Spectrum and Propagation Measurements

The radio spectrum is an inexhaustible yet finite resource which is in ever-increasing demand by users. Accommodating this demand necessitates greater efficiencies through technological advancement and improved spectrum management.

Historically spectrum has been allocated and managed by assigning channels to users and regulating transmitter emissions within certain limits. Working within these constraints, engineers have developed modulation and coding schemes that have dramatically improved efficiencies — and increased system complexity. Similarly, improvements in spectrum management require a more complex spectrum management process.

The engineers of the Spectrum and Propagation Measurements Division draw upon decades of institutional knowledge to perform radio frequency measurements of telecommunications systems and the radio channel environment. Their advanced measurement techniques and sophisticated custom-built test fixtures allow them to fully exploit test equipment capabilities.

In November 2007, one member of the division, Jeffery Wepman, was part of a team from NTIA awarded the Department of Commerce Silver Medal, the second highest honor given by the Department (see p. 89 for more information). The team was recognized for outstanding work in designing the rules for the Digital Television Coupon Program.

The following areas of emphasis are indicative of the work done recently in this Division to support NTIA, other Federal agencies, academia, and private industry.

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Areas of Emphasis

Radio Spectrum Measurement Science (RSMS) Program The RSMS program encompasses the equipment and operational expertise employed in sophisticated radio frequency measurements. The program supports continuous improvements in measurement system capabilities and performance in both the near and long term. This culminates in enhanced engineering expertise and development and deployment of a sophisticated toolbox of laboratory equipment, analysis tools, and mobile facilities to assess spectrum occupancy and usage, electromagnetic compatibility, and to resolve interference problems. Two RSMS projects are funded by NTIA:

RSMS Operations

RSMS 4th Generation System Development

Table Mountain Research Program The Table Mountain Field Site is the principal experimental field site for the Department of Commerce Boulder Laboratories. Designated by Congress as a protected radio quiet zone where the magnitude of external signals is restricted, the site facilitates various advanced research and measurement programs. Research at this site includes development and evaluation of measurement methods for spectrum occupancy, radio noise, antenna design, laser testing, and radar emissions conducted through NTIA funding as well as cooperative research agreements with non-Federal entities. These projects are funded by NTIA and private organizations.

Antenna Polarization Mismatch Loss Measurements Working closely with NTIA's Office of Spectrum Management (OSM) to develop best practices for frequency planning tools, ITS engineers measured antenna polarization mismatch for a variety of combinations of field and antenna polarizations. The project is funded by NTIA/OSM.

Radio Noise and Spectrum Occupancy Measurement Research ITS engineers are developing a next generation noise measurement system based on Vector Signal Analyzer (VSA) technology. VSA technology captures magnitude and phase information and allows for wider bandwidth noise measurements than those historically conducted at ITS. The project is funded by NTIA.

Radio Spectrum Measurement Science (RSMS) Operations

Outputs

- Measurements to validate compatibility between off-the-shelf 5-GHz dynamic frequency selection (DFS) devices and a 5-GHz radar.
- Measurements of broadcast TV harmonic interference into a Federal Earth station receiver.
- Measurements of WiMAX device emissions.

