
- Chriss Hammerschmidt presented at MILCOM2016 on "Extracting Clutter Metrics From Mobile Propagation Measurements in the 1755-1780 MHz Band" during the Technical Paper Session on Channel Modeling and Antenna Design, Baltimore, MD, November 1, 2016.
- Bob Johnk and Chriss Hammerschmidt participated in the 2017 IEEE International Symposium on Electromagnetic Compatibility, Signal and Power Integrity, presenting during a Special Session on "Technical Solutions for The Spectrum Crisis," Washington DC, August 10, 2017.
- Bob Johnk and Joe Parks attended the 83rd International Conference of the Association of Public-Safety Communications Officials (APCO) International and demonstrated an ITS-developed public safety app in the exhibit hall at the 2017 APCO symposium, Denver, CO, August 14-15, 2017.
- Peter Mathys, "Efficient Band Occupancy and Modulation Parameter Detection," GNURadio Conference 2017, San Diego, CA, September 11–15, 2017.
- Margaret Pinson gave a video quality seminar for the Interdisciplinary Telecom Program at the University of Colorado, Boulder, CO, February 8, 2017.
- Margaret Pinson participated as an exhibitor and a presenter in the 2017 PSCR Public Safety Broadband Stakeholder Meeting, presenting some of her findings about the

quality problems first responders are experiencing with images, videos, and camera systems, San Antonio, TX, June 18-20, 2017.

- Frank Sanders presented course modules on the Institute for Telecommunication Sciences and on Spectrum Measurements and Monitoring as part of NTIA's annual Federal Spectrum Management Course, July 28, 2017.
- Frank Sanders presented "RSEC Compliance Measurement Methodology" at a G46 EMC Subcommittee Meeting during the 2017 IEEE International Symposium on Electromagnetic Compatibility, Signal and Power Integrity, Washington DC, August 8, 2017.
- Frank Sanders participated as teaching faculty in the OSM-sponsored United States Telecommunications Training Institute (USTTI) Radio Spectrum Monitoring Techniques and Procedures Course, September 22, 2017.
- Steve Voran presented at the 2017 IEEE International Conference on Acoustics Speech and Signal Processing, New Orleans, LA, March 5-9, 2017. ■

STANDARDS LEADERSHIP ROLES

At a Glance: ITS staff held 38 positions on 42 different bodies in 8 standards developing organizations, including 13 Chair, Co-chair, and Vice-chair positions

- ***Kenneth R. Baker***: Member, IEEE Standards Association WG802.22 Wireless Regional Area Networks Working Group, Project P802.22.3 Standard for Spectrum Characterization and Occupancy Sensing
- ***Christopher J. Behm***: U.S. Chair of International Telecommunication Union Radiocommunication Sector (ITU-R) Study Group 3 (SG 3, Radiowave Propagation). International Chair and U.S. Chair of SG 3 Working Party (WP) 3L, Ionospheric Propagation.
- ***Randall S. Bloomfield***: U.S. Department of Commerce Delegate to 3GPP SA (Service and System Aspects) Working Group 2 (Architecture) .
- ***John E. Carroll***: U.S. Delegate to ITU-R Study Group 1 (SG 1, Spectrum Management) WP 1A (Spectrum engineering techniques) and Study Group 5 (SG 5, Terrestrial Services) WP 5B (Maritime mobile service including the Global Maritime Distress and Safety System (GMDSS); the aeronautical mobile service and the radiodetermination service).
- ***Michael G. Cotton***: Member of IEEE Standards Association WG802.22 Wireless Regional Area Networks Working Group, Project P802.22.3 Standard for Spectrum Characterization & Occupancy Sensing
- ***Erik R. Hill***: U.S. Chair of ITU-R SG 3 WP 3J (Propagation Fundamentals)
- ***William Kozma***: Head of U.S. Delegation to ITU-R SG 3, U.S. Chair of ITU-R SG 3 WP 3K (Point-To-Area Propagation)
- ***Paul M. McKenna***: International Chair of ITU-R SG 3 WP 3K (Point-To-Area Propagation).
- ***Margaret H. Pinson***: U.S. Representative to ITU-T SG9 (Broadband Cable and TV), ITU-R SG6 WP 6C. Member of ITU-T SG9 Intersector Rapporteur Group Audiovisual Media Accessibility (IRG-AVA). Associate Rapporteur ITU-T Questions 2/9 (Measurement and control of the end-to-end quality of service for advanced television technologies) and 12/9 (Objective and subjective methods for evaluating perceptual audiovisual quality in multimedia services within the terms of Study Group 9). Co-chair of the Video Quality Experts Group (VQEG) and of VQEG's Independent Lab Group and Audiovisual HD Quality group.

STANDARDS LEADERSHIP ROLES (continued)

- ***Andrew P. Thiessen***: U.S. Department of Commerce Delegate to 3GPP Technical Specifications Group (TSG) Radio Access Network, TSG Service and System Aspects, and Working Group SA1 (Services). Member of the ATIS Wireless Technologies and Systems Committee Systems and Networks Subcommittee. Vice-Chair of the Technology and Broadband Committee and Chair of the Broadband Working Group, National Public Safety Telecommunications Council.
- ***Bruce R. Ward***: U.S. Department of Commerce Delegate to 3GPP Technical Specification Group for Service and System Aspects Working Group 1.
- ***Arthur A. Webster***: Co-chair of VQEG. Member of the U.S. Delegations to the ITU-T Study Group 16 (Multimedia), Review Committee, Telecommunication Standardization Advisory Group, ITU-R SG 6 WP 6C (Programme production and quality assessment), and Coordination Committee for Vocabulary. U.S. Department of Commerce voting member for ATIS Packet Technologies and Systems Committee. NTIA voting member for the Society of Cable Telecommunications Engineers Data Standards Subcommittee. Observer for ITU-T SG 12 and Standardization Committee for Vocabulary. ■

FISCAL YEAR 2017 PROJECT LIST

Cooperative Research and Development Agreements

Areté Associates. Conduct field experiments at the Table Mountain Field Site (TMFS) in support of advanced LIDAR systems under development, in atmospheric conditions and at distances relevant to potential applications.
Project Leader: J. Wayde Allen
(303) 497 5871, jallen@ntia.doc.gov

Ball Aerospace. Use the Table Mountain Field Site as a field location to safely test and demonstrate the functionality of new lidar systems during product development.
Project Leader: J. Wayde Allen
(303) 497 5871, jallen@ntia.doc.gov

E&S International. Test the responses of new NOAA Weather Radio (NWR) receivers under development to determine whether the receivers comply with the standards set down in CEA 2009.
Project Leader: Raian F. Kaiser
(303) 497 5491, rkaiser@ntia.doc.gov

FIRST RF Corporation. Use the Table Mountain Field Site as a field location to fully test the functionality of new antenna designs during product development.
Project Leader: J. Wayde Allen
(303) 497 5871, jallen@ntia.doc.gov

Intel. Conduct subjective testing to model the impact of image resolution, display size, and display resolution on user perception of photos captured by mobile devices. As one of the related tools, create a set of test images and make them available royalty-free to other researchers and developers for similar investigations.
Project Leader: Margaret H. Pinson
(303) 497-3579, mpinson@ntia.doc.gov

Halo Smart Labs. Test the responses of new NOAA Weather Radio (NWR) receivers under development to determine whether the receivers comply

with the standards set down in CEA 2009.
Project Leader: Raian F. Kaiser
(303) 497 5491, rkaiser@ntia.doc.gov

Public Safety 700 MHz Broadband Demonstration Agreements (53 businesses). Operate various elements of an LTE network in a laboratory test bed and over-the-air (OTA) network to test interoperability of public safety communications equipment under simulated field conditions.

