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ISART 2011 Proceedings

Developing Forward Thinking Rules and Processes to Fully Exploit Spectrum Resources: An Evaluation of Radar Spectrum Use and Management

July 27–30, 2011, Boulder, Colorado, USA

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U.S. DEPARTMENT OF COMMERCE

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DISCLAIMER

These proceedings are a best effort to summarize information presented and articulated at the conference. Speakers were given the opportunity to review the write-ups. Questions and requests for clarification should be forwarded to individual speakers. Certain products, technologies and corporations are identified in this report to adequately specify aspects of subjects discussed during this conference. In no case does such identification imply recommendation or endorsement by the National Telecommunications and Information Administration, nor does it imply that they are in any way superior to or more noteworthy than similar entities that were not mentioned.

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EXECUTIVE SUMMARY

The International Symposium on Advanced Radio Technologies (ISART) is a U.S. government-sponsored conference hosted by the National Telecommunications and Information Administration's Institute for Telecommunication Sciences (NTIA/ITS). ISART is a discussion-based conference that brings together government, academia, and industry leaders for the purpose of forecasting the development and application of advanced radio technologies within the context of spectrum management and regulation. Starting in 2010, the principle-based goal of ISART has been to develop forward-thinking rules and processes to fully exploit spectrum resources.

The emphasis of ISART 2011 was radar spectrum usage and management. The symposium included radar tutorials, inventory briefings, and moderated discussions about radar policy, spectrum management, research, technology, and regulatory issues related to sharing radar spectrum. Overall, ISART 2011 successfully brought the radar and communications communities together to identify the issues and discuss ways to make radar systems and spectrum use more efficient. The conference was organized into five broad categories: policy, spectrum management, technology, business, and regulation.

Policy: Keynote Speakers and High-Level Overview Discussions

Thomas Power and Phil Weiser addressed the conference with some guiding questions and directives. Power highlighted six questions to facilitate discussion. The six questions were: (1) can any of the missions be accomplished in higher bands; (2) is there maritime or aviation radar functionality that could be provided by radionavigation satellite service (RNSS); (3) can we be more efficient in packing radars together; (4) if we can cut out a portion of these bands, and implement wireless broadband, can these services live with each other as close neighbors; (5) can new systems share with radar; and (6) is the commercial wireless industry interested in or able to share radar spectrum?

Phil Weiser also provided context for the discussion by asking the participants to organize their thoughts into three broad ideas: (1) sharing and cooperative uses of spectrum; (2) the role of the institutional side of managing spectrum; and (3) the importance of incentives and data. He encouraged the participants to build communities among themselves and stay engaged, to develop shared and broadly held viewpoints, and to cultivate compelling narratives around those viewpoints to get policymakers engaged in the issues.

The goal of the Overview panel was to provide an overview of the topics to be discussed in the conference and to establish context related to the political pressure to find 500 MHz for fixed and mobile broadband and the implications for radar. The panel discussed NTIA's plan to contribute to the 500 MHz goal, budgetary constraints, institutional obstacles, incentives, collaboration between the private and public sector, and sharing radar bands with the commercial sector. Some pervasive themes in the Overview Panel were funding, incentives, rules, trust, and lack of information.

Spectrum Management: Inventory Briefings and Compatibility Discussions

The goal of the Inventory Briefings was to give some technical background on where radars are currently located in the spectrum and general characteristics of radar. Some of the important characteristics highlighted included: radars have high-power transmitters and noise-limited receivers; no two radar models are alike and systems continue to evolve; many air- and ship-based radar systems operate in coastal regions; and radars have long lifecycles, are expensive, and alternatives are limited.

The International Compatibility panel provided an understanding of the regulatory regimes and current interference issues facing the radar community. The current radar spectrum management and interference issues discussed included:

- Adjacent-band broadband compatibility around 3 GHz
- Fast-track wireless broadband service issues at 3550-3650 MHz
- Compatibility between RNSS and ground-based airport surveillance radar systems in the 1215-1300 MHz band
- Co-channel dynamic frequency selection (DFS) radio frequency interference to terminal Doppler weather radar (TDWR) at 5 GHz
- HF oceanographic radar and 5 GHZ band radar interference issues in Korea.

Technology: Radar Tutorials and R&D Discussions

To provide technical background for the broad range of engineers in attendance, the conference was preceded by a series of tutorials on radar technology chaired by William Melvin of Georgia Tech Research Institute. The topics covered basic radar fundamentals, adaptive interference mitigation in the receiver, and an overview of transmitter technologies.

The Radar R&D panel addressed the technological roadmap to next generation radar that achieves greater spectrum utilization by leveraging emerging radio technologies. Session chair Joe Guerci established the challenges and constraints (in addition to the points made previously by Frank Sanders in the inventory briefings) that currently exist for radar as: (1) airborne radars have a panoramic view and long line-of-sight range, (2) radars require relatively long periods of useable spectrum, (3) current radars are highly restricted with regard to waveforms, (4) security constraints associated with government radars, (5) radar systems have long development times, and (6) changing radar bands can degrade capabilities.

Business: Broadband Industry Making a Case to Share Radar Bands

The goal of the Sharing Radar Bands with Commercial Systems panel was to explore sharing possibilities and make the case for sharing radar bands with commercial systems. Topics covered by the panelists included:

- Costs and benefits in Sharing Radar Bands
- WISPA’s perspective on Radar Band-sharing at 5GHz and 3.4 GHz

- Operation of wireless broadband services in the 3550-3650 MHz band identified under the NTIA Fast-Track Evaluation
- Opportunistic primary-secondary sharing with rotating radar
- Medical devices coexisting with radar in the 420-450 MHz band
- Incumbent spectrum users' DSA requirements.

Regulation: Reform to Facilitate Spectrum Sharing

The goal of the Regulatory panel was to describe a roadmap for DSA deployment with radar, with practical first steps to advance both the development of new technology and new regulatory approaches. Time limited leases, software assurance and conformity assessment, improved monitoring of new technology rollouts, robust enforcement capability, more resilient systems, and model-based spectrum management were all discussed as possible sharing models for radars.

Conclusion

There were a number of significant findings. The problem of encouraging more efficient use in the radar bands is a multi-faceted problem spanning economic, regulatory, and technological issues. A number of technical solutions for improving radar spectrum utilization were identified including cognitive radar, adaptive antennas, modern radar transmitter front-ends with improved out-of-band emission characteristics, advanced waveforms, signal processing, and multifunction systems. However, the most significant obstacles were found to be not technical but rather institutional, e.g. incomplete information, lack of incentives for incumbent to change, and lack of resources.

The path forward will require incremental changes in technology and regulatory reform. Some regulatory reforms that could be helpful first steps include commitments to developing strategic agendas and transparency in the regulatory process. The most significant lingering questions involved funding models, structuring incentives, building trust among stakeholders, security, and protecting radars' critical safety-of-life missions.

ISART 2011 PROCEEDINGS

DEVELOPING FORWARD-THINKING RULES AND PROCESSES TO FULLY EXPLOIT SPECTRUM RESOURCES: AN EVALUATION OF RADAR SPECTRUM USAGE AND MANAGEMENT

Michael Cotton, Madelaine Maior, Frank Sanders, Eric Nelson,[1] and Douglas Sicker[2]

These are the proceedings for the 2011 International Symposium on Advanced Radio Technologies hosted by the National Telecommunications and Information Administration's Institute for Telecommunication Sciences in Boulder, Colorado. The conference focused on radar spectrum usage and management. It included radar tutorials; spectrum inventory briefings; and moderated discussions about radar policy, spectrum management, research and technology, and regulatory issues related to sharing radar spectrum. Overall, ISART 2011 successfully brought together the radar and communications communities to identify spectrum issues and discuss ways to make radar systems and spectrum more efficient. Conclusions drawn at this year's conference were that better spectrum management in radar bands is a multi-faceted problem spanning economic, regulatory, and technical issues. Technical concepts and solutions were identified that could improve radar spectrum efficiency. Examples include radar transmitter upgrades to improve out-of-band emissions; using adaptive and cognitive antennas and signal processing to avoid, mitigate, and prevent interference; and consolidation of multiple radar systems, functions, and/or operational bands into a single platform. In regards to sharing radar spectrum as a means to increase spectrum utilization, radar usage models that offer whitespace opportunities were identified. Radar spectrum improvement projects, however, have technical challenges and tend to be large and expensive. Further, current funding models do not support wide scale development for the sake of spectrum efficiency. The path forward involves the development of a cohesive long-term radar spectrum strategy that reduces large radar projects into incremental and manageable steps with limited risk. Similarly, incremental regulatory reform is needed to enable spectrum sharing rules to be implemented in manageable increments with a "crawl-walk-run" approach.

Keywords: adaptive radar; adaptive radio; cognitive radar; cognitive radio; International Symposium on Advanced Radio Technologies; ISART; radar policy; radar spectrum management; radar spectrum usage; RF interference; signal processing; spectrum efficiency; spectrum inventory; spectrum management

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1 INTRODUCTION BY CONFERENCE CHAIR MICHAEL COTTON

The International Symposium on Advanced Radio Technologies (ISART) is a U.S. government-sponsored conference hosted by the National Telecommunication and Information Administration's Institute for Telecommunications Sciences (NTIA/ITS). ISART brings together government, academia, and industry leaders for the purpose of forecasting the development and application of advanced radio technologies. In the first 10 years, ISART was primarily a science conference based on presentations of technical papers. There were a few policy papers and round table discussions, but the format suited the focus of science and engineering (which matches ITS's role within NTIA). In the last couple of years, ISART has changed in format and focus to address the current spectrum policy environment and its challenges.

1.1 Current Spectrum Policy Landscape

The political spectrum landscape in the U.S. has changed in recent years. In March 2010, the Federal Communications Commission (FCC) released the National Broadband Plan (NBP) [1] calling for 500 megahertz (MHz) of Federal and non-Federal spectrum to be repurposed in order to free up that spectrum for new mobile, fixed, and unlicensed broadband use over the next ten years, with 300 MHz of that to come from the 225 MHz to 3.7 GHz range in the next five years. In June 2010, President Obama issued a Memorandum entitled "Unleashing the Wireless Broadband Revolution" [2], which was in line with the NBP. The Presidential Memo, in particular, is important because in it, President Obama says that finding 500 MHz for broadband is important and commands it to happen, which has really set things in motion. Subsequently, NTIA's "Plan and Timetable to Make Available 500 MHz for Wireless Broadband" [3] was released in October 2010. It identified 2200 MHz of Federal and non-Federal spectrum that NTIA and FCC consider prospects for repurposing and set an aggressive timetable for repurposing the 500 MHz. Also released in October 2010 was an assessment commonly referred to as "NTIA's Fast Track Recommendations" [4], which made recommendations and gave conditions on repurposing 115 MHz in four Federal bands over the next five years. There have been a number of bills working through the legislative process; notable bills include Hutchinson and Rockefeller's Public Safety Spectrum and Wireless Innovation Bill [5] as well as Snowe and Kerry's Radios Bill [6].

Finding new spectrum is difficult because there are many layers of complexity to the spectrum management process. Change is difficult because there is an established legacy built from large investments on which stakeholders want to continue realizing returns. There is a lack of incentive for incumbents to share or become more efficient because they have working business models based largely on current uses of the spectrum. Budgetary constraints make it difficult to upgrade, repurpose, or re-engineer systems and increases pressure for exclusive rights. Modern radio technologies use wider bandwidths, causing more spectrum scarcity. Advanced technical knowledge in many areas of expertise is needed to forecast success or failure of repurposing, e.g., electronics, communications, and network engineering; physics, economics, mathematics, and computer science; political science and telecommunications and Internet policy; and business management (to ensure that systems make good sense fiscally). The variety of systems and usage models, each with unique characteristics, must be understood to identify available whitespace and good possibilities for sharing. There is also a diverse array of stakeholders, roles, and relationships, which leads to competing influences and self-interests.

Examples of the groups of stakeholders and roles include: government; international communities; spectrum managers and regulators; Federal and licensed incumbents; big business and lobbyists; think tanks and academia; unlicensed users and small business; acquisition offices and investors; technologists, innovators, and R&D communities; standards bodies; and application users. Examples of competing influences and self-interests include: Federal vs. commercial; licensed vs. unlicensed; science vs. politics; regulator vs. regulated; profit vs. social benefit; long-term vs. short-term; business X vs. business Y; agency X vs. agency Y; business X vs. agency Y; and service X vs. service Y. These can make negotiation of a scarce resource like spectrum all the more difficult. One noteworthy case of competing self-interests is between the "have's" and "have-not's", which naturally falls into a conservative vs. liberal political debate. And we all have experience, from our national political debates, on how political debates can drag on without any real progress.

1.2 ISART 2010—Spectrum Sharing Technologies

Since 2010, the principle-based goal of ISART has been *to develop forward-thinking rules and processes to fully exploit spectrum resources*. We transformed ISART from a science format to a multi-stakeholder/multi-disciplinary open discussion approach in an effort to address challenges identified previously, promote transparency, and seek consensus amongst stakeholders [7]. The emphasis of ISART 2010 was *spectrum sharing technologies* as a means of improving overall spectrum utilization. Under the assumption that reallocation alone cannot achieve our long-term spectrum goals, spectrum sharing was discussed as an alternative means of making better use of the spectrum and taking advantage of modern radio technologies. We held sessions on the critical spectrum sharing topics, i.e., Dynamic Spectrum Access (DSA) technology and rules; measuring spectrum occupancy; interference protection criteria; spectrum management; sharing land-mobile radio bands; sharing radar bands; business; context awareness; and research. The following high-level conclusions were drawn from last year's discussions:

- There are spectrum-sharing successes: disparate government and Department of Defense (DOD) systems, carriers offloading data onto Wi-Fi networks.
- There are other DSA solutions beyond sensing, e.g., database, beaconing.
- Primary obstacles are lack of trust and complexity of the problem—the regulatory and operational challenges of implementing DSA far outweigh the technological barriers.
- DSA technology is somewhat captured in R&D until regulatory reform provides a big/good enough sandbox to justify private investment.
- Conflicting self-interests and goals cause trust and information-sharing asymmetries that need to be resolved before spectrum sharing can evolve.
- There is a need for more flexible funding structures, incentives, and continued administration and legislative support.

1.3 Orthogonal Approaches to Spectrum Discussions

Questions remained unanswered last year because of how the discussions were framed. Consider Figure 1, which describes the spectrum discussion space. As described earlier, spectrum discussions have many layers and dimensions, but for our purposes let's pick two primary dimensions: (1) Along the vertical axis, we have means to further exploit spectrum resources, e.g., reallocation; relocation; spectrum sharing; technology upgrade, re-engineering, and R&D; and regulatory reform. (2) On the horizontal axis, we have individual radio services, e.g., radiodetermination (satellite); fixed (satellite); broadcast (satellite); mobile (satellite); and science services.

There are orthogonal approaches in discussing spectrum issues where one can choose a horizontal approach, like we did last year when we covered spectrum sharing technologies across all radio services. This approach, however, caters to a more high-level discussion that doesn't address technical problems with much depth and is not tailored enough to really develop solutions. It's difficult for technical people to contribute in this style of discussion, and technical complexities are amplified when details are glossed over. Starting this year, we took a vertical approach that limits the scope on the x-axis, and focuses on a single radio service. By focusing on an individual radio service, we can take the following systematic approach to answering the questions left over from the high-level discussions:

1. Inventory allocations, usage models, operational parameter, and propagation effects to identify underutilized spectrum and whitespace.
2. Evaluate compatibility with other like and unlike systems.
3. Re-engineer to achieve optimal spectrum efficiency, e.g., reduce out-of-band emission, reduce susceptibility to interference, and enable information sharing/cooperation.
4. Assess viability of sharing business models and markets.
5. Develop rules and a regulatory framework for improving compatibility between systems.

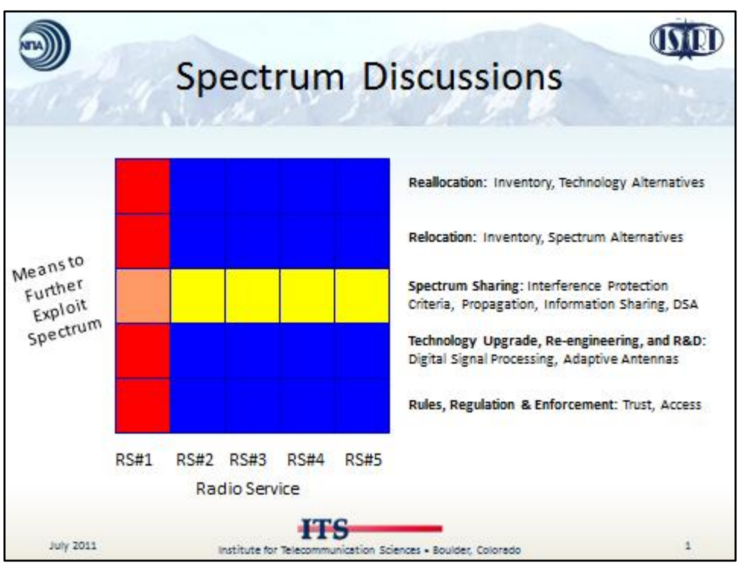

Figure 1. Orthogonal approaches in discussing spectrum issues.

1.4 ISART 2011—Evaluation of Radar Spectrum Management and Usage

This year, the emphasis is on radar. An important point to be highlighted is that there is little or no overlap in the radar and communications (comm) communities. This is understandable, given that radar stakeholders are primarily in the Federal domain, while communications stakeholders are largely in the private sector. As different as radar and comm systems are in some ways, however, there are a lot of commonalities: the math is similar and antenna theory, propagation effects, and a lot of the RF equipment are all the same. Also, there is a huge benefit in bringing these two communities together to discuss the current spectrum management problem. Hence, our format goal for this year was to bring together the radar and comm communities in an open dialogue to promote idea sharing, cooperation, and collaboration in an effort to engineer the radar spectrum for maximum benefit to all stakeholders.

1.4.1 Rationale for This Year's Topic

There are many important reasons to emphasize radar, e.g.,

- **Critical safety-of-life missions:** Examples of radar functions include air traffic control (ATC), weather forecasting and monitoring, and national security. Performance degradation is undesirable.
- **Uses a lot of spectrum:** Of the spectrum between 300 MHz and 3700 MHz, 45% is used by radar.
- **Old technology:** There is some likelihood of inefficient use of radar spectrum given that most allocations and initial deployments were made decades ago, when the technology was far less advanced.
- **Potential for quality whitespace:** Some radar systems are stationary, have co-located transmitters/receivers, and/or are constrained geographically (all conditions lending to whitespace opportunities).
- **Highly advanced R&D:** Most radar research projects are about improving performance. It begs the question—what could the radar R&D community achieve if they applied themselves to the spectrum efficiency problem?
- **Isolation from the comm community:** To a large extent, the radar and comm disciplines have developed along two independent paths, and the communities interact infrequently. Hence, there is potential benefit in bringing the two disparate communities together for information exchanges and collaboration.

1.4.2 Organization of the Conference

The ISART 2011 agenda included lectures, inventory briefings, keynote presentations, and panel discussions. To provide a technical basis for discussions, a lecture series (Section 2) was given on basic radar fundamentals, adaptive interference mitigation in the receiver, and an overview of transmitter technologies. Next, in order to demonstrate the breadth and importance of current radar applications, we dove deeper into specific radar applications and usage models in a band-by-band radar spectrum inventory (Section 3). Two outstanding keynote presentations (Sections 4 and 5) and an Overview Panel (Section 6) provided the political context and high-level perspectives on the topics to be covered over the remainder of the conference.

With radar first principles and political perspectives established, the rest of the agenda was divided into four discussion topics:

- International Radar Compatibility
- Radar Research and Development
- Sharing Radar Bands with Commercial Systems
- Regulatory Reform to Facilitate Spectrum Sharing

Within each session, panelists were asked to provide a short oral presentation on their perspective on the topic, after which session moderators directed the discussions and fielded question from the audience. The International Radar Compatibility Panel (Section 7) centered on current interference and compatibility issues facing the international radar community. From diverse technical perspectives, the Radar R&D panel discussed a technological roadmap to a next-generation radar that achieves greater utilization and leveraging of emerging radio technologies (Section 8). In the Sharing Radar Bands with Commercial Systems Panel (Section 9), the panel, comprised mostly of industry representatives looking to share radar spectrum, attempted to make the case for sharing radar bands. Finally, forward-looking perspectives on impending new regulatory schemes and approaches for building trust between incumbents and spectrum sharing stakeholders were the topics of the panel on Regulatory Reform to Facilitate Spectrum Sharing (Section 10).

2 LECTURE SERIES ON RADAR BASICS

A lecture series on radar first principles in the context of spectrum management was coordinated by Dr. William Melvin, Director of the Sensors and Electromagnetic Applications Laboratory at the Georgia Tech Research Institute (GTRI/SEAL). Radar is very broad and diverse, so with the limits on time the goal of this lecture series was to provide a broad overview of radar technology. Melvin suggested [8] and [9] for those interested in pursuing the topic further. Specific lectures given at ISART included:

1. Radar Fundamentals—Dr. Gregory Showman and Michael Davis (GTRI/SEAL)
2. Radar Adaptive Interference Mitigation—Dr. William Melvin (GTRI/SEAL)
3. Radar Transmitter Technologies—Larry Cohen (NRL), Dr. Charles Baylis (Baylor Univ.)

2.1 Introduction by Session Chair William Melvin

The radar community talks about the diminishing spectrum problem, but we are really more focused on the performance issues. My radar career started with looking for radar targets in the sky; the targets have become smaller and more difficult to detect, e.g., vehicle columns, single vehicles, and people on the Earth's surface. Another important part of radar R&D is in radar and platform design to provide the appropriate level of electronic protection (EP). EP focuses on what a threat looks like and then preventing the adversary from denying radar capability.

For a long time we've been trying to fix airport route surveillance radar (ARSR), i.e., the Federal Aviation Administration's (FAA) long-range radars, which have a challenge of navigation satellites being in the same band. The Russians have GLONASS, Europeans have GALILEO, Chinese have COMPASS, and all of these countries are putting more satellites in the air. The current approach is to avoid looking in an area when satellites come into site. No one has modeled it or asked, "How much to fix it?" It's not a difficult problem to fix, but no one is willing to step up and do it. No one up the chain wants to pay for it, so stakeholders will wait until the problem gets really bad.

There is "whitespace" and there is also "solution space." If we put the right people on the problem, then we can prove capability. There will be more pressure on radar. Congress is looking to fix the debt problem. Their second line item (second to fixing Fannie Mae and Freddie Mac) is sales of the radio spectrum. Instead, I might pose the question as follows, "Can you give back a billion dollars in spectrum if we invest fifty million in technology solutions?"

2.2 Radar Fundamentals—Gregory Showman and Michael Davis

Gregory Showman and Michael Davis combined to give lectures on Radar Fundamentals according to the following outline:

- Background and Range Measurement
- Radar Range Equation
- Signal-to-Noise Ratio and Matched Filter

- Detection in Noise
- Pulse Compression
- Multiple Pulses

2.2.1 Background and Range Measurement

Radar stands for RADio Detection And Ranging. As illustrated in Figure 2, range (R) is estimated by transmitting a pulse and measuring the time delay between transmission and reception of the target echo (T_D). Radar applications can be divided into two categories—target identification and imaging. In moving target identification (MTI), radar systems work with small isolated returns from point targets, e.g., cars—police radar, aircraft—ATC radar, reentry vehicles—ballistic missile early warning radar. In general, the MTI task sequence is (1) *detection*—decision on whether or not there is a return of interest at a specific {range, angle, Doppler location}; (2) *estimation*—if there is a return of interest then estimate desired parameters; and (3) *tracking*—where the radar revisits the scene, tracks the target over time, and allows for predictions of its position in the future. Imaging radar systems work with continuum targets (e.g., range profile in 1-D, clutter and terrain in 2-D, and weather in 3-D). Examples of these imaging systems are ground-mapping systems and weather radars.

Radar systems can also be divided into two categories: continuous wave (CW) versus pulsed. CW systems transmit (TX) and receive (RX) continuously, so the receiver is always seeing what is going on. This allows for good Doppler measurements and there are frequency- and phase-modulated tone schemes to get range; CW radars, however, tend to be either power limited or bistatic (where TX is displaced from RX) in order to avoid overwhelming the receiver. Low power limits the radar range, and bistatic configuration is costly and complicated. Henceforth, this lecture focuses on traditional high-power and monostatic pulsed radar systems.

Pulsed systems time-share the RX/TX hardware by transmitting high-power pulses when the RX is off and receiving the low-power return when the TX is off. The pulsed waveform hierarchy involves pulse-to-pulse modulation (e.g., frequency agility, stepped frequency) as well as intra-pulse modulation (e.g., linear and non-linear FM, bi- and poly-phase modulation).

2.2.2 Radar Range Equation

Radar design is about manipulating degrees of freedom to achieve a desired level of performance. As illustrated in Figure 3, the radar range equation (RRE) allows one to predict mean received power (P_r) as a function of effective radiated power at the transmitter (P_tG), radar cross section (RCS) of the target (σ), range, and wavelength (λ). Typical RCS at 1–10 GHz are on the order of 1–100 m^2 for aircraft, 10–10,000 m^2 for ships, and 1 m^2 for personnel. Note the dependence on R^4, which requires radar to typically be designed with large dynamic range.

It is important to note that large radar antennas provide high gain on TX, large collection area on RX, low energy on TX to spectrum users outside the main beam, reduced power on RX from sidelobe returns, improved angle resolution against multiple targets, and increased angle measurement accuracy on one target.

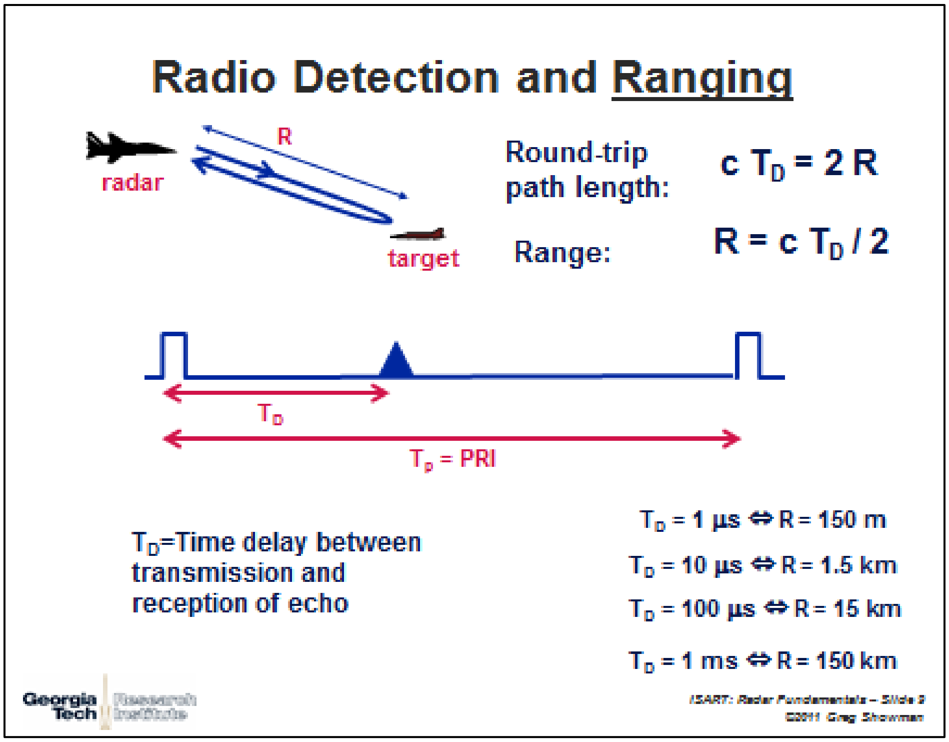

Figure 2. Estimating range with a pulsed radar system.

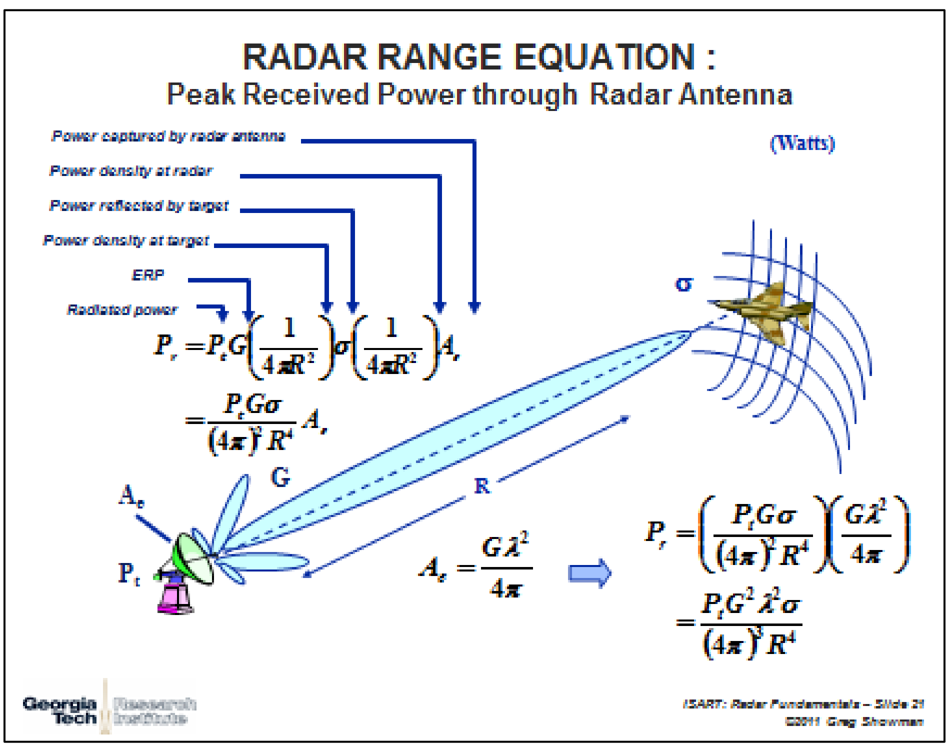

Figure 3. Radar range equation.

2.2.3 Signal-to-Noise Ratio and the Matched Filter

There is a finite amount of white noise in the RX which limits the ability to detect a pulse. For a given threshold, both probability of detection and measurement accuracy are a function of signal-to-noise ratio (*SNR*). At the detector, $SNR = P_r\tau/(N_0 L_s F)$, where N_0 is the thermal noise power density, $\tau \approx 1/B$ is pulse duration, B is bandwidth, F is the receiver noise factor, and L_s is system loss. The scheme to maximize *SNR* is to collect the energy of the finite duration pulse and make a measurement at an optimal time. This is achieved via matched filtering (performed via correlation in time) of the received signal with the time-reversed conjugate of the TX waveform. The matched filter maximizes *SNR* when the filter is aligned with a point target return. The RX signal is sampled at a rate greater than or equal to τ in order to (hopefully) find the maximum of the matched filter output, which is a triangular function for rectangular pulses (see Figure 4).

2.2.4 Detection in Noise

Radar signals and noise are random variables, which are described by a probability density function (pdf). Figure 5 shows a cartoon development of the received signal as a function of time along with corresponding pdf of RX noise and target plus RX noise. Radar receivers decide there is a target present when the RX signal crosses a threshold, which is set high enough to avoid significant noise crossings yet low enough to detect a small return. The figures of merit for radar detection are probability of detection (P_d) and probability of false alarm (P_{fa}). Mathematically, P_d is found by integrating the signal-plus-noise pdf above the threshold voltage, and P_{fa} is calculated by integrating the noise pdf above the threshold. A good reference point is at SNR = 13.2 dB which provides P_d = 90% and $P_{fa} = 10^{-6}$.

In practice, RX noise is not known a priori or it can fluctuate, so constant false alarm rate (CFAR) receivers utilize adaptive schemes to adjust the threshold according to noise estimates inferred from mean noise power measurements made before and/or after target detection. In contrast to communications theory, where one tries to figure where a symbol falls within a constellation to determine whether a bit is a zero or one, radar detection theory is a two-step process where the threshold is set to meet false alarm requirements and then detections are realized/predicted.

2.2.5 Pulse Compression

Range resolution (δ_R) is the minimum separation at which two point scatterers of equal size are distinguishable as separate scatters—higher resolution (smaller δ_R) is desirable. For unmodulated-pulse range resolution, δ_R is proportional to τ; reducing τ, however, requires increasing the pulse amplitude in order to maintain *SNR*, which can cause problems (e.g, voltage breakdown and other non-linear effects in transmissions lines and amplifiers). With matched filtering, δ_R is proportional to $1/B$. *Pulse compression* allows radar to simultaneously achieve the *SNR* of a long pulse and resolution of a short pulse by modulating the long pulse to achieve $B \gg 1/\tau$. Fine-resolution imaging radar systems (requiring δ_R on the order of inches) commonly use linear and non-linear frequency modulation. Airborne radar often uses phase-code modulation.