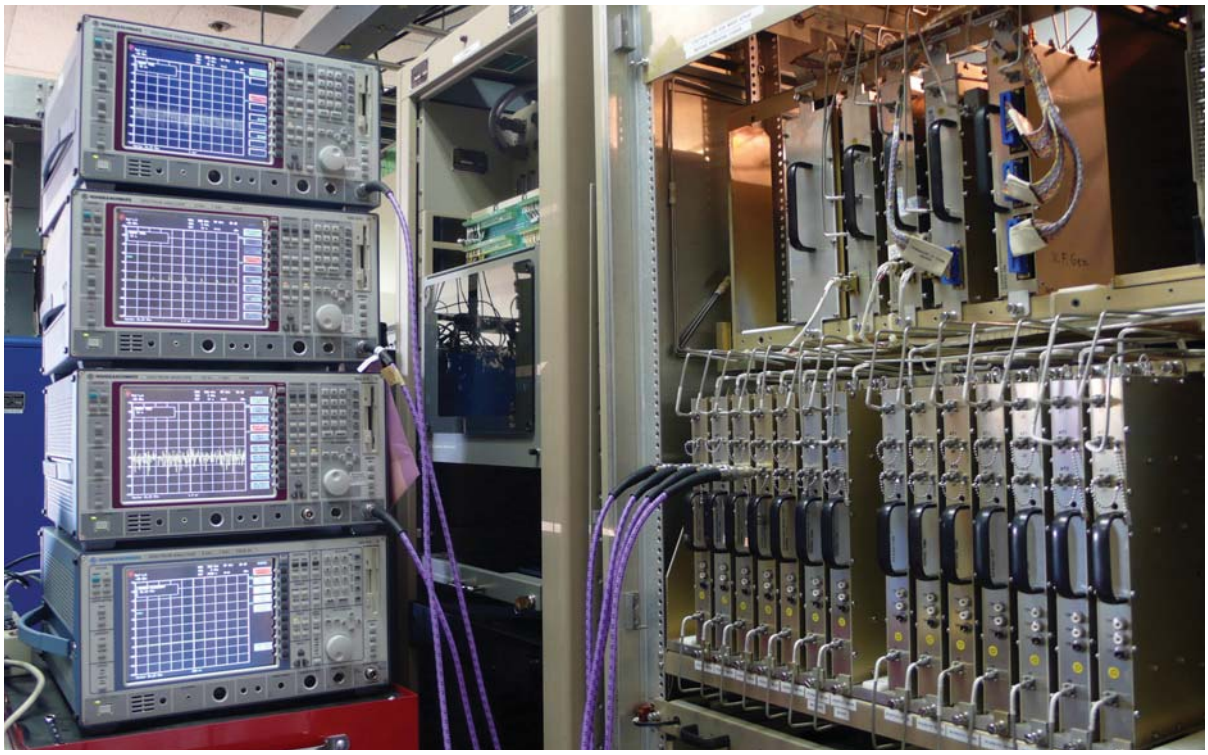
The Radio Spectrum Measurement Science (RSMS) program has the task of performing critically needed radio signal measurements necessary for making decisions regarding Federal Government spectrum allocations. As stated under Departmental Organization Order 25-7, issued 5 October 1992, and amended December 1993, the NTIA Office of Spectrum Management (OSM) is responsible for identifying and making arrangements for measurements necessary to provide NTIA and various Federal agencies with information to ensure effective and efficient use of the spectrum. The RSMS team is based in Boulder, Colorado, and performs measurements in support of OSM as required to fulfill this mission.

ITS, through the RSMS Operations Project, provides OSM and the executive branch with critically needed radio spectrum data, data analyses, reports, and summaries. The four basic areas of RSMS are measurements of 1) spectrum surveys and channel usage, 2) equipment characteristics and compliance, 3) interference resolution and electromagnetic compatibility, and 4) signal coverage and quality. In FY 2008, several different measurements were performed in support of the RSMS mission.

In the summer of 2008, field measurements were conducted to determine compatibility between off-the-shelf 5-GHz dynamic frequency selection (DFS) devices and 5-GHz radars. DFS is a method whereby Unlicensed National Information Infrastructure (U-NII) devices, which use the 5-GHz band for unlicensed operations, must detect the operations of radars and promptly vacate the channel if local radar signals are present. U-NII devices are defined as devices that provide short-range, high-speed, wireless digital communications. The FCC adopted compliance rules and procedures for U-NII devices in FY 2006. In order to monitor the performance of the devices that are currently on the market, NTIA purchased four 5-GHz U-NII devices "off the shelf" and tested them to the published compliance standards. The results obtained to date have been reported to the FCC, and more of this type of testing is expected to occur in FY 2009.

In January of 2008, measurements were conducted to resolve interference between a Federal Earth station and a harmonic spectrum emission from a broadcast television (TV) station in New Hampshire. An initial NTIA study of the problem had found that a harmonic from the TV station was interfering with the Earth station operations. After installation of an emission filter on the TV station transmitter failed to solve the problem, NTIA was asked to re-assess the problem with the intent of identifying the harmonic-generation mechanism and potential solutions. After careful examination of the TV station emissions for local oscillator (LO) leakage and intermodulation (IM) products with other signals, it was determined that the TV station transmitter was not emitting the harmonic, nor was the signal an IM emission. Rather, the harmonic was due to the re-radiation of energy from a non-linear interaction with either the TV station's broadcast tower or one of the nearby transmitter towers, an example of the so-called rusty-bolt effect. Direction-finding by the ITS team on the source of the energy confirmed the rusty-bolt hypothesis. The problem should resolve itself when the digital television transition takes place on February 17, 2009 and the existing analog TV signal goes off the air.