Lockheed Martin Coherent Technologies. Use the Table Mountain Field Site for field-testing and characterization of components, subsystems, and systems for eyesafe coherent laser radar
Project Leader: J. Wayde Allen
(303) 497 5871, jallen@ntia.doc.gov

University of Colorado Research and Education Center for Unmanned Vehicles. Use the Table Mountain Field Site as a field location to safely and accurately test collective and autonomous sensing and communication technologies for small unmanned aircraft.
Project Leader: J. Wayde Allen
(303) 497 5871, jallen@ntia.doc.gov

NTIA / ITS Science and Engineering Projects

Aggregate Emission Modeling. Accurately predict the distribution of interference power generated by an entire LTE network using open-source Monte Carlo simulation software. The simulations should produce CDFs that are useful for planning and in good agreement with measured data.
Project Leader: Joel Dumke
(303) 497 4418, jdumke@ntia.doc.gov

CMMI. Achieve Level 2 Capability Maturity Model Integration (CMMI) to improve project management practices and standardize business processes using a continuous integration approach and regularly soliciting employee feedback for process improvement.
Project Leader: Kristen Davis
(303) 497-4619, kdavis@ntia.doc.gov

Computational Electromagnetic Cluster. Created a proof-of-concept of a high performance computer cluster and and performed large-scale computations of short-range propagation scenarios at both 1776 MHz and 3500 MHz using the finite-difference time-domain (FD-TD) technique.
Project Leader: Earl Dean
(303) 497 5465, edean@ntia.doc.gov

Greyhound Sensor Development and Deployment. Prototype a low-cost RF sensor to deploy around Boulder and perform long-term continuous measurements.
Project Leader: Michael G. Cotton
(303) 497 7346, mcotton@ntia.doc.gov

IF-77 Upgrade. Create a report detailing the theoretical underpinnings of the IF-77 model, including derivations, assumptions, and simplifications
Project Leader: William Kozma
(303) 497 6082, wkozma@ntia.doc.gov

IoT Laboratory Development. Provide a test bed to allow for characterization of IoT devices across the spectrum of IoT verticals so as to inform NTIA and ITS research on topics such as aggregate IoT emissions, Smart City wired/wireless infrastructure investment related to IoT, etc.
Project Leader: Jaydee Griffith
(303) 497 7490, jgriffith@ntia.doc.gov

IPC Estimation Methods. Develop new methods for determining receiver IPC by replacing and enhancing IPC measurements with computer simulation. Verify the simulation by comparison to measurements.
Project Leader: Robert J. Achatz
(303) 497 3498, rachatz@ntia.doc.gov

FY 2017 PROJECTS (continued)

ITU-R Standards Support. Provide objective, expert leadership and key technical contributions in ITU-R Study Group 3 (Propagation).
Project Leader: Christopher J. Behm
(303) 497 3640, cbehm@ntia.doc.gov

Open Propagation Architecture Toolkit. Develop an open standard for a modular propagation modeling toolkit.
Project Leader: Kristen Davis
(303) 497-4619, kdavis@ntia.doc.gov

Precision Geolocation. Upgrade geolocation information in spectrum measurement systems to increase positional accuracy to within 5 cm.
Project Leader: Anna Paulson
(303) 497 7891, apaulson@ntia.doc.gov

Propagation Modeling Upgrade & Validation. Develop enhanced propagation measurements, modeling, and large-scale computational capabilities.
Project Leader: Robert T. Johnk
(303) 497 3737, rjohnk@ntia.doc.gov

Quality of Experience. Develop technology to assess the performance of digital video transmission systems, bridge the gap between engineering measurements and user experience, promote standards that identify proven technologies, and actively transfer this technology to other government agencies, end users, standards bodies, and the telecommunications industry.
Project Leader: Margaret H. Pinson
(303) 497 3579, mpinson@ntia.doc.gov

RSMS Development. Provide new and innovative measurement hardware and software tools for current and future RSMS capabilities. Project future needs and develop long-term strategies for building the necessary tools.
Project Leader: Geoffrey A. Sanders
(303) 497 6736, gesanders@ntia.doc.gov

RSMS Operations. 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.
Project Leader: John E. Carroll
(303) 497 3367, jcarroll@ntia.doc.gov

Spectrum Monitoring. Design and deploy a prototype nationwide spectrum monitoring network anchored by a federated Measured Spectrum Occupancy Database (MSOD) that collects spectrum data from remote sensors and allows authorized users to view usage data.
Project Leader: Michael G. Cotton
(303) 497 7346, mcotton@ntia.doc.gov

Speech Intelligibility. Continue development of innovative and efficient speech intelligibility measurement tools including objective algorithms, subjective test protocols, and a rigorous statistical framework that integrates these two diverse approaches.
Project Leader: Stephen D. Voran
(303) 497-3839, svoran@ntia.doc.gov

Systems Engineering. Provide an ability for several small scale projects that were low cost, but with high risk and potential for return in the form of future S&E project work, to occur. An example project in this space was the building of intellectual knowledge within the Institute on vehicle to vehicle standards being developed within 3GPP.
Project Leader: Andrew P. Thiessen
(303) 497-4427, *athiessen@ntia.doc.gov*

Systems Modeling and Simulation. Investigate advancing Institute capabilities for systems modeling and

simulation.
Project Leader: Randall S. Bloomfield
(303) 497 5489, rbloomfield@ntia.doc.gov

Table Mountain Modernization. Maintain and upgrade the Table Mountain Field Site infrastructure, ensure a safe working environment there, and provide logistical support for research activities at the field site.
Project Leader: J. Wayde Allen
(303) 497 5871, jallen@ntia.doc.gov

NTIA / Office of Spectrum Management (OSM) Support Projects

GMF Spectrum Usage Contour Measurement and Quantification. Perform signal level measurements as a function of distance from two radar transmitters to help OSM validate their methodology of determining spectrum usage contours.
Project Leader: Jeffrey Wepman
(303) 497 3165, jwepman@ntia.doc.gov

Interference Protection Criteria Simulation. Develop new methods for determining receiver IPC by replacing and enhancing IPC measurements with computer simulation. Verify the simulation by comparison to measurements.
Project Leader: Robert J. Achatz
(303) 497 3498, rachatz@ntia.doc.gov

Propagation Engineering Support. Provide propagation engineering technical support to NTIA/OSM in response to propagation questions and inputs from NTIA/OSM, the IRAC, the FCC, other federal agencies, and the private sector.
Project Leader: Paul M. McKenna
(303) 497-3474, pmckenna@ntia.doc.gov

Propagation Modeling Support. Assist OSM in achieving the President's 500 MHz goal through sharing/compatibility analyses, exercising or developing propagation models as needed.
Project Leader: Paul M. McKenna
(303) 497-3474, pmckenna@ntia.doc.gov

5 GHz Spectrum Sharing Lessons Learned. Produce an NTIA Technical Report on Lessons Learned from the Dynamic Frequency Selection (DFS) spectrum sharing experience. Additionally, provide engineering support to OSM for revisions to the RSEC, to solve radar interference problems, and to support OSM and the Administration with radar spectrum issues in ITU-R and other fora.
Project Leader: Frank H. Sanders
(303) 497-7600, fsanders@ntia.doc.gov

Spectrum Efficiency Study. Develop Spectrum Efficiency Metrics by conducting necessary literature review and laboratory testing. Document results in NTIA Report.
Project Leader: Frank H. Sanders
(303) 497-7600, fsanders@ntia.doc.gov