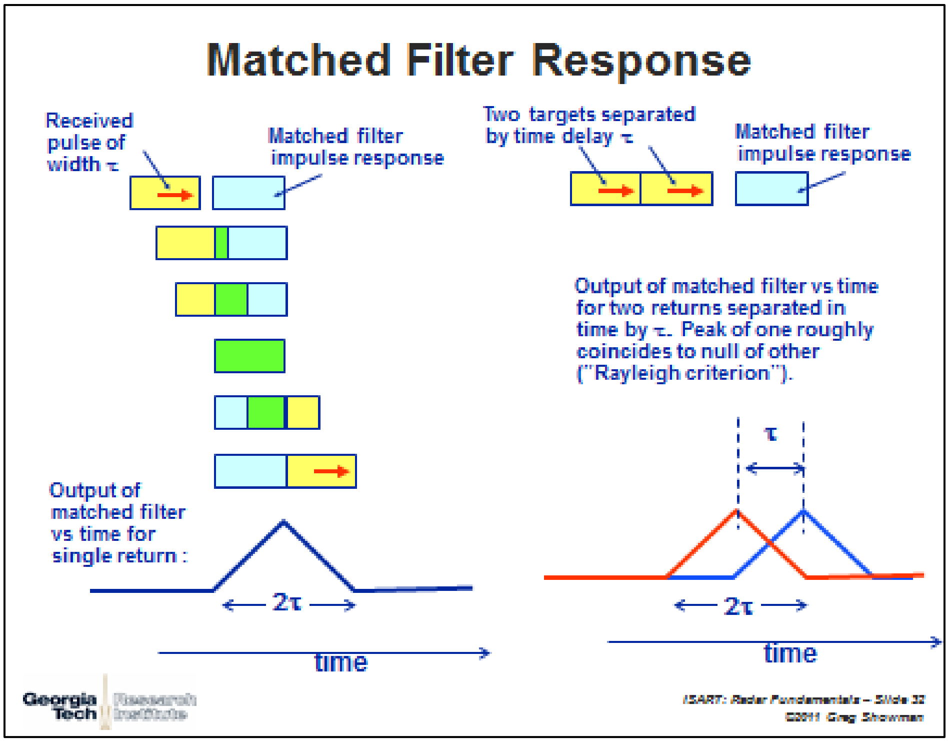

Figure 4. Radar matched filter response of one and two targets.

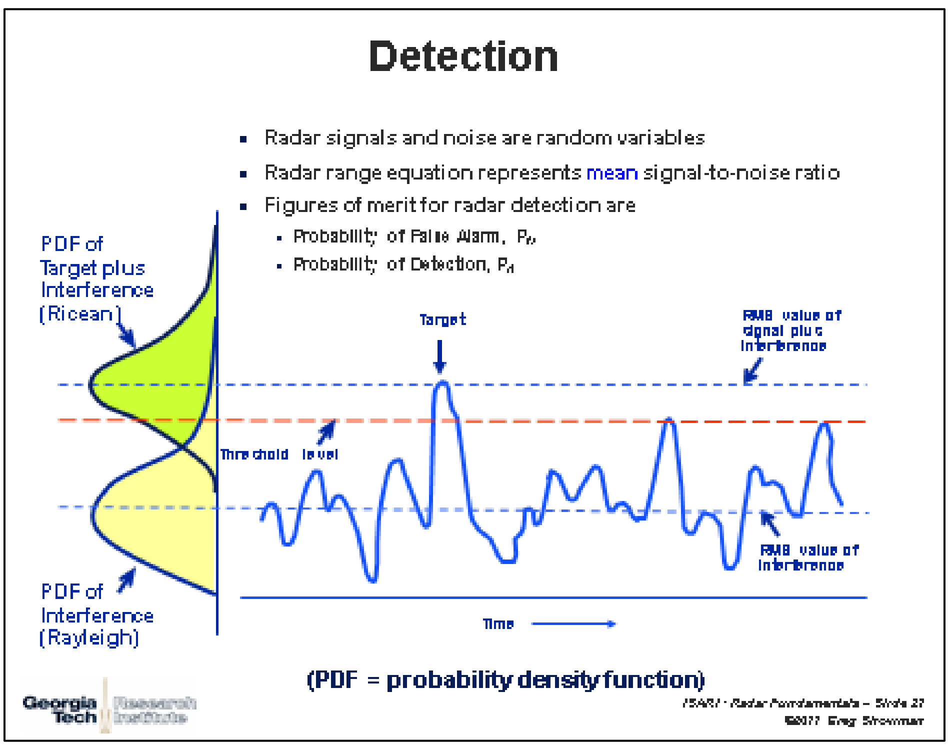

Figure 5. Illustration of radar amplitude detection.

2.2.5.1 Ambiguity Function

A Doppler shift, $f_d = 2v_r/\lambda$, is imparted on a radar signal when a radial velocity component (v_r) exists between the radar and a target. Without a priori knowledge, the Doppler shift represents an unintentional mismatch between the received waveform and the matched filter. The ambiguity function, $A(t, f_d)$, is used to characterize the response of the matched filter of different waveforms in the presence of uncompensated Doppler. Figure 6 gives the ambiguity function and an illustration for a simple rectangular pulse. Notice on the cardinal axes that for the zero-Doppler cut, the ambiguity function reduces to the magnitude of the matched filter response, and the time-delay cut characterizes the decrease in the peak value as a function of f_d.

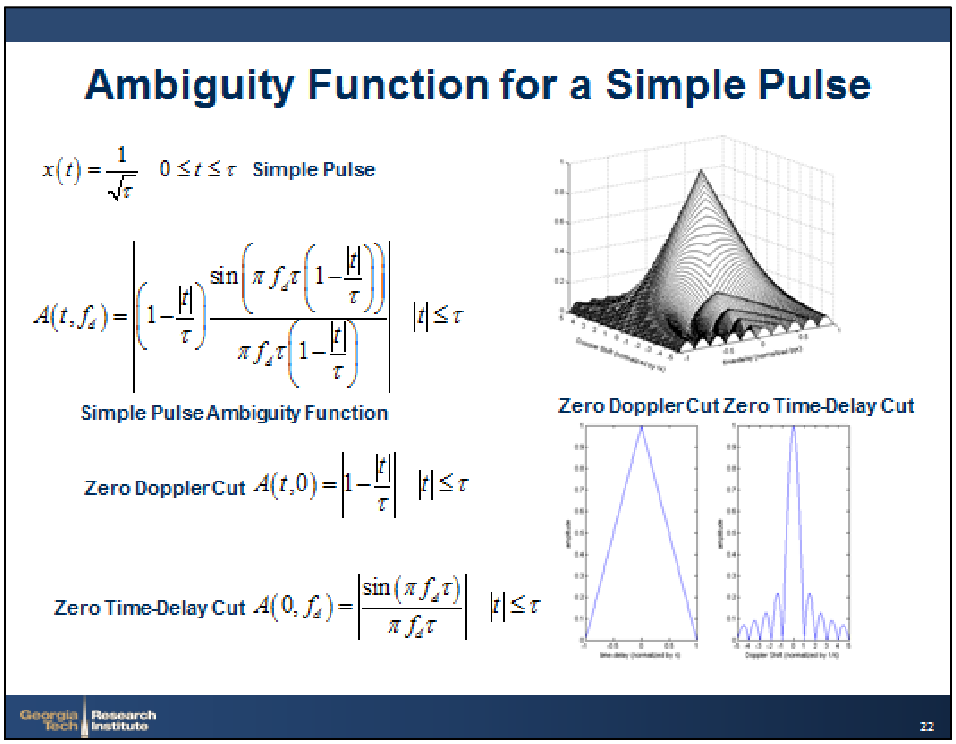

Figure 6. Ambiguity function for a rectangular pulse.

2.2.5.2 Linear-Frequency-Modulated Waveforms

The linear-frequency modulated (LFM) or "chirp" waveform can be described as a sinusoid whose frequency changes linearly with time. As illustrated in Figure 7, the LFM spectrum is approximately rectangular, which corresponds to a sinc match-filter response with relatively high nominal sidelobes. Sidelobes degrade radar performance by placing energy up and down range from its source. Amplitude weighting can be applied to the spectrum to reduce nominal sidelobes, at a cost of degraded resolution (increased mainlobe width) and loss in *SNR*. Taylor weighting is often applied to achieve minimum mainlobe width for a given peak sidelobe level. LFM waveforms are characterized as Doppler tolerant [9] in that the sidelobe structure of the match filter response is preserved in the presence of large fractional Doppler shifts. LFM also enables stretch processing, which reduces the required bandwidth in high-resolution systems.

Figure 8 illustrates how LFM stretch processing at different bandwidths enables synthetic aperture radar (SAR) imaging to resolve structures down to 1 m and 10 cm resolutions.

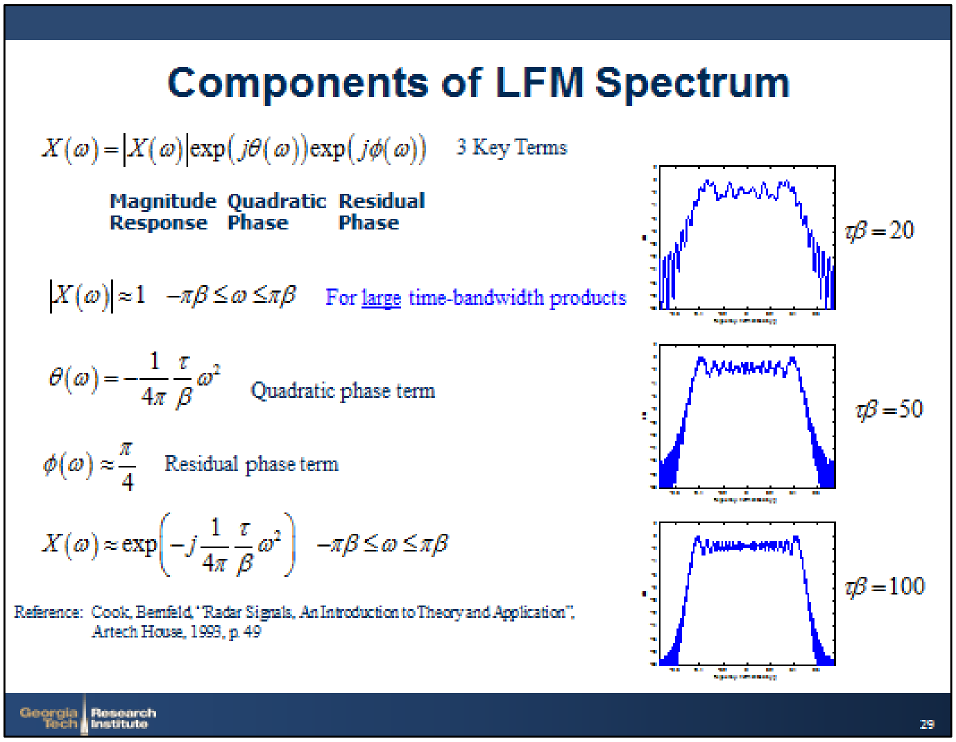

Figure 7. Frequency characteristics of LFM waveforms.

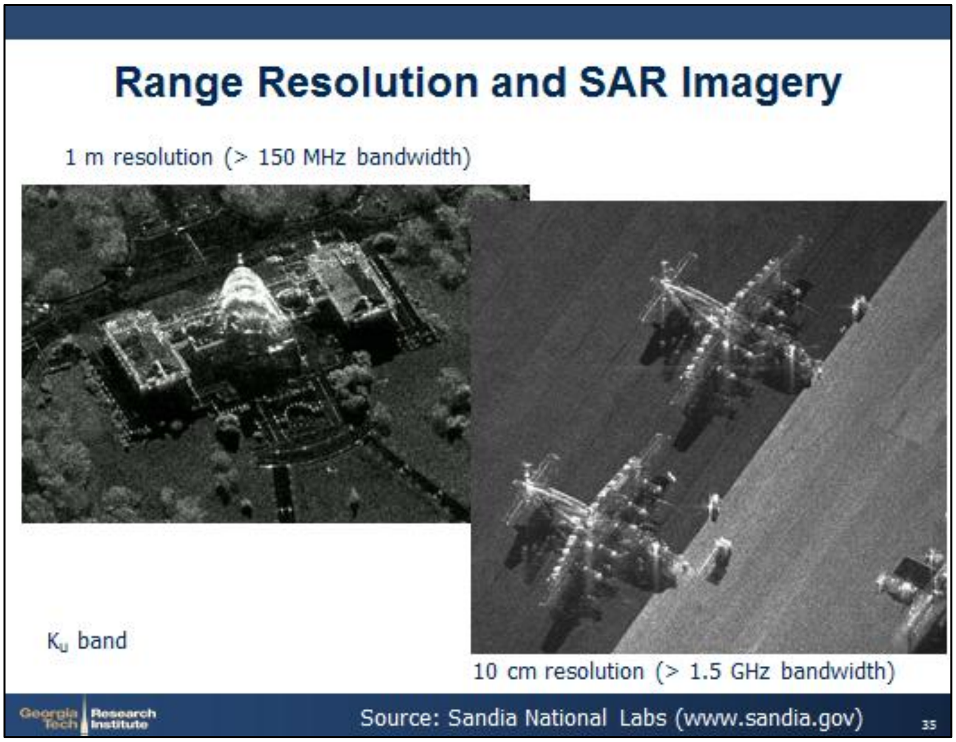

Figure 8. SAR imaging enabled by LFM stretch processing.

2.2.5.3 Phase-Coded Waveforms

Phase-coded waveforms are composed of concatenated sub-phases (or chips) where the phase sequencing is chosen to elicit a desired response, e.g., mainlobe, sidelobe, and Doppler tolerance. A matched filter is applied to the received signal to compress the waveform in range and maximize *SNR*. Increasing chip duration (τ_{chip}) degrades range resolution, δ_R=c $\tau_{chip}/2$. Energy in the waveform is proportional to the total pulse duration, $\tau=N_{chip}\,\tau_{chip}$ where N_{chip} is the number of chips.

Focusing on bi-phase codes, which flip between 0 and 180 degrees, Barker codes are optimal in the sense that they exhibit constant sidelobe levels with a peak sidelobe ratio of $20\log_{10}(1/N_{chip})$ with units in decibels (dB). The longest known Barker code, however, is N=13 with a corresponding peak sidelobe ratio of -22.3 dB. Longer sequences with lower peak sidelobe ratios are desired, which motivates exhaustive searches for minimum peak sidelobe (MPS) codes. “Good” MPS codes are available but are sub-optimal. In general, bi-phase codes are Doppler intolerant as demonstrated in Figure 9.

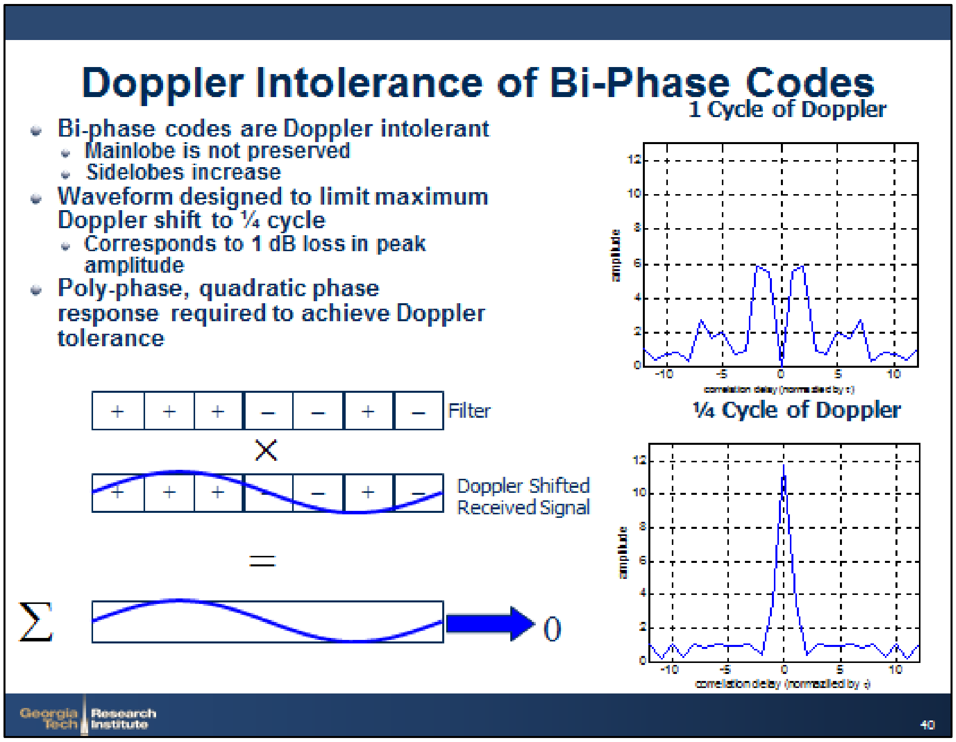

Figure 9. Doppler intolerance of bi-phase codes.

2.2.6 Multiple Pulses

Coherent integration (Doppler processing) was originally motivated for its ability to separate (by Doppler frequency) moving targets from ground clutter. Airborne radar, for example, can detect a person (RCS ~1 m^2) walking 1 m/s on the ground (RCS on the order of thousands of m^2). Another motivation for Doppler processing is fine-resolution imaging via SAR or inverse SAR, which stitches together returns taken over a period of time as the platform moves along. The Doppler-processing data set is an *N* x *M* matrix of fast-/slow-time (range/pulse number) coherent digital samples (with amplitude and phase) as shown in Figure 10. Each row of the matrix represents a series of measurements from the same range bin over *N* successive pulses. Performing a Fast Fourier Transform (FFT) over each range bin produces the Doppler spectrum. Figure 11 shows a Ground Moving Target Indicator (GMTI) Range-Doppler map, where the ground clutter is shown in the endo-clutter region centered at Doppler bin 30, and the moving targets are observed in the exo-clutter region to left and right of the dashed lines. Figure 12 shows a SAR image of the same scene; the SAR system employed a wider bandwidth waveform and integrated over a longer period of time to increase the resolution along both dimensions.

In Doppler processing, tradeoffs and design considerations are associated with the discrete sampling parameters, e.g.:

- Range ambiguities occur when a transmitted pulse does not return before the next pulse is transmitted, which can be avoided by ensuring that pulse repetition interval (*PRI*) is large enough, i.e., $PRI \geq 2R_{max}/c$. In terms of pulse repetition frequency (PRF), this condition is written as $PRF \leq c/(2R_{max})$.

- Doppler ambiguities occur when the Doppler shift is greater than the principal period of the Doppler spectrum, i.e., $\pm PRF/2$. This is because the Doppler spectrum is periodic in frequency due to the nature of the FFT causing echoes with $|f_d| > PRF/2$ to be aliased, i.e., replicated in the principal period at an apparent Doppler frequency. Doppler ambiguities can be avoided by ensuring that $PRF \geq 4|v_{r,max}|/\lambda$.
- Range eclipsing occurs because pulsed radar cannot receive while transmitting.
- Doppler blind zones occur when a target is observed with the same Doppler as the clutter.

Consequently, there are three operational regimes that differ in PRF according to the type of ambiguities that are tolerable: (1) low PRF with no range ambiguities and many Doppler ambiguities; (2) high PRF with many range ambiguities and no Doppler ambiguities; and (3) medium PRF with some of each.

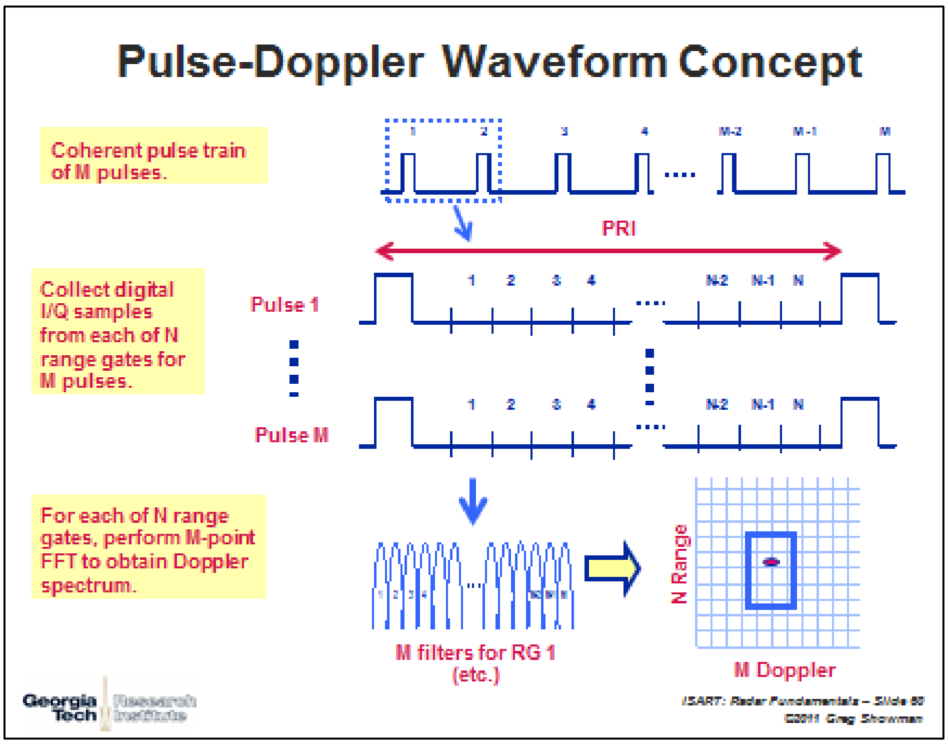

Figure 10. Doppler processing.

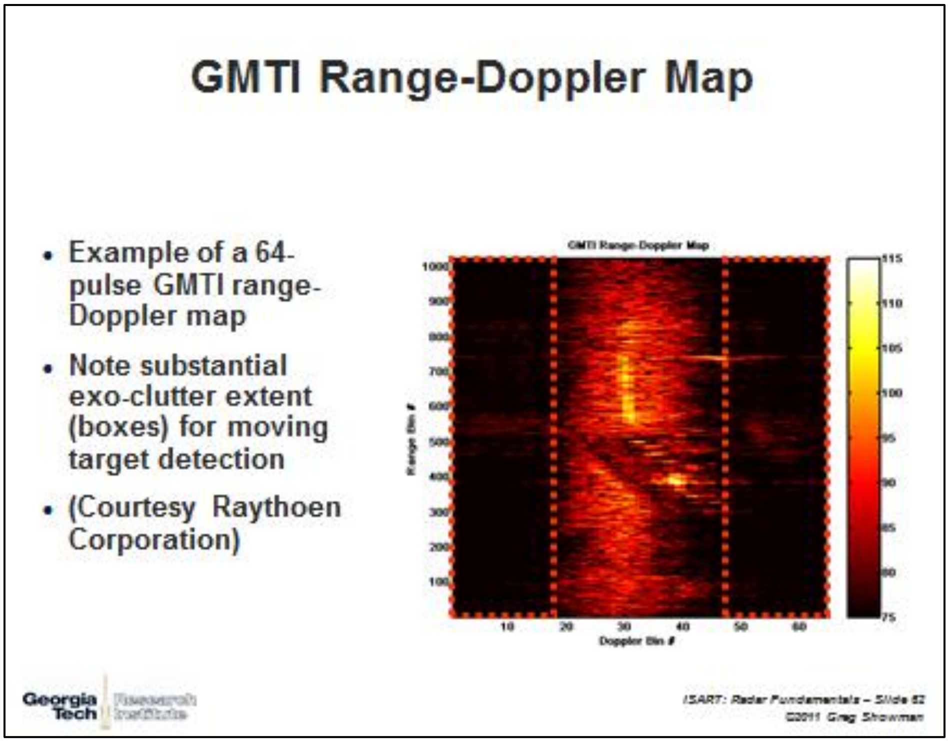

Figure 11. GMTI range-Doppler map.

Figure 12. SAR Image.

2.3 Radar Adaptive Interference Mitigation—William Melvin

Interference mitigation is a driving cost for radar after you've dealt with the link budget problems. Clutter, jamming, and radio frequency interference (RFI) are all interference sources affecting radar detection. If one formulates the problem and properly accesses the data, then the receive data can be filtered in a way that adapts to the changing environment and subsequently reduces the interference. Adaptive nulling is the focus of this lecture, and the information is given in the context of traditional radar operations. Adaptive nulling, however, does not justify proliferation of Wi-Fi in radar bands. Wi-Fi sources will look uncorrelated to radar; the adaptive nulling can only drive M-1 nulls, where M is the number of receive channels. A radar person would model the distribution of Wi-Fi sources, probably with a Poisson distribution, and take a look at how it affects the radar (taking into account the link budgeting). On the other side, a lot of the communications protocols have a lot of structure that is exploitable in removing the associated interference effects and may not require sophisticated antenna design techniques.

Objectives for this lecture are to:

- Understand the basics of adaptive interference mitigation for radar
- Highlight the fundamental radar measurements and their utility in interference suppression
- Describe typical canceller architectures
- Consider spatial nulling as a primary example

2.3.1 Radar Signal Processing and Degrees of Freedom

Manipulation of radar system degrees of freedom (DOFs) in different ways has developed over time. Airborne Warning and Control System (AWACS) is an airborne moving target indication system, deployed in the 1970s, that relies on Doppler processing to look for targets. Joint Surveillance and Target Attack Radar System (JSTARS) was deployed in 1991 to the Gulf War as an adaptive array technology demonstration program. It uses a long X-band array antenna with three phase centers to look for slow-moving targets on the Earth's surface. The Multi-Platform Radar Technology Insertion Program (MP-RTIP) radar on the Global Hawk unmanned aerial vehicles (UAV) has multiple channels and is basically a mini-JSTARS. Space Based Radar (SBR) is heavily reliant on adaptive array technology, because it's difficult to get a lot of antenna into space and super resolution is a desired requirement for those systems.

Radar applications can be grossly categorized into two functions: (1) imaging via collecting EM backscatter from fixed scenes and (2) detection of moving targets resulting in an array of "dots" on a map. These two functions largely coincide with SAR and MTI radar, respectively. Increasing noise would cause contrast in a SAR image to degrade making it difficult to interpret things in that scene. Increasing noise in the MTI case would lead to false positives, i.e., additional dots on the surveillance screen. Interference can be intentional or non-intentional.

Both SAR and MTI systems have a requirement to remove interference, and exploiting the radar measurement space is the key to improved performance. There are a number of ways to mitigate interference; recognizing and cancelling the interference source in signal processing is one of those tools. Depending on the application and design, radar measurements can be processed in four different time-scales:

- **Fast-time** (→ range) is associated with sample rate of the analog-to-digital converter (A/D) and is in the microsecond or tenths of microsecond regime
- **Slow-time** (→ Doppler frequency) is associated with *PRI* and is in the millisecond regime
- **Spatial-time** (→ angle of arrival) is associated with time delay between closely spaced array elements and is in the nanosecond regime
- **Glacial-time** (→ changes in the scene), associated with multiple scans

Polarization is another means to exploit DOFs. For linear polarization, for example, one can transmit horizontal (H) or vertical (V) and receive co- or cross-polar yielding three DOFs, i.e., HH, VV, and HV (or VH which is reciprocal for passive targets).

The basic flow diagram for a radar signal processing architecture is illustrated in Figure 13. Radar systems are heavily reliant on sophisticated antennas. The main antenna is often broken into pieces (typically called spatial channels). Auxiliary channels, e.g., low-gain horns or parts of the main array, are a common means to deal with sources of RFI in the far outside lobes. Blankers or guard channels are often used to find the source of large impulsive noise. Moving down the flow chart, data comes from the receive elements into the EP module that attempts to remove the bad components in the data, e.g., RFI, jamming. Eventually, processing steps are taken to either recognize and locate targets of interest or remove clutter, look for things that cross the threshold, estimate (range, velocity, angle of arrival), and feed the dots into a display where analysts watch the targets evolve.

Besides providing adequate power-aperture product, one of the key elements that drive the cost of the system is clutter and jammer suppression capability. Related factors include number of channels and antenna sophistication and design. Collectively, the radar community refers to clutter and jamming as interference. Overall detection performance is a function of the signal-to-interference-plus-noise ratio (*SINR*) and the specified P_{fa} threshold. *SINR* is typically written in terms of *SNR* and loss factors (between 0 and 1) that characterize the impact of clutter or jamming. It’s not uncommon for the jammer or clutter to be 60 dB stronger than the target signal. Data processing has a big impact on *SINR*. Figure 14 illustrates the receiver operating characteristic (ROC) for a non-fluctuating target at three different values of P_{fa}. Notice that small changes in *SINR* lead to big changes in detection performance.

The effectiveness of adaptive array processing depends on how one exploits the available data; different DOFs are used to solve different problems.

- Clutter is coupled in angle (i.e., spatial-time) and Doppler (i.e., slow-time), and GMTI takes advantage of differences between clutter and target angle-Doppler responses to enable detection of moving targets.
- Wideband RFI are uncorrelated over fast- and slow-time but can be correlated in angle, so spatial-time DOFs can be exploited to place a null in the angle of the RFI source.

- Relatively narrowband interfering signals can be correlated over small numbers of fast-time intervals, and spatial processing alone is sufficient to remove this type of jamming.
- Interference in the main lobe cannot be efficiently mitigated by using spatial DOFs; polarization diversity, however, might provide the DOF necessary to mitigate that interferer.

Spatial and temporal signal diversity enhances radar detection performance and enables discrimination between target and interference. The 3-D plot in Figure 15 describes pictorially different DOF exploitation schemes, where the goal is to separate the target from the interference. The Fourier transform of any of the measurement spaces leads to the power spectral domain. The y-z projection might be a range-Doppler plot for a GMTI target in ground clutter. In the case shown, the target is on top of the interference (maybe because the target is at zero radial velocity); this is an impossible filtering problem. Hence, one must have the right measurements and the right ways to process the data in order to solve the problem. Figure 15 also captures the formulation of the adaptive detection process in terms of a decision statistic, parameter estimator (f, which is typically non-linear), weight vector, observation vector, and decision threshold. Implementation of an optimal filter that meets specified goals, e.g., to maximize *SINR*, is data dependent and requires knowledge of the environment.

As an aside, it occurs to me that spectrum is not limited if we can take advantage of wave number. The key to manage spectrum is to take all the DOF and map the information we want to gather into one of those channels. We don't do that now. Nobody tells us how to fit our data into certain time slots, and radar guys won't do that on their own.

An interfering signal can cause correlations between two random variables possibly at different instances (i.e., with non-zero second-order statistics). In adaptive signal processing, these correlations can be leveraged to remove the effect of the interfering signal on the performance quality metric. Covariance provides a measure of the strength of the correlation between two or more sets of random variables. Elements of the covariance matrix in the m, n position are $\mathrm{cov}(\boldsymbol{X_m}, \boldsymbol{X_n}) = \mathrm{E}[(\boldsymbol{X_m}-\mu_m)(\boldsymbol{X_n}-\mu_n)^*]$ where bold denotes a random variable, * denotes complex conjugate, $\mathrm{E}[\cdot]$ is the expectation operator, and μ_m is the mean of $\boldsymbol{X_m}$. Vector notation allows for a more compact formulation, i.e., $\mathrm{cov}(\mathbf{X}) = \mathrm{E}[(\mathbf{X}-\mathrm{E}[\mathbf{X}])\,(\mathbf{X}-\mathrm{E}[\mathbf{X}])^{\mathrm{H}}]$ where $^{\mathrm{H}}$ is the conjugate transpose operator.

An optimal weight vector that meets specified goals, e.g., maximize *SINR*, can be developed via simulation where target waveforms and statistical characterization of the channel are known. In contrast, the adaptive filter tries to improve performance by incorporating information from the environment. The adaptive weight vector tries to estimate the optimal filter based on an estimated covariance matrix and a hypothesized steering vector. Challenges associated with adaptive filter theory include (1) modeling the environment and how it changes, (2) real-time implementation on digital signal processors (DSPs) and field programmable gate arrays (FPGAs), and (3) picking the appropriate architecture.

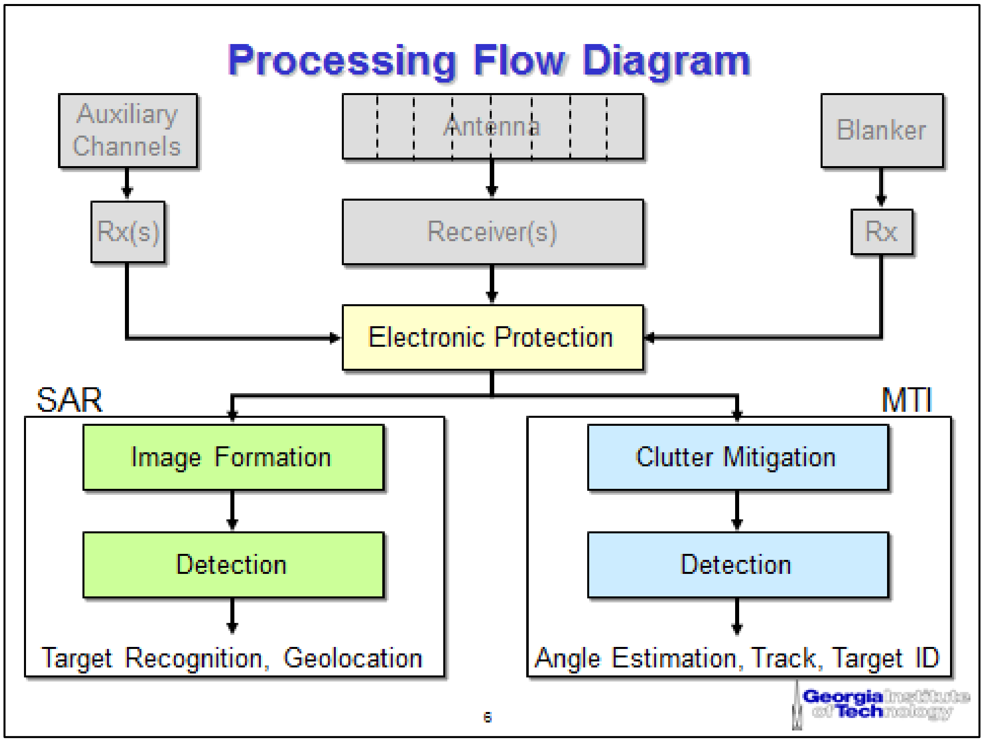

Figure 13. Processing flow diagram for a generalized radar receiver.