In early FY 2008, ITS examined and recorded the emission spectra of two Worldwide Interoperability for Microwave Access (WiMAX) devices supplied by two manufacturers. WiMAX is a telecommunications technology that provides for the wireless



Examining the electromagnetic compatibility of a radar and a Radionavigation Satellite Services (RNSS) signal (photograph by F.H. Sanders).

transmission of data, from point-to-point links to full mobile cellular-type access, at rates of up to 70 Mbps. Wide-scale deployment of this technology is expected to occur in the near future. The measurements performed by ITS on the devices were part of a larger effort to examine the electromagnetic compatibility of WiMAX devices and radars operating in the same band.

Later in 2008, ITS provided support for three separate measurements to determine interference potential to radars in the 1215-1400 MHz band (L Band) from new Radionavigation Satellite Services (RNSS) now sharing that band. The Department of Defense, the Federal Aviation Administration, NTIA, and other Federal agencies have expressed concerns about the operations of the RNSS devices. Specifically, NTIA measurements and analyses show that RNSS signals coupling into L-Band radars could cause interference which could result in loss of targets and/or reduced detection range. Within the International Telecommunication Union — Radiocommunication Sector (ITU-R), work has continued on a study of the issues, and the results of the NTIA studies have been submitted to ITU-R Working Party 5B. The so-called L-Band Group in the United States has been formed to perform a unified and comprehensive review of the issues and determine how to resolve them domestically and at the ITU-R.

Recent Publication

J.E. Carroll, J.R. Hoffman, and R.J. Matheson, "Measurements to characterize land mobile channel occupancy for Federal bands 162-174 MHz and 406-420 MHz in the Denver, CO area," NTIA Report TR-08-455, Sep. 2008.

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RSMS 4th Generation System Development

Outputs

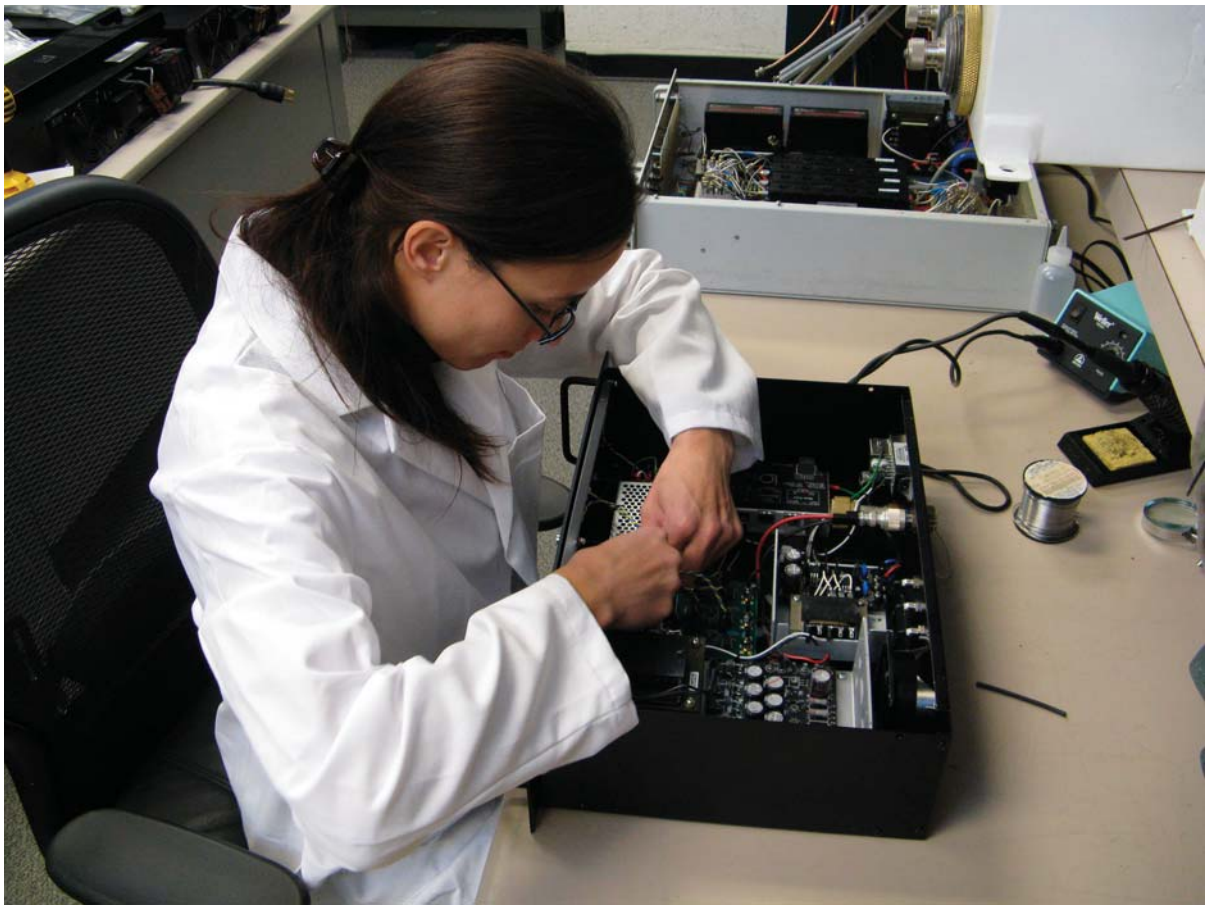
- Development of low-frequency preselectors and duplication of high-frequency preselectors.
- Several new ITS custom designed software modules for instrument control and measurement.
- Maintenance of normal operations through repairs, lab improvements, and calibrations.
- Specialized training for new entry-level hires.