Spectrum Management Support. Quick reaction propagation modeling, interference characterization, and FCC compliance support. ITU-R Study Group 3 support.
Project Leader: Paul M. McKenna
(303) 497-3474, pmckenna@ntia.doc.gov

Terrain & Clutter Propagation Measurement and Modeling. Improve our ability to model the effects of terrain, vegetation, buildings, and clutter through extensive measurements, intensive modeling, framework development, and analysis.
Project Leader: Christopher R. Anderson
(303) 497-3414, canderson@ntia.doc.gov

FY 2017 PROJECTS (continued)

Department of Commerce (DOC)

First Responder Network Authority (FirstNet)

Public Safety Broadband Standards. Provide engineering support, scientific analysis, technical liaison, and standards body participation to advance the development of standards for public safety communication system products and services intended to operate over the nationwide first responder broadband network under development.
Project Leader: Andrew P. Thiessen
(303) 497-4427, athiessen@ntia.doc.gov

National Institute of Standards and Technology / Communications Technology Laboratory

FirstNet Standards. Provide engineering support, scientific analysis, technical liaison, and standards body participation to advance the development of standards for public safety communication system products and services intended to operate over the nationwide first responder broadband network under development.
Project Leader: Andrew P. Thiessen
(303) 497-4427, athiessen@ntia.doc.gov

Public Safety Communications Research. Provide applied science and engineering expertise to advance telecommunications interoperability and information sharing among local, state, federal, tribal, and international Justice, Public Safety, Homeland Security agencies.
Project Leader: Andrew P. Thiessen
(303) 497-4427, athiessen@ntia.doc.gov

National Oceanic and Atmospheric Administration (NOAA)

Radio Frequency Spectrum Coordination Portal. Support NOAA in developing and deploying the Radio Frequency Coordination Portal (RFCP) to coordinate the use of the 1695-1710 MHz band between federal and non-federal users.
Project Leader: Kristen Davis
(303) 497-4619, kdavis@ntia.doc.gov

NOAA / National Environmental Satellite, Data, and Information Service (NESDIS)

Radio Frequency Interference Monitoring System. Provide both technical subject matter expertise and engineering support to NOAA/NESDIS in the acquisition of a Radio Frequency and Interference Monitoring System (RFIMS) to be deployed at the site of each of the 17 NOAA Federal Earth stations to protect NOAA weather satellites from interference from commercial LTE wireless entrants in the 1695–1710 MHz band.
Project Leader: John E. Carroll
(303) 497 3367, jcarroll@ntia.doc.gov

NOAA / National Weather Service

National Weather Service Propagation Modeling Website (NWS PMW). Develop and enhance the Propagation Modeling Website, a web-based multipurpose GIS propagation modeling tool, used to predict NOAA Weather Radio coverage and integrate Census data to verify that NWR "All Hazards" radio transmissions reach 95% of the population of the U.S. as mandated by law.
Project Leader: Doug Boulware
(303) 497-4417, dboulware@ntia.doc.gov

Department of Defense (DOD)

Defense Advanced Research Projects Agency (DARPA)

Aerial Dragnet. Develop a software-defined radio based PN channel sounder (transmitter and receiver) with receiver

integrated to unmanned aerial system platform.
Project Leader: Kenneth R. Baker
(303) 497-3861, kbaker@ntia.doc.gov

Tactical Encryption & Key Management Workshop. Organize a stakeholder workshop to explore solutions to the problem of how to dynamically key and re-key different groups with varying levels of access and for varying lengths of time using existing infrastructure or over an ad hoc network which is reliable and user-friendly.
Project Leader: Joseph Parks
(303) 497-5865, jparks@ntia.doc.gov

Defense Information Systems Agency (DISA) / Defense Spectrum Organization

Clutter Measurements in the 1755-1780 MHz Band, Phase 2. Measure clutter loss values in various dense urban, urban, and suburban environments to collect data for use in refining and validating propagation models applicable to spectrum sharing in the 1755-1780 MHz band.
Project Leader: Chriss Hammerschmidt
(303) 497 5958, chammerschmidt@ntia.doc.gov

IF-77 Propagation Model Development. Create an IF-77 API compatible with early entry portal analysis capability (EEPAC) software architecture.
Project Leader: William Kozma
(303) 497-6089, wkozma@ntia.doc.gov

Spectrum Engineering Support to 1755-1780 MHz Spectrum Sharing Test & Demonstration (SST&D) Program. Provide subject matter expert support to the SST&D Steering Group and technical working groups, and support for "Post-60 day analyses."
Project Leader: Eric Nelson
(303) 497-7410, enelson@ntia.doc.gov

Joint Warfare Analysis Center (JWAC)

Propagation Modeling Website (JWAC PMW). Expand the current Propagation Modeling Website, a web-based multipurpose GIS propagation modeling tool, by enhancing the current capability, adding in new features, and incorporating new cutting-edge ITS propagation models.
Project Leader: Doug Boulware
(303) 497-4417, dboulware@ntia.doc.gov

U.S. Air Force

AWS-3 Out of Band Emission Measurements. Develop a rigorous testing methodology and measure the out-of-band emissions of Long Term Evolution (LTE) and LTE-Advanced (LTE-A) devices that operate in the Advanced wireless Services-3 frequency band.
Project Leader: Frank H. Sanders
(303) 497-7600, fsanders@ntia.doc.gov

Radio Frequency Spectrum Coordination Portal. Support the U.S. Air Force in developing and deploying the Radio Frequency Coordination Portal (RFCP) to coordinate the use of the 1695-1710 MHz band between federal and non-federal users.
Project Leader: Kristen Davis,
(303) 497-4619, kdavis@ntia.doc.gov

U.S. Army

Propagation Modeling Website (U.S. Army First IO Command PMW). Enhance the GIS functionality of PMW to include color-coding of radio transmitters on a map based on frequency range, geographic selection of an analysis area, and pin clustering to improve map display.
Project Leader: Doug Boulware
(303) 497-4417, dboulware@ntia.doc.gov

FY 2017 PROJECTS (continued)

U.S. Navy

Radio Frequency Spectrum Coordination Portal. Support the U.S. Navy in developing and deploying the RFCP to coordinate the use of the 1695-1710 MHz band between federal and non-federal users.
Project Leader: Kristen Davis
(303) 497-4619, kdavis@ntia.doc.gov

Department of Energy

Sandia National Laboratories

ACES RSEC Measurements. Perform measurements of emissions from new radars under development to demonstrate compliance with the Radar Spectrum Emission Criteria (RSEC).
Project Leader: Frank H. Sanders
(303) 497-7600, fsanders@ntia.doc.gov

Department of Homeland Security (DHS)

Office for Interoperability and Compatibility

Public Safety Audio and Video Quality. Conduct scientific analyses, laboratory and field measurements, and test and evaluation activities to evaluate emerging public safety communications technologies including voice and video information transfers.
Project Leader: Stephen Voran
(303) 497-3839, *svoran@ntia.doc.gov*

Public Safety Communications Equipment Test and Evaluation. Conduct scientific analyses, laboratory and field measurements, and test and evaluation activities to evaluate emerging public safety communications technologies, including P25 CAP support on LMR to LTE integration.
Project Leader: Andrew P. Thiessen
(303) 497-4427, athiessen@ntia.doc.gov