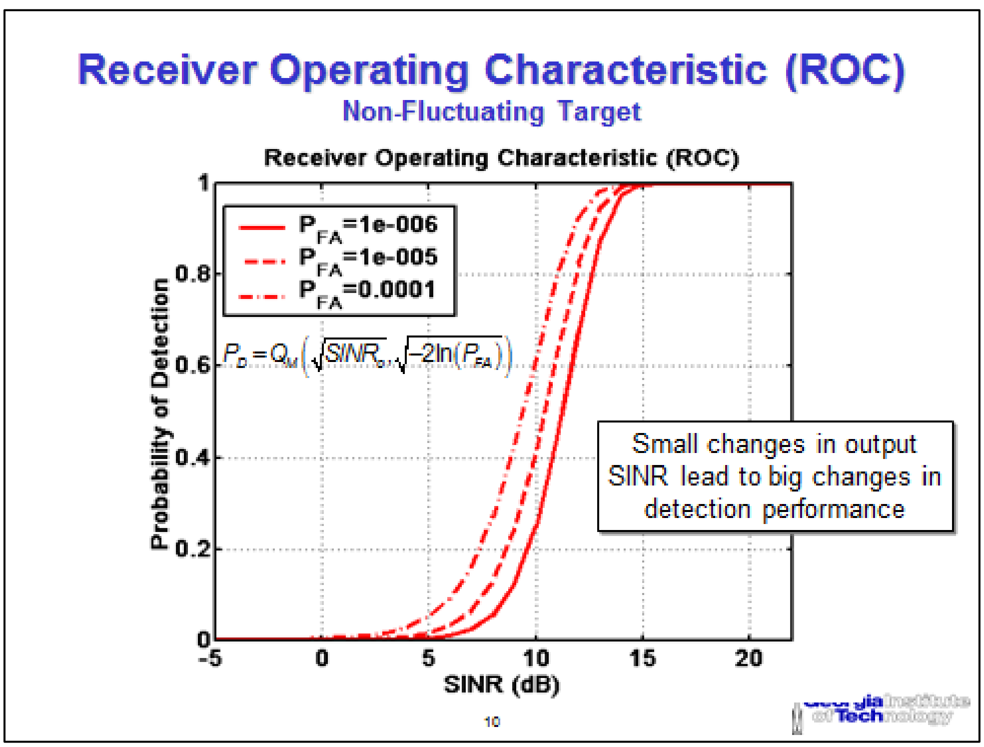

Figure 14. P_d versus *SINR* for a non-fluctuating target.

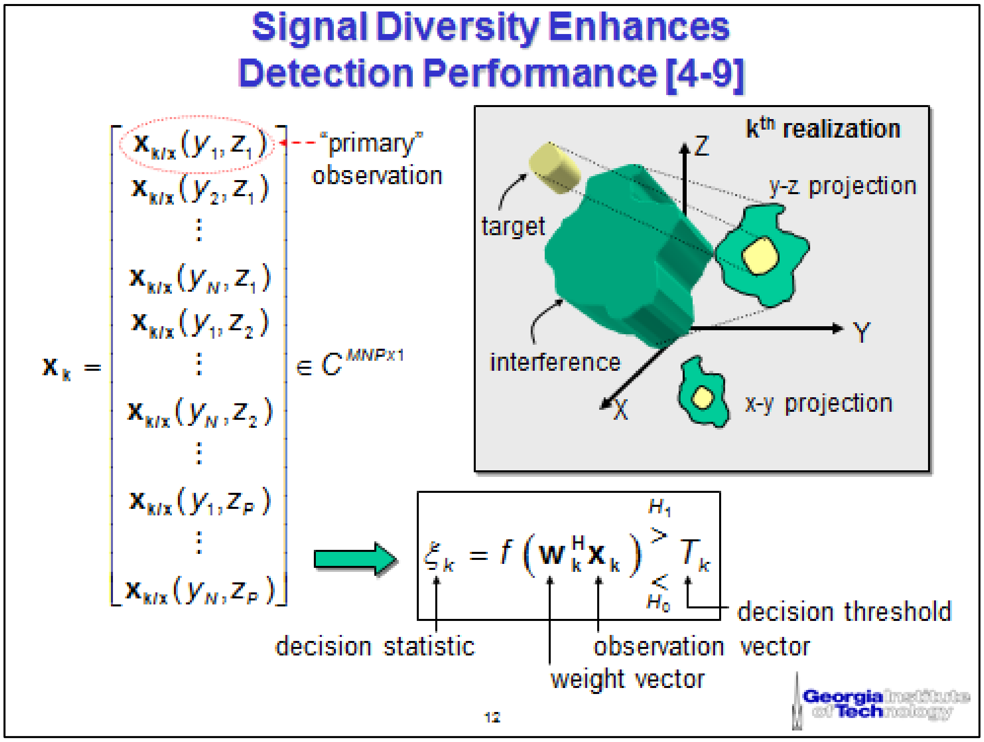

Figure 15. Signal diversity enhancements to detection performance—references in slide refer to [12], [13], [14], [15], [16], and [17].

2.3.2 Array Processing

Digital beam forming is based on spatial sampling. Figure 16, for instance, illustrates a uniform linear array (ULA) of *M* linear channels (each with its own receiver and A/D) separated by the distance *d*. This figure is an oversimplification of the antenna implementations that occur in practice (e.g., each channel can have overlapping and sharing elements). Under plane wave conditions (as opposed to a spherical wavefront), the EM energy arrives at each element with linear delay, resulting in a phase ramp over the aperture; different phase slopes across the array correspond to different spatial frequencies or directions of arrival. Hence, spatial frequencies are used (like Doppler frequencies) to separate out different sources at different points on the Earth's surface that have different waved number vectors (for example).

The narrowband model for the phase shift between adjacent channels (γ_s) is given in Figure 16. The ULA spatial steering vector, $s_s(\gamma_s) = [1\ \exp(j\gamma_s)\ldots\ \exp(j(M\text{-}1)\gamma_s)]$, characterizes the signal angle of arrival, representing the phase progression through each channel. The received signal can be calculated by multiplying $s_s(\gamma_s)$ by a complex gain term representing the received signal at a reference point. Maximum *SNR* is achieved when $\boldsymbol{w}$ is equal to $s_s(\gamma_s)$ times some scalar, and the achieved upper bound *SNR* of the array is equal to the single channel *SNR* times a spatial gain equal to *M*. Arrays, however, are not just built to form *M* simultaneous beams and improve *SNR* by a factor of *M*; arrays are built to access the digital data, manipulate the data, and remove sources of interference.

A narrowband jammer signal corrupts reflected signals with a noise-like waveform occupying at least part of the victim radar receiver bandwidth. It is spatially correlated, uncorrelated in slow-time; hence, there is no information in the slow-time that can be exploited to remove this source of interference; this is a spatial nulling problem. Expressions for the single narrowband jammer spatial snapshot and subsequent spatial and spatio-temporal covariance matrices are given in Figure 17. For multiple jammers that are statistically independent, the snapshots and covariance matrices simply add. Each narrowband jammer requires a spatial DOF for cancellation, so the number of expected sources of interference influences the design of the antenna array.

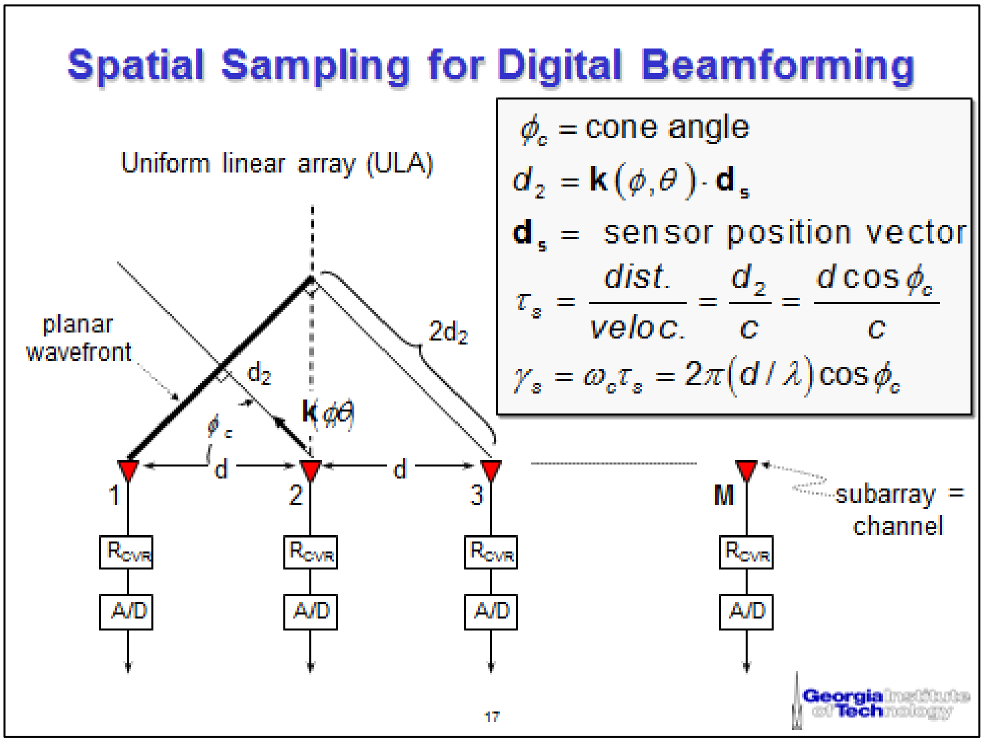

Figure 16. Spatial sampling for digital beamforming.

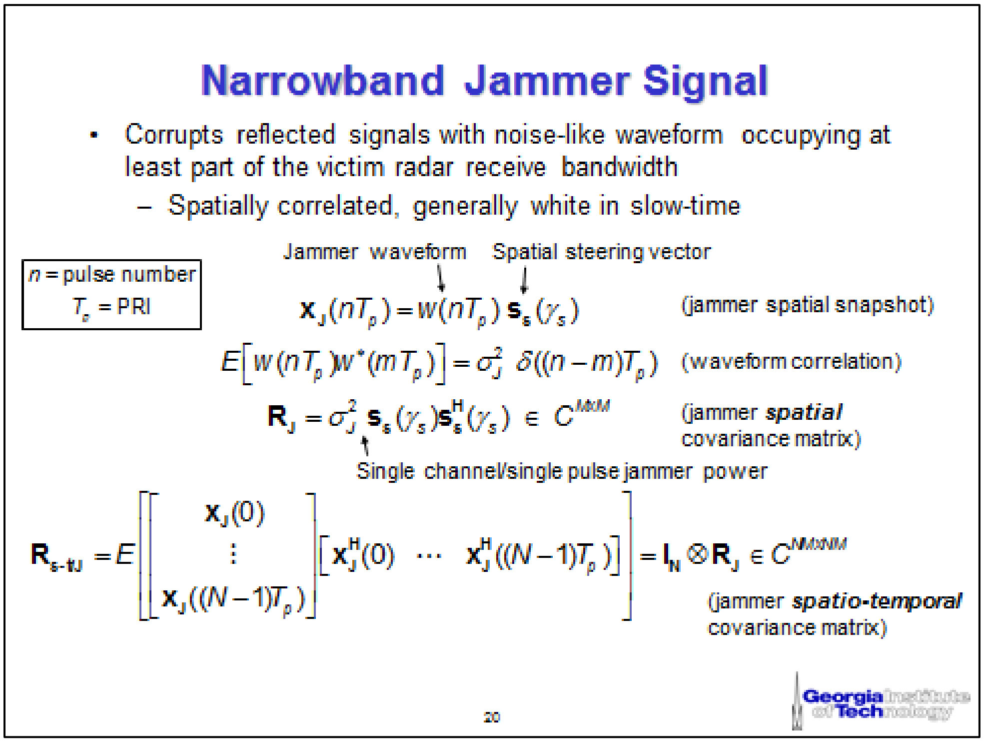

Figure 17. Formulation of the single narrowband jammer incident on a radar array antenna.

2.3.3 Adaptive Architectures

Adaptive digital beamforming [10], [18] is a process that selects filter weights (based on data from the environment) to drive nulls in the direction of interference sources. Adaptive processing is only used when colored noise, jamming, or RFI is present; otherwise, there will be unnecessary performance degradation due to unjustified additive noise and processing time and ill effects on beam patterns due to difficulties that Gaussian processes pose to beamforming algorithms. Note that these algorithms can also be applied to DOFs other than angle, e.g., polarization space-time adaptive processing [28]. The following are examples of adaptive digital beamforming architectures:

- The **Multiple Sidelobe Canceller (MSLC)** structure, shown in Figure 18, is comprised of a main antenna and auxiliary elements. The output of the main antenna is equal to the sum of the weights times the voltages measured at each channel. Nominally, the gains of the auxiliary elements are set to the peak sidelobe level of the main antenna. The basic (linear prediction) problem is to weight the auxiliary signals in order to estimate the jamming energy that comes in through the sidelobe of the main antenna and then subtract that from the main antenna signal. There are challenges in this implementation, e.g., signal energy coming into the auxiliary elements.
- **Maximum-*SINR* Weighting.** Brennan and Reed [12] tried to form a sufficient statistic to maximize P_d, and showed that maximum P_d corresponds to maximum *SINR*. As shown in Figure 19, maximum-*SINR* weighting is equal to the inverse of the interference-plus-noise covariance matrix (R_n) times $s_s(\gamma_s)$ times an arbitrary scalar. Notice that if R_n^{-1} is ignored in

this expression, then the expression for the matched filter remains. An eigen-decomposition of R_n^{-1} shows that each of the dominant sub-spaces spans all of the sources of interference incident on the array.

- **Minimum Variance Distortionless Response (MVDR**) spectrum started with the MVDR beamformer, which aimed to design a linear filter to pass the target signal with unity gain while minimizing power from other directions. MVDR weighting is proportional to maximum-SINR weighting. The subsequent minimum power at the MVDR beamformer output is a good spectral estimator, i.e., peaks are sharper than traditional Fourier-based methods (see Figure 20). MVDR spectrum is super-resolution, which means that R^{-1} is a super-resolution technique, which allows corresponding adaptive array techniques to null interference sources within a fraction of a beamwidth (with the exception of the interference source being at the same angle as the target).
- The **Generalized Sidelobe Canceller (GSLC)** [22], illustrated in Figure 21, estimates the colored noise portion of the desired signal and subtracts it off. The challenge with GSLC is associated with the need to calculate new inverse covariance matrices with every steering direction. GSLC is great in theory, but should not be implemented in practice.
- **Orthogonal Projection** [23] performs an eigenvector decomposition of the covariance matrix, which allows for the subtraction of the interfering eigenvectors (see Figure 22). This works well if there are strong sources of interference.
- **Sample Matrix Inversion (SMI)** uses a maximum likelihood covariance estimate (as shown in Figure 23). Convergence is not a function of eignenvalue spread, i.e., characteristics of the interferer. Reed, Mallet, and Brennan [19] identified the probability distribution and mean for *SINR* loss and derived the RMB rule that requires an averaging interval of roughly two times the number of DOFs in order to obtain average convergence within 3 dB of optimum.
- **Hung-Turner Projection (HTP)** [25] is another computational method of computing adaptive array weights formulated in Figure 24. HTP is cheap to implement and works well for strong sources of interference. It has application to large arrays with many spatial DOFs.

Figure 25 gives example beam patterns from the various beamforming techniques for a scenario where two narrowband jammers are operating at 15 and 30 degrees direction of arrival (DOA). Quiescent refers to a non-adaptive architecture. Notice how the orthogonal projection and HTP approaches (plots on left) drive (approximately) 50-dB nulls at the appropriate DOAs; these approaches, however, degrade with weak sources of interference, when it becomes difficult to distinguish strong from weak eigenvalues, i.e., interference from noise. The upper-right plot shows SMI results for averaging intervals (K, given in terms of numbers of DOFs); notice that the undesirable high-sidelobes come down as K increases. Loaded SMI is an approach to address the high-sidelobe issue by adding a diagonal matrix to condition the covariance matrix prior to inversion, suppressing variability among the noise eigenvalues, and taking some of the adaptivity out of the system. As demonstrated in the lower-right plot, loaded SMI reduces the high-sidelobes at the expense of null depth reduction.

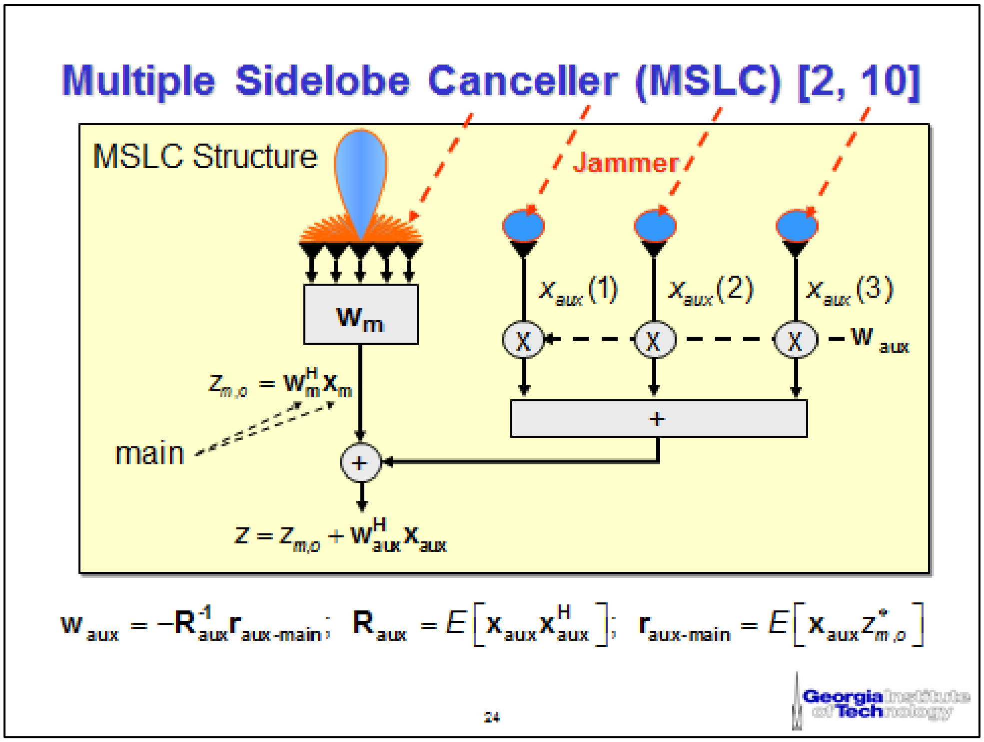

Figure 18. Multiple sidelobe canceller—references in slide refer to [10] and [18].

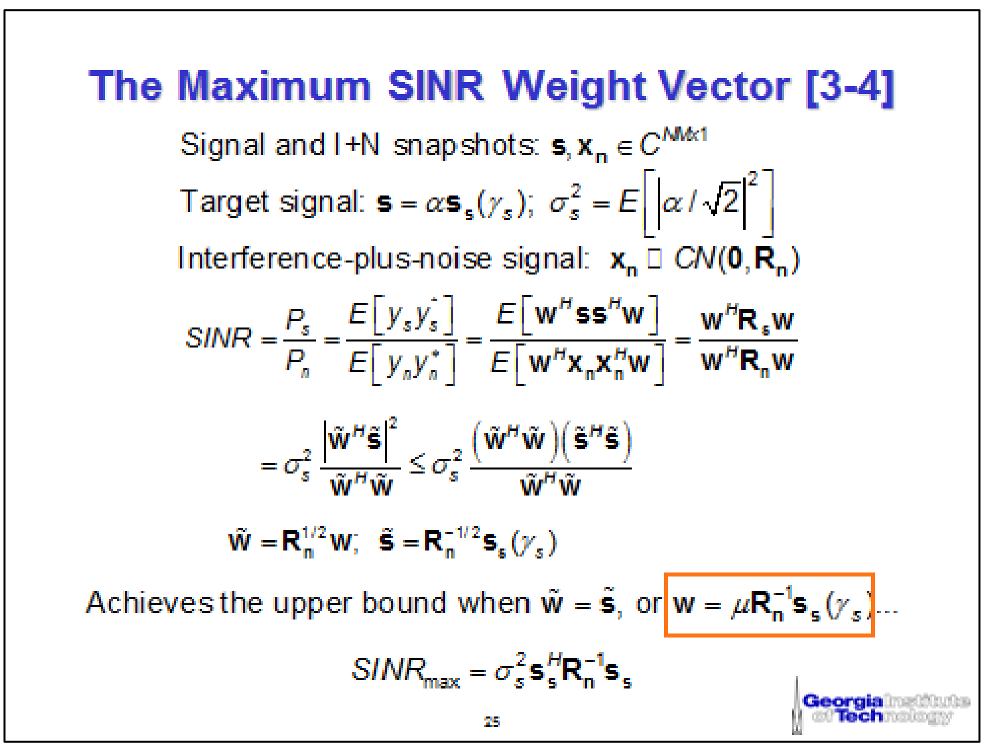

Figure 19. Maximum-SINR weight vector—references in slide refer to [11] and [12].

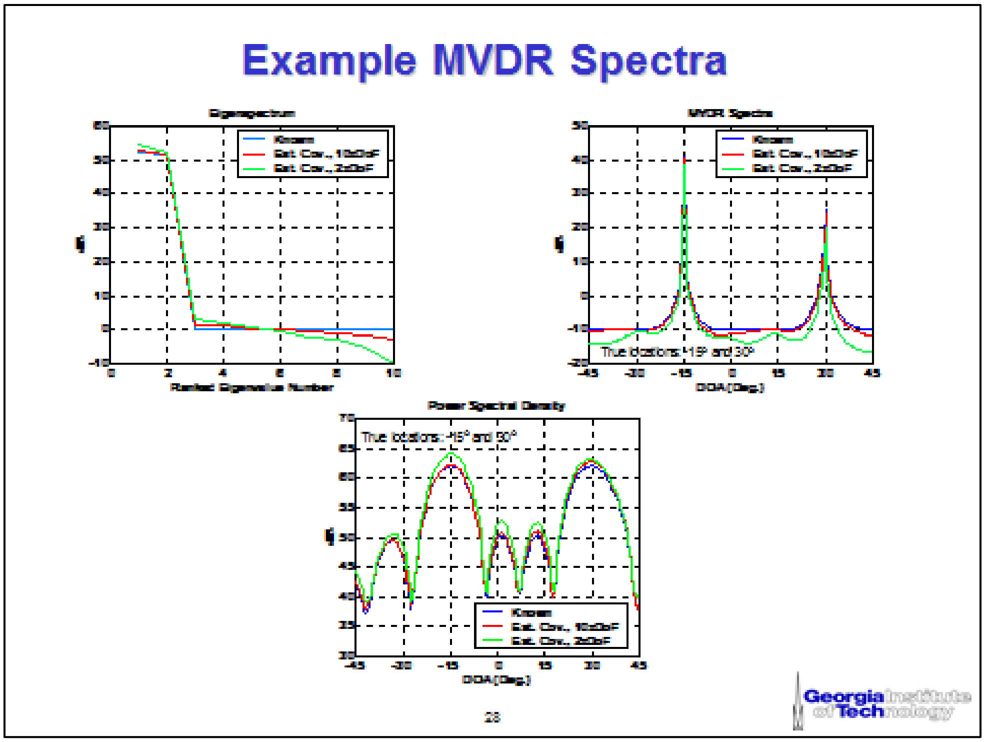

Figure 20. Example MVDR spectra.

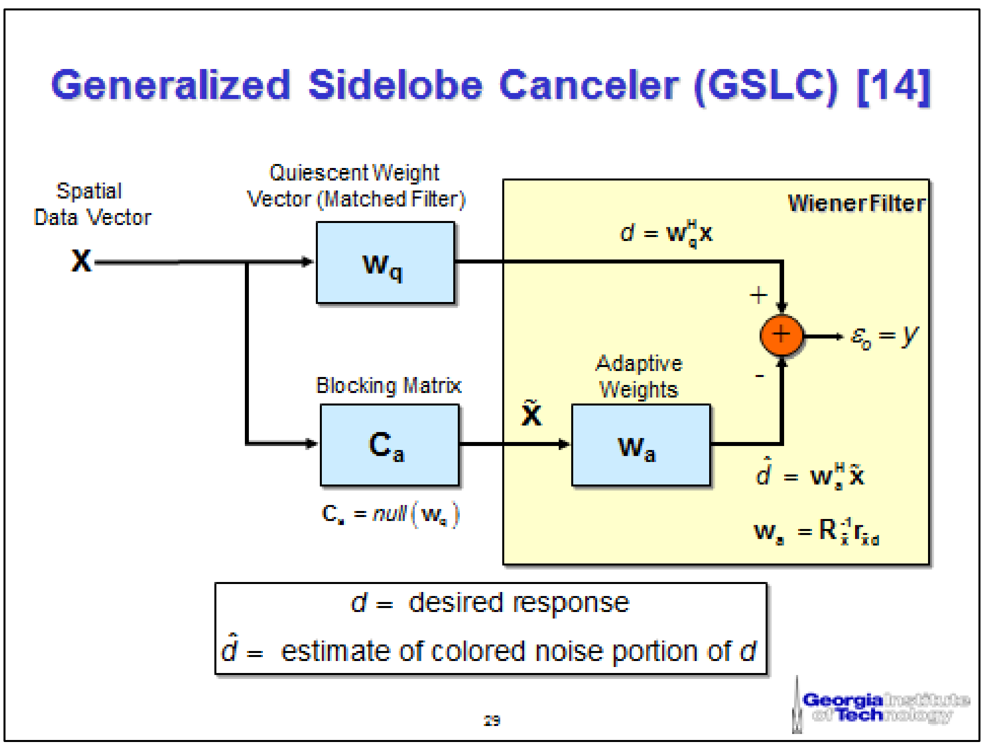

Figure 21. Generalized sidelobe canceler—reference in slide refers to [22].

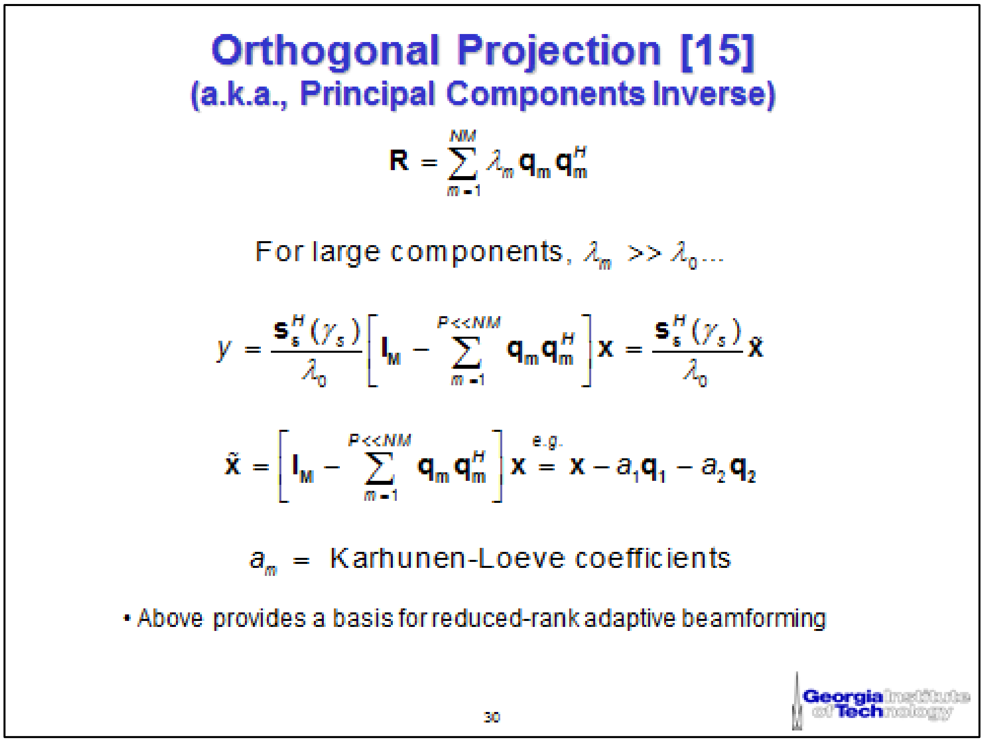

Figure 22. Interference mitigation via eigenvector cancellation—reference in slide refers to [23].

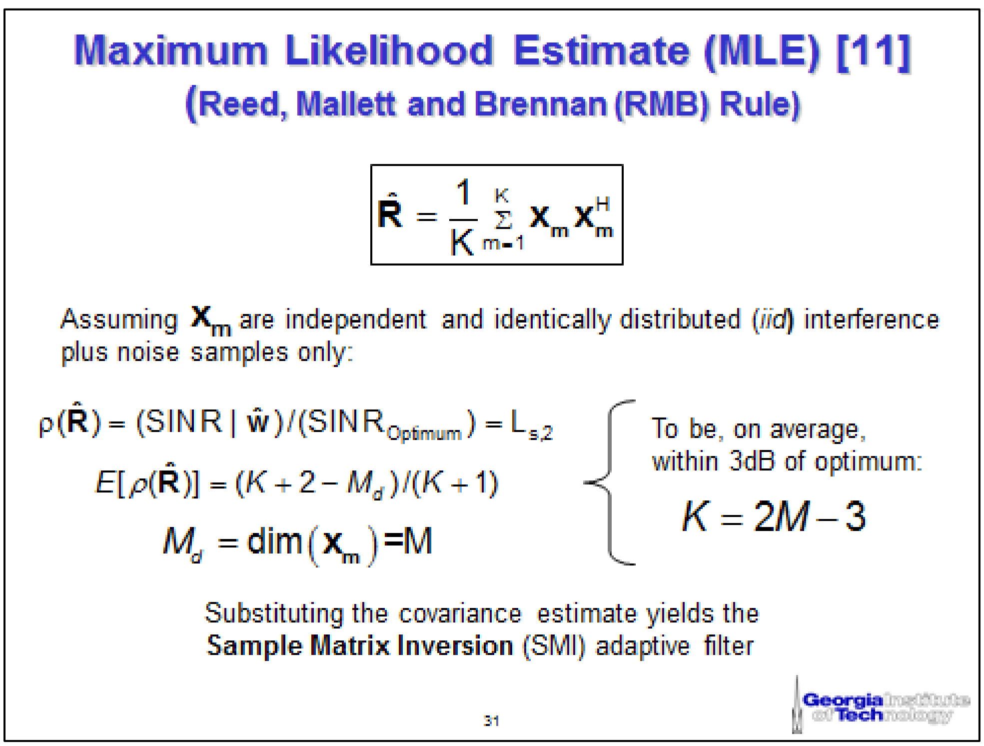

Figure 23. Array weights via SMI and MLE of the covariance matrix—reference in slide refers to [19].

Hung-Turner Projection (HTP) [17]

- Given the snapshots…

$$\mathbf{x}(t_1) = \mathbf{j}_1(t_1) + \mathbf{j}_2(t_1) + \ldots + \mathbf{j}_P(t_1) + \mathbf{n}(t_1)$$
$$\mathbf{x}(t_2) = \mathbf{j}_1(t_2) + \mathbf{j}_2(t_2) + \ldots + \mathbf{j}_P(t_2) + \mathbf{n}(t_2)$$
$$\vdots$$
$$\mathbf{x}(t_P) = \mathbf{j}_1(t_P) + \mathbf{j}_2(t_P) + \ldots + \mathbf{j}_P(t_P) + \mathbf{n}(t_P)$$

- Use Gram-Schmidt to form the orthogonal basis $\{\mathbf{v}_1, \mathbf{v}_2, \ldots, \mathbf{v}_P\}$

(Notice $\mathbf{v}_m \in span\{\mathbf{j}_1, \mathbf{j}_2, \ldots, \mathbf{j}_P\}$)

- Form the weight vector $\overline{\mathbf{w}}_Q^o = \overline{\mathbf{w}}_Q - \sum_{m=1}^{P} \left(\mathbf{v}_m^H \overline{\mathbf{w}}_Q\right)\mathbf{v}_m$

($\overline{\mathbf{w}}_Q$ is the quiescent weight vector)

- Set the adaptive weight vector as $\overline{\mathbf{w}}_A = \dfrac{\overline{\mathbf{w}}_Q^o}{\left\|\overline{\mathbf{w}}_Q^o\right\|_2}$

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Figure 24. Array weights via Hung-Turner Projection—reference in slide refers to [25].