The 4th generation system for Radio Spectrum Measurement Science (RSMS) consists of state-of-the-art tools (vehicle, software, and hardware) necessary for making measurements to characterize spectrum occupancy, ensure equipment compliance, determine electromagnetic compatibility, and analyze interference problems. The development of the 4th generation system originated out of the recognized need to upgrade to the latest technology used in RSMS operations. RSMS operations, in turn, directly supports NTIA by providing critical measurements for determining policies affecting both the public and private sectors. To this end, several new capabilities and improvements were added to the system in FY 2008.

Integral to the RSMS measurement system has been the development of customized preselector units that filter out unwanted signals and amplify the input to increase system sensitivity. Over the last few years, two new computer-controlled 4th generation preselectors have been designed and constructed — one for frequencies between 0.5–18.0 GHz and the other for frequencies between 18.0–26.5 GHz. To provide redundancy in case of failure or dual system requirements, a second set of each preselector is currently under construction. Both types of preselectors are protected against strong signals by highly shielded enclosures and are controlled via fiberoptic connections to prevent signals from coupling into control lines. In addition to these higher frequency preselectors, a 4th generation low-frequency preselector (1.5–1000 MHz) was designed, parts were purchased, and construction is nearly complete. Under the development of the 4th generation software, computer automated control of each of the units — new and old — has been integrated into the larger software package. Modularized instrument software units have made it possible to seamlessly swap out units for different applications of the same measurement capabilities.

During FY 2008, several improvements were made to existing tunable YIG filter systems frequently used for radar measurement. Specialized gain-offset circuits were developed for voltage conversion in situations where frequency tracking voltages are provided by spectrum analyzers. For spectrum analyzers that do not provide frequency tracking voltages, a YIG tracking system incorporating an arbitrary waveform generator was developed for the purpose of sweeping a YIG control voltage to coincide with the frequency sweeps of the spectrum analyzer.

Several new additions and improvements were also made to software measurement routines, as well as instrument control modules. These include the advent of a new automated bandwidth progression measurement, and an instrument module for an HP8566 spectrum analyzer. The bandwidth progression measurement determines signal power contained in different bandwidths and is useful for determining the optimal bandwidth for performing radar emission characterization measurements. The HP8566 is an older spectrum analyzer in the RSMS inventory that, while not used as extensively as the newer instruments, is still a useful instrument. Improvements were also made to the “stepped” measurement and the amplitude probability distribution (APD) measurement. The “stepped” measurement is an automated routine used frequently to characterize the emission characteristics of radars. Improvements to this routine include an event table that provides multiple automated measurement without interruption and a data viewer that allows examination of data and the ability to re-measure designated sections of the spectrum. The APD measurement is an automated routine used for statistical analysis of signal and noise power levels. Improvements to this routine also include the addition of an event table and a data viewer. Modifications were also made to



ITS engineer building a preselector control module (photograph by J.R. Hoffman).

the "swept" and "swept calibration" measurements to accommodate use of the new YIG tracking system.