Public Safety Communications Research. Provide applied science and engineering expertise to the DHS and Project SAFECOM. Solve telecommunications interoperability and information sharing problems among local, state, federal, tribal, and international Justice, Public Safety, Homeland Security agencies by addressing voice, data, image, video, and multimedia information transfers.
Project Leader: Margaret Pinson
(303) 497-3579, *mpinson*@ntia.doc.gov

Speech Intelligibility and Degraded Radio Channels. Measure the speech intelligibility of five candidate Mission Critical Voice over LTE codecs in the presence of degraded radio channels.
Project Leader: Stephen D. Voran
(303) 497-3839, svoran@ntia.doc.gov

Office of Emergency Communications

NGN-PS Priority Services. Perform research on extending existing Wireless Priority Services by enabling Next Generation Network Priority Services over commercial LTE networks in support of National Security and Emergency Preparedness.
Project Leader: Angela McCrory
(303) 497-5351, *amccrory*@ntia.doc.gov

U.S. Coast Guard

Radar-to-Radar Interference Analysis. Perform electromagnetic compatibility analyses and parametric studies of potential interference among marine radars operating in the same or adjacent bands. Develop recommended marine radar receiver selectivity standards to minimize interference from and define reasonable adjacent band/

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PUBLIC SAFETY
TECHNOLOGY TRANSFER
RESEARCH FACILITIES

out-of-band emissions limits.
Project Leader: Robert J. Achatz
303) 497 3498, rachatz@ntia.doc.gov

Department of the Interior

Radio Frequency Spectrum Coordination Portal. Support the Department of the Interior in developing and deploying the Radio Frequency Coordination Portal (RFCP) to coordinate the use of the 1695-1710 MHz band between federal and non-federal users.
Project Leader: Kristen Davis
(303) 497-4619, kdavis@ntia.doc.gov

Department of Transportation / Federal Highway Administration

Evaluation of 802.11ac/DSRC Modeling. Perform electromagnetic compatibility analysis for the Dedicated Short-Range Communication System, as it relates to sharing spectrum with unlicensed devices operating in and adjacent to the 5850 to 5925 MHz band.
Project Leader: Nicholas DeMinco
(303) 497-3660, ndeminco@ntia.doc.gov

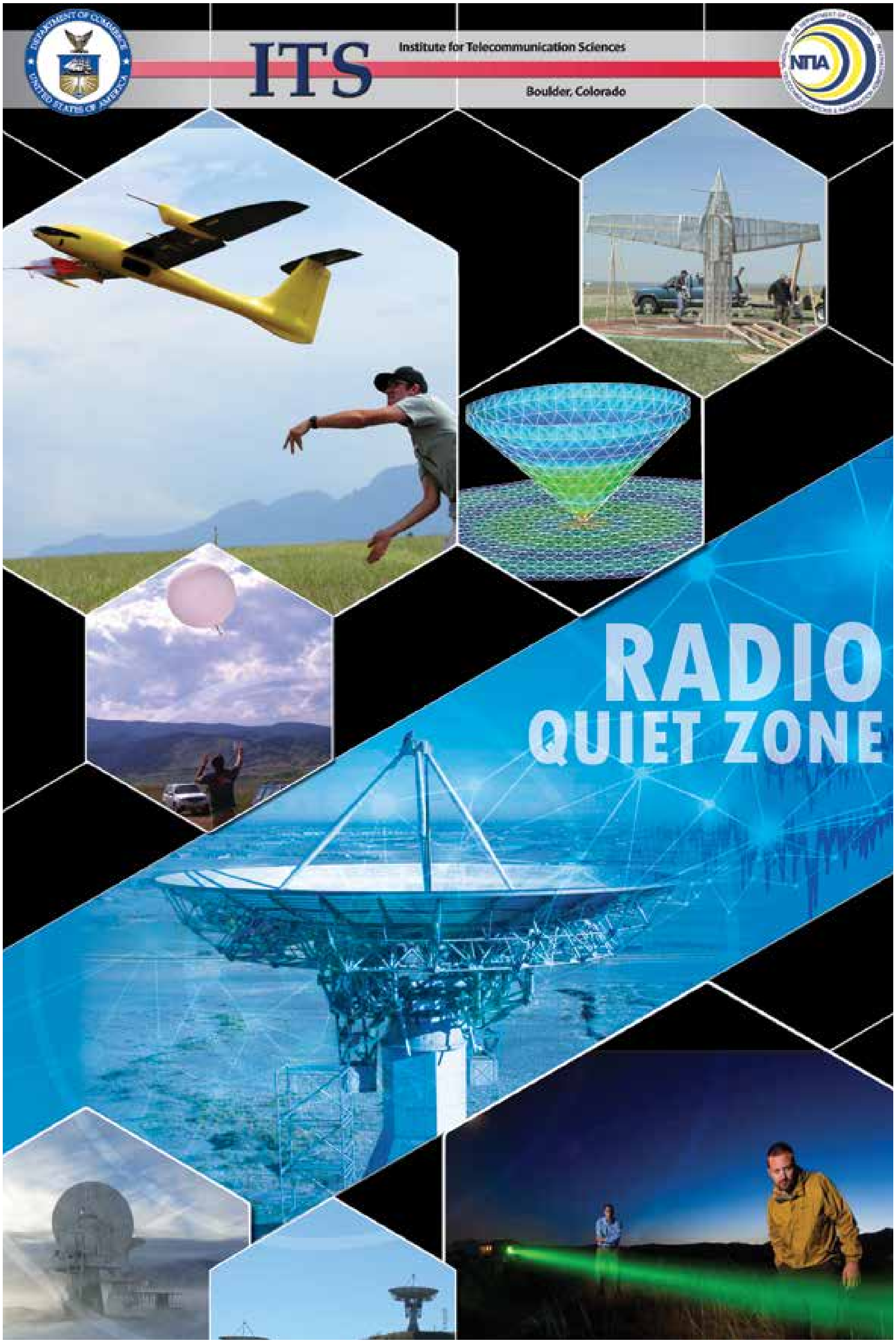
Next Generation Spectrum & Communications Analysis. Provide research and analysis in support of DOT Intelligent Transportation System Joint Program Office strategy to develop a comparative framework and document the changes and impacts to transportation with the next generation of communications technologies.
Project Leader: Andrew P. Thiessen
(303) 497-4427, athiessen@ntia.doc.gov

Federal Communications Commission (FCC)

ESC Certification Test System for the 3.5 GHZ CBRS. Develop and validate a test certification system to assess compliance of an Environmental Sensing Capability sensor as a unit under test with FCC Part 96 rules.
Project Leader: Rebecca Dorch
(303) 497 5221, rdorch@ntia.doc.gov

SAS Certification Test System. Leveraging the standards and development work of the WInnForum, verify and validate a test certification system to assess compliance of a Spectrum Access System as a unit under test with FCC Part 96 rules.
Project Leader: Rebecca Dorch
(303) 497 5221, rdorch@ntia.doc.gov

SAS Release 1-Phase2-Cert Test System for 3.5 GHz. Demonstrate a test certification system that produces a useful report for the FCC on the ability of a SAS as a UUT to perform in compliance with the FCC Part 96 rules.
Project Leader: Rebecca Dorch
(303) 497 5221, rdorch@ntia.doc.gov ■



Artistic depictions of our core strengths adorn the halls of the Institute

Section 6: Research Tools & Facilities

The Institute for Telecommunication Sciences is located at DOC's Boulder Laboratories—a 206-acre campus in the foothills of the Rocky Mountains in Boulder, Colorado. With 34 structures and nearly 2,000 personnel, Boulder Labs is a hub of scientific research and engineering for three agencies: NTIA (home of the Institute), NIST, and NOAA.