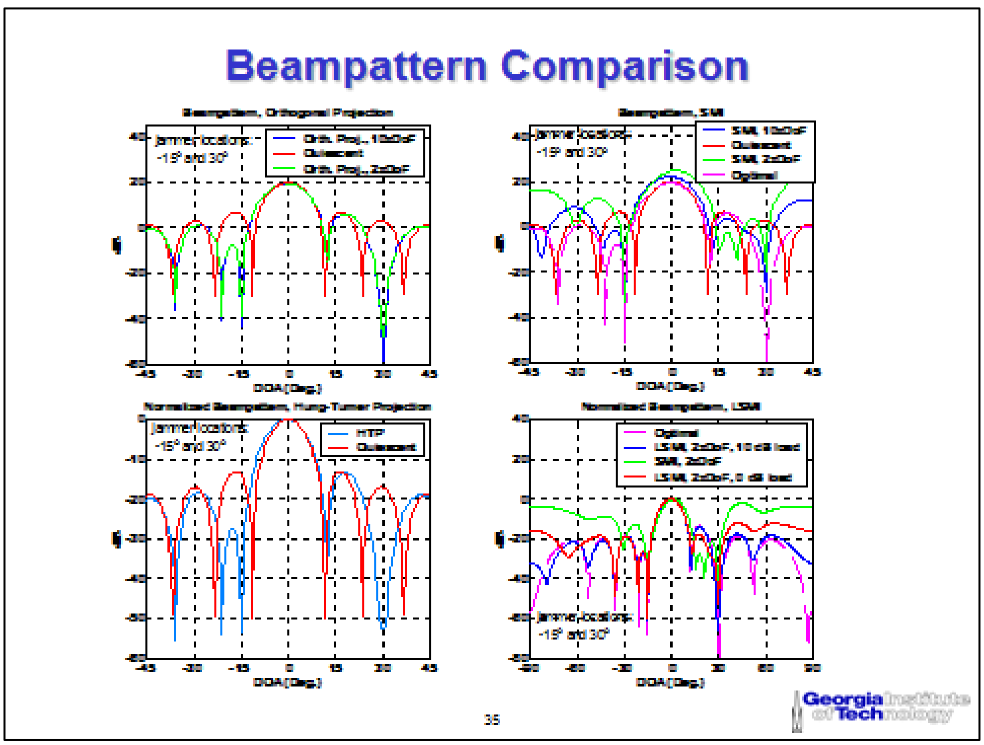


Figure 25. Comparison of different adaptive beampattern.

2.3.4 Wideband Arrays

Wideband arrays experience phase dispersion due to the dependence of phase on time delay and frequency. Subsequently, a single interfering signal will disperse across a wideband array and appear like multiple sources at different frequencies (see Figure 26). Therefore, effective interference cancellation would require multiple spatial DOFs to mitigate a single source of interference, which is generally unacceptable, especially in a complex RFI environment.

STAP is used in these cases for spatial nulling with fast-time taps (see Figure 27), which allows for the generation of patterns in RF frequency and angle. The tradeoff with this architecture is associated with the computational burden associated with adding elements to the adaptive processor. Figure 28 provides an example of wideband cancellation. The left plot illustrates how multiple spatial DOFs are required to drive nulls across wide angle to mitigate the interfering signal. Using STAP, sharp nulls can be driven using just two fast-time taps and there will be DOFs left over to mitigate other sources of interference, as shown in the plot on the right.

Another approach is sub-band adaptive cancellation, where poly-phase filtering is used to break the wideband received signal into nice sharp filter banks, narrowband adaptive cancelers are applied in each of the banks, and then the interference-cancelled outputs are coherently recombined. This approach is preferred over STAP in many cases because the computational loading is less.

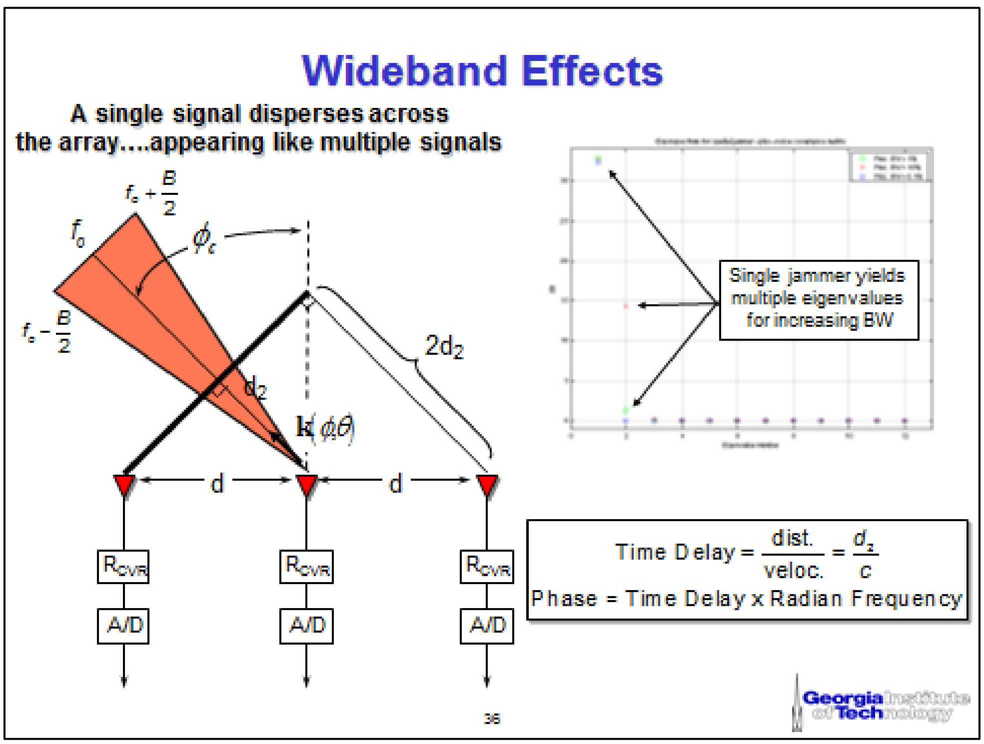


Figure 26. Interference effects on a wideband receive array.

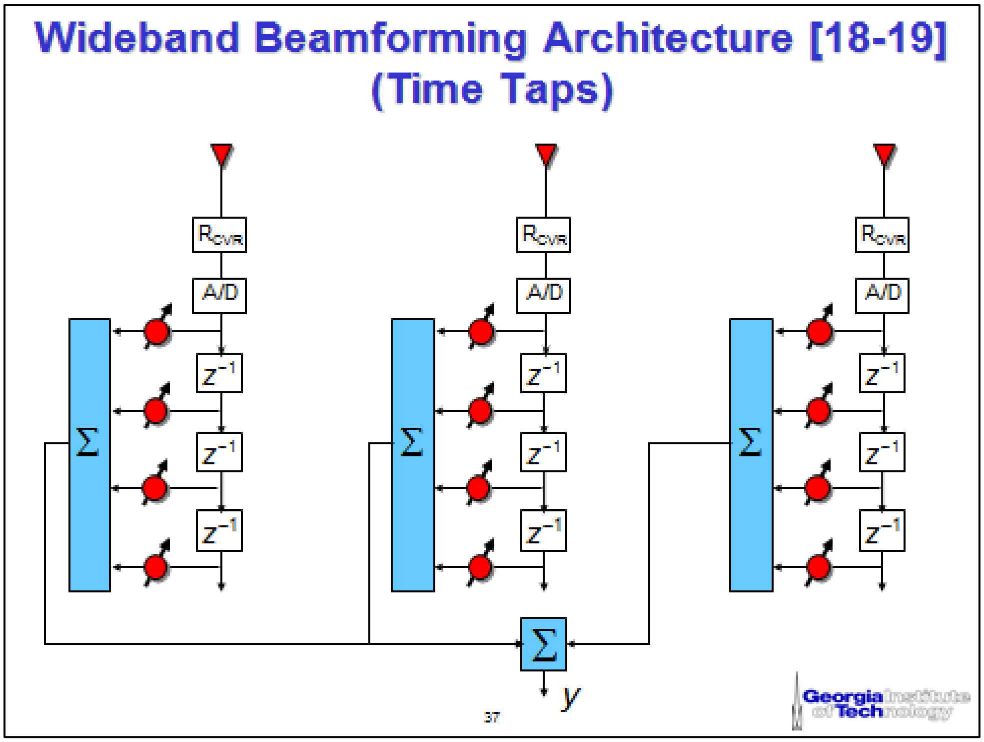


Figure 27. Wideband beamforming architecture used for STAP.

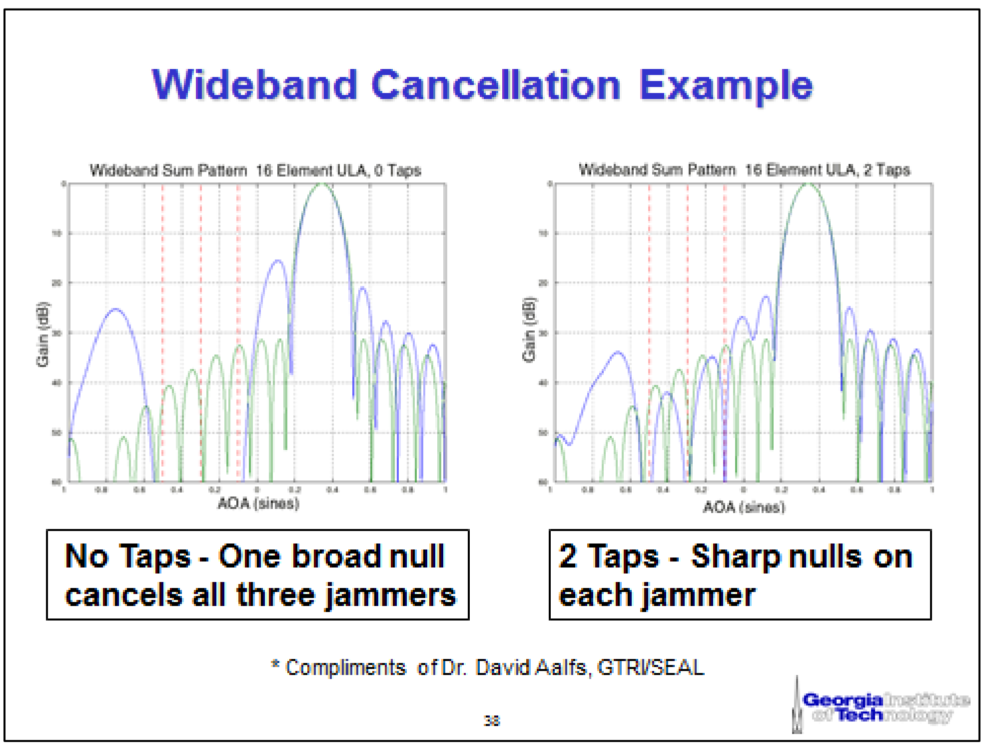


Figure 28. Example of wideband cancellation.

2.4 Radar Transmitter Technologies—Larry Cohen and Charles Baylis

2.4.1 Radar Transmitter Overview—Tube and Solid State

The radar transmitter subsystem generates the RF required to illuminate a remote target. Both thermionic tube transmitters and solid state transmitters are used, depending on the application. This presentation will cover both types of transmitters and discuss elements related to radar electromagnetic compatibility (EMC). Attributes of an ideal transmitter include: (1) stable, noise-free signal generation, (2) ability to generate required waveforms and energy required to identify target, (3) adequate bandwidth, (4) high efficiency and reliability, (5) easy maintenance, and (6) low cost of acquisition and operation.

Tube transmitters are designed to generate a pulsed-CW signal. The primary categories of tube amplifiers (and their characteristics shown in Table 1) include:

- **Cavity-based magnetron** was developed by John Randall and Henry Boot of the UK and further developed by the MIT Radiation Laboratory in the early years of World War II. Coaxial magnetrons are currently used today in the SPN-43 ATC radar, which is used on all U.S. carriers and amphibious ships.
- **Travelling-wave tube (TWT)** components are used in the U.S. Navy X-band AN/SPQ-9B air and surface tracking radar. In low-power TWTs, a helix delay-line structure is used to induce interaction between the electron beam and the signal to be amplified. In high-power TWTs, a sequence of cavities (instead of the helix structure) is used to induce interaction.
- **Cross-field amplifier (CFA)** is a type of tube commonly used in high-power radar over the past 35 years. CFAs are used on AN/SPY-1 radars on AEGIS Cruisers and Destroyers. CFA is a combination of magnetron and TWT, because there is a spiraling electron cloud emanating from the cathode (as in a magnetron) along with a slow-travelling wave transmission structure (common to TWT). The interaction between these two elements results in amplification, albeit relatively low gain.
- **Klystron** was invented in the early 1940s by Russell and Sigurd Varian. It is used in the U.S. Navy SPS-49 UHF air-search radar. It relies on a cathode and resonant cavities to bunch electrons. The microwave input interacts with the bunched electrons, which creates an amplified output. Multi-beam klystrons (with as many as 24 beams) can give bandwidths of greater than 10% and achieve 350 kW peak power.

Table 1. Comparison of radar tube characteristics.

Category	**Magnetron**	**TWT**	**CFA**	**Klystron**
Function	Oscillator	Amplifier	Amplifier	Amplifier
Efficiency		≤ 25%	>50%	>60%
Power			Megawatt peak, kilowatt mean	100 kilowatt peak
Gain	N/A	40 dB	10 dB	25 dB
Bandwidth		Octave	10–20%	5–6%

Noise	High	Low		Low
Out-of-band performance	Large spectral sidelobes	Low	Poor	Low sidelobes
Cost	Relatively Inexpensive			

Solid state RF power amplifiers are inherently low power and low gain and cannot operate at high peak power. For example, a 50 W average power transistor cannot operate at >200 W peak power without overheating. Pulse compression is needed for reasonable range resolution. To increase output power, transistors often operate in parallel with more than one stage. The U.S. Air Force PAVE PAWS missile and space surveillance radar system, for example, uses solid state transmit-receive (T/R) modules. Another example, is the Thales Active Phased Array Multifunction Radar (APAR) automatic detection and tracking system that uses >3000 T/R modules per face and achieves coverage by multiple beams (120 degrees in azimuth and 85 degrees in elevation. DC power purity to the T/R modules is critical from an EMC standpoint.

Figure 29 illustrates mean power and frequencies where tube versus solid state amplifiers are preferred. Tubes will be with us for 25–30 more years; there are three (soon to be two) companies still making tubes today. Solid state amplifiers are getting cheaper and are able to perform adequately at higher frequencies.

EMC in radar systems is a significant issue because radar involves high power (megawatt) transmitters collocated with sensitive (microwatt) receivers. EMC is concerned with unintentional generation, propagation, and reception of EM fields. A critical aspect of radar EMC is how and where the system is installed. It is not uncommon, for example, to have EMC issues between two ships in a task group. Unwanted EM energy can couple into the radar system via

- **Radiated coupling** when source-victim separation is large ($\geq\lambda$);
- **Capacitive and/or inductive coupling** when source-victim separation is small ($<\lambda$).

EMC is most effective and lowest cost when designed in from the beginning. EMI mitigation is dependent upon proper mechanical design (e.g., chassis, bonding, grounding, and shielding), electrical design (e.g., PCB layout and construction, hardware partitioning and location), system design (e.g., signal distribution, power conversion and distribution), and emission control (e.g., suppression of undesired spectrum products). Suppression of undesired products can be done in many ways, e.g.:

- Antenna design
- Frequency selective surfaces in the radome or as part of the antenna
- Amplifier linearization techniques
- Cancellation techniques in amplifiers
- Filtering on output
- Back-off from compression so that tubes operate in the linear regime

- Spectrum-friendly waveforms without sharp transitions (e.g., phase) when changing states
- Pre-distorted waveforms

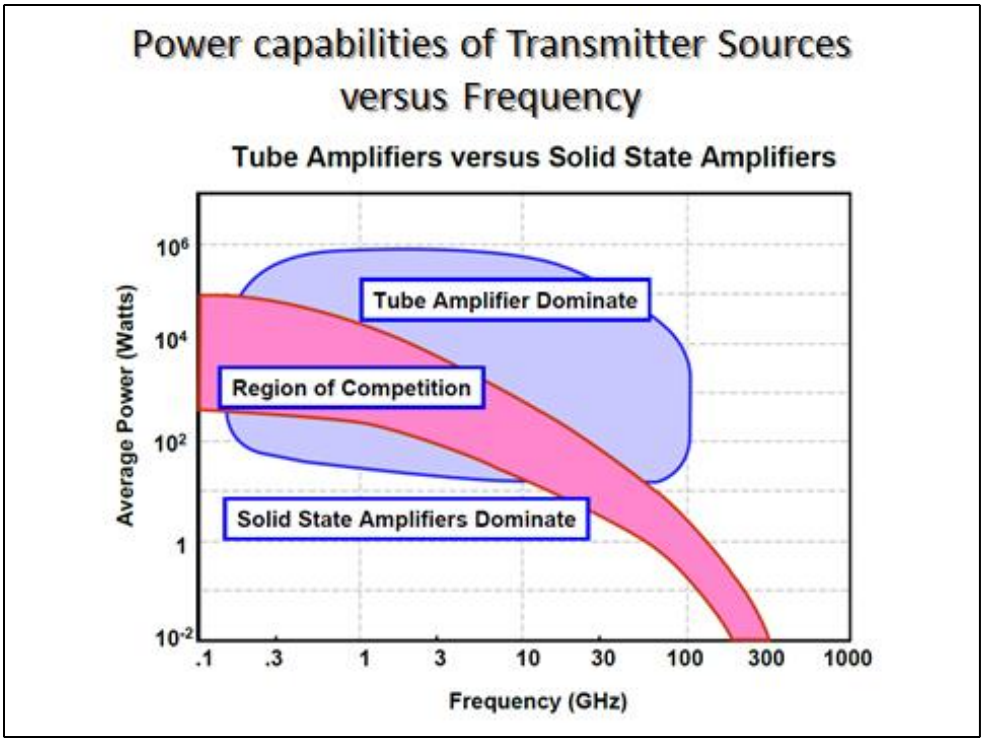


Figure 29. Tube versus solid state amplifier regions in terms of power and frequency.

2.4.2 Solid State for Next-Generation Radar Transmitters

Input signals to radar amplifiers often have widely varying envelopes, which require operations over a large portion of their transfer curves (including nonlinear regions). Amplifier nonlinearities generate undesirable out-of-band spectral content. Spectral spreading due to non-linear amplifier performance is associated with third-order intermodulation distortion. Mathematically, the output voltage of an amplifier (v_{out}) can be obtained from the input voltage (v_{in}) via the equation $v_{out}(t) = G(v_{in}(t))$, where G is the non-linear transfer function. For a two-tone input signal with fundamental frequencies ω_1 and ω_2, v_{out} will be comprised of signal components at the fundamental frequencies as well as intermodulation products (IMP) at linear combinations of those frequencies. Two of the third-order IMPs are only $|\omega_2 - \omega_1|$ away from the fundamental frequencies (see Figure 30), which is problematic because it generates unwanted artifacts next to the operational band. For a bandpass signal (where each frequency with a non-zero signal component represents a "tone"), all pairs of "tones" intermodulate and produce in-band modulation and out-of-band intermodulation or spectral spreading.

The effects of nonlinearities may be reduced by backing off the output power level and operating in the linear regime. Output power back off, however, has the undesirable effect of reducing power efficiency, which is typically maximized near saturation where the amplifier nonlinearities are greatest.[3] Spectral spreading can be reduced via filtering or amplifier linearization. In many cases, however, linearizing the amplifier is more cost effective than procuring a microstrip cavity filter to operate at power levels greater than one kilowatt. The following is a survey of useful design approaches to improve amplifier efficiency and linearity [29].

- **Predistortion** is an approach where a nonlinear device with an inverse shaped P_{out} versus P_{in} characteristic is placed before the amplifier. Predistortion linearizers are simple to implement, but require an accurate model for amplifier characteristics. When characteristics change over time, an adaptive predistortion lookup table is required.
- **Feedforward** is an approach where an auxiliary amplifier is used to generate a signal that is 180 degrees out of phase with the distortion at the output of the main amplifier. The outputs of both amplifiers are summed to produce a distortion-free signal (see Figure 31). There is an unwanted efficiency cost associated with DC power required for the auxiliary amplifier and loss associated with the combiners.
- **Envelope tracking** [30] adjusts the amplifier supply voltage according to the signal envelope to ensure that the amplifier remains in its most efficient operating region (i.e., in saturation). Efficiency is improved (especially at high peak-to-average power ratio), but buck/boost converters require additional DC.
- **Envelope elimination and restoration (Kahn Technique)** removes the amplitude modulation from the signal and re-inserts it after the power amplifier [31]. This allows the amplitude to run at optimum efficiency without amplitude distortion. Implementation of this technique, however, is complicated because it requires alignment of amplitude and phase modulations.
- **Doherty amplifiers** achieve higher efficiency and gain by employing two amplifiers: carrier and peaking. The carrier amplifier is biased to operate in class B mode, and the peaking amplifier is biased to operate in class C mode. As shown in Figure 32, the input signal is split by a power divider equally to each amplifier with a 90 degree difference in phase. Both amplifiers operate when the input signal peaks, and each is presented with load impedances that maximize power output. As the input signal decreases in power, the class C peaking amplifier turns off and only the class B carrier amplifier operates.
- **Linear amplification with non-linear components (LINC)** is a distortion-free transmitter under ideal conditions. In the LINC process, illustrated in Figure 33, amplitude modulation $M(t)$ is “hidden” in the phase of two component signals such that the sum of the component signals results in the source amplitude modulated signal. The component signals with constant magnitudes experience constant gain and linear amplification. The outputs of the two amplifiers are summed and the phased modulated signals cancel out. LINC is ideally distortion free, but in practice it is sensitive to component impairments. Implementation of the summer, for instance, involves tradeoffs.

[3] There are a number of efficiency and linearity metrics, e.g., drain efficiency ($\eta = P_{out,RF}/P_{DC}$) quantifies efficiency and adjacent channel power ratio (ACPR, i.e., ratio of adjacent-band power to in-band power) quantifies linearity. Amplifiers are classified as class A, B, or C. Class A amplifiers have poor efficiency ($\eta \leq 50\%$), but have the best intrinsic linearity. Class B amplifiers have moderate efficiency ($\eta \leq 78.5\%$), with a reduction in linearity. Class C amplifiers have higher efficiencies, but less linearity. Radar systems typically use Class C amplifiers.

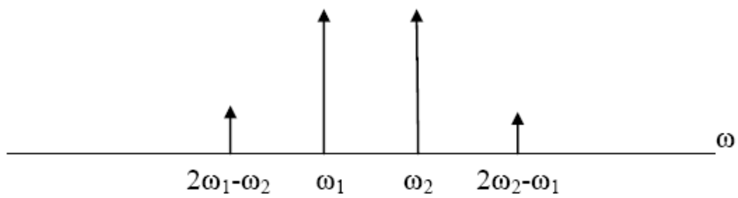


Figure 30. Example of intermodulation products for a two-tone input signal.

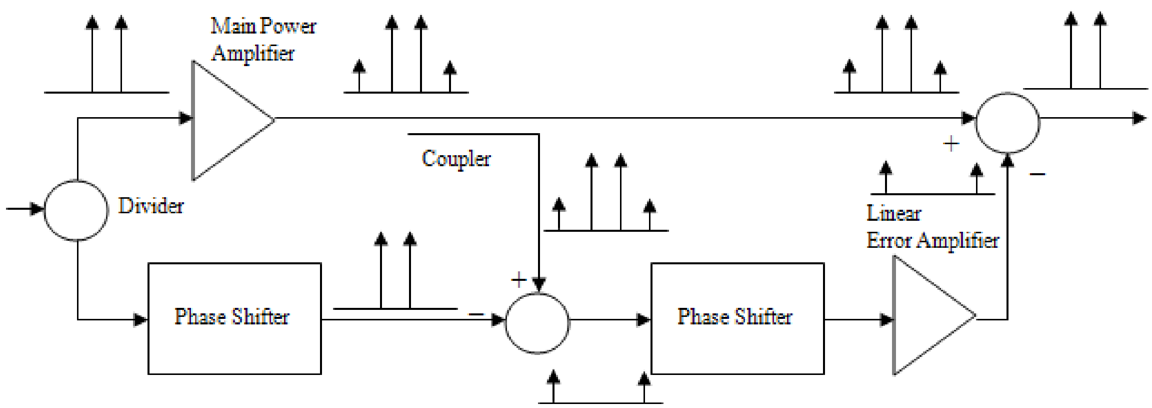


Figure 31. Feedforward approach to subtracting out IMPs.

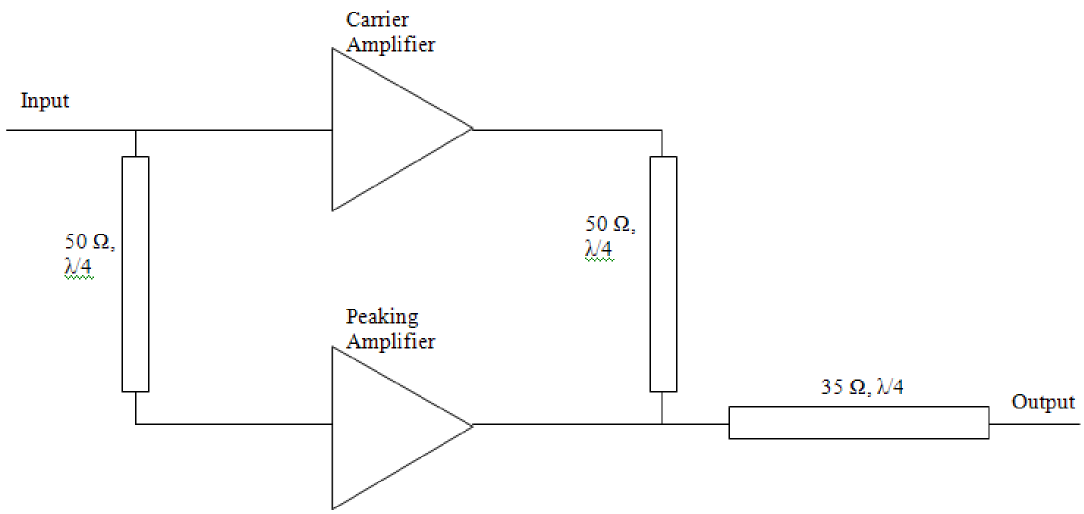


Figure 32. Doherty amplifier.

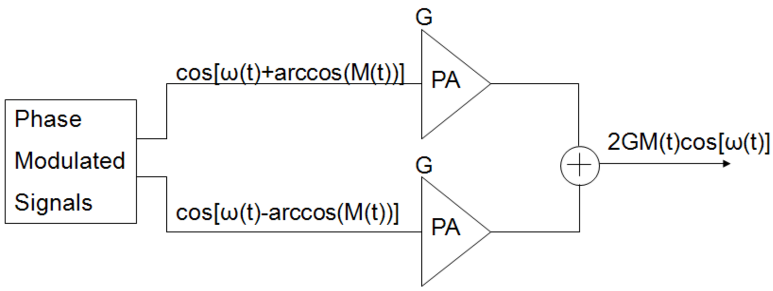


Figure 33. LINC transmitter.

3 RADAR INVENTORY

Matthew Hussey provided a Congressional perspective on spectrum inventory and then systematically guided a series of band-by-band briefings given by radar subject matter experts. The goal of the Radar Inventory Session was to provide information on radar applications, usage models, and missions, as well as to answer the following questions: (1) Why are specific frequencies and bands being used for the different applications? (2) Could other bands be used? (3) Is radar the best technology to achieve the different functions? Details were provided by band (i.e., HF, VHF/UHF, L, S, C, X, Ku/Ka/mm). When available, briefings were based on information from draft inventory reports from NTIA's Office of Spectrum Management (NTIA/OSM). The following presentations were made

- Congressional Perspective—Matthew Hussey (Senator Olympia Snowe's Office)
- Technical Overview—Frank Sanders (NTIA/ITS)
- HF—Frank Sanders (NTIA/ITS)
- P (VHF) Band—Frank Sanders (NTIA/ITS)
- Lower L Band—Frank Sanders (NTIA/ITS)
- L Band—Robert Sole (NTIA/OSM)
- Lower S Band—Robert Sole (NTIA/OSM)
- Upper S Band—Frank Sanders (NTIA/ITS)
- Maritime S Band—Joe Hersey (U.S. Coast Guard)
- C Band—Frank Sanders (NTIA/ITS)
- TDWR C Band—Chris Tourigny (Federal Aviation Administration)
- X Band—Robert Sole (NTIA/OSM)
- Ku/Ka/mm—David DeBoer (UC Berkeley, CORF[4])

3.1 Congressional Perspective by Session Chair Matthew Hussey

The first thing to mention is the President's Wireless Spectrum Initiative [2], which calls for 500 MHz of spectrum to be made available for new uses in the next 10 years. The reason for the major push for 500 MHz is that wireless broadband has been a major driver of the economy; more explosive growth in this area is possible but we need to find more capacity and more competition. One thing we have to remember, however, is that spectrum is also in demand for

[4] The Committee on Radio Frequencies (CORF) deals with RF requirements almost exclusively for the passive services. CORF provides responses to FCC and NTIA filings on behalf of US scientists, working with NSF and NASA. CORF advocates good-neighbor spectrum citizenship. CORF is primarily concerned with the radio astronomy (RAS) services and the Earth Exploration Satellite Service (EESS) (passive). RAS investigates the origins and evolution of the universe, the nature of matter, and life in other solar systems. EESS provides microwave measurements from satellites for weather forecasting (e.g., Hurricane Katrina) and long-range climate studies (e.g., ice cover).

non-commercial, non-communication uses, e.g., military operations, public safety communications, anti-terrorism uses, security needs, surveillance needs, utilities, and smart grids. Recently, even railroads need more spectrum for rail safety and other issues. The major problem is that, as you can see from the NTIA spectrum chart shown in Figure 34, there's not a lot of whitespace, i.e., there is really no new spectrum available to simply allocate. There's going to have to be some jockeying, some maneuvering around, and it presents a difficult scenario.

What's our first step? Senator Snowe believes that there has to first be a comprehensive survey of spectrum use. That will give us a clear, up-to-date understanding of how the spectrum is actually being used, and by whom. Another issue is that there are two separate agencies doing spectrum management, the FCC and NTIA. This makes issues for how we coordinate and manage this valuable resource. We've had some activities with inventories at both agencies. The FCC has informed Congress that it's done a baseline inventory, and NTIA has done a fast-track inventory and a more comprehensive inventory. Senator Snowe has been calling for a comprehensive inventory as a follow-up to the baseline effort, if necessary. In any case, we are still pushing for passage of the Snowe-Kerry Inventory Act, to peel the layers of the onion back more. We're pushing for a centralized portal where members of the public can go to single site to see the results of these surveys. Figure 35 illustrates how we see inventory data (e.g., transmitter/receiver characteristics, locations, etc.) feeding a public portal to foster a robust dialog on what measures can be implemented to optimize use of the spectrum.

The next step is to start doing measurements, actual measurements of what the real-world spectrum occupancy actually looks like. We can look at usage patterns where maybe we can exploit greater sharing and re-use opportunities. This could lead to re-allocation, sharing, and better strategic planning, which is critically important. This collaboration, along with public participation, ought to give greater sharing and efficiencies. We can get better, more robust designs and better coordination between Federal and non-Federal systems. The sandbox is going to get more crowded as we work with neighbors on both sides.

Lastly, we need a comprehensive spectrum committee that works with Federal and commercial stakeholders toward improved collaboration in utilization of spectrum resources. Currently, there are a number of public-private advisory committees, e.g., Commerce Spectrum Management Advisory Committee (CSMAC, hosted by NTIA), Inter-department Radio Advisory Committee (IRAC, hosted by NTIA), Policy and Plans Steering Group (PPSG, hosted by NTIA), Spectrum Policy Task Force (SPTF, hosted by FCC), and Technology Advisory Committee (TAC, hosted by FCC). These committees, however, are siloed; we don't have commercial and Federal advising both commercial and Federal.

Figure 36 illustrates the foundations for how a spectrum inventory will provide for better long-term planning, greater clarity on how we ought to allocate this resource, and better long-term utilization of spectrum. Planning is absolutely critical in moving forward.

At this year's conference, we focus on radar because comparisons of radar to non-radar uses of spectrum are like comparing apples to oranges. This session will present an inventory on radar systems and applications. Let's see how this plays out and try to get some new information for moving forward.