Every year, approximately 20% of RSMS 4G project resources are reserved for maintaining equipment readiness. This includes repairs and maintenance to the measurement vehicle, as well as various instruments. It also includes periodic equipment calibrations, upgrades to the labs, characterization and record keeping for discrete components such as amplifiers, filters, and cables, and the purchase of components required to complete specified measurements.

Funds were also reserved this year for additional training of two new entry-level employees. In an effort to expedite the knowledge and skill base of these employees, additional on-the-job experience was provided that would not normally be available under other tightly budgeted projects. Because measurements frequently have time and monetary constraints that prevent adequate training in the field, this allocation of funds provided financing for duplicate personnel in the field who are still learning and may not be able to provide the necessary skills to accomplish the task at hand without working with other more senior engineers. This allows the work to be accomplished in a timely manner within budget and still provide training of new employees.

Further developments expected in FY 2009 include enhanced data file management, a scheduler for automated control of multiple measurements, improvements to the swept and stepped APD programs, work on an FPGA re-programmable instrument module, and the completion of the second set of preselectors.

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Table Mountain Research Program

Outputs

- NOAA Weather Radio receiver performance testing and validation.
- Antenna characterization.
- Geospatial data representation and visualization.
- Lidar system testing and evaluation.

The Table Mountain Field Site and Radio Quiet Zone (see p. 73) supports fundamental research into the nature, interaction, and evaluation of telecommunication devices, systems, and services. Activities this year have included:

Studies in Geospatial Data Representation
Radio spectrum measurements are typically associated with location, time, bandwidth, and antenna characteristics. However, such a sample does not give a complete representation of the distribution of electromagnetic energy in three dimensions (3D). In FY 2008, ITS explored the use of geographic information system (GIS) technology to research radio spectrum measurements and preserve the geospatial relationship between spectrum measurements. ITS created the first phase of a Table Mountain Frequency Coordination Website (TMFCW) to store and analyze two-dimensional (2D) frequency propagation data originating from transmitters that are within 80 miles of the Table Mountain Research radio quiet zone. Modeling 2D radio propagation data at Table Mountain is the first step in utilizing GIS technology to provide a more complete picture of the radio environment. As GIS technology improves, ITS plans to perform more sophisticated radio analyses in 3D.

Laser Research
The Table Mountain field site provides a large, open, unobstructed area that is ideal for the study of laser systems. Researchers from the National Oceanic and Atmospheric Administration (NOAA) and private research partners perform tests that include: atmospheric effects on laser light, imaging and ranging using laser based systems, and even laser based systems for counting the fish in the ocean.

NOAA Weather Radio Testing
NOAA Weather Radio (NWR) is an information broadcasting service operated by NOAA to provide continuous information on the latest weather conditions. Per a 1975 White House Policy statement, NWR was designated as the sole government-operated radio system to provide warnings regarding natural and other disasters and hazards directly to the public. ITS operates a laboratory at the Table Mountain Field Site for the purpose of measuring the performance of these radios. This test facility provides NOAA with performance data based on tests outlined by the Consumer Electronics Association standard CEA-2009.

NOAA Weather Radio research at Table Mountain (photograph by J.W. Allen).

Antenna Performance and Evaluation Testing
The controlled radio environment at the Table Mountain Field Site is an ideal place to study the radiation pattern, gain, and polarization of radio antenna systems. Experiments have included: testing the effects of vehicles on mobile antenna systems, evaluating the performance of new antenna designs, and studying the polarization of antenna side-lobe emissions.

FY 2008 Cooperative Research and Development Agreement (CRADA) Partners at Table Mountain

- Arete Associates
- Lockheed Martin/Coherent Technologies
- First RF Corporation
- University of Colorado, Ad hoc UAV Ground Network (AUGNet)
- Deep Space Exploration Society (DSES)

Laser research at Table Mountain (photograph courtesy Lockheed Martin/Coherent Technologies).