ITS researchers and executive staff can be found in Building 1, an historic building constructed in 1954 with architecture reminiscent of a radio antenna. Its single-story, on-grade construction minimizes vibration and other conditions that might interfere with research instruments. The building is highly prized in the Boulder Labs research community.

A 2017 Campus Master Plan commits to renovating Building 1 in accordance with the National Historic Preservation Act, maintaining its unique character and expanding laboratory facilities.

Along with research labs in Building 1, the Institute maintains two nationally important offsite facilities. We employ these facilities in our own research and coordinate their use in *collaborative research agreements* with industry and other agencies. The following sections describe the key laboratories and offsite amenities that enable our research. ■

IN THIS SECTION:

NIST DOC Boulder Laboratories Master Plan

Building 1 at the Department of Commerce Boulder Laboratories is nicknamed the "Radio Building," after its unique architecture reminiscent of a radio antenna.

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 (see Figure 18). Additionally, we maintain a library of waveforms that can be used to simulate interference for testing and measurement of receiver responses. An extremely high frequency (EHF) measurement system for frequencies from 40 to 300 GHz is currently under development.

Measurement System	Key Capabilities	Frequency (Distance)
Ultrawideband Propagation	▪ Takes high-precision S-parameter transmission measurements ▪ Transmits low power levels (+5 dBm) ▪ Permits isolation of selected propagation events through range resolution capabilities ▪ Outputs S21 amplitude and phase data	20 MHz–18 GHz (2–300 m)
Mobile Propagation	▪ Measures fast- and slow-fading phenomena and path loss ▪ Operates in narrowband and broadband channel probe modes ▪ Delivers high accuracy, dynamic range, sensitivity, and immunity to interference	20 MHz–30 GHz (several km)
Microwave Frequency Propagation	▪ Features high dynamic range and excellent immunity to RF interference ▪ Records I/Q waveforms as a function of environment ▪ Outputs Doppler characteristics and attenuation of transmitted signal	20 MHz–18 GHz (~10 km)
Radiated LTE	▪ Receives uplink and downlink transmissions from three different LTE base stations (eNodeBs) and associated devices ▪ Collects samples at a rate of over 30 million samples per second ▪ Provides spectrum analysis traces	380 MHz–6 GHz

Figure 18 Key ITS radio frequency measurement systems and their features.

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 to ship to the laboratory (e.g., radars), 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 (see image, next page). 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 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 it can perform accurate and complete RF measurements of 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 fourth 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.


FL70

RSMS-4

The iconic RSMS-4 mobile radio frequency propagation measurement laboratory

RADIO FREQUENCY MEASUREMENT CAPABILITIES (continued)

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

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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. ■

INTERFERENCE PROTECTION CRITERIA LABORATORY

BACKGROUND: PROTECTING COMMUNICATIONS SYSTEMS FROM INTERFERENCE

In today's spectrum-sharing scenarios, interference is acceptable as long as it does not significantly degrade the performance of the system experiencing interference, called the *victim system*. To minimize the likelihood of interference, spectrum managers limit the interference power received by the victim system and separate the systems in frequency by introducing a *frequency offset* between the systems' carrier frequencies.

Spectrum managers safeguard victim system operation for each spectrum-sharing scenario by implementing *interference protection criteria (IPC)* recommended by the Institute's researchers. These IPC recommendations are generated through the process of IPC estimation.

IPC ESTIMATION PREDICTS, GIVEN A SPECIFIC FREQUENCY OFFSET, HOW POWERFUL AN INTERFERING SIGNAL CAN BE BEFORE THE VICTIM RECEIVER'S PERFORMANCE DEGRADES BEYOND THE POINT OF ACCEPTABILITY.

The purpose of the Institute's **IPC Laboratory** is to advance the science of IPC estimation by orchestrating (a) measurement (see inset box, this page) and (b) simulation (see next page) of interference scenarios.

IPC LABORATORY MEASUREMENT CAPABILITIES

The Laboratory's measurement activities and test instruments include:

- ***Characterizing receiving devices***: 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.
- ***Generating interference signals***: Interference signals are generated by using a vector signal generator to play back signals that were previously digitized by a VSA. These signals are stored for reuse in the Laboratory's own repository (see below).
- ***Predicting receiver performance under interference conditions***: The equipment used to assess performance depends on the type of receiver the victim system uses. In the case of handheld personal communications devices, tests can be done in the laboratory with in-house test fixtures such as receivers

A typical interference protection criteria (IPC) measurement test fixture.

Whether measurements are taken in the laboratory, using test fixtures like the one pictured above, or the field, necessary performance metrics such as bit error rate (for handheld devices) or probability of detection (for radar devices) are not always included in the standard outputs of receiving devices we test. Therefore, the IPC Laboratory develops software to obtain custom outputs from the devices, sometimes writing new software code for each new experiment. This is a time-consuming but valuable process that enables us to precisely understand how the receiver is likely to perform under certain conditions.

THE IPC LABORATORY

Simulation Capabilities The Institute's IPC Laboratory has invested significantly in computer

SEE ALSO

The highlights of the Institute's FY 2017 IPC estimation work are reported in the following articles:

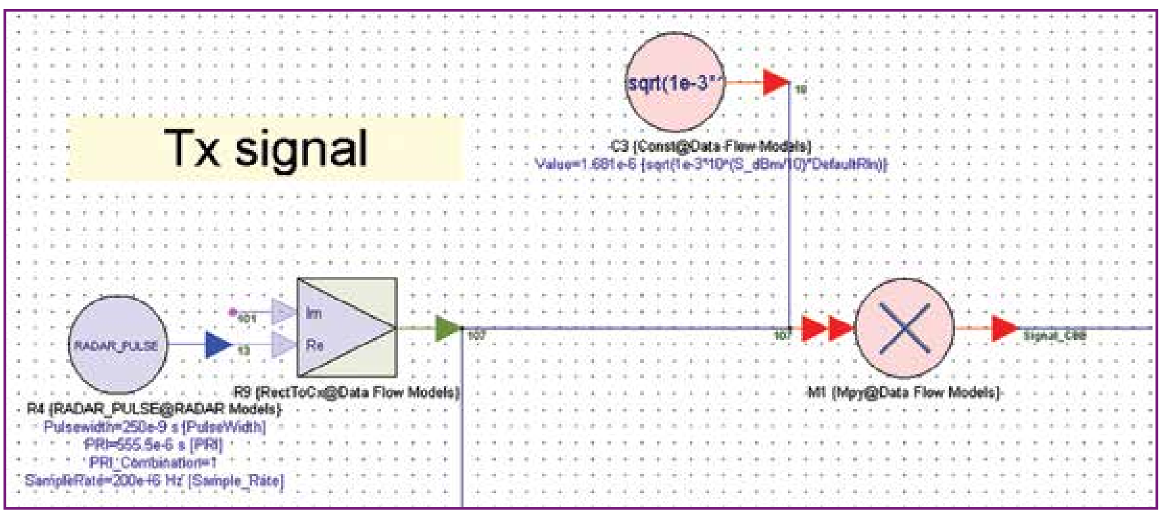
- ***Interference Protection Criteria Estimation*** on page 30
- ***Maritime Surveillance Radar Interference*** on page 56

IPC LABORATORY (continued)

simulation capabilities. Simulation is useful for generating interfering signals and verifying measurement results. In the future, simulation is expected to play a larger role. As the need to share spectrum increases, it becomes less practical to conduct tests for all of the many IPC estimations that spectrum engineers need. Therefore, precise and reliable simulation is a major future research direction for the Laboratory. We perform simulation using two commercial radio system software simulators running on separate desktop workstations. The simulators can emulate interference scenarios involving:

- radar
- satellite communications
- global navigation satellites
- tactical mobile communications
- wireless local area networks (WLANs)
- LTE personal communications

The Laboratory's ability to simulate this broad range of systems is sufficient to address many of today's spectrum sharing questions. A typical screen shot of a simulated measurement test fixture is shown below.