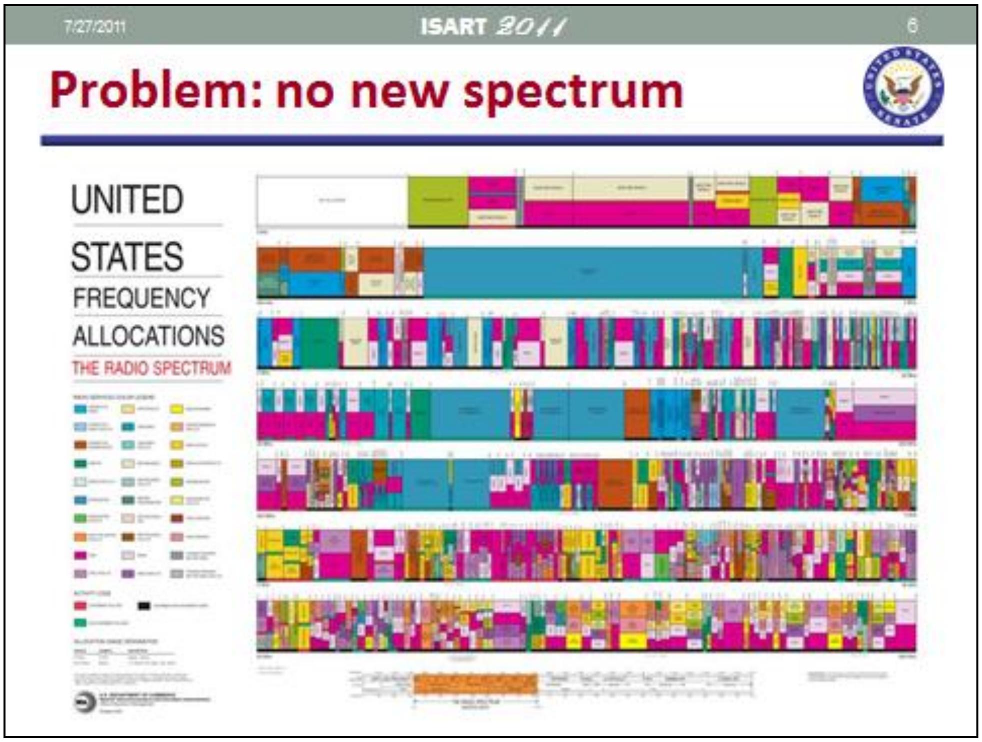


Figure 34. NTIA spectrum chart.

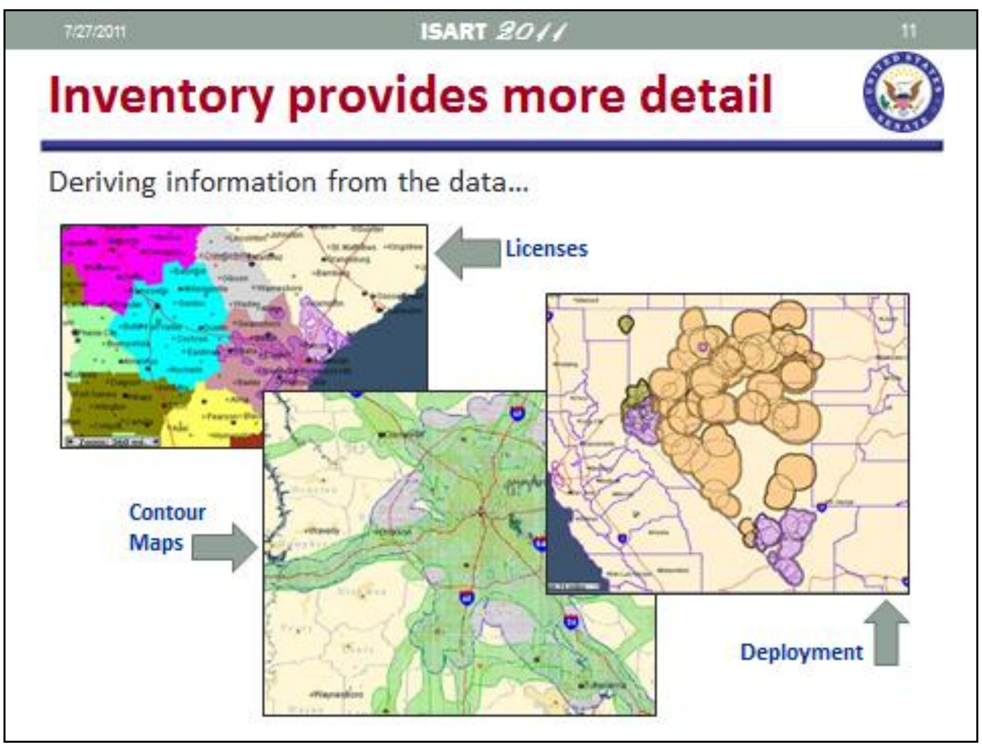


Figure 35. Deriving information and facilitating spectrum debate from inventory data.

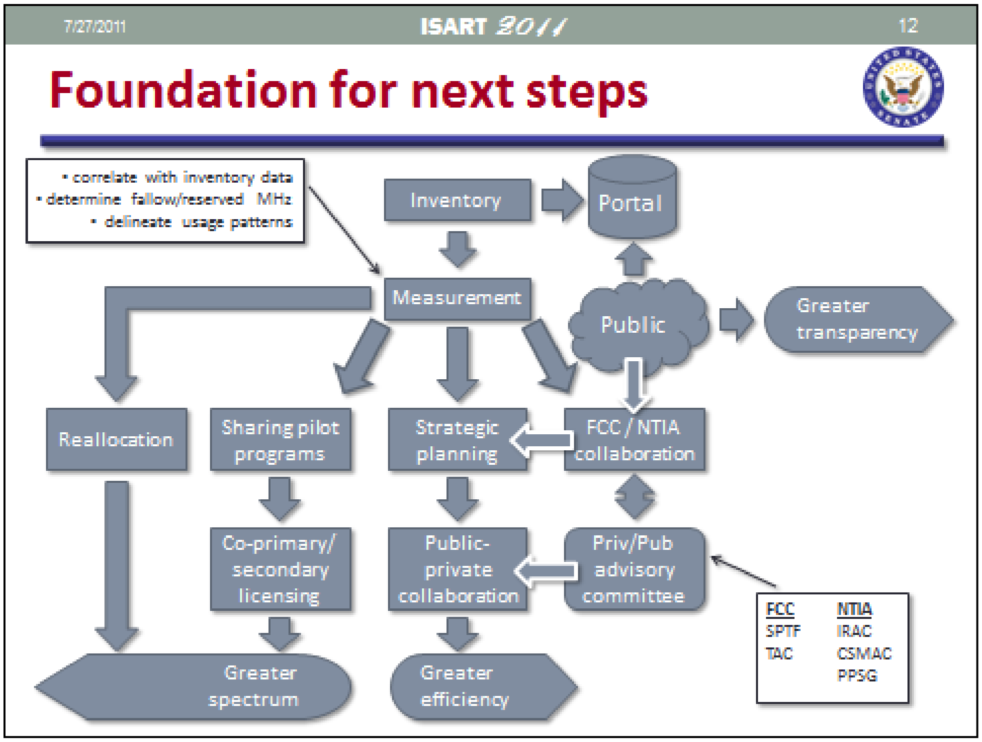


Figure 36. Foundations for next steps to optimize use of the spectrum.

3.2 Technical Overview on Radar Inventory—Frank Sanders

As we review band-specific radar characteristics in this session, it may be useful to keep the following information in mind:

- **High-power transmitters.** Radar transmitters typically produce effective isotropic radiated power (EIRP) levels between hundreds of kilowatts and 40 gigawatts of peak power.
- **Sensitive receivers.** During the "listen" part of their duty cycles, radars often need to detect target echoes at levels down to 1⁄100 of a picowatt. This emphasizes the need, so far as radar people are concerned, for having some quiet spectrum in which to operate effectively.
- **No two radar models are alike.** Each model has been designed to strike a balance between tradeoffs and accomplish a specific mission. The result is that radars tend to be idiosyncratic in their design and operation from one model to the next. Hence, it is difficult to answer the question: How does one share with radars? That is because there is not a single generic radar design. That said, there are some bands where some types of radars do predominate.
- **New radar systems continue to evolve.** Dual-band radars, for example, are a current hot topic.
- **Many radar systems operate in coastal regions**, on ships and aircraft and shore-based installations. The U.S. population is concentrated along its coasts. According to a NOAA analysis of U.S. Census Bureau data, 55% of all Americans live within 50 miles of the U.S. coastlines (highlighted in green in Figure 37). Hence, numerous radar systems exist where

there are large numbers of customers wanting commercial and government wireless services, so this is where spectrum contention is most likely to occur.

- **Long lifecycle and high cost.** In general, radar system lifecycles are multiple decades. Existing systems are relatively low-cost to operate. Replacement costs would be substantial.
- **Limited alternatives.** No readily available alternative technologies are available to replace any given radar system. Futuristic alternatives (e.g., space-based surveillance or GPS for aviation and maritime navigation) could be much more costly. Radars have the unique characteristic of being active, self-contained systems for sensing surrounding environments. For tracking aircraft, for example, radars do not depend on beacon replies or GPS based information from aircraft cockpits. Instead, planes can be followed even if beacons are switched off or fail (as happened on 9/11) or GPS based information is not available. For maritime navigation, shipborne radars show mariners other vessels and hazards which cannot be located using charts and beacons in conjunction with GPS. This is not to preclude GPS and beacon-based solutions for aeronautical and marine navigation, but radar provides fail-safe capabilities that the aeronautical and marine communities currently rely on. Some radar missions might be accomplished in higher bands; however, since existing radar designs already take advantage of optimized atmospheric propagation, changing bands can be problematic. Use of higher bands means needing to cope with different, and often worse, propagation for a given mission.

Radar band designations (shown in Table 2 with associated frequencies and wavelengths) were developed during WWII to confuse the enemy. Now, they just confuse everyone except radar engineers. K stands for kurtz, which means short in German; Ku is under K, and Ka is above K. To make things even more confusing, radar band designators are not the same as NATO band designators (e.g., the radar C band is not the same as NATO C band). Further, U.S. radar band edges do not necessarily match the limits that exist internationally. For example, although internationally the radar L band ranges between 1215 and 1400 MHz (the L band), the U.S. administration only uses 1215–1390 MHz for that band. Similarly, the upper S band is internationally allocated between 2700 and 3700 MHz, but the U.S. administration only uses 2700–3650 MHz for this band.

Table 2. Radar band designations and frequencies.

Designation	Radar Frequencies	Corresponding wavelengths
HF	5–28 MHz	10-60 m
P (VHF)	420–450 MHz	~0.7 m
Lower L (UHF)	902–928 MHz	~0.3 m
L	1215–1390 MHz	~24 cm
Lower S	2700–2900 MHz	~10 cm
Upper S	2900–3100; 3100-3650 MHz	~10 cm
C	5250–5925 MHz	~5 cm
X	8.5–10.5 GHz	~3 cm
Ku	13.4–14.0; 15.7–17.7; 24.05–24.5 GHz	~2 cm
Ka	33.4–36.0 GHz	~1 cm

Radar systems are named according to a broader system for generally categorizing DOD radio systems. The naming convention follows *A/N-i*P*j(k)* with nomenclature defined in Table 3. This convention predates the spin-off of the USAF as an independent service in 1947, and the USAF is still not acknowledged. Not all radars use the DOD *A/N* designators; for example, ASR = airport surveillance radar, ARSR = air route surveillance radar, TDWR = Terminal Doppler weather radar, NEXRAD = next-generation weather radar (also called WSR-88D, for weather surveillance radar, Doppler capable, type-accepted in 1988).

Table 3. DOD radar system nomenclatures—*A/N-i*P*j(k)*.

Designation	Radar Frequencies
A/N	Service: A=Army or N=Navy
i	Basing mode: S=shipborne, A=airborne, T=transportable, G=ground
P	"P" stands for radar; "R" was originally taken for "radio", and "P" is an "R" without a leg.
j	Primary function: N=navigation, S=search, etc.
k	Variation within radar model: A, B, C, etc., or "(V)"=variant, version, or production units vary from one to the next.

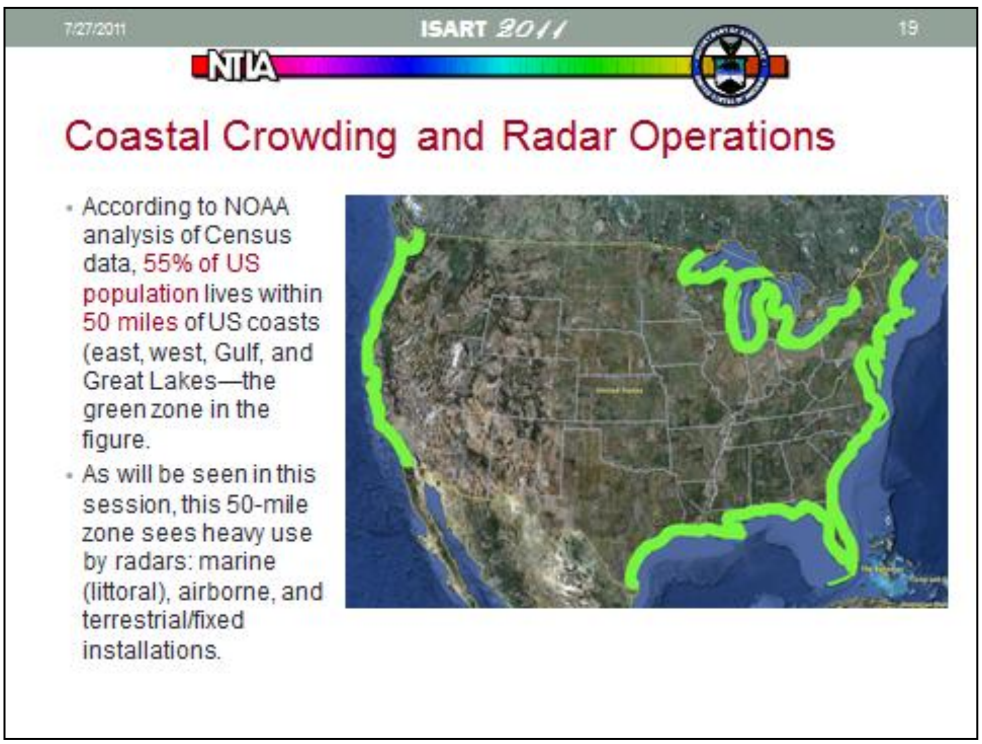


Figure 37. Coastal crowding and radar operations.

3.3 HF Radar—Frank Sanders

HF is an acronym to describe the 3–30 MHz frequency range, which was considered high frequency at the time. U.S. HF radar systems operate between 5 and 28 MHz. HF radar systems do not operate via line-of-sight. These over the horizon radar (OTHR) systems use ionospheric bending of the electromagnetic waves to see ocean areas thousands of miles from the transmitters. Also, HF atmospheric noise from worldwide lightning strikes can be a limiting factor for performance. In summary and with some additional notes:

- **Application/function.** Wide-area ocean surveillance (although other geographic zones could be covered in the future), propagation research studies, ionospheric physics studies. A major system (see Figure 38) that operates in this band is the Relocatable Over-the-Horizon Radar (ROTHR, also known as TPS-71).
- **Installations.** Semi-permanent (primarily) in coastal regions.
- **Operations.** OTHR transmitters operate continuously 24/7/365 at narrow bandwidths. Receivers cannot be co-located with the transmitters, because the transmitters operate with 100% duty cycles. Instead, the receivers are separated by tens or hundreds of miles from the transmitters. This contrasts with microwave radars where the propagation is line-of-sight and the transmitters and receivers are usually co-located. The ionosphere propagation channel is time-varying and frequency-dependent; hence, HF radars need all of the 5–28 MHz because operators are constantly searching for optimal frequencies for the different long-range propagation channels.
- **Antennae.** Relatively large (in general), but are typically small compared to a wavelength and have appreciable backlobes. HF atmospheric noise is the limiting factor.
- **Spectrum crowding.** Current, OTHR systems share this band with many other HF systems.

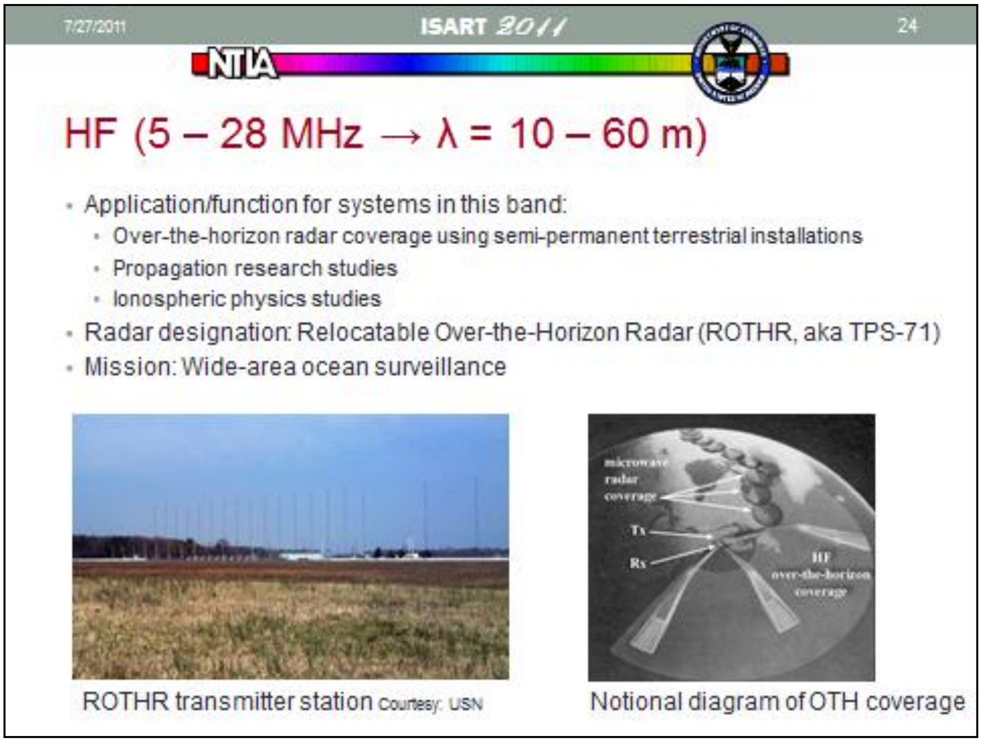


Figure 38. HF over the horizon radar.

3.4 P (VHF) Band Radar—Frank Sanders

U.S. VHF radar systems operate in the P band from 420 to 450 MHz. VHF propagation is ideal for long-range radar applications, foliage penetration, and wind profiling. These systems are summarized by the following:

- **Application/function.** Radiolocation of aircraft at very long ranges, air (with *R* on the order of hundreds of miles) and space (with *R* on the order of thousands of miles) surveillance and warning, foliage penetration, vertical atmospheric wind profiling, and operations at test ranges and space launch facilities. A major system that operates in this band is the U.S. Air Force FPS-123(V) or PAVE PAWS (Phased Array Warning System) missile and space surveillance radar system (Figure 39).
- **Installations.** Fixed ground-based, shipborne (mobile), and airborne (mobile).
- **Operations.** 24/7/365 at fixed terrestrial sites; time-varying around and above the continental U.S. and U.S. territories for ships and aircraft. Multiple frequencies are needed across VHF band to improve probability of detection, compensate for time-varying propagation factors, de-conflict operations between multiple radar systems, and help electronic counter-countermeasures (ECCM).
- **Antennae.** A typical dish antenna for this frequency range has 30 dBi gain antennae and is 10 meters (30 feet) across. Surveillance systems typically perform repetitive rotational scanning or electronic pencil-beam scanning. There is no overall regularity or predictability for beam scanning in this band. Wind profilers typically have nearly constant beam directions

usually within 15 degrees of vertical. The nominal noise figure is associated with the internal electron noise in the receivers (typical values are 3-5 dB).

- **Spectrum crowding.** The P band is already shared between radars and a variety of non-radar systems, unlicensed, including some beacons. The P band radars are airborne, naval, and terrestrial fixed, so this band is already fairly crowded.

Figure 39. FPS-123(V) PAVE PAWS missile and space surveillance radar system (courtesy: USAF).

3.5 Lower L-Band Radar—Frank Sanders

Lower L-band radar systems operate from 902 to 928 MHz, and have similar characteristics and functionality to P-band radar systems because the operational frequencies are in a similar part of the spectrum, i.e., below microwave frequencies. There are, however, not as many radar systems working in the lower L band, i.e., there are no space search and airborne applications. VHF propagation is ideal for long-range radar applications, foliage penetration, and wind profiling. These systems are summarized by the following:

- **Application/function.** Radiolocation of aircraft at long ranges (up to two hundred miles), air surveillance and warning, vertical atmospheric wind profiling (see Figure 40), and operations at test ranges and space launch facilities.
- **Installations.** Fixed ground-based, shipborne (mobile).
- **Operations.** 24/7/365 at fixed terrestrial sites; time-varying around and above the continental U.S. and U.S. territories for ships and aircraft. Multiple frequencies are needed across VHF band to improve probability of detection, compensate for time-varying propagation factors, de-conflict operations between multiple radar systems, and help ECCM.
- **Antennae.** A typical dish antenna for this frequency range has 30 dBi gain antennae and is 4 meters (14 feet) across. Surveillance systems typically perform repetitive rotational scanning or electronic pencil-beam scanning. There is no overall regularity or predictability for beam

scanning in this band. Wind profilers typically have nearly constant beam directions, usually within 15 degrees of vertical. Then nominal noise figure is associated with the internal electron noise in the receivers (typical values are 3-5 dB).

- **Spectrum crowding.** Industrial, scientific, and medical (ISM) devices operate at 902–928 MHz.

Figure 40. Lower L-band wind profiler radar.

3.6 L-Band Radar—Robert Sole

U.S. radar systems operate in the L band from 1215 to 1390 MHz, which breaks up into the following sub-bands and allocations: 1215–1240 MHz for radiolocation, 1240–1300 MHz for aeronautical radionavigation and radiolocation, 1300–1350 MHz for aeronautical radionavigation, 1350–1370 MHz for aeronautical radionavigation (US & Canada), and 1350–1390 MHz for radiolocation. Hundreds of high-power long-range ARSR systems operate across the U.S. and its territories in this band to monitor the national airspace. L-band radar can be summarized by the following bullets:

- **Application/function**
  - Long-range (333 km (180 nmi)) ARSR systems are used by the FAA to detect aircraft (range and azimuth) in the en route (high altitude) phase of flight. The data collected by these systems are displayed on a plan position indicator (PPI) scope at the radar site and also transmitted to ATC centers, air defense sectors, and Homeland Security centers for further processing. These systems also provide weather data to ATC that is combined with other weather data sources. The information is used for the safety and regularity of flight operations, national defense, and the security of the homeland.
  - Tactical, defense and security (e.g., DOD/DHS: TPS and TPQ series systems, and others)

- Airborne surveillance and collision avoidance

- **Installations**
  - Long range ARSR systems are ground-based fixed installations throughout the national airspace system and along the border areas. ARSRs are not airport radars.
  - Tactical defense and security radar systems are generally located on border areas, near/on military bases or training areas with intermittent usage, however these radars can be located anywhere in the U.S. and its territories as required for a particular defense or security mission. Tethered aerostat radar (TAR) systems, as the one shown in Figure 41, are balloon-mounted (weather permitting) and are used for monitoring the U.S. borders and Caribbean airspace for border protection and drug interdiction.

- **Operations**
  - Long-range ARSR systems (mostly between 1240 and 1370 MHz) operate continuously 24/7/365. Emission bandwidths are 2–10 MHz. Some systems require one operational frequency and one hot stand-by frequency, some require two frequencies separated by a fixed value, some require two frequency pairs, and some systems use multiple channels for frequency hopping.
  - Tactical defense and security radars in the 1215–1390 MHz band are transportable and have to adapt to the environment. Many use frequency hopping or agility and solid state transmitters.

- **Antennae**
  - ARSR and FPS series radar systems use antennas with narrow horizontal and wide vertical beamwidth with mostly mechanical scanning (see Figure 42). The newest radar will use the existing antennae of the older systems but contain a new transmitter and receiver. Typical horizontal rotation rate is 5 rpm with gain of 33 dBi with operations from fixed locations.
  - Tactical radar systems use antennas with narrow horizontal and narrow vertical beamwidth, with electrical and mechanical scanning, variable rotating speeds, and typical gain of 24 dBi. Many are transportable.

- **Spectrum crowding.** GPS L2 (1227.6 MHz)[5] with civilian and defense usage; DOD tactical land and sea data/communication systems (1350–1390 MHz)[6]; DOD airborne telemetry used

[5] The Federal Radionavigation Plan provides a detailed description of Federal agency use of GPS for aviation, maritime, space and land navigation. Non-navigation applications (e.g., geodesy, mapping, agriculture and natural resources, Geographic Information Systems, meteorological and timing) are also described. The requirements of civil and military users for radionavigation services based on the technical and operational performance needed for military missions, transportation safety, and economic efficiency are also described. The GPS L2 radionavigation signal is transmitted in the 1227.6 ± 15.345 MHz segment of the 1215–1240 MHz RNSS band.

[6] DOD transportable stations like those operated in the band 1350–1390 MHz are used to extend wideband communications for battlefield command-and-control to any part of the globe rapidly. Military operations and training make extensive use of transportable microwave terminals that are designed to be transported to an overseas combat or support area, set up rapidly, configured into a communications network, and used for critical operational command and control communications for the duration of the mission. These capabilities are also used domestically (intermittently at military facilities and test/training ranges with a small radius of operations) to support training and to provide support of disaster relief and similar missions. DOD also uses this band for mobile services. The

for flight instrumentation and timing; and nuclear burst detection system, remote sensing, and radio astronomy observations above 1350 MHz. Generally, radar assignments are not given on or near the GPS frequency to limit interference to GPS. Coordination occurs with the tactical point-to-point and telemetry systems in the band 1350–1390 MHz.

- **Compatibility.** Compatible operations between different L-band radar systems are accomplished through careful system design, frequency selection, and NTIA spectrum standards (RSEC Criteria C). FAA is the national coordinator for the band. Various types of circuitry and signal processing are used in their receivers to reduce or eliminate the effects of pulsed low duty cycle interference from other radars. Interference to and from these radars in the event of band sharing is a major concern, because the systems were not designed to share spectrum with non-radar systems. Figure 43 shows map contours due to radar transmitter operations in this band. Any receiver inside the shaded area will have an interference-to-noise (I/N) ratio greater than -6 dB .This map does not represent the coverage zone of the radars, nor are all LRRs, included on the map. The map only shows the ranges within which interference may be expected with co-channel operations with one of these radars.
- **Planned use.** L-band radiodetermination service will remain the same for the foreseeable future. Although many of the fixed-based programs are "built out" and no new installations are planned in the immediate future, new radar sites could be added if the need arises to monitor additional airspace or other vital assets. Flexibility in frequency assignment will remain necessary to mitigate interference due to new or unexpected sources to better manage the exiting fleet's spectrum requirements as systems are upgraded, and to provide spectrum for transportable systems. Some of the newer radar transmitters and receivers are replacing older equipment that was built in the 1950s, so long-term spectrum requirements for long-range radars in this band can be expected for at least twenty years.

aeronautical telemetry, air-ground-air, and ship-shore-ship operations are vital to test range/aircraft instrumentation operations and reliable command and control communication links between shore and ship stations.

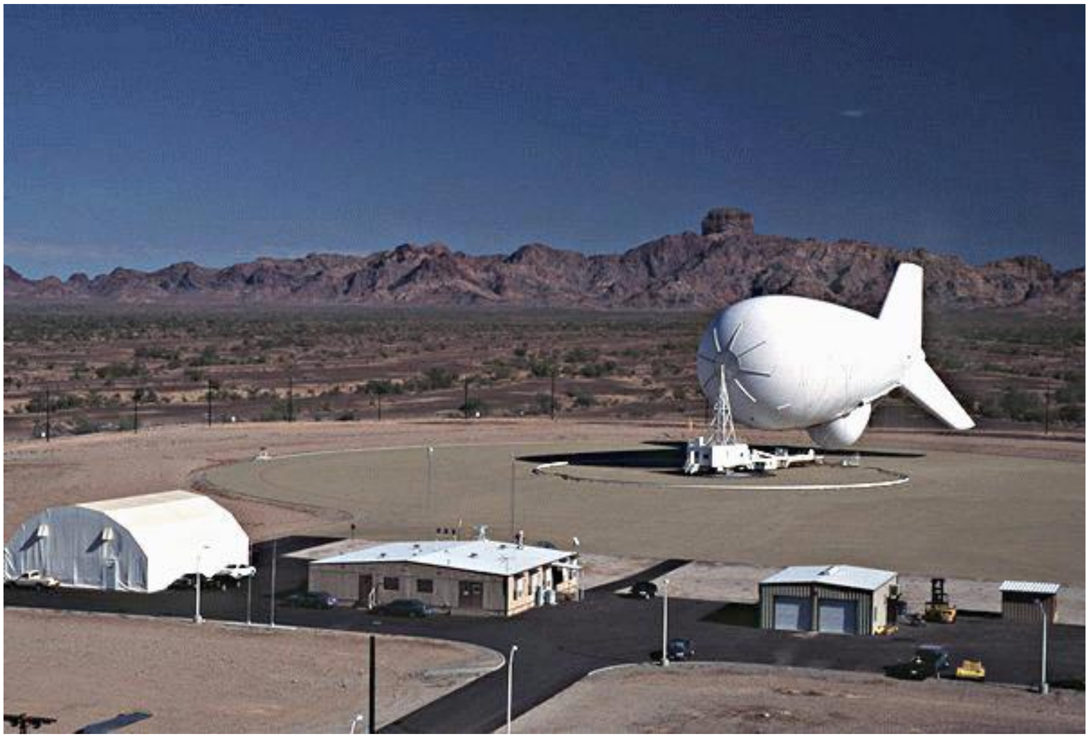


Figure 41. Balloon-mounted Aerostat L-band long-range radar.

Figure 42. Long-range ARSR (antenna is encapsulated by radome).

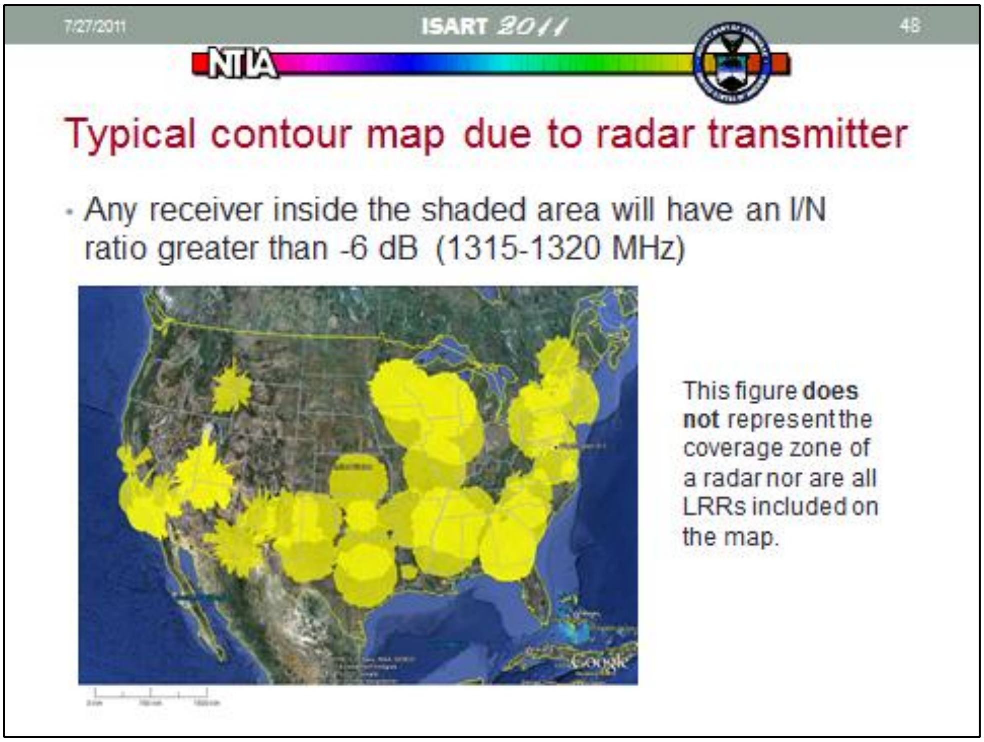


Figure 43. Typical L-band contour map (NTIA/OSM).

3.7 Lower S-Band Radar—Robert Sole

Lower S-band radar systems operate from 2700 to 2900 MHz. Major systems include NEXRAD and airport surveillance radar (ASR) and GPN systems. Lower S-band radar can be summarized by the following bullets:

- **Application/function**
    - Weather radar (e.g., NOAA National Weather Service (NWS)/USAF/FAA: NEXRAD WSR-88D) used for detecting precipitation and winds from a nationwide network of fixed Doppler radars (fielded in the late 1980s). NEXRAD provides severe weather coverage out to 125 miles and storm tracking out to 250 miles. NEXRAD data is converted into visual images and used by NWS/FAA/DOD to provide weather information and real-time conditions to the nation via the Internet and TV weather broadcast, including NOAA Weather Radio emergency broadcasts.
    - Air Surveillance Radar (ASR) systems, such as those shown in Figure 44, provide flight long range (111 km (60 nmi)) safety via surveillance in and around airports/airfields, departure and arrival traffic control, and weather detection at fixed locations. ASR information is commonly displayed on a plan position indicator (PPI) like the one shown in Figure 45. ASR systems also provide precipitation detection data, which is combined with other radar data to produce a composite weather product. DOD GPN systems provide defense and security via detection, tracking, and display of airborne objects.