Recent Publications

J. Carroll, R. Hoffman, and R. Matheson, "Measurements to characterize land mobile channel occupancy for Federal bands 162–174 MHz and 406–420 MHz in the Denver, CO area," NTIA Report TR-08-455, Sep. 2008

T. Brown, B. Argrow, E. Frew, C. Dixon, D. Henkel, J. Elston, and H. Gates, "Experiments using small unmanned aircraft to augment a mobile ad hoc network," in B. Bing, ed., *Emerging Technologies in Wireless LANs: Theory, Design, and Deployment*, pp. 695-718, 2008.

E.W. Frew, C. Dixon, J. Elston, B. Argrow, and T.X Brown. "Networked communication, command, and control of an unmanned aircraft system," *AIAA Journal of Aerospace Computing, Information, and Communication*, vol. 5, no. 4, Apr. 2008, pp. 84-107.

D. Henkel and T.X Brown, "Delay-tolerant communication using mobile robotic helper nodes," in *Proc. The First Workshop on Wireless Multihop Communications in Networked Robotics*, Berlin, Germany, Apr. 2008.

E.W. Frew, D.A. Lawrence, and S. Morris, "Coordinated standoff tracking of moving targets using Lyapunov guidance vector fields," *AIAA Journal of Guidance, Control, and Dynamics*, vol. 31, no. 2, Mar.–Apr. 2008.

C. Dixon and E.W. Frew. "Maintaining optimal communication chains in robotic sensor networks using mobility control," in *Proc. of the First International Conference on Robot Communication and Coordination (Robocomm)*, Athens, Greece, Oct. 2007.

T.X Brown. "The role of communication in UAS in the next 10 years," *First Community Symposium dedicated to Civilian Applications of Unmanned Aircraft Systems (CAUAS)*, Boulder, CO, Oct. 2007.

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Antenna Polarization Mismatch Loss Measurements

Outputs

- Co- and cross-polarized azimuthal antenna patterns.
- Antenna polarization mismatch loss plots.

Radio waves have a property called polarization, which is defined as the orientation of the electric field vector. The three polarization types are linear (which has common subdivisions of vertical, horizontal, and slant), circular, and elliptical. An antenna's polarization is the same as the polarization of a radio wave that would be produced if the antenna was energized by a transmitter. For example, an antenna that transmits a vertically polarized radio wave would have a vertical antenna polarization.

Generally, in a communication system involving a transmitting antenna and a receiving antenna, the maximum radio wave energy is transferred when both antennas have the same polarization.

For an electromagnetic compatibility (EMC) analysis, there can be an effect on the received level of an interfering signal caused by differences in antenna polarization between a potentially interfering transmitter and a victim receiver. The polarization of an antenna remains relatively constant throughout the main lobe of the antenna pattern, but can vary considerably in the minor lobes. This variation can create a significant additional loss to be considered when doing an EMC link analysis. The loss due to differences between transmit and receive antenna polarizations is called antenna polarization mismatch loss.

Figure 1. Physical setup used for antenna polarization mismatch loss measurements (photo by B. Bedford).

In FY 2008, ITS performed measurements of antenna polarization mismatch loss between many combinations of an electromagnetic field's polarization and the polarization of an antenna under test (AUT). The measurements were performed using two AUTs, a linearly polarized double ridged guide horn and a right hand circularly polarized cavity backed planar spiral. Both linear and circularly polarized electromagnetic fields were generated to measure the mismatch loss with various combinations of field polarizations and antenna polarizations.