Screenshot of a typical simulated interference protection criteria (IPC) test fixture.

Interfering Signal Repository Interfering signals generated by measurement or simulation represent a significant value to the Institute, because they can be reused in future measurements and simulations. Therefore, to maximize return on investment, the IPC Laboratory stores these signals in an interfering signal repository. The signals are stored in a common format to facilitate reuse, since the same signals can be used in both measured and simulated performance testing. ■

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BROADBAND NETWORK AND LABORATORY

The Institute maintains several laboratories to provide system-level broadband testing and engineering support. Much of our work focuses on the layers above the physical aspects of a telecommunications stack, such as network control and audiovisual data transmission.

Our laboratory is available for use in interagency agreements and in collaborative research and development agreements (CRADAs) with manufacturers and carriers. As a neutral laboratory environment, the Institute protects proprietary information. Interested public agencies can observe systems and execute specific test cases that are unique to their operational environments, while vendors observe how their target end users actually use the equipment in the field. A multi-server blade system and five virtual hosts provide high performance computing capacity for hosting network applications and core network services, and for processing test data. Facilities support testing for LTE, land mobile radio (LMR), and Internet of things (IoT) technologies.

LTE

The laboratory currently supports testing on Band 13 Commercial LTE networks using eNodeBs from multiple vendors, a virtualized Evolved Packet Core (EPC), and test equipment to provide significant network load and wireless priority services testing. This allows us to conduct multi-vendor testing to verify the resilience of networks used for national security or emergency preparedness (NS/EP) telecommunications systems (such as those first responders use to communicate). We are also equipped to test commercial network resiliency to answer questions about how network traffic will be prioritized in NS/EP scenarios.

P25 LAND MOBILE RADIO

The lab has two P25 trunked land mobile radio (LMR) systems, providing VHF and UHF capabilities. These systems have been used in LMR-LTE integration projects using both the P25 native inter-RF subsystem interface and baseband audio over session initiation protocol to provide audio and control integration over the LTE networks.

INTERNET OF THINGS

In FY 2016, The Institute launched an IoT laboratory. This laboratory serves as a testbed for characterizing the wired and wireless networking components of IoT devices. The results of these tests can then be used to simulate IoT networks, including those used for smart cities and wearable devices. Such simulations are necessary to identify potential technical barriers or spectrum occupancy constraints that may arise as IoT devices become more widespread. ■

SEE ALSO

In FY 2017, ITS engineers used the Broadband Network and Laboratory in a key project for the Department of Homeland Security. See ***LTE Priority Mechanisms for Emergency Preparedness*** on page 88.

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AUDIOVISUAL LABORATORIES

The ITS audiovisual laboratories allow us to conduct complex testing and analysis of the audio and video signals necessary for television broadcasting, Internet streaming, video teleconferencing, mobile phone audio and video, voice-over-internet protocol (VoIP), and voice-over-LTE (VoLTE) applications

The Audiovisual Laboratories enable ITS researchers, along with government and industry research partners, to identify ways to improve both the quality and efficiency of audiovisual data transmission. For example, public safety depends on audio signals that are clear and intelligible, even in extremely noisy or chaotic environments. However, emergency response agencies often do not have the capacity to rigorously test and compare equipment. ITS maintains the facilities to help fill this gap.

Broadly, the ITS audiovisual laboratories consist of equipment to conduct two types of testing: ***subjective testing*** and ***objective testing***.

Subjective Testing The Institute is a leader in subjective audiovisual testing, or bringing groups of users into controlled environments to gather opinions on how they perceive audio and video under various conditions. Because subjective testing gathers input directly from human users, it provides the reference against which all other measurements may be judged. We can identify the most efficient ways to encode and transmit audiovisual signals if we can understand when changes in audiovisual quality are noticeable by the human eye or ear.

In subjective testing, we examine variables like the following:

- *Perceived quality*: How good or bad do users think an audio or video stream is?
- *Degradation*: How noticeable are impairments to a video or audio stream under certain conditions?
- *Intelligibility*: How much of the information in a speech signal can be retrieved by the person who receives it?
- *Usability*: For a given application (e.g., generating vehicle descriptions from a surveillance video), to what extent does the audio or video stream enable success?

These variables are important from social and commercial perspectives, because the value of audio and video products decreases rapidly if users perceive them as having inadequate quality relative to their intended application or price point.

The ITS subjective testing facilities include controlled test environments:

1. Two identically constructed sound isolation chambers, compliant with International Telecommunication Union (ITU) recommendations for

SEE ALSO

- ***Audio Quality and Speech Intelligibility*** on page 38
- ***Video Quality Characterization*** on page 41
- ***Image Quality Study*** on page 82
- ***Speech Codec Comparison*** on page 87

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. This type of testing can reveal problems that arise in interactive communications, such as mobile phone calls or teleconferences.

2. One quiet room with a window. This room can be configured to mimic real-world environments like home living rooms. The quiet room enables testing of how people perceive variations in audiovisual streams when they are in more relaxed and realistic conditions.

In these test rooms, lighting and background noise are controlled, and there are no visual distractions.

Objective Testing Objective testing is a pragmatic alternative to subjective testing. Objective tests use signal processing algorithms to analyze signals and estimate the response of a group of human users. Objective tests are faster and less expensive than subjective tests, and they offer exact repeatability. However, objective tests provide only estimates of responses that users might give in subjective tests.

The Institute's Audiovisual Laboratories support numerous objective testing algorithms. We apply them to efficiently evaluate devices and systems, and to allow comparisons with subjective test results. ■

AUDIOVISUAL LAB EQUIPMENT

ITS laboratory equipment supporting subjective and objective audiovisual testing:

- **Head and torso simulators with artificial ears and mouths**
- **Studio-quality digital and analog video recorders with 2–8 audio channels**
- **A full range of video monitors, speakers, and headphones**
- **Video editing equipment**
- **Audio recording, mixing, filtering, equalization, and conversion equipment**
- **Telephone handsets**
- **Software and hardware to encode and decode media**
- **ITU-T Rec. G.1050 compliant channel network simulators for conducting research on the quality of Internet transmissions**

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

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SPECTRUM MONITORING LABORATORY

The Institute established the ***Spectrum Monitoring Laboratory (specmon lab)*** to support testing and prototyping of emerging telecommunications technologies and tools, including fiber-optic and broadband networking technologies.

***Spectrum monitoring** is long-term, continuous measurement of the radio frequency environment, providing real-time information about the use of radio frequencies.*

In the specmon lab, a development network (devNet) supports connectivity and provides a secure sandbox, enabling work with hardware that, out of the box, may not conform to government IT security requirements. devNet virtualization also enables users to improve the security of the technologies they use and develop, through a process called hardening, or identifying and resolving potential security issues in a test environment. Our specmon lab infrastructure facilitates the quality assurance testing that hardens sensor and server software—an essential step before releasing production-level devices and applications.