- Radiolocation (secondary), which needs to accept interference from the other applications.

- **Installations**
  - Figure 46 illustrates the 159 fixed ground-based NEXRAD sites. The coverage contours on this map illustrate the areas where the systems can receive reliable weather data.
  - FAA ASR systems are located at over 250 airports. DOD operates approximately 150 GPN systems.
- **Operations**
  - NEXRAD operates continuously 24/7/365 and transmits 1 MW of power at one frequency (within the 2705–2995 MHz band) with duty cycles ranging from 0.05–0.21%. Approximate pulse parameters are one microsecond pulse width and one millisecond pulse repetition interval.
  - FAA ASR and DOD GPN systems operate continuously 24/7/365. Emission bandwidths are 2–10 MHz. Some systems require one operational frequency, some require one operational frequency and one hot stand-by frequency, some require two frequencies separated by a fixed amount, some require two frequency pairs, and others use multiple channels for frequency hopping.
- **Antennae**
  - Nominal NEXRAD antenna gain is 45 dBi, and the antenna height is approximately 27.5 meters (90 feet).
  - ASR/GPN antennae have approximately 32 dBi gain.
- **Spectrum crowding.** Hundreds of FAA and DOD air traffic control ASRs and Weather Service NEXRADs occupy this band across the U.S. The NTIA RSEC-D was designed and developed specifically to crowd as many radars as possible into this band, rather than expand the band by another 200 MHz in the late 1970s. Because the RSEC-D accomplished this goal, this band is now arguably the most crowded of all radar bands.
- **Compatibility.** The FAA is responsible for managing the 2700–2900 MHz band, including frequency assignments. FAA spectrum engineering criteria for the various systems are used to safely and efficiently provide spectrum to users, and the FAA participates in mitigation efforts when hazardous interference is experienced and reported.
- **Planned use**
  - Existing NEXRAD systems will continue to operate for the foreseeable future. No new NEXRAD installations are planned at this time.
  - Current ASR systems will remain operational for the foreseeable future. There are no plans to replace the radar systems with a technology that could meet the safety-of-life and other requirements for ATC, weather surveillance, and national security-related missions.
  - A Multifunction Phased Array Radar (MPAR) has been proposed to replace all ASR and weather radars with one platform that provides both functions. However, the specifications for this system are still being defined and the technology is being tested and evaluated.

Figure 44. S-band ASR test and research systems.

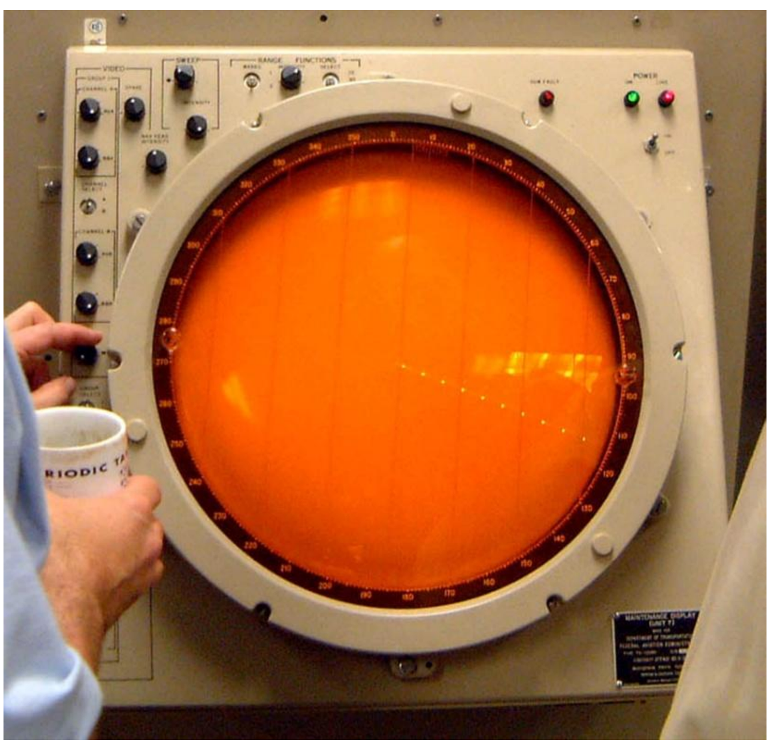


Figure 45. ASR plan position indicator display.

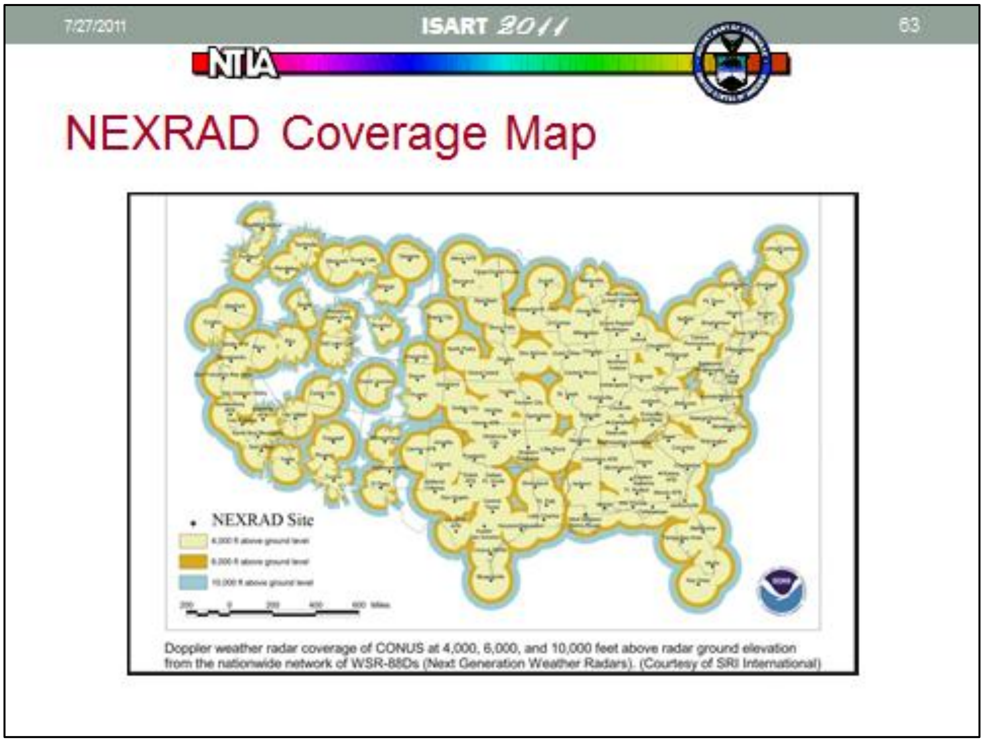


Figure 46. NEXRAD coverage map.

3.8 Upper S Band Radar—Frank Sanders

Upper S-band radar systems operating at 2900–3650 MHz are air radiolocation, maritime surface search, aerial- and ground-based navigation, ATC, and short-range artillery search, track, and warning. Propagation effects at these frequencies permit a wide variety of ranges, e.g., thousands of feet for some specialized functions, a few miles for some navigation and warning systems, and hundreds of miles for some air search systems. These frequencies are ideal for short to medium range applications. Note that some NEXRAD radars operate in the upper S band up to 2995 MHz. Upper S-band characteristics, excluding NEXRAD (covered in the previous subsection) can be summarized by the following

- **Application/function**
  - Short- to long-range air radiolocation and surveillance (e.g., USAF: TPS-43E)
  - Short- to long-range maritime radionavigation (surface search)
  - Aerial and ground-based navigation
  - Naval ATC (e.g., Navy: SPN-43C—see Figure 47)
  - Short-range artillery/projectile search, track, and warning
  - Test range operations
  - Bird tracking

- **Installations.** Shipborne (mobile) air search radars throughout U.S. littoral waters and navigable rivers, airborne (mobile) radars across the U.S., terrestrial transportable, and (mostly) fixed weather radars across the continental U.S.
- **Operations.** Applications are time-varying around and above the continental U.S. and U.S. territories for ships and aircraft, respectively. Operational parameters of existing systems are evolving over time. Multiple frequencies are needed to improve probability of detection, compensate for time-varying propagation factors, de-conflict operations between multiple radar systems, and help ECCM.
- **Antennae.** In general, in this band a 30 dBi gain antenna is 1.4 m (4.7 feet) across. ATC and other systems employ repetitive rotational scanning with vertical fan beams. Other systems use electronic pencil-beam scanning with no overall regularity or predictability. Nominal noise figures are associated with the internal electron noise in receivers, and are typically 3–5 dB.
- **Spectrum crowding.** Crowding is still substantial because NEXRAD systems are assigned to frequencies as high as 2995 MHz, and maritime navigation/surface search radars are ubiquitous across this band in all littoral waters around the U.S. coasts (East Coast, West Coast, Gulf Coast, and the Great Lakes and major navigable rivers, especially the Ohio and the Mississippi. There are also other non-radar applications that operate in the upper S band, e.g., multi-capability tactical operational support, operations at space launch facilities, ongoing development of new defense systems, antenna-range testing, operations at test ranges, and geostationary satellite links.
- **Planned use**
  - There are new dual-band radar systems being designed and planned for future introduction.
  - Maritime radars predominantly use magnetrons, but solid state units are coming on-line as we speak. The problem with solid state units is that they seem to cause more interference from radar-to-radar than do the older magnetron-technology units. As a result, they may need to have additional frequencies available to avoid co-channel interference to the magnetron units. This means that possibly more, not less, spectrum may be needed for maritime navigation/surface search radars in the future.

Figure 47. SPN-43C naval ATC (navigation) radar (courtesy: Defense video and imagery).

Figure 48. TPS-43E transportable air surveillance radar (courtesy: USAF)

3.9 Maritime S Band Radar—Joe Hersey

The maritime community use of radar is in two bands: S (tens of thousands of ships) and X (hundreds of thousands of ships). The Safety of Life at Sea (SOLAS) convention (treaty instrument maintained by the International Maritime Organization (IMO)) requires that S-band radars be fitted on ships greater than 3,000 tons. There are approximately 70,000 SOLAS vessels and thousands of non-SOLAS vessels.

Figure 49 illustrates X- and S-band target detection ranges for various cross-sections in different weather conditions (i.e., wet snow, heavy to light rain, and clear). Ships carry S-band radars because smaller targets (e.g., small ships) can be detected at ranges ten times greater than X-band systems. Sudden storms that cause lost visibility can also render X-band radar systems useless.

Up until recently, maritime radar systems used magnetrons exclusively. Maritime magnetron radar operational (e.g., 3020–3080 MHz operational frequency range, 30–75 kW peak power, 26–28 dBi antenna gain, 0.0018–0.48 duty cycles, 2.75–3.65 m (9–12 foot) rotating array) and susceptibility characteristics are well documented [32]. Maritime radars operate continuously while afloat. The well-characterized magnetron frequency standards allowed for the negotiation for a limited number of NEXRAD installations to operate up to 2995 MHz without causing interference to maritime radar systems.

The maritime radar manufacturing industry has changed and is moving toward solid state amplifiers. The three major companies that manufacture these radars are JRC (Japan), Furuno (Japan), and Kelvin Hughes (UK). Transmit/receive modules (see Figure 50) are all up near the antenna now, which requires difficult and expensive maintenance and replacement high on the mast. Solid-state amplifiers have significantly longer lifecycles than magnetrons, so the industry is moving toward solid state. Unfortunately, solid state radar is not as well understood as magnetron radar, primarily because the manufacturers are not forthcoming with their designs. The U.S. Coast Guard is funding an NTIA/ITS research effort to characterize the interference susceptibility of solid state radar.

An emerging problem in the maritime service is magnetron to solid state and solid state to magnetron interference. The Federal maritime and hydrographic agency in Germany (BSH) that certifies type-approved radars to ensure that they meet IMO requirements is studying the problem and has stated that there are interference problems that the manufacturers have not admitted to yet. Both solid state and magnetron radars are currently being built for operation in 3020–3080 MHz band to save cost on antennas and other components that would need to be redesigned. The interference may cause manufacturers to change their stance on that. Kelvin Hughes has moved down outside the 3050 MHz range to avoid the interference problem, and over time the rest may follow.

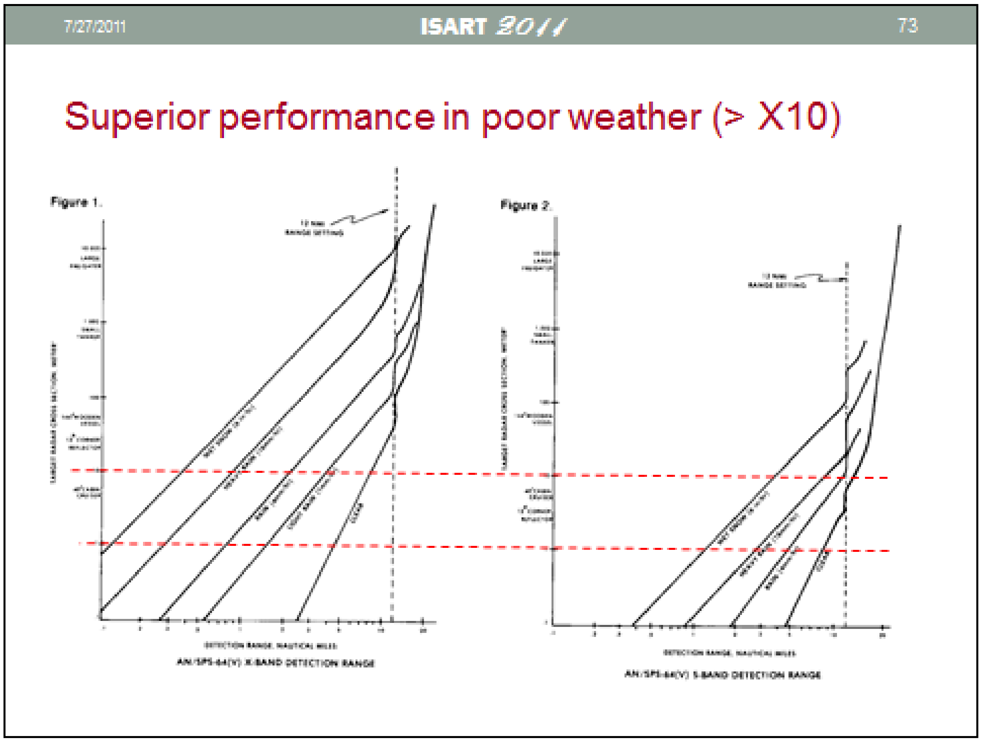


Figure 49. Performance comparison of X- to S-band maritime radar systems operating in different weather conditions.

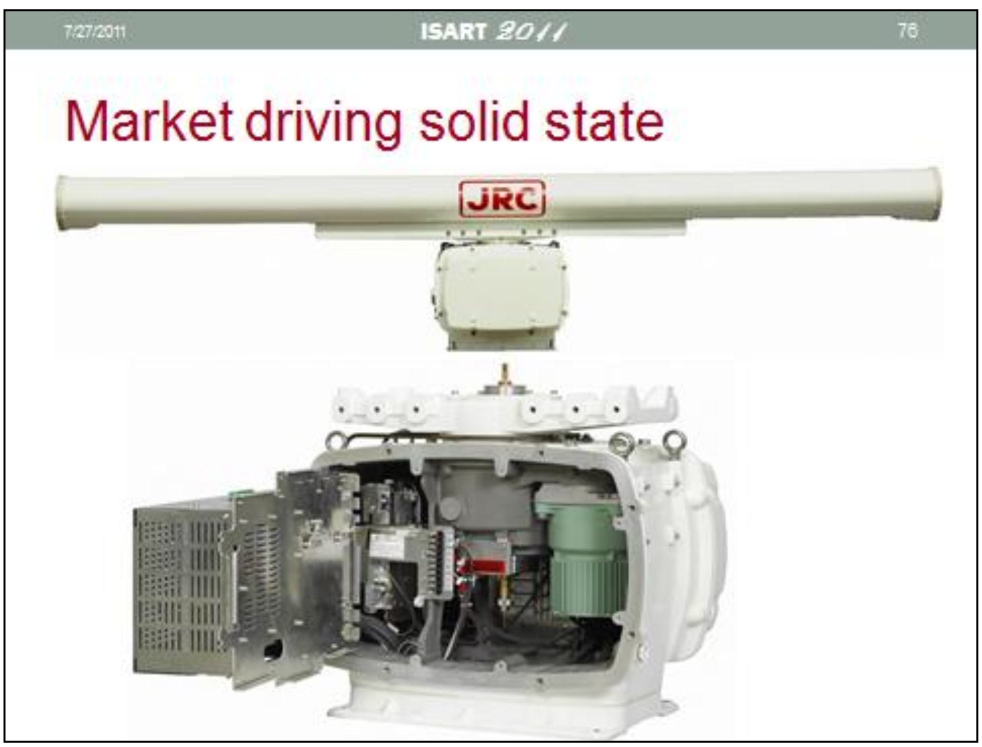


Figure 50. Maritime radar T/R module and antenna.

3.10 C-Band Radar—Frank Sanders

C-band radar systems operate in the 5250–5925 MHz band.[7] Terminal Doppler Weather Radar (TDWR) is the C-band analog to the S-band NEXRAD system and is discussed in the next session. In addition to TDWR, these frequencies are used for tracking and searching, and airborne Doppler weather radar (avoiding storms). Propagation at these frequencies is ideal for medium-range operations. Achievable ranges vary from thousands of feet to hundreds of miles, depending on the application and system design. C-band radar systems and applications (excluding TDWR) are described below.

- **Application/function**
  - Medium-range radiolocation
  - Aeronautical and maritime radionavigation
  - Airborne surveillance (including active precipitation and turbulence) for flight safety
  - Tracking targets at test ranges
  - Border security
- **Installations.** Radars in this band operate from terrestrial, maritime, and airborne platforms. Every commercial aircraft has an airborne Doppler weather radar system mounted in its nose (see Figure 51). Airborne (mobile) radars can be located anywhere across the U.S. Shipborne (mobile) radars are located throughout U.S. littoral waters and navigable rivers. There are transportable radars in this band.
- **Operations.** Applications are time-varying in the U.S. and its territories for ships and aircraft. Operational parameters of existing systems are evolving over time. Multiple frequencies are needed to improve probability of detection, compensate for time-varying propagation factors, de-conflict operations between multiple radar systems, and help ECCM.
- **Antennae.** In this band a 30 dBi gain antenna is 0.7 m (2.437 feet) across. Maritime radar systems employ repetitive rotational scanning with vertical fan beams. Some systems use non-repetitive and unpredictable electronic pencil-beam scanning techniques. Many airborne radars use repetitive sector scanning techniques to identify upcoming weather and turbulence. Nominal noise figures are associated with the internal electron noise in receivers, and are typically 3–5 dB.
- **Spectrum crowding.** Overall the band is crowded due to its large number of operational radars, communication systems, and the missions that those systems accomplish.

[7] Airborne radar altimeters also operate in the 4200–4400 MHz band in all phases of flight for terrain avoidance, helicopter auto-hover, and aircraft landing assistance. This is a specialized sub-band, and the rest of this section will focus on the 5250–5950 MHz band.

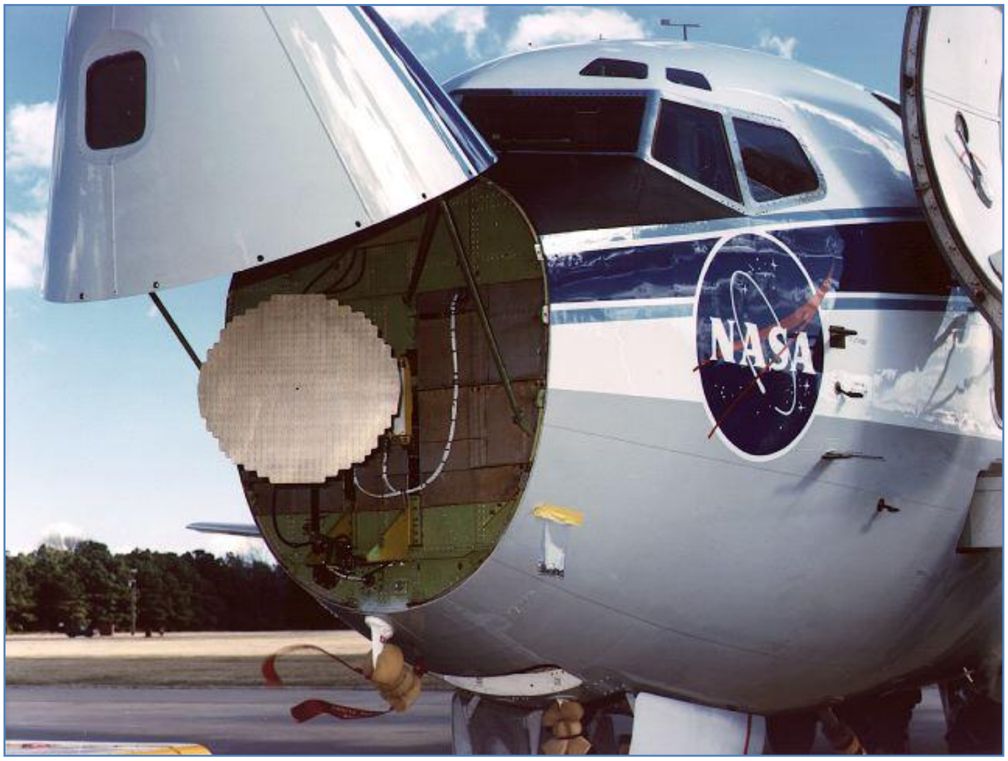


Figure 51. Airborne weather radar used in airliners.

3.11 TDWR Radar—Chris Tourigny

The three topics to be discussed in this presentation are: (1) Next Generation Air Transportation system (NextGen), (2) Delta Flight 191, and (3) TDWR.

NextGen is transforming the National Airspace System (NAS) from a ground-based system of air traffic control to a satellite-based system of air traffic management. The goals of NextGen are to enable growth in air traffic capacity, increase safety, and reduce aviation's environmental impact. The integrated approach includes surveillance and broadcast services, where data communications is used instead of traditional radar. Multiple NextGen programs are also involved in this transformation including improved data communications throughout the entire system, improved cockpit-to-ground communications, collaborative air traffic management, and network-enabled weather. This transformation depends on adequate interference-free availability of aeronautical communications, navigation, and surveillance spectrum.

Transformation of weather detection systems was precipitated by the crash of Delta Flight 191, which occurred on August 2, 1985, in Texas and killed 134 people on board and one highway motorist. Thorough investigation revealed that the most probable cause of the crash was a microburst encounter. As illustrated in Figure 52, the classic microburst encounter involves a fast transition from strong head wind to down draft to strong tailwind. Without the appropriate adjustment, this condition causes an abrupt loss in altitude which is dangerous when landing an aircraft.

The National Transportation Safety Board (NTSB) concluded that existing weather sensors were not adequate for avoiding conditions like those that led to the Delta Flight 191 crash and recommended the FAA expedite the development of better wind shear detection systems. In April 1986, the FAA produced a draft of the Integrated Wind-Shear Program Plan that involved: (1) aircraft crew training, (2) enhanced Low Level Wind-shear Alert System (LLWAS), (3) TDWR, and (4) airborne wind shear detection (airborne Doppler weather radar).

C-band TDWR (see Figure 53) systems and applications are described below

- **Application/function.** Wind shear detection system used to increase the safety of NAS (also display precipitation reflectivity). Capable of microburst detection up to 29.6 km (16 nmi) and gust front detection up to 60 km (32.4 nmi) at 0.55 degree angular resolution and 150 meter range resolution.
- **Installations.** 45 commissioned systems at the largest airports vulnerable to wind shear.
- **Operations.** Operates continuously 24/7. Specifications include: power = 250 kW, tuning range = 5600-5650 MHz, pulse length = 1.1 microsecond. The two modes of operation are (1) monitoring (used to search all directions for microburst activity) and (2) hazardous (one-minute near surface scan update to capture rapid evolution of wind shear).
- **Antennae.** Uses a 360-degree scan strategy to build a series of circular scans at various elevations.

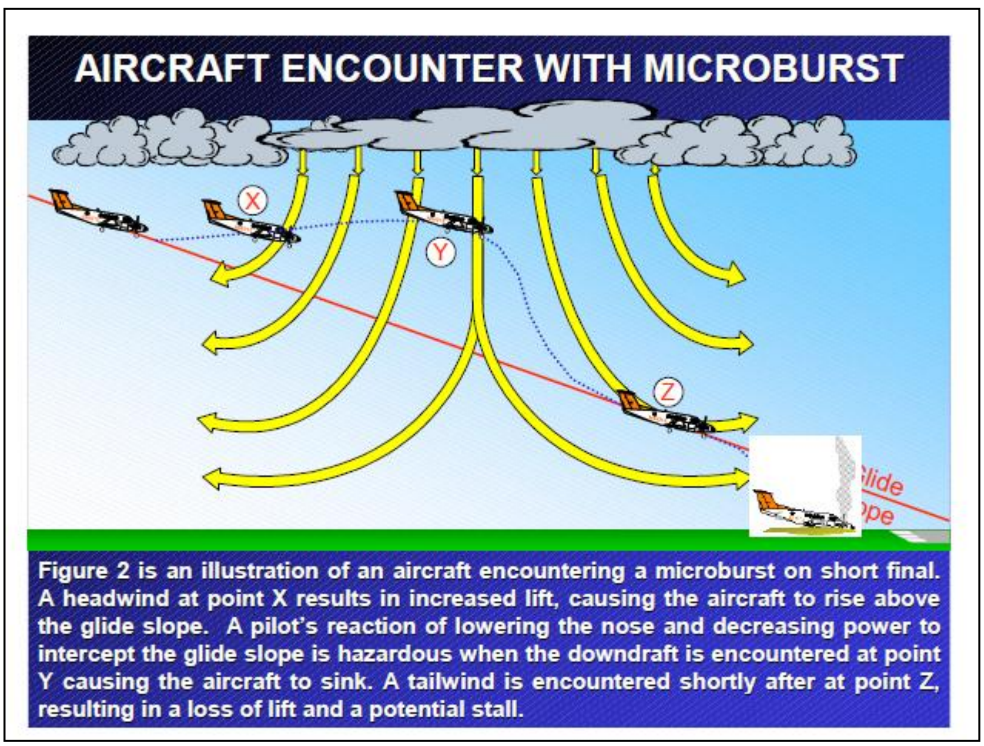


Figure 52. Aircraft microburst encounter.

Figure 53. TDWR antenna.

3.12 X-Band Radar—Robert Sole

Nominally, X-band is 8–10 GHz, but specifically for radar there are six sub-bands at 8000–8550 MHz, 8750–8850 MHz, 9000–9200 MHz, 9200–9300 MHz, 9300–9500 MHz, and 9500–9800 MHz. The short wavelengths of this band make it well-adapted for systems that need to use small antenna sizes. The primary X-band applications include aeronautical and maritime radionavigation, aeronautical radiolocation, airborne Doppler radar for storm avoidance, precision approach radar (PAR), and airport surface detection equipment (ASDE) for collision avoidance. There are also assignments for research, development, testing and evaluation of new and modified radars; active Earth exploration satellite service (EESS); space research; and mobile telecommand.[8] In general, military and aviation systems are permitted to operate when their mission requires it. The 9000–9200 MHz band is protected for PAR and ASDE applications, which are essential for transportation safety-of-life and national defense. Maritime systems are protected by imposing geographic limits of operations (i.e., within some distance of the shorelines) on some assignments. There are a variety of disparate land-, sea-, and air-based X-band systems and applications. Instead of broad generalizations, the rest of this section gives descriptions of systems in the six sub-bands.

[8] For example, a widely used data link system is used for air-ground-air communications at 9500–10,500 MHz. The airborne transmitter has a power level of 70 watts into a 24dBi antenna and the ground transmitter has a power level of 200 watts into an antenna with a gain of 43 dBi. This is a duplex link, where uplink and downlink are separated by 500 MHz.

Types of radar systems operating in the 8000–8550 MHz sub-band include:

- **Ship based target tracker:** Shipboard systems with high-resolution narrow beam antenna (one-degree beamwidth) for air and surface target detection and tracking. Typical peak power is 50 kW with 42 dBi antenna gain.
- **Instrumentation:** Radars that are transportable and used by test ranges to support various missions for tracking and monitoring aircraft. Systems operate in 8500–8975 MHz band. Typical peak power is 300 kW with 27 dBi antenna gain.
- **Ship based tracking and surface search:** These systems are used for tracking air and surface targets. Systems operate in 8500–9600 MHz band (excluding 9000–9200 MHz). Typical peak power is 250 kW with 42 dBi antenna gain.
- **Airborne surveillance/multi-purpose:** Airborne search radar used for surveillance and reconnaissance on multiple aircraft. Systems operate over Atlantic Ocean in 8500–9600 MHz band (excluding 9000–9200 MHz). Typical peak power is 50 kW with 34 dBi antenna gain.

Types of systems operating in the 8650–9000 MHz sub-band include:

- **Transportable ground surveillance:** Transportable surveillance radar systems used by the Federal agencies for detecting and tracking vehicle- and human-sized targets. Typical Peak power is 5 W with 31 dBi phased array antenna gain.
- **Airborne multi-mode:** Multi-mode airborne Doppler radar systems, usually installed on HC-130J aircraft, used for surface search and reconnaissance for anti-smuggling and search-and-rescue missions over the U.S. and its territories. Typical peak power is 3.5 kW with 33 dBi antenna gain.

Types of systems operating in the 9000–9200 MHz sub-band include:

- **ASDE-X:** Fixed radar systems that provide a comprehensive view of airport air traffic, surface movement, and approach corridors for advance ATC purposes. Systems are located at 35 major airports across the continental U.S. plus Hawaii. Peak power is 155 W with 35 dBi antenna again. ASDE-X systems are being upgraded incrementally.
- **Ground Based PAR:** Transportable or fixed integrated all-weather ATC and PAR systems which can be configured as a complete Radar Approach Control (RAPCON) or Ground Controlled Approach (GCA) facility (see Figure 54). The primary radar coverage is up to 111 km (60 nmi) and the secondary radar coverage is 370 km (200 nmi). Typical peak power is 120 kW with 38 dBi antenna gain.
- **Shipboard PAR:** PAR systems used on U.S. Navy vessels to direct landing operations and precision aircraft approaches during adverse weather conditions. There are 35 Navy land-based systems primarily for training purposes. Ship-based systems typically do not radiate within 100 miles of shore and are usually aimed away from shore to limit the potential for interference. Typical peak power is 200 kW with 34 dBi antenna gain.

Types of systems operating in the 9200–9300 MHz sub-band include:

- **Airborne multi-purpose:** Lightweight all-weather airborne radar systems that provide information for ATC, radar surveillance, and ground controlled approach of aircraft. Typical peak power is 200 kW with 38 dBi antenna gain.

- **Instrumentation and research:** General-purpose instrumentation radars that support research, testing, and development. Authorized for occasional (not limited to work-week hours) operations at test ranges. Typical peak power is 225 kW with 39 dBi antenna gain.
- **Airborne Surveillance:** Airborne radars installed on C-130 aircraft operated by the U.S. Coast Guard for sea surveillance above the U.S. and its territories. Its mission is to detect surface ships, sea ice and oil slicks due to pollution spills. Typical peak power is 250 kW with 34 dBi antenna gain.

Figure 54. X-band PAR radar.

3.13 Ku/Ka/Millimeter Band Radar—David DeBoer

Ku (12–18 GHz), Ka (27–40 GHz), and mm-wave (30–300 GHz) are bands with a scientific focus for radio astronomy and earth exploration satellites. The specific frequencies are set by physics, either in molecular spectroscopic lines (at possibly red-shifted frequencies) or bulk geophysical scattering. Nature will not change these frequencies to satisfy allocation issues and these frequencies provide unique information on the state and evolution of the Universe, and critical climatic, weather and atmospheric issues. Small wavelengths make these bands good at resolving small things and measuring the bulk properties of big things. Higher frequency means high gain in small antennas, but also small fields of view. Hence, these frequencies are good for localized and point-to-point applications.