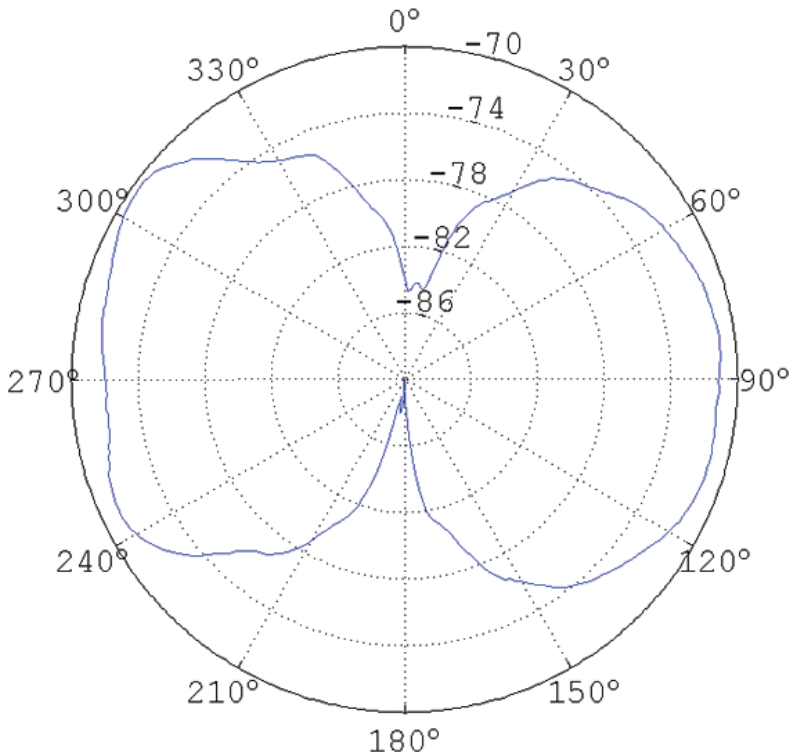

Figure 2. A polarization mismatch loss pattern for a lobe on a double ridged guide horn antenna at 311 degrees in the cross-polarized azimuthal antenna pattern.

First, points in the AUT antenna pattern had to be identified where the polarization mismatch loss measurements would be made. Since many EMC analyses involve terrestrial links, terrestrial azimuthal antenna patterns were measured for each AUT. Polar plots of the patterns were created for co- and cross-polarized field cases. The cross-polarized cases were defined as vertical vs. horizontal and right hand circular vs. left hand circular. Lobes in these patterns were selected for further measurements.

For each selected lobe, the lobe was immersed in a vertically polarized field and the lobe was rotated through 360 degrees of polarization angles. A polar plot was made of the received signal level vs. the lobe polarization angle, illustrating any polarization mismatch loss that may exist. An example plot is shown in Figure 2. In this plot, a lobe on a double ridged guide horn antenna at 311 degrees in the cross-polarized azimuthal antenna pattern was selected for measurement. At a polarization angle of 3 degrees, the lobe is cross-polarized with the field, yielding a maximum mismatch loss. As the angle increases, the mismatch loss mostly decreases to a minimum at around 85 degrees. Further angular progression results in an increase in the mismatch loss up to 179 degrees. For a theoretical model of this antenna in free space, this pattern would be expected to exhibit symmetry about the 5 degree axis but the measurement shows that for a real antenna with a coaxial cable attached to it, there is some deviation from perfect symmetry.

The co- and cross-polarized azimuthal antenna patterns show the degree of isolation that can be achieved with real antennas including the effects from coax cable. The polarization mismatch loss patterns provide information about how real antennas, with effects from coax cable, deviate from theoretical predictions. This new information may potentially be used to improve electromagnetic compatibility link analyses in the future.

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Radio Noise and Spectrum Occupancy Measurement Research

Outputs

- Design and development of an automated wideband noise measurement system.
- Characterization measurements of the noise measurement system.

The proper design of a radio communication system requires, among other considerations, knowledge of the noise and interference environment at the receiving location. While distinguishing between what is considered noise and what is considered interference is subject to interpretation, one interpretation is that interference arises from intentionally radiated signals whereas noise arises from either natural sources or from unintentionally radiated signals from man-made sources. Noise can be further categorized as being internal to the receiving system or external to the receiving antenna. External man-made noise was studied extensively at ITS in the 1960's and 1970's and culminated in the development of a man-made noise model that is still in use today (see Recommendation ITU-R P.372-9). However, the proliferation of computers, cellular telephones, and other electronic devices as well as increases in spectrum crowding, use of RF overlay technologies, aging of the power distribution infrastructure, and improvements in auto ignition systems suggest that the man-made radio noise environment may have changed since the 1970's. Thus, there has been a renewed, worldwide interest in measuring, quantifying, and modeling man-made radio noise.