One of the key capabilities of the specmon lab is connectivity prototyping. A portion of the devNet is fiber-optic, providing high-speed connectivity to a limited set of real-world sensor installation sites, while maintaining a secure environment. We expect that, in coming years, the devNet fiber connectivity will extend to a larger number of installation sites, as we connect to the Boulder Research and Administrative Network (bouldercolorado.gov/information-technology/bran-fiber-optic-network).

Finally, the specmon lab provides an extensive hardware inventory to support radio frequency (RF) sensor design, fabrication, calibration, and performance testing. We have been able to leverage this resource in collaborative projects, for example by supporting the deployment of hundreds of sensors in the Boulder Wireless Test City. Hardware in the specmon inventory includes dongles, software-defined radios, single-board computers, RF enclosures, cables, antennas, and laboratory-grade test and measurement equipment. ■

SEE ALSO

The Institute's FY 2017 spectrum monitoring work is reported in **Spectrum Monitoring** on page 34.

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GREEN MOUNTAIN MESA FIELD SITE

Green Mountain Mesa Field Site is located on the DOC Boulder Laboratories campus, several hundred feet above the campus buildings. The site's hilltop location allows us to provision wireless services across a wide area for robust testing. The site is used year round for outdoor wireless network research. In FY 2017, Green Mountain Mesa hosted ITS researchers investigating signal clutter and the transmission of first responder network signals within buildings.

Currently, we are constructing a fiber extension to the edge of the mesa to enable the evaluation of 5G radio technologies. This improvement adds to the refurbishment of the Green Mountain Mesa site conducted in FY 2010. Improvements included installation of a portable building situated on a concrete pad to securely house the fiber and power distribution. A new 16.8 meter (55 foot) tower was also constructed and raised to support research on LTE 4th generation (4G) wireless technology.

The site is connected to the ITS laboratories via fiber-optic link, and to the Table Mountain Field Site via microwave link. The fiber-optic link provides access to the ITS local area network. The site can provide six independent duplex fiber channels to the ITS lab. A 24 meter (80 foot) tower provides a structure on which to mount transmitting antennas to perform propagation measurements or other radio frequency experiments. ■

Rob Stafford.

Antenna tower at the Green Mountain Mesa Field Site.

SEE ALSO

In FY 2017, ITS researchers used the Green Mountain Mesa Field Site in our investigations of signal strength variation:

- ***Clutter Measurements*** on page 68
- ***Public Safety Indoor Broadband Coverage App*** on page 84

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TABLE MOUNTAIN FIELD SITE AND RADIO QUIET ZONE

Table Mountain Field Site and Radio Quiet Zone is located north of Boulder and has a total area of approximately 1,800 acres. It extends about 4 km (2.5 miles) north-south by 2.4 km (1.5 miles) east-west.

Table Mountain is one of only two Federally mandated radio quiet zones in the United States. Since 1954, Table Mountain has provided an ideal environment for the sensitive experiments that ITS researchers, government users, and industry research partners conduct. Table Mountain has a number of features that make it an ideal site for our field research:

- ***Federal and state protection as a Radio Quiet Zone***: As the air becomes increasingly crowded with radio signals, the availability of a Radio Quiet Zone is deeply valuable to our work. This designation prohibits strong external signals from passing through the Table Mountain site, ensuring that users can study electromagnetic radiation in a real-world environment with minimal external interference.
- ***Unique geophysical characteristics***: The soil at Table Mountain is homogenous, ensuring that there are no discontinuous underground structures that modify near-ground radio propagation, cause spurious reflections, or disturb Earth's gravitational and magnetic fields.
- ***Location***: Table Mountain is elevated on all sides from the surrounding area (see aerial photo, below), providing an unobstructed view of the sky. This is important, for example, for tracking satellites.

Collaborative Research Government, industry (including small business), and academic researchers studying the electromagnetic spectrum share this unique resource through collaborative

Map data ©2017 Google Imagery, ©2017 DigitalGlobe, U.S. Geological Survey, USDA Farm Service Agency.

In FY 2017, engineers at the Table Mountain Field Site and Radio Quiet Zone (pictured) focused on tracking satellites to verify the operation of our 3.7 meter (I10C) dish antenna. In FY 2018, we plan to upgrade the site with a new 2.4 meter dish antenna.

TABLE MOUNTAIN FACILITIES

- ***Spectrum research laboratory***: A fully equipped research facility with power distributed by means of buried cable, minimizing the risk of interference.
- ***Open field radio test site***: A flat-topped butte with a uniform 2% slope, relatively homogenous ground, and a lack of perimeter obstructions.
- ***Radar test range***: A large open space for testing radar and lidar systems.
- ***Two 18.3 m (60 ft) parabolic dish antennas***: Steerable in both azimuth (angle) and elevation (height), have been used at frequencies from 400 MHz to 6 GHz.
- ***One 3.7 m (12 ft) dish antenna***: This computer controlled antenna is capable of tracking low Earth-orbiting satellites.
- ***Mobile test vehicles***: To bring test equipment to the open field test sites, we use vehicles including four-wheel drive trucks and mobile laboratories.
- ***Large turntable***: A 10.4 m (34 ft) rotatable steel table mounted flush with the ground. Underneath, a laboratory houses test instrumentation and control equipment. The motors that rotate the table can be operated remotely.

research agreements. The Institute maintains Table Mountain and administers such agreements, ensuring that users do not exceed Table Mountain's field strength limits (see Figure 19).

Frequency range (kHz)	Field strength (mV/m)	Power flux density (dBW/m²)
< 540	10	-65.8
540–1,600	20	-59.8
1,600–4,700	10	-65.8
4,700–8,900	30	-56.2
≥ 8,900	1	-85.8

Figure 19 Table Mountain field strength limits.

The Table Mountain facilities enable research with the potential for wide-ranging applications, such as:

- Developing radio frequency sensing capabilities for unmanned aircraft, potentially enabling improved navigation and sense-and-avoid[1]
- Testing technologies for backcountry applications like search and rescue and wildlife tracking[1]
- Verifying the performance telecommunications systems like GPS
- Observing atmospheric conditions and solar radiation patterns[2]
- Calibrating laser systems, gravimeters, and other sensitive equipment ■

[1] Austin Anderson, Eric Frew, and Dirk Grunwald, "Cognitive Radio Development for UAS Applications," 2015 International Conference on Unmanned Aircraft Systems (ICUAS), 2015, https://ieeexplore.ieee.org/abstract/document/7152352.

[2] National Oceanic and Atmospheric Administration Earth System Research Laboratory Global Monitoring Division, "SURFRAD Network: Boulder, CO, n.d., https://www.esrl.noaa.gov/gmd/grad/surfrad/tablemt.html.

Learn more online at: https://www.its.bldrdoc.gov/resources/table_mountain.
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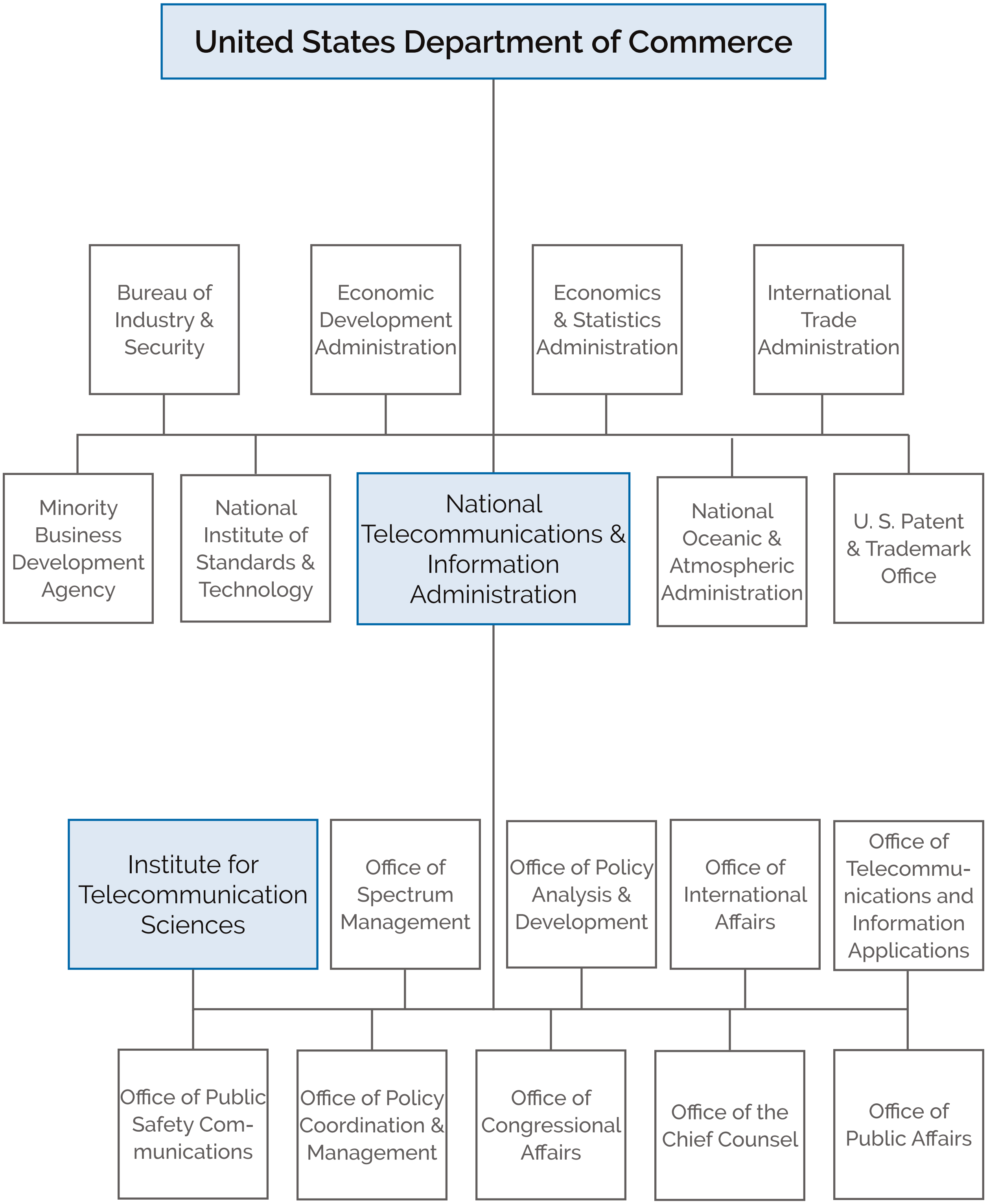
ABBREVIATIONS AND ACRONYMS

3G	3rd generation cellular wireless
3GPP	3rd Generation Partnership Project
4G	4th generation cellular wireless
5G	5th generation cellular wireless
AACB	Automatic Access Class Barring
ABC-MRT16	Articulation Band Correlation Modified Rhyme Test
AELTE	Aggregate Emissions from Long-Term Evolution
APCO	Association of Public-Safety Communications Officials
API	application programming interface
AWS	Advanced Wireless Services
CAP	Compliance Assessment Program
CBRS	Citizens Broadband Radio Service
CBSD	citizens band service device
CEC	Coors Events Center
CMMI	Capability Maturity Model Integration
CMRT	Crowdsourced Modified Rhyme Test
CRADA	cooperative research and development agreement
CU	University of Colorado at Boulder
C-V2X	cellular vehicle-to-everything
CW	continuous wave
DARPA	Defense Advanced Research Projects Agency
dB	decibels
dBm	decibel-millitwatts
devNet	developer network
DFS	Dynamic Frequency Selection
DHS	Department of Homeland Security
DISA	Defense Information Systems Agency
DOC	Department of Commerce
DOD	Department of Defense
DOT	Department of Transportation
DSO	Defense Spectrum Organization
DSP	digital signal processing
EEPAC	Early Entry Portal Analysis Capability
EHF	extremely high frequency
EK&M	Encryption and Key Management
EMC	electromagnetic compatibility analysis
EPC	Evolved Packet Core
ESC	Envrionmental Sensing Capability
FCC	Federal Communications Commision
FirstNet	The First Responder Network Authority of the United States
FTP	file transfer protocol
FY	fiscal year
GHz	gigahertz
GIR	Government Industry Requirement
GPS	Global Positioning System
HATS	head and torso simulator
IAA	interagency agreement
IPC	interference protection criteria
ISART	International Symposium on Advanced Radio Technologies
ISSI	Inter-RF Sub-System
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
LIDAR	laser radar
LMCT	Lockheed Martin Coherent Technologies
LMR	land mobile radio
LNA	low noise amplifier
LTE	Long Term Evolution
MCData	mission-critical data

MCPTT	mission-critical push-to-talk
MCVideo	mission-critical video
MHz	megahertz
MNO	mobile network operator
MRT	Modified Rhyme Test
MSR	maritime surveillance radar
NASA	National Aeronautics and Space Administration
NATO	North Atlantic Treaty Organization
NESDIS	National Environmental Satellite, Data, and Information Service
NGN-PS	next generation networks priority services
NHTSA	National Highway Traffic Safety Administration
NIST	National Institute of Standards and Technology
NOAA	National Oceanic and Atmospheric Administration
NPSBN	Nationwide Public Safety Broadband Network
NR	New Radio
NS/EP	national security and emergency preparedness
NTIA	National Telecommunications and Information Administration
NWR	National Oceanic and Atmospheric Administration Weather Radio
NWS	National Weather Service
OATS	open-area test site
OEC	Office of Emergency Communication
OIC	Office of Interoperability and Compatibility
OPCM	Office of Policy Coordination and Management
OSM	Office of Spectrum Management
OTA	over-the-air
P25	Project 25
PMW	Propagation Modeling Website
PN	pseudo-noise
PSCR	Public Safety Communications Research
RF	radio frequency
RFCP	Radio Frequency Coordination Portal
RFIMS	Radio Frequency and Interference Monitoring System
RSMS	Radio Spectrum Measurement Sciences
RSRP	reference signal received power
RTCM	Radio Technological Committee Maritime
SAS	Spectrum Access System
SCOS	Spectrum Characterization and Occupancy Sensing
SG	study group
SME	subject matter expert
SST&D	Spectrum Sharing Test & Demonstration
STP	Solar-Terrestrial Physics
SURFRAD	Surface Radiation
TDD	Time Division Duplex
TDWR	terminal Doppler weather radar
TMFS	Table Mountain Field Site
UAV	unmanned areial vehicles
UE	user equipment
UHF	ultra high frequency
U-NII	unlicensed national informa-tion infrastructure
USAF	United States Air Force
USCG	United States Coast Guard
USGS	United States Geological Survey
V2I	vehicle-to-infrastructure
V2V	vehicle-to-vehicle
VNA	vector network analyzer
VoIP	voice over Internet protocol
VoLTE	voice over Long Term Evolution
VQEG	Video Quality Experts Group
VSA	vector signal analyzer
VSG	vector signal generator
WLAN	wireless local area netowrk
WPS	wireless priority service
YIG	yttrium-iron-garnet

DOC/NTIA Organization Chart



Boulder, Colorado