Geophysical absorption and emission characteristics are complicated at these frequencies; hence, frequencies for a given application are chosen for geophysical reasons as well as propagation characteristics. Ku and Ka bands are relatively well-behaved in terms of transmission. In the mm-wave region, however, there is a forest of high-absorption resonant lines associated with quantized energy transitions between atmospheric molecules and incident electromagnetic fields. These spectral features are useful in remote sensing applications and other science applications—e.g., oxygen emission signatures near 60 GHz permit atmospheric temperature profile measurements. There are also natural sources of emission from the atmosphere, rain, clouds, land, oceans, scattering, and cosmic background noise (at 2.7 Kelvin) from the aftermath of the Big Bang. Many of the passive radio-astronomy services are in the mm-wave region because interstellar and intergalactic molecules have resonances there. It's important to note that radar is essentially a "passive" service during the time in which it is listening. An important point is that "passive" users are not non-users. That is, the "receive-only" science done at this band is an important part of the panoply of spectrum use.

Ku/Ka/mm radar system characteristics can be summarized as follows:

- **Application/function**
    - High-resolution mapping (Ku and Ka)
    - Shipborne search, tracking, and gun fire-control (Ku)
    - Active Earth Exploration Satellite Services (EESS), i.e., satellite altimetry and observations and measurements of precipitation, clouds, ocean winds (Ku)
    - Airborne Doppler weather (Ku)
    - Airport surface detection (Ku)
    - Military combat surveillance, airborne weapons control, and unmanned aerial vehicle (UAV) based radar systems
    - Short-range tracking (Ka)
    - Radar speed guns (Ka)
    - Military airborne precision mapping (Ka, mm)
    - Smart munitions (mm)
    - Experimental (mm)
    - Remote sensing (mm)
- **Installations.** Many of the EESS applications and systems are international spaceborne missions (see Figure 55). Military systems are mounted on ships, airplanes, helicopters, and UAVs.
- **Operations.** EESS systems are fairly low-power, except for the CLOUDSAT.
- **Antennae.** Higher frequency means high gain in small antennas, but also small fields of view.
- **Planned use.** The military has a number of Ku and Ka radar systems in research and development. Automotive radar at 77 GHz is an important new allocation in this band, that will become ubiquitous over time.

Currently Operational Spaceborne Active Sensor Missions (Updated: June 2011)				
Mission	Agency	ITU Name	Frequency (MHz)	Radiated Power (W)
Aquarius Scatterometer	NASA	AQUARIUS	1260	200
ERS-2 SAR/WS/RA	ESA	ERS-1	5300/5300/**13800**	4800/4000/134
RADARSAT-1/2 SAR	CSA	RADARSAT-1A RADARSAT-2C RADARSAT-2D RADARSAT-2E RADARSAT-2F	5300	5000
ENVISAT ASAR/RA-2	ESA	ENVISAT	5300/**13575**, 3200	4800/114, 65
COSMO-SkyMed	ASI	COSMO SKYMED	9600	2800
TerraSAR-X SAR	DLR	TERRASAR	9650	2260
JASON-1 (OSTM) SSALT	CNES	PROTEUS-TPFO	5300, **13575**	25, 7
JASON-2 (OSTM) SSALT	CNES	JASON2	5300, **13575**	25, 8
MetOp ASCAT	ESA/EUMETSAT	METOP	5300	120
QUIKSCAT SEAWINDS	NASA	QUIKSCAT	**13400**	110
TRMM PR	NASA/JAXA	TRMM	**13800**	518
CLOUDSAT CPR	NASA	USCLOUDSAT	**94050**	1500

Some upcoming missions				
Mission	Agency	ITU Name	Frequency (MHz)	Radiated Power (W)
Global Precipitation Monitor Dual-Frequency Precipitation Radar (GPM/DPR)	NASA/JAXA		**13597,13603, 35547,35553**	
SARAL/ALTIKA Ka-band altimeter	CNES/ISRO		**35,750 GHz**	2

Figure 55. Current and planned active sensor missions.

3.14 Q&A

Anonymous: My comment is related to spectrum inventory. Remote-sensing frequencies need to be included in inventories because of their importance. Measurements don't see everything. How do we account for low percentages of time that some systems operate and for receivers and passive users that cannot be seen via measurement?

Hussey: Last year, Frank Sanders gave an excellent presentation on how measurements can give distinctly different usage patterns depending on how the measurements are performed. So we have to be careful to get an accurate and a comprehensive picture, including passive and remote sensing. By no means is an inventory easy, but it is critical to reach out to all of you and to work with FCC and NTIA to make sure that we get the most effective and accurate picture.

Joe Mitola (Stevens Institute): What is your justification for your coverage maps related to interference to communication systems from radar pulses?

Sole: Those graphics are not coverage maps of the radars, they show the zones where a generic communications-type receiver, if it's within the shaded area, will experience I/N in its passband of -6 dB or more.

Mitola: How do you think of communications as being interfered with. Maybe communications people have their own criteria that you might not know or have.

Sole: We used textbook, reference, typical numbers of -6 dB I/N as published for communications receivers.

Sanders: I can add one more thing, which is that NTIA does not tell Federal or non-Federal entities what the criteria are for degradation to the performance of their radio receivers or radio systems. We rely on the FAA, for example, to tell us what their own criteria are for degradation to their systems, and we would do the same for private-sector systems. Now, as Bob says, we will review the literature for references to existing, published criteria for interference to some systems. But we don't create those criteria ourselves. We look to the people who own and operate radio systems to tell us what the criteria are for degradation.

William Grigsby (U.S. State Department): I have a comment and a question regarding Mr. Hussey's presentation. First, with respect to the slide that referenced the President's June 20, 2010 memo on the 500 MHz over 10 years, one item that you did not include are the several dozen radio frequency bands that are subject to international agreements, including with Canada and Mexico. I wanted to mention that because it's an important criterion as we examine bands for re-purposing. The question concerns the spectrum inventory. Can you clarify that the intent of the legislation for the inventory is to cover the U.S. and Possessions, and not locations outside the area?

Hussey: The intent would certainly be domestic, initially. Obviously, there is the discussion of international harmonization (e.g., 1755–1780 to pair with AWS-3). There are caveats to ensure the proper handling of classified or sensitive information regarding radio services or systems.

Peter Tenhula (Shared Spectrum): The 902–928 MHz band has been sharing with other services. Any experience with how that's been going? Any issues? Any plans to improve/upgrade radar systems in the band and how that might impact other users in that band?

Sanders: Regarding whether there are any existing EMI issues or problems between the 900 MHz radars and the existing Part 15 industrial, scientific, and medical (ISM) applications, devices in the band, I can say that wind profiler radars in the band do sometimes experience problems with interference from ISM devices in the band. This is mitigated somewhat because the profilers look up and only couple weakly to interfering terrestrial sources via their sidelobes. However, some interference does occur. As for interference to or from other 900 MHz radars, I'd defer to one of the Navy people in the room.

Sole: There are some problems when Navy radars are close to shore. When cellular systems first came on-line there were some initial problems.

Larry Cohen (NRL): Yeah we're careful about operating. As a matter of fact there was an issue where I was on detail to NAVSEA, where we changed the channel selection on one of our radars to mitigate interference. The Navy operates their computer program, AESOP, throughout the globe and uses it to minimize interference around the globe. It goes into spectrum allocation as well as stand-off distances from shore to minimize interference with wireless assets.

Sanders: Would it be a fair statement, then Larry, to say that basic de-confliction technique between the Navy radars in the 900 MHz band and the other systems on shore is that the Navy radars either try to use frequencies that de-conflict, or else try to not operate within some number of miles from shore?

Cohen: That is correct.

Tourigny: I've got a quick little thing on that. The wind profile radars that the FAA operates, there are only four of them. They are in Juneau, Alaska. And the FAA has determined that the quality of service that can be expected anywhere in the U.S. at 915 MHz will not be adequate to ensure adequate safety-of-life protection. So the FAA will not be using these radars at 915 MHz, in this unlicensed device band. We will not be operating these radars in this band in CONUS.

Questioner 4: So you're yielding to the unlicensed devices, even though you're the licensed service?

Tourigny: Yes, because we can't guarantee the service of our systems in that environment.

Rich Lee (Greenwood Telecom): It regards L band, where maybe communications and radar could share. Do you need the entire spectrum from 1200–1400 MHz? If each radar is 8–10 MHz bandwidth, why do you need the entire band? Is there an opportunity for frequency re-use among the radars in the band?

Sole: There may be ways to shrink the frequencies better. But we have a big country and it takes a lot of radars to cover it. And there are limits on how close you can get from one radar to the next, in distance and frequency, before you get interference between them. Now could a better job be done in putting them closer? Maybe. Up until recently there was no big push to do that. We're a small agency, with 200 or 250 people. So we don't have a lot of time to do that kind of thing. If we were told to do such a study, we could. The inventory may require that. In terms of siting rules, I'll turn to Chris of the FAA.

Tourigny: Yes, there are some rules, criteria for that. One frequency has to be assigned above 1300 but below 1350. And the second frequency at each radar site has to be set below 1300 but above 1240 MHz. Actually, in the U.S. and Canada we can go up to 1370, and some radars do. We also have to share with satellite systems in the lower part of the band. One of the requirements for the new CARSR is that it has to have two sets of frequencies to avoid interference.

Lee: But in theory couldn't you pack all of the long-range radars across the country into one pair of frequencies, to the limit that you don't interfere radar-to-radar?

Tourigny: I'll give you a real-life example. Putting in the CARSR system was really tough in the 130 MHz that we had available to work with. The number of systems is so large and the potential for system-to-system interference is so high that we took the step of designing a GPS-based antenna alignment system to keep all of the CARSR antennas rotating synchronously, so that they all look north simultaneously. We had to take that step because otherwise we would get main-beam-to-main-beam interference between the radars, even with the tightest frequency packing that we could work out. So it is already really difficult to operate in the amount of spectrum that we already have, to the extent of having to synchronize the radar rotations across the entire country.

Sole: And there are other radars in the band, including DoD radars like the TPS-59 and TPS-63 that I didn't show on my slide. It's not just ARSR systems in that band. There are frequency-hopping and frequency-agile radars in there too. And when you try to integrate DoD tactical, including antiballistic radars, then it becomes an even harder problem to pack the frequencies tighter.

Tourigny: We've gone through a couple of iterations of reducing the amount of available spectrum in that band. The first one was due to GPS. We had to vacate around 1227 MHz. So all of the core assets are now jammed into a tighter band. Other systems had to go above 1370 or below 1240. We can't go above 1390 anymore. So what we've done is concentrated the core assets in the center of the band, with other assets in other parts of the band. Above 1390 has been given to the cell phone industry.

John Mettrop (CAA): I fully agree with my American colleague. From a European perspective, of course you've got GLONASS and Galileo. The UK has done studies, and the government will need to find a way to move all of our L band radars, because Galileo will cause interference, and I believe in the U.S. you've found the same result. So now we're operating between 1260 and 1350 MHz. Actually we will have to find a way to work entirely above 1300 MHz. As far as planning is concerned, we're looking for 500 MHz, too. But within that we've got some work to do to actually look and say, "How tight can we pack radars"? We're not sure if we've got an optimal plan. We don't know if we're currently over-protective or under-protective. We're talking to radar manufacturers to get a better feel for this.

Hussey: You raise good point, several good points. One that really resonates is to make sure that the government has adequate resources in any reallocation. Frank has already mentioned that these systems will have to operate indefinitely where they are if there are not additional, adequate resources made available to upgrade them. So Congress has to make hard decisions on making resources available to allow better utilization, improved efficiency. OK, yes, maybe we can do that somewhat with some auction proceeds, but it's a question of whether that's going to be enough, will provide enough resources. I think that concludes the panel.

4 KEYNOTE REMARKS BY NTIA CHIEF OF STAFF THOMAS POWER

Good morning and thank you for joining us today. NTIA is pleased to be hosting this 12th Annual International Symposium on Advanced Radio Technologies here at our research and engineering laboratory in Boulder.

As many of you know, NTIA is the principal advisor to the President on communications and information policy. Although Federal spectrum policy has always been a core mission of this agency, our work on spectrum issues is more important now than ever before as spectrum is fast becoming a pillar of America's digital infrastructure. Spectrum has enabled the mobile broadband revolution, changing the way that Americans communicate and do business.

Last year, ISART provided a platform for a broad range of perspectives on spectrum sharing. The focus of this year's conference on radar bands is a great place to further this dialogue. Radar bands have frequently been identified as candidates for sharing and radar technologies are a key factor in our work surrounding future spectrum policy making and our ongoing Federal spectrum management efforts.

In my remarks today, I would like to first discuss progress NTIA has made in response to the President's Executive Memorandum [2] to make available 500 megahertz of Federal and non-Federal spectrum over the next 10 years. Next I will look at how our work here relates specifically to radar technologies and uses. Lastly, I will point out several points for consideration related to how our work in this area, and our approach to radar bands specifically, might be shaped to maximize efficient use and the benefits to the American people.

With the rapid growth of mobile broadband, it should come as no surprise that President Obama and policymakers have made it a key priority to increase the amount of Federal and commercial spectrum available for mobile broadband.

To expand America's available spectrum resources, we know the government must use its existing spectrum more efficiently, we must free up more spectrum for new uses, and we must provide the private sector with the incentives to transfer spectrum from current uses to higher-value ones.

President Obama's State of the Union address this past January contained significant news on the spectrum front. The President called for a National Wireless Initiative to make available high-speed wireless services—the "4G" technology now being deployed in the United States by leading carriers—to at least 98% of Americans. The President's initiative will make it possible for businesses to achieve that goal, while freeing up spectrum through incentive auctions, spurring innovation, and creating a nationwide, interoperable wireless network for public safety.

A critical component of the National Wireless Initiative is the President's directive to NTIA to collaborate with the FCC to make available 500 megahertz of Federal and non-Federal spectrum over the next 10 years. The initiative—to nearly double the amount of commercial spectrum over the next decade—will spur investment, economic growth, and job creation while supporting the growing demand by consumers and businesses for wireless broadband services.

To make this happen, the President directed the Secretary of Commerce, working through NTIA, to collaborate with the FCC to produce a ten-year plan and timetable for making available the 500 megahertz of spectrum, all while protecting vital government missions that rely on spectrum use.

Pursuant to that directive, NTIA delivered to the White House, within three months, a plan and timetable for performing this work. In November, NTIA released two complementary reports. First, we issued the Ten-Year Plan and Timetable [3]. This report, developed with input from other Federal agencies and the FCC, identifies 2,200 megahertz of spectrum for evaluation, the process for evaluating these candidate bands, and the steps necessary to make the selected spectrum available for wireless broadband services.

In addition, NTIA released a second report—the results of a fast-track review we undertook to identify some spectrum reallocation opportunities that exist in the next five years [4]. This allows us to make a down payment on the President's overall ten-year goal. Our report identified and recommended a total of 115 megahertz of spectrum to be made available for wireless broadband use within five years, contingent upon the allocation of resources for necessary reallocation activities.

And we continue to make progress on the President's spectrum initiative. Earlier this year, we selected the next spectrum band to be evaluated for potential repurposing to commercial use. The band we selected with input from other Federal agencies, 1755–1850 MHz, is a priority for review based on a variety of factors, including industry interest and the band's potential for commercial use within 10 years. We plan to complete our review of this band by the end of September. This spring we also issued our first status report on the overall progress of the 500 megahertz initiative.

We are also working for our Federal and non-Federal partners to ensure our spectrum efforts reflect the needs of the stakeholders. Yesterday, the Commerce Spectrum Management Advisory Committee met in Boulder to review progress on the President's ten-year plan and review recommendations and highlight priorities of industry and non-Federal stakeholders.

Traditionally, calls for more spectrum have led to Federal agencies' being required to relocate operations to free up spectrum for commercial users. But today, it is not so simple. Meeting the goals of the president's memorandum will require the reallocation of spectrum from both commercial and Federal users. Moreover, many of the bands that will be considered in this effort will involve sharing of some sort.

My boss, Assistant Secretary Strickling, has been very vocal about arming agencies with adequate resources for Federal relocation activities, especially upfront planning expenses.

Last month he testified on Federal government spectrum use and reiterated the importance of supplying agencies with the necessary funding to plan for reallocation as well as to investigate more efficient spectrum-sharing options. We believe that funding is critical for agencies to maximize their efficient use of spectrum resources. However, I'm pleased to report that we are encouraged that legislation recently reported by the Senate Committee on Commerce, Science, and Transportation makes important strides in better accommodating the costs of relocating Federal users.

While solutions such as spectrum re-allocations are critical to meeting national needs, so is the development of the next generation of technologies that can enable more efficient use of the radio spectrum. NTIA, along with its Federal agency partners, is committed to developing and improving new and innovative spectrum sharing capabilities to further our mission of increasing the efficiency of Federal spectrum use.

In step with this, on Tuesday here in Boulder, the Wireless Spectrum Research and Development Senior Steering Group, which was formed to coordinate spectrum-related R&D activities across the Federal government, hosted a technical workshop to coordinate Federal and private sector research to help identify R&D opportunities that may have large potential payoffs for the national wireless industry and the nation's economy at large and which are consistent with the Federal Government's development goals and lay the framework for long-term research that may result in yet-to-be-conceived improvements in spectrum utilization. Thank you to NTIA's own Byron Barker who co-chaired this group. We look forward to reviewing the resulting report from this workshop.

Yesterday the Commerce Spectrum Management Advisory Committee met in Boulder.

In our effort to address the President's spectrum initiative full circle, additionally we are working closely with the White House and Congress to move forward incentive auctions to open broadcast and MSS spectrum.

So, as you can see, there is much work to be done but we are working aggressively toward the President's goal. So, after we complete our review of the 1755–1850 MHz band, where do we look next? We have been working with the agencies to prioritize our review. We will be evaluating opportunities for making spectrum available for wireless broadband. This may include bands from which we might relocate incumbent systems or spectrum where sharing between incumbents and wireless broadband is possible, whether licensed or unlicensed.

Our search quickly draws us toward radars and radar spectrum. Your focus at this conference is timely for our work. I look forward to the next couple days of discussions. I want to encourage you to push the envelope to stir ideas regarding how we can make use of this spectrum to meet our broadband goals while ensuring that the missions supported by radar technology continue to be met.

So why are radars and radar spectrum so important to our work to identify spectrum for wireless broadband? Of the 2263.9 MHz identified for review by NTIA and the FCC within our ten-year plan, 1240 MHz of that, or almost 55% , is spectrum currently used for radar operations. Not all of that spectrum is Federal exclusive. Most of it has some sort of non-Federal allocation. But the reality is that the Federal presence dominates most of these bands. Let's take a look at which bands we are talking about.

The 1300–1350 MHz and 1350–1390 MHz bands, taken together support the aviation and defense communities' use of radars for long range air surveillance for air route flight control in a friendly environment and target tracking when needed in a tactical environment. We are talking about approximately 400 radars that reach out 200–400 miles to monitor air traffic across the country. Many of us remember during 9/11 the pictures of the “big board” that the FAA uses as a national composite picture of the whereabouts of all air traffic. This picture is drawn from this data. It supports the regional air traffic centers’ ability to direct traffic. These systems represent a significant investment in our air traffic safety infrastructure. Furthermore, while modern communication systems (especially commercial wireless) have rapid development cycles (a couple of years at most), radars last for decades. This makes it difficult to modify and evolve radars in a timely fashion. Defense use, while also supporting air traffic management, has a critical tactical role since they also double in terms of tracking aircraft and other potential airborne threats. In recent years, radar use in this range has expanded as we have added aerostat-borne radars to our tool chest in our efforts to interdict drug smugglers and secure our borders. We understand that this frequency range offers significant advantages in being able to provide range and resolution needed to support these functions. Reaching these long distances through heavy rain at higher frequencies presents challenges.

The 2700–2900 MHz band also supports airport ATC all around the country. However, in this case, it represents the take-off and landing approach control, moving our aircraft efficiently and safely in and out of about 700 airports. At the same time, the weather community uses this band for almost 200 weather radars that support our weather prediction and storm tracking efforts. As we have witnessed this past year the destruction caused by tornadoes and other violent storms, we can see clearly how critical the warnings that these systems provide are to the saving of lives. Families are now able to watch reports on television and make necessary safety preparations.

Some of these weather radars also operate above 2900 MHz as the spectrum below 2900 MHz becomes more congested. However, the 2900–3100 MHz band is predominantly used by the maritime community to operate radar devices on ships for navigation. In addition to providing detection of other ships and terrain obstacles, these radars also trigger radio beacons, the electronic equivalent of the light house. These modern tools are more widely distributed, unmanned and require significantly less real estate. But they do require spectrum.

Mobile military radars begin at 2900 MHz and go up through 3650 MHz to meet a variety of missions. The systems include air and ship borne operations, and power levels often exceed a megawatt. We understand that in the current tactical environment, these radars must also be flexible and jam resistant. For that reason, they use techniques that make them more difficult for the enemy to pin down. However, this quality may also make difficult the formulation of sense-and-avoid strategies for spectrum sharing. At the same time, the high levels that they emit would probably cause interference to broadband wireless operations. Airborne operations would spread that interference over very large areas.

So these are the bands that we have to review. We face some tough questions in looking at them and hope bringing together experts like you will help us to understand what we can do.

- **Can any of the missions be accomplished in higher bands?** We understand that there are technical links between radio applications and their preferred operating bands. Because existing radar designs take advantage of atmospheric propagation, changing bands can be problematic. Use of higher bands means needing to cope with different, and often worse, propagation for a given mission. However, some of these bands were probably selected as the next available band as we were marching up the spectrum with new developments. Are there new techniques that would allow us to move higher and overcome limitations? What is the timeframe that would be required for real redesign?

- **What will be the impact of the Radionavigation Satellite Service (RNSS) on requirements for aviation via NextGen and for maritime radars?** Most people assume that with the widespread availability of GPS and the development of NextGen that some radars will not be needed. However, radars have the unique characteristic of being active, self-contained systems for sensing surrounding environments. For tracking aircraft, for example, radars do not depend on beacon replies or GPS-based information from aircraft cockpits. Instead, planes can be followed even if beacons are switched off or fail (as happened on 9/11) or GPS based information is not available. For maritime navigation, ship borne radars show mariners other vessels and hazards which cannot be located using charts and beacons in conjunction with GPS. This is not to preclude GPS and beacon-based solutions for aeronautical and marine navigation, but radar provides fail-safe capabilities that the aeronautical and marine communities currently rely on.

- **Can we be more efficient in packing radars together?** Our tools for selecting radar frequencies for fixed location radars probably need to be updated. Many or our “rules of thumb” were developed long before our computerized modeling and terrain information came into being. If we can pack these bands more closely, then possibly we can free some of this spectrum.

- **If we can cut out a portion of these bands, and implement wireless broadband, can these services live with each other as close neighbors?** We understand that radar signals are not clean. Many radars are fairly old and their receivers were designed during times when they had no neighbors. We also have seen some indication that broadband systems also have challenges in reducing levels outside their operating band.

- **Can new systems share with radar?** By geographic location or by sensing or other time sharing methods? As I have said, there are a lot of megahertz set aside for radar operations. We have some experience with Wi-Fi sensing radars and we expect to see more tools available for using geolocation databases to support sharing. Experience gained with Dynamic Frequency Selection (DFS) communication systems sharing spectrum with 5 GHz weather radars has provided valuable lessons that can be applied to future band sharing technologies. While some compatibility problems have occurred with DFS at 5 GHz, many DFS systems currently share spectrum with weather radars without causing interference. In cases where interference has occurred, engineering solutions have been developed or are within reach. The DFS experience has provided technical staff and policy people with new knowledge regarding certification testing and enforcement processes that can be applied to future dynamic sharing. Geolocation databases have potential in some circumstances, but challenges will need to be overcome regarding data release on radar characteristics and locations. Many government radars are classified, and many unclassified radars cannot have their frequencies and locations made available in public listings. We are not sure whether sharing with fixed radars opens sufficient geographic areas to provide significant access. Geolocation by itself cannot support sharing spectrum with mobile radar incumbents. With mobile radars, you have some hope that the intermittent operation may allow access to most locations for most of the time via sensing.

- **Is the commercial wireless industry interested or able to share in radar spectrum?** In the end, this is a critical point. We need to free up spectrum in workable chunks. Ultimately, the question of whether industry will find sharing approaches feasible will depend on the amount of spectrum that can be made available, where it is available and for how much of the time.

Frequently, as we discuss spectrum, we view things from a communications technology perspective and often a perspective that is limited to land mobile or even cell phone techniques. The community and policy makers must begin to understand the challenges and constraints that currently exist for radar. Radar transmitters are more powerful than most communications systems (sometimes more than a gigawatt radiated power) making them a potentially greater source of interference. Also, radar receivers are more sensitive than most communications systems (e.g., receiving 1/100 picowatt of echo energy from targets at 80 miles range) making them more vulnerable to interference.

Those of you with skills and knowledge in radar technology are critical to our efforts. I want to encourage you to roll up your sleeves. Be creative in your efforts. Get your ideas out on the table. Let's look for how we can increase use of the spectrum and not just get trapped by all the reasons, all the barriers that limit us. We are working at a critical time and your work is a key part of this effort. I look forward to a healthy discussion over the coming days in continuation of the collaboration between government, industry, and academia that has always marked ITS's activities.

5 KEYNOTE REMARKS BY DEAN PHIL WEISER OF UNIVERSITY OF COLORADO LAW SCHOOL

The overarching theme here is how important the work you all are doing is. This conference plays and extraordinarily important role in the spectrum policy constellation. You really do have the key thought leaders here and that is for a very good reason. So, let me start off with a few basic points.

First, it is worth remembering how much ideas matter. Three ideas of particular importance in this space are (1) Coasian bargaining, (2) sharing spectrum, and (3) secondary markets. In the first, regulatory distinctions that have an artificial thumb on the scale are not easy to get unstuck and Larry Summers, while working on the outline of the spectrum policy for the Obama administration immediately said, “spectrum, water rights in California.” This was an important realization because valuable assets, when people have an interest in keeping them, get much more complicated than you would expect to unravel. So, the U.S. very quickly gave out a lot of great spectrum to broadcasters, other countries haven’t done that, and today we are living with that legacy, literally. Facilitating Coasian bargaining, voluntary transactions that allow for market win-win deals, is not easy. However, the ideas that underpin that have been very powerful. A second idea that is very important, first advocated for by Michael Marcus, is about unlicensed low power uses and it has spawned a revolution of technological developments that take advantage of that possibility. A third idea, that also had some heretical roots, was that of secondary markets in spectrum, pushed most powerfully by Dale Hatfield. Initially in spectrum, there had been a legal tradition that the licensee had a special role and it was heretical to imagine leasing that license. It did take some creative legal work to square this with the statute. As you are in engaged in the enterprise, it is important to keep your eyes on the prize about how much ideas matter and this group is particularly good at coming up with ideas and that is such an important and crucial enterprise.

Second, science and technical merit matters. There is a premium in Washington on rhetoric and it takes a lot to cut through the rhetoric. Low power FM, not so long ago, was a big policy debate. The question was would allowing these stations create harmful interference to the incumbent FM stations? As spectrum policy debates go, the tried and true move was to find out if you could find any interference anywhere and create some record based on that and oppose the entire regime. The NAB was successful in that rhetorical move and even got Congress to pass a law at the time and undid an FCC decision. But for reasons I don’t know, someone in Congress, I think it might have been John McCain, said why don’t we do a study and see what is actually going to happen. And they did, MITRE did the study, and the study vindicated Dale Hatfield in that it underscored the technical merits of low power FM. So, those are two important guideposts: that ideas matter and science and technical merit matters. As we go forward I would like to mention three more points that I’m sure you all know better than I but that provide some valuable context.

One is the role of sharing and cooperative uses of spectrum. Second is the role of the institutional side of managing spectrum use. And the third is the importance of incentives and data.

So, first, sharing and cooperative use of spectrum. This is a concept I would probably add to my list as great ideas in spectrum. It is an idea that is still developing and taking root around legal and technical insights. It is basically in a somewhat formative stage. But I would submit that there is no going back on this. As part of spectrum policy under president Obama, there is this 500 MHz goal. What gets lost sometimes is that the goal includes spectrum that is shared among different users. There is a lot of different sharing that is going on today; there is going to be a lot more. As a precious resource, like water in California, this is a very sound approach, because if you dedicate spectrum for one use and preclude any kind of sharing, you are using it inefficiently. Obviously, many people would rather not share than share, if other things were equal. But other things are not equal and having both the opportunities and the incentives to enable sharing is critical and there is increasing pressure to find those opportunities. The first round of looking at government spectrum identified one such opportunity. There is a band at 3650 MHz that is used by the Navy and for years the Navy had exclusive use of that band from coast to coast, which upon some reflection people said well we don't have the Navy in Colorado, why can't we use the spectrum in Colorado? The Navy didn't really have answers that were all that convincing so the decision was made to free up those bands in those places where you can have sharing.

We have different kinds of sharing: geographic areas, time and this is a type of sharing that is being introduced. Sharing is going to require different kinds of cooperation. This is why the effort in whitespaces is under-appreciated sometimes; it is not merely about using that spectrum and giving people a service but also about testing out that technology, that if it scales for cooperative use, it is going to have broad applicability and that is an exciting opportunity that we need to be watching. More generally, it is important to test out cooperation when opportunities arise.

I would mention another one too. Public Safety has come a very long way. I remember years ago there was a paper at TPRC, that said we should have public safety allow opportunistic sharing of its spectrum. At the time public safety was very resistant for an unfortunate political economy reason, it often leads people to be somewhat cynical, it is about incentives people face. Public safety said one reason we are afraid of this is that we are unsure about whether we will actually keep the budget—if we do give out access to our spectrum they will just cut our budget by the same amount of that access. In today's economy people are thinking about their budgets in a different way. Our budgets are getting cut anyway. This may actually help us make more money if we are using our resources more efficiently. So, public safety has become much more bullish than they've ever been. How do we allow access provided that we have it when we need it?

There are two other points that will get increasing attention. One is the institutional side. This is where lawyers can add value and technologists need to understand and work with lawyers. In many cases, we have a hazard that is lurking. People say I might be able to enter into some cooperative arrangements or I might be willing to use spectrum a little bit more aggressively (or let others use my spectrum more aggressively) if I knew we had dispute resolution mechanisms that could put a halt to otherwise interfering uses. But if people don't believe that those institutional mechanisms will operate that actually is a huge chill on efficient use of this resource. In the most painful case, XM and Sirius were for years in a sort of open and notorious fashion not following the rules of their license. That was finally remedied, unfortunately not as part of an enforcement process but as part of a merger review. That shows that, as it exists today, the FCC's enforcement capabilities aren't set up to deal with this issue. And what is important to realize is that the collateral consequences of a lack of trust in enforcement is fairly significant.

This can be true on the Federal side as well, if Federal users want to share with non-Federal users, they need to know that both in technology and in practice there will be a mechanism to address bad behavior. That, today, is one of the unsolved challenges that we need to figure out. It doesn't need to be government per se, there can be mechanisms where government authorizes or empowers some other body that can do this effectively. But until and unless we get that regime, the efficiencies from sharing are going to be chilled.

Finally, incentives and data. To the extent that uses of spectrum are unknown or under-known, the opportunities for sharing and experimentation are going to be chilled. As Louis Brandeis once put it, sunlight is the best of disinfectants. There has been an effort at FCC and NTIA and Congress has talked about it in an inventory context to develop better data about who is using the spectrum, when, what, where, how. We have a lot of work to do in that area because while we don't have knowledge of it, people are less able to be effective actors and the market is poorer for that information asymmetry, particularly those actors who are less sophisticated. I did have an interesting discussion with Paul Margey who said, we can figure out who uses spectrum, we just have to have my associate spend a few hours in the database, and I said that is my point, that's not the mashable Google maps type of knowledge that people are familiar with in a web 2.0 world. How do we bring spectrum to that world?

As for incentives, this is one of the most formidable challenges. It is particularly challenging for government users where there is not always a confidence that their cooperation in more efficient spectrum usage is going to redound to their benefit, because if government users say I have to go through all this brain damage and then I have to take a risk as to potential interference and what's the benefit that I get at the back end? Nothing. It's hard to make the case to your principal that that's worth doing; sure the fact that we need it as a nation counts for a lot but also if it's your neck on the line and you can't make the internal ROI, that's a much harder case to make. That's one reason why part of the overall agenda includes giving the tools to the Federal government to allow agencies to make this a win-win proposition. And the same is true on the private side with respect to incentive auctions. Some people have said over the years, just take the spectrum back from the broadcasters. That's not exactly a win-win scenario. Instead, if you can allow them to benefit and give the government a way to benefit as well, then we are talking about a win-win scenario that has a much more likelihood of going into action.

Q&A:

Eric Mokole, NRL: As I understand it, the 3650 band is able to be shared across the nation, but did you analyze the impact it would have so many miles out to sea? Because you do have fleet that travel along the coast and that will impact the air traffic radars on the ship. The other question I have for it is did you consider Air Force assets?

Weiser: First, I was relying on Karl, et al., so I didn't do anything on it. But the part of your question that I can address is that I think it underscores that the techniques around sharing, the tool kit, is something we need to better perfect, articulate, and kick the tires on. For example, there was a band 1657 that NOAA was using and they had a need for an exclusion zone. In some cases there is an opportunity to upgrade the facilities themselves to make them more resistant to interference. There are some cases where you can have more intelligence and situational awareness. And if you can spend money on that side and free up more spectrum, then that is a win-win opportunity. You need the institutional incentives in order to make that happen. So you have to scope out the opportunity. You have to have the money available to make it work. But there are huge benefits to society if you can make that work. Now, there are crude mechanisms, like the exclusion zones, there are more sophisticated mechanisms, investing in radars that are more resilient, there are also all sorts of other rough justice ways that things get done. That is the process we are in now, of developing that toolkit and it is only going to intensify in the years ahead.

Larry Cohen, NRL: About a month ago we had a spectrum workshop at the tri-service radar symposium that has been going on for 57 years; the workshop's been going on for 8 years. This year we had 35 very good radar technologists and the resounding theme was that we have some good ideas about how to share spectrum but where's the money? And that is a big problem. People talk to us about sharing from various departments, but there is no money for R&D to develop and implement these techniques.

Weiser: So, we as a nation have a set of challenges that are made even more difficult by the current environment that we are in. The bill that the senate commerce committee passed 21-4 had two things in it that speak directly to this. One, it had a significant amount on spectrum development focused on technologies, DARPA and NSF and NIST were singled out to spur technological advancements that would aid that very causes I've noted. Number two, it gives NTIA working with OMB the ability to provide funds to agencies who identify and implement solutions of the kinds we mentioned. It doesn't help to free up spectrum with more advanced radar if you are not given the advanced radar. It is worth recognizing, in days when spectrum was seen as a resource that was plentiful, people didn't feel the need or weren't pushed to build sophisticated radar that used spectrum efficiently. Today, spectrum is not plentiful and down the road that trend is not going to turn around so we have to be more thoughtful about how we use it. If we are not willing to make those sorts of investments, then we can't have it both ways, because we can't endanger our mission critical purposes. At the same time if there are opportunities for those same systems to be more advanced using modern technologies and techniques that I've mentioned we should do that and the bill that I mentioned (S. 911) did call for and pursue that very strategy, so that does provide some hope that there is an awareness of this issue. At the same time, one of the great challenges for those of us who live in the world of ideas is translating ideas into language that ordinary people can understand. And nowhere is that more challenging than in spectrum. We have to be able to explain this to people so that the bill can be passed.

Peter Eckelson, Cisco: Interference management has to happen at the local level and it has to be cost effective, e.g. traffic court or small claims court.

Dale Hatfield, Silicon Flatirons: As Kevin Kahn pointed out yesterday, we are not using all the tools we could to do the kind of distributed enforcement that we are capable of. In most cases, a lot of these devices that we are bringing into the spectrum have communications capability which means for example if you see interference from a particular router or something you could shut all of those off remotely. There is an issue of due process but we haven't thought about it completely. We are carrying all these smart devices around in our pockets which are little receivers and there are all kinds of people researching the crowd sourcing capabilities based on the fact that we are carrying all these receivers. Can they play some role in a more decentralized enforcement activity? I think probably so. But I agree that enforcement is always the last thing at the FCC, it has never been given the kind of priority that it should have.

Weiser: As discussions happen on FCC reform, it is my hope that this issue is addressed more fully. The two pieces I think are critical are the data collection piece (which, by the way, the two are not unrelated: more situational awareness about how spectrum is being used can fit with more effective enforcement). Some unlicensed uses involve cooperation through a framework that is conducive to enforcement. So they say, you're all going to use your system in a way that allows us all to continue to thrive; if you start turning your power up and I start turning my power up and we're both trying to crowd each other out, that's not good for anyone. I believe that the Bay Area had this kind of cooperative where they were able to create a kind of framework. So, the question is how, in a more self-conscious way, can government policy facilitate those sorts of frameworks?

Brett Glass: The House Energy and Commerce Committee recently circulated a draft bill that would essentially prevent the FCC from allocating anymore unlicensed or shared spectrum by forcing entities to bid on it even though they weren't going to get it exclusively. There are other rumblings that if we were going to find ways to free up Federal spectrum or make the government's use of spectrum more efficient, immediately what congress would do would insist that it be auctioned off to cover short term budget short falls. How can we avoid this? How can we reach the people in Congress who have the ability to affect this and make sure that they don't sell off our seed corn just to cover the next short term budget short fall? And therefore mortgage our future?

Weiser: It is a huge challenge and I think it is a matter of getting the right ideas, the right people and the right message so that people can understand it. The Administration's commitment was to promote both licensed and unlicensed, as you know that House committee bill doesn't necessarily share that perspective. One reason why there may not be the consensus view that I would hope there would be is that it is easy to under-appreciate the value of unlicensed. Because it is hard to capture the market value of free, and so some people think that because people don't pay anything to use unlicensed, it is not worth anything. That, to my mind, is an unfortunate and wrong-headed perspective but it has a certain rhetorical force to it. Here's another perspective that Hal Varian, the chief economist of Google, offered about the iPhone using Wi-Fi: if AT&T is charging you $50 a month for your data plan and half the time you are using Wi-Fi, that means $25 a month is attributable to the unlicensed spectrum. That type of case needs to be made and the folks who benefit from unlicensed are entrepreneurs who don't have time to make that case. So, the good news is that there is a broad consensus which is at risk. The spectrum policy people made it very clear that we need both licensed and unlicensed, and the Congress bill about auctions supports unlicensed. So, there is this rhetorical shorthand that is not supportive of unlicensed, but what needs to happen is to develop a strong narrative with good data to support it which makes the case for unlicensed, and my prediction is that will prevail. But it won't happen without people making the case.

Mike Cotton, NTIA: One theme you will see within the scope of this conference is the high magnitude of the problem. With radar you have long lifecycles and really high costs and these characteristics aren't in sync with the problem-solving mechanisms that we are talking about in the legislative stuff and the presidential memorandum. I made an effort to get the right people here and collect ideas, but a two day conference is not the right process. I envision more of a European model, where groups of people come together on a periodic basis to work the problem over a longer timeframe. So, I wonder if you could share some of your insights on your work in D.C. Is there any way that we could enable that type of process?

Weiser: A few answers. First, what you are doing is to develop both more formal and informal networks of thought leaders who can work together. There is a first step, it would be great to come out of the conference and have some set of shared broadly held viewpoints that point the way towards hard work in the future. You've already said a few of them in your short speech. With respect to radars in particular, legacy radar systems are more demanding of spectrum than, from today's perspective, we want to continue to indulge. It's also true that we can't compromise our radar systems and their critical missions. Finally, to get from here to there, it is going to require planning and investments that will ultimately pay extraordinary dividends. And there may well be other forms of dividends too, by the way. For example, it is possible these more sophisticated radar systems will be more secure also. So there are other forms of benefits. So, we need to develop the broad contours of the challenge then develop a way forward and also be able to explain to key people these premises so they don't end up in an "either or" decision. Which is, "Oh just forget it, it is too hard," or "It will take too long." Because ultimately, the impending challenges are pushing us in a direction. And we don't want to either say "screw radar, if they don't want to work, whatever" nor do we want to say "screw all these users of spectrum because we can't touch radars." So there is an opportunity, and I think your question is how do we map it out and continue to make progress. To come out of the conference with a broad set of principles and a better understanding of the networks of people who are involved, many of whom are in this room and need to find ways to continue to collaborate and move forward, it's fair to say from CU and Silicon Flatirons, we want to be a part of this and Pierre de Vries will continue to be involved. We can come out of this conference with some broad principles and goals. That matters a lot, to the extent that we can be self-conscious about what other communities (CSMAC, TPRC, DySPAN, Silicon Flatirons) are around and how to communicate with each other. Over time, these conversations that we have are going to make a difference. It is better to be more organized and patient (which is not easy in a political system that is often looking for the quick gains) but this a long term challenge.

Charles Baylis, Baylor: I think not only is the question: "Where is the money?" but also if government is where we need to go for this source of funding. What are some ways that we as engineers who are not politicians become politicians and make people aware of the technical challenges and budgetary needs? Is there anything that we can do as technology people to move that forward?

Weiser: What's really important to start to build around thought leaders is an awareness. For example, if one of the challenges we face is in eating the seed corn temptation, we are preventing tomorrow's advancing, how do we show the advances that we enjoy today because of what our prior generation did. So, it's not impossible to imagine a world without GPS: had the government never invested in GPS, we would not have GPS. If the government had not invested in unlicensed spectrum, we would not have Wi-Fi. Had the government not developed radar systems, our nation's security would be at risk. If one is in the deepest sense ready to eat all the seed corn because we are starving, we have to say wait a minute and go back and show all the great things that the previous generation did with the seed corn. We have to develop that narrative in terms that people can understand and then link it to what we want to do in spectrum.

That actually is extraordinarily hard to do and it is one of the things I came back from Washington understanding, about how innovation is so hard because it's not easy to make the case in those terms. Often what we are saying is that you need to believe in R&D investments even though I can't tell you for sure exactly where the benefit will come from. One of the challenges of R&D is that you may have a broad direction but then the things that emerge are pleasant surprises. The best way I would suggest is to then go back in time and look at some of the success stories and say listen, we can do more things like this but we need the right policy direction. Whether it is people who are in congress, whether it is people who you are working with, that is not an awareness that is widely appreciated and one of the challenges we have as a community is how do we contribute to the broader awareness. There's an interesting perspective from the 60s of when there was a heyday of government commitment to R&D, part of what motivated it was the sense of space race with the Soviet Union, and the fact that there could be a man on the moon made it all the more powerful. So one of the challenges we can think of is, is there an overarching narrative that frames this whole area.

So there is both the tactical approach that Dale [Hatfield] is talking about so that when the money comes you will know how to use it. We didn't spend a lot of time thinking about what would happen if we had $7 billion to put into broadband but that means that the people who had to consider it were kind of under the gun. Don't get too discourage, there is a lot of power that good ideas will have their time and that those who've worked on them will enable good things to happen. It is also important to have an overarching narrative to encourage that time to come sooner but it's really important to be doing that work.

Baylis: Just one quick follow-on…who do we talk to with this narrative and how do we get it to the people in power?

Weiser: Well, I'm biased but do you have a law school there at Baylor? Anyone in the law school who cares about science and technology, my personal belief is that interdisciplinary collaboration pays extraordinary benefits, so I would reach out to those colleagues and see about ways to frame this agenda in broader terms and see about ways in educating and engaging others. There are also a lot of blogs on the Internet that are engaged in this dialogue and you should join that dialogue as well. We are lucky to live in an age that makes that possible.

John Mettrop: Civil Aviation Authority: I am a little concerned that we would put money into enforcement and detection of interference because by the time we can find the interference it is too late. If you want to come and share you have to be able to fit into our safety cases and we so far haven't seen anyone prepared to make that case. Thoughts? The world economy is struggling and there has been a lot of research to show that getting together on an international scale to work some of these problems is problematic because they all have different needs. We should be working as an international community to solve these problems, because the cellular companies are global, and we want to capitalize on the standards set in the U.S. because it is a big enough market to set the standards and we should take advantage of that in the international realm. If you harmonize those bands throughout the world then you've got an even bigger market.

Weiser: First, yes, this process needs to be international because these markets are international, I don't disagree at all and we have to start somewhere. Second, there is a nice saying "where you stand depends on where you sit." If your lens is from the perspective of aviation, then it is true that interference can be terrifying if identified too late, but there are many uses of spectrum where the consequences of interference are not quite so dire. For those uses of spectrum, the need to have enforcement is still very important because if you do take the perspective that you took everywhere, it would be like saying you will never allow a car on the road because you might have a reckless driver. Now, there are people who are working on cars that can drive themselves, but if we required no cars on the road until we had cars that could drive themselves and could never be driven recklessly, that would limit the use of the highways. Instead we have a system that has enforcement. That is not a perfect way to avoid bad behavior, but it is better than trying to engineer against every possible problem.

Jim Lancer, CSR Technology, Adjunct in the ITP: One opportunity we have here is to put together a group of people that can give suggestions about how to make sharing work. I particularly like the idea of a database, you could tell the database back "these are the ones I'm going to use" and that kind of closes the loop on this whole spectrum regulation. What are your thoughts on how to help the regulators feel their way through this brave new world of being able to turn the knobs dynamically?

Weiser: It is a major change. I think it is probably something that Julie Knapp is better able to answer. But I'll do my best. One way is to start test cases for people. Give people certain bands that are able to have an experiment that can help enable people to feel comfortable. So, like the first auction for PCS was the camel's nose under the tent, and the idea for holding auctions for spectrum became the only way to go—it started as an experiment. The same is true with secondary licenses, the same is true with unlicensed. It's a matter of finding an initial test case to build confidence.

Anonymous: Look at political science and history people to partner with as well. We have both policy and technical issues here. One is that I think a lot of our solution approaches are still very evolutionary in the sense that we are trying to improve this or tweak that. There needs to be some way of encouraging more and getting DARPA involved somehow and going towards revolutionary approaches and trying to relook at the paradigm of how we design radar systems because we kind of do what we've always done instead of thinking: "What function do I want to achieve for what purpose?" Secondly, there are other policy perspectives that need to come into this. A lot of the big radar companies see that radars are a dual use technology and so you have to walk a thin line of trying to do things that are beneficial commercially but don't run afield of ITAR and international treaties, etc. Quite frankly there are a lot of companies that are rather edgy about that sort of thing because the pendulum has swung pretty far the other way in some respects. Finally, there needs to be inventory not just of spectrum, but also of solutions, policies, risks. People don't really understand risks, understanding that there is a big difference between a dropped call and a dropped airplane is very important. How to quantify that so it can be folded into tradeoff studies, I think that is an under-looked at area.

Bruce Naley, Naval Surface Warfare Center: One of the frustrations we end up having is trying to articulate the value of having spectrum available for national defense purposes. It seems simple but there is no dollar value put to it. One example is the SPY-1 radar in the 3 GHz region.

That's a region that is strongly being considered for sharing or to be given to commercial interests. It has the type of characteristics that seemingly make it amenable to sharing: it is on a ship, it is mobile, you can just stay off the coast and then what is the big deal? But when 9/11 happened one of the first things occurred was that an AEGIS cruiser came up the Potomac river to protect Washington, D.C. Protecting the same people who want to give that same spectrum away. Unofficially, we know from reports that when the ship went up into these populated areas where we don't normally operate the radar that there were all kinds of problems with civilian communications systems. So, I am trying to express some of our frustration of trying to articulate the importance of something that is so seemingly inefficient. We rarely use the radars this way, but when we have to, we have to, and it's got to work, and it's got to work now. It's hard to get the importance of the dollar figure attached to that.

Michael Calabrese, New America Foundation: I'll just tee this up because we can talk about it in the Overview Panel but I'd like to see if you have a reaction to it based on your service. Yesterday, at the CSMAC meeting a concept came up from the Getting-to-500 subcommittee. Instead of talking primarily about exclusion zones, we should be thinking about instead sharing zones. In other words, there is probably some continuum of constraints on sharing bands and it isn't necessarily a black and white exclusion. And you mentioned that the Administration all put great stock in not just querying bands for auction, which has a finite possibility, but in more sharing and more unlicensed and so on. So, I'm just wondering, there hasn't been much focus on when you're talking about the bands in the exclusion zones through the lens of low power and close to the ground, where there might be a lot more opportunity.

Weiser: So, one construct to think about both of these questions, is how do we think about zoning the spectrum to allow for different sorts of uses. And one of the very big challenges with the zoning code is, once you make it, it's hard to change it. Here we have a doubly hard problem, in that we already have lots of facts on the ground that we have to be sensitive to. They are not impossible constraints—over time you can move radar systems—but it's just really hard. So, yes, as you think the framework of zoning the spectrum, there are all sorts of tools and possibilities and one of the challenges that we are still working our way through is we haven't totally self-consciously identified what that all looks like, what the toolkit is, and that is part of the overall project that we are undertaking.

6 OVERVIEW PANEL

The goal of the Overview Panel was to discuss at a high level topics covered in more detail over the course of the conference and to establish context related to the political pressure to find 500 MHz for fixed and mobile broadband and what the means for radar. The panel discussed NTIA's plan to make the 500 MHz available, budgetary constraints, institutional obstacles, incentives, collaboration between the private and public sector, and sharing radar bands with the commercial sector. In their opening remarks, the panelists discussed the following topics

- Session Overview—Michael Calabrese (New America, moderator)
- Searching for 500 MHz Considering Radar Bands—Karl Nebbia (NTIA)
- Naval Research Laboratory Perspective on Radar Spectrum and Usage—Dr. Eric Mokole (NRL)
- Incentives to Promote more Efficient use of the Spectrum—Dr. Dale Hatfield (Silicon Flatirons)
- Investment to Modernize Radar Technologies—Richard Reaser (Raytheon)
- Sharing with Radar Bands—Mary Brown (Cisco)
- Radar R&D—Dr. Joe Guerci (Guerci Consulting)
- Active Accommodation of Radar Bandsharing—Dr. Paul Kolodzy (Kolodzy Consulting)

6.1 Introduction by Session Chair Michael Calabrese

This is the Overview Panel and we will be trying to preview and tee up the key issues and themes that you will hear about in the rest of the conference. We have a diverse set of perspectives that will focus quite a bit on the commercial demand and political pressure to find 500 MHz for fixed and mobile broadband and what that means for radar, including the budgetary constraints, institutional obstacles, incentive issues, and collaboration between private and public sectors that are all part of the puzzle if we want to do more radar band sharing with the private sector. I think this will be a few thousand feet higher than the remaining panels, but it is a good way to get the key issues up.

6.2 Opening Remarks from Panelists

6.2.1 Karl Nebbia, NTIA

As Tom Power mentioned, spectrum related to radar use is particularly critical to our search for 500 MHz because of the fact that it represents such a significant portion. Over 55% of the spectrum that was identified during NTIA's ten-year plan and timetable was radar spectrum. Most of that is fixed radar and some of it is mobile radar; there are significant differences when looking at that, but nonetheless if we're going to solve our problem of identifying 500 MHz, a significant portion of it is going to have to deal with radar spectrum in one way or another. I wanted to draw attention to the specific bands that I think are most likely to be under review once again because industry has certain limits on looking up at higher bands, at least for the standard commercial wireless. We realize that Wi-Fi supplements that now and provides opportunities even at higher frequencies like 5GHz, but we've got these four major band ranges that we will be looking at:

- The 1300–1390 MHz band, which actually has two segments. The lower portion (1300–1350 MHz) has approximately 330 assignments across the country that support en-route air travel (255 of those are FAA specific). The other segment has more military systems that are geared for target identification rather than ATC. They are fixed locations across the country.
- The 2700–2900 MHz band is ATC and weather radar systems. There are almost 900 radars in that band; approximately 550 are FAA ATC and almost 190 are weather related. They are all fixed location systems.
- Above 2900 MHz, we start getting into these systems where we've got maritime users, radar beacons along coastlines and intracoastal waterways and rivers, and so on. Although we've got a limited number of those locations, we've still got twenty-some aeronautical radio navigation or ATC radars and about 70 different types of land systems, probably weather radars, and then about 100 maritime beaconing systems. The critical thing about these systems is that they are talking to ships that are moving, so it is a slightly different situation.
- In the 3100–3650 MHz range, there are mobile military radar systems. The uses often go outside of where we would normally expect them to be. So, we've got some major challenges there. Those systems are trying not to be identified and to avoid jamming, so their techniques are very creative.

In the few minutes remaining, I just wanted to call attention to this last slide (Figure 56), which was presented by Bob Sole in yesterday's Inventory Briefings. We are showing radar locations for two separate 20 MHz bands. We chose 20 MHz, because that is what LTE folks are generally asking for. Any radar frequency assignment that falls into one of those bands, whether it's the assigned center frequency or the bandwidth of the system, is shown here with its contour. The contours are based on peak transmit power and propagation models that take terrain data into account. The thing that I think is interesting is the differences from 20 MHz to 20 MHz in available locations. It is important to ask ourselves: "Are the gaps we are seeing there of value?" If we can fine tune this process the gaps will get greater as we shrink the size of those contours based on the roll off of the signal or other techniques. Ultimately, there is a lot of radar activity along eastern coastlines, and major cities. So, as we consider this type of geolocation approach for sharing, we must ask: "Is this form of Swiss cheese something that industry can actually work with?" The portrayal is in fact limited, e.g., we have not taken into account that the antennas are rotating, or the duty cycle. In the past, Mike Marcus has proposed the idea of communications systems that would pop up and down essentially as the radar was rotating. I'm not sure how realistic that is in the commercial world, but we've not taken that into consideration. As we get better information on the types of systems that might come into the band, we can alter these contours. I think, however, this gives a good picture of the types of open space there is. If these contours are used as exclusion areas, then obviously these places are kind of off bounds. If, on the other hand, we can come up with an arrangement where the newcomers to the band accept the interference in these areas, then potentially we open up a whole lot more.

Figure 56. Radar contours from NTIA spectrum inventory.

6.2.2 Eric Mokole, Naval Research Laboratory

In this short address I will provide a summary of the R&D that has been taking place in the radar division of the NRL over the last decade on compatibility of radar with other systems, as well as some of my views on the subject. Since 2001, when we recognized that the tremendous explosion of communications devices would cause significant interference problems for high-powered DOD radars and vice versa, we've been trying to address how efforts could mitigate such EMI while maintaining a radar's desired performance. Because the requisite power for detecting and imaging targets at relevant distances is so high in existing legacy radar systems, reducing interference to acceptable levels in environments that are densely populated by telecommunications devices is very challenging, as it is no simple matter to change hardware and introduce new waveforms into these legacy systems. Now, newer systems, there is a lot greater chance of that happening.

In 2002, Dr. Michael Wicks suggested that we take advantage of impending hardware advances in electromagnetics, waveform generation, timing and control, and signal/data processing that would greatly increase the performance of radio frequency devices, thereby allowing significantly more flexibility in modulating both radar and communications signals. We felt that this improved flexibility coupled with dynamic re-programmability would result in the capability of generating adaptive waveforms that optimize a user specific application, whether it be in communications, navigation, countermeasure, or radar systems. So Mike coined the phrase waveform diversity, and off we went to form the tri-service waveform diversity working group, whose goal was to pursue a long-term roadmap and funding to do research in spectrum as well as waveform diversity. Now let me define waveform diversity: it is dynamic and coordinated use of multiple transmit and receive signals from one or more platforms to exchange, extract, or exploit information. Now, at that time, we were fortunate to obtain some seed money for some workshops and conferences from the forward-looking DARPA manager Dr. Joseph Guerci. This working group developed multiple R&D programs in the Army, Air Force and Navy and often has a workshop at DOD's annual Tri-Service Radar Symposium. In addition, the working group established the IEEE sponsored International Waveform Diversity Conference.

Since the availability of funding for R&D in radar spectrum has been very limited, if not non-existent, my division developed a series of low level internally funded waveform diversity programs, beginning in 2003 with the investigation of designs of class A power amplifiers for achieving spectrally fine radar waveforms. Over the linear range of the amplifier we were able to reduce the amplitude spectrum by at least 100 dB outside a 20 MHz band about a peak transmission frequency of 10 GHz. And these measurements matched our theoretical predictions. However, the amplifiers and high power radars typically operate in saturation, and this nonlinear regime generates undesirable contributions outside the 20 MHz bands—called spectral splatter—that interfere with users in adjacent bands. In a follow-on program, we tried to overcome this spectral splatter problem by independently investigating power amplified circuitry and waveform design. Since we weren't as successful as we would have liked, we recently decided that a better approach is jointly optimizing the power amplifier circuitry and waveform design. Now we've been discussing this line of research with an earlier speaker at this forum, Dr. Charles Baylis, who has been investigating this area also. In additional related research since 2005, we've been studying the joint optimization of transmit waveforms and receiver processing structures that adapt to the electromagnetic environment that mitigates mutual interference and is transparent to non-users.

Parallel to our own internally funded efforts, through the efforts of Larry Cohen and Dick Ford, we've been supporting DOD's electromagnetic environmental effects (E^3) program which is sponsored by DISA. This program promotes communications, coordination and commonality, and synergy for E^3 engineers and spectrum management professionals. It also provides an information exchange forum for the DOD, the Federal government and industry to address policy, operational, doctrine, standardization and so on.

For the past eight years, Larry has been conducting radar spectrum workshops at the Tri-Service Radar Symposium to alert radar designers about spectrum issues and their possible solutions. Sometimes we feel we are working against our own community because we are pushing that boundary, but there is great resistance, especially in legacy systems. In addition, he's involved in obtaining better characterizations of the noise contributions of cross-field amplifiers and radars to out-of-band interference, especially on users like WiMAX in adjacent channels and in reducing that EMI. In particular, in 2007 he conducted a test on the impact of the SPY-1 system on WiMAX in Virginia. The effort was the DOD's first attempt to identify and report EMI effects of transmission from a major DOD radar on WiMAX.

From an international perspective, we recently initiated collaborations with NATO colleagues through two of their tasks groups on solutions to spectral problems. That just began this year and we had our first meeting in May. People are welcome to join—you have to go through the

NATO national committee office, so you can contact me, but that can be arranged. I think we have a dozen to a half a dozen countries from NATO involved.

In my discussion to this point, I've been giving indications of the radar spectrum R&D that we've been doing. Ones that we believe are worth pursuing include:

- Distributed autonomous netted cognitive radar, which is an area that Joe Guerci is heavily involved in
- Joint optimization of the power amplifier circuit and waveform design using multi-beam klystron tubes in place of the old cross-field amplifiers, which are very dirty and in fact they are used on this SPY-1 radar system, which really emits a dirty spectrum
- Spectrally compatible waveforms

In an effort to have a more robust and complete attack on these spectrum issues, my group has been trying to form a strong university team to work with us, which is difficult based on the previous comments about the availability of R&D funding. Before finishing with a general comment I have the following wish list:

- More collaboration between the FCC and the NTIA.
- Significant funding needs to be identified for R&D spectrum; this funding should be disseminated to teams with members from academia, industry and the government research laboratories, and I would offer that the government research laboratories ought to be the lead on it.
- NTIA and the DOD must take a stronger role in helping the wireless community develop systems that are more robust to radar emissions, perhaps through the WiMAX forum and the IEEE standards committee on 802.16.
- Greater involvement of DOD system acquisition program managers. I don't know if anyone is here from the actual program offices that fund the development of the actual big, god-awful, expensive Navy radar systems, and they should be involved because that is where the money is. So, guess what? If we are going to have a collaboration and interaction they have to be heavily involved.
- The wireless community and the policy makers need a better understanding of radar requirements. I'm getting a sense from a top level that that is happening. And an understanding of how the operation of wireless can adversely affect radar.

More generally, with growing world-wide contention over radar spectrum usage and management, it seems to me that this is a contest between the commercial benefits of wireless expansion and the need for a national defense and public safety radar. The political pressure to find 500 MHz for mobile broadband use can have a lasting and perhaps life-threatening effect. For example, several years ago we were involved with an analysis of alternatives for the Navy's ATC air-marshaling radar, the ANSPN 43C, when the 3650–3700 MHz band was auctioned. That loss of 50 MHz has severely limited the performance of the radar and the replacement still has not been determined. Basically, you lose so many channels to aircraft and if you have a bunch of aircraft out there that are not controlled, there are problems with collision and so on. If the U.S. DOD is to achieve its goal of full electromagnetic spectrum dominance, the radar and communication communities will need to work very closely in commercial and military sectors. Currently, my sense is that there is not enough interaction between the DOD and the wireless community in the U.S. and that significant misunderstandings exist.

6.2.3 Dale Hatfield, Silicon Flatirons

I'm sort of hung up on this issue of incentives. I come to a conference like this and there are so many good ideas out there, technical ideas and challenges. As in life, however, it ultimately all comes back to incentives and disincentives. So I'll focus on that because that is what I've been thinking a lot about recently. Having served in the government quite a bit as well as in the private sector, I think I'm aware of some of those incentives and disincentives. We are talking about incentives to share. In walking around and chatting with people who are radar users, I hear the real challenge being disincentives. What are some of the disincentives? Look at the analogy of selling a house, if I'm a motivated seller and you are a motivated buyer then, boy, are we going to have a deal in a hurry. If there are strong disincentives to the deal for whatever reason, however, then the transaction won't occur. When I look at the disincentives in this scenario, I look at it both on the employee level (employee of the agency) and also at the agency level.

One of the real disincentives is that there is a real scarcity of highly trained technical people able to solve some of these problems. The kind of person that we are looking for does not just perform the normal interference analysis (which is critical), but also looks at the economics of the problem. That skill set is especially scarce. Another problem at the individual level is that these problems are really hard. In your career, one likes to work on solvable problems. Finally, there is risk. If one engages in a sharing arrangement and it turns bad, then there is a risk that he/she ends up in front of Congressional hearing that can be very ugly. There is not a strong motivation to engage in the sharing solution.

At the agency level, there is generally no payoff for the agency. Even if there is a logical way to share spectrum, your budget doesn't necessarily increase. After listening to the talk today about how feds might be willing to pay for the cost of moving or setting up new technology, I would say this limits disincentives but it doesn't really move it over into the realm of a positive incentive. On the commercial side, at least in the right conditions, if one has an idle asset and leases it to someone, there is a positive incentive associated with revenue payments. Also, when considering the scarcity of technical people that can do the stuff, agencies need adequate funding to employ these people. Finally, there is always the chance that if you enter into a sharing arrangement with someone and it goes badly, you will end up in front of Congress. I think too, when we talk about sharing as opposed to an out-and-out reallocation, the fear is that if it turns out to be widely successful, then the spectrum may get reallocated to the person that's sharing with me. As my good friend Pierre de Vries often points out, a license from the FCC to use spectrum is not a very enforceable contract and is subject to the granting body's policy to act in the public interest. It goes back to the analogy of leasing the house. If my house is leased, then I may make money on the rent, but I need government to say, at the end of this when I move back into my house, that I can get it back.

The summary here is that I don't see us making very much progress in this entire area unless we get the incentives right. We are nibbling at it, but I'm not sure that the incentives are strong enough to get to a really rich sharing environment.

6.2.4 Richard Reaser, Raytheon

I'm going to talk about a couple things that deal with how we move forward in the world of spectrum sharing. But first, I'd like to talk about something I find very interesting about the radar engineering community. I had dinner last night with a bunch of people from the conference and one was a man who has been working in this industry a long time and installs radar antennas underneath planes and he had a billion ideas about how to share and so forth. There is no shortage of ingenuity in the engineering community to come up with ways to solve this problem. If fact, it's pretty amazing to hear all these ideas here and at the Tri-Service Radar Symposium.

One thing we have to remember is that radar is the domain of governments, not the commercial private sector. Most of us don't run around with household radars. There's not personal radar, and so in terms of investment and sharing, there isn't a commercial incentive for me to do better or not. Generally, a defense contractor will get a contract that dictates what bands to use and when we bid on a contract there is no evaluation factor that says we are going to give you extra points in comparison with other bids for having great radar spectrum efficiency, or for approaches to share with commercial wireless, or for techniques for sharing in the other direction. There is absolutely no incentive for contractors to do this and the only we way we get money to go and do these types of things is from the government, because there is no commercial market on this stuff. So unless there is competition for the contract that gives points to us for coming up with these solutions, we don't have any incentive to do it.

A couple of things need to happen. First, since the government owns the world of radar, it needs to go out and fund the technology to build better radars that can track at longer distance and deal with higher noise environments and handle jamming. If it is important to the government that we are able to share spectrum with commercial wireless, it needs to start paying for the R&D for that to happen. It is great to have a test bed, but Raytheon is not in the test bed because we would have had to put our own money into the test bed and there is no contract out there that we are going to bid on that actually incentives our ability to share or to do the kinds of things that are being done in the test bed. Second, we need to start modifying some of these systems to make them more amenable to sharing. Put up the money to modify the AN-XYZ to coexist with DFS and put it into real operational systems. We haven't seen a move towards doing this. We have seen this on the commercial wireless side, but we haven't seen the opposite where we are trying to modify radars to make them more amenable to sharing.

The deal is that until we put requirements into the acquisition contracts for new systems to be procured, nothing is going to get the attention it needs. Also, it takes a long time to build new systems, so we need to start actually implementing some of this stuff so that it actually can get working in the next ten years.

We had a saying when I was in program management: "If it ain't funded, it ain't." So if we ain't going to fund spectrum sharing technologies and implement them in real systems, it ain't going to exist. And that is going to be the responsibility of the government, because there really is no private sector incentive on the part of a defense contractor to do it on their own.

One other thing I'd like to mention. One thing we haven't really investigated at all is that it has always sort of been like the "one way deal." As a radar guy, I kind of feel a little uncomfortable, because radar needs to share with other guys, and because radar needs more spectrum. But we aren't really trying hard enough to get more spectrum. And we need to put money against it in order to find ways to get more spectrum.

6.2.5 Mary Brown, Cisco

I wasn't going to address the incentive issue except to say that it is a real issue. What really resonated with me were the comments from Phil Weiser about the need to keep the conversation going, because when I look out at the landscape for spectrum use, I see many of the things that you guys do—the demand for wireless data is absolutely exploding. The high power mobile guys need a lot more spectrum if they are going to keep up with the consumer demand. Unlicensed uses like Wi-Fi need more spectrum as well. Cisco has evaluated this, and by 2015 about half the wireless data traffic when it gets to the edge of a network—whether it is a wired network or a high powered cellular network—it is going to finish its transmission on Wi-Fi