To respond to this interest, ITS designed and developed a new, automated wideband noise measurement system. Unlike previous noise measurement systems at ITS, this new system uses a vector signal analyzer (VSA). The VSA-based system permits wideband noise measurements in up to 36 MHz of bandwidth and permits the recording of digitized in-phase/quadrature (I/Q) samples of the entire noise signal. Previous noise measurement systems at ITS were limited to much narrower bandwidths and only recorded amplitude values of the measured noise. Measurements in the wider bandwidth and recording the actual I and Q signal data provide many more options in how the data can be processed and further utilized.

Figure 1. Characterization measurements of the noise measurement system in a radio quiet area in Boulder Canyon (photograph by R.F. Kaiser).

The measurement system consists of an antenna, ITS custom-built RF preselector, VSA, and personal computer. Due to their omnidirectional pattern and gain predictability when mounted on a measurement vehicle and to provide better comparison with historical noise measurement results, quarter-wave monopole antennas tuned to the desired measurement center frequency and mounted on a circular ground plane are used.

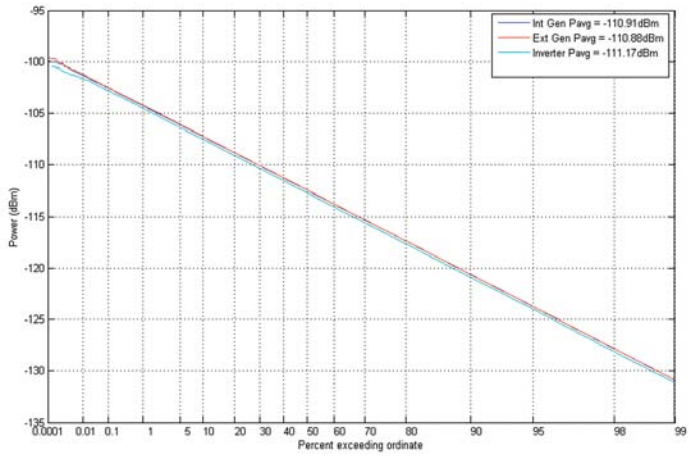

Figure 2. Comparison of the amplitude probability distributions of measured noise power at 761 MHz for different AC power sources.

The preselector is able to switch between three different filter paths, which currently are configured as manually tunable bandpass filters but can be replaced with fixed bandpass filters to achieve narrower bandwidths for better interfering signal rejection. Switching of the filter paths is accomplished with coaxial RF switches under automated software control using ethernet-based electro-mechanical relays. After filtering, an ultra low-noise amplifier is used to minimize the overall system noise figure.

The VSA downconverts the preselected signal from RF to IF, digitizes the signal, performs a digital downconversion to produce baseband I and Q samples, digitally filters and decimates this data, and saves the data to a file. A key benefit in using the VSA is the capability of capturing and storing a very large number of I and Q noise data samples.

The noise measurement system is controlled by custom software developed by ITS that runs on a personal computer. The software allows the user to select measurement parameters such as the time between data recordings and the total duration of the measurements. The software also allows the user to select a center frequency, VSA span, and the number of points to save to a file. The capability to perform and display results of noise diode calibrations, spectrum captures, and single, manual noise measurement data captures is included in the software.

Currently the noise measurement system is housed in the RSMS-4G measurement vehicle (see pp. 8-9), which provides AC power, temperature control, and shelter for the equipment. Even more importantly, the vehicle provides a high degree of shielding between any electromagnetic interference (EMI) generated by the equipment housed inside and the receive antenna mounted on the roof of the vehicle. Since it is critical in a noise measurement system to ensure that the system does not receive EMI from its own equipment, extra precautions are taken. High shielding, low-loss RF cabling is used between the antenna, the preselector, and the VSA. In addition, the preselector was constructed within an RF shielded enclosure.

The noise measurement system software is able to prevent the air conditioning and heating system from turning on during data acquisition. This eliminates any possibility that EMI generated by the air conditioning and heating system will be measured.

Characterization measurements of the noise measurement system were made using the RSMS-4G vehicle in a radio quiet area in Boulder Canyon (see Figure 1) to test the system and to determine (1) the susceptibility of the system to self-generated EMI and (2) the effects of using different AC power sources. Figure 2 shows a comparison of the amplitude probability distributions of measured noise power at 761 MHz during system characterization for different AC power sources. No difference in noise power levels was seen between the internal and external generators; the noise power level is only slightly lower for the inverter (located completely inside the shielded area of the vehicle).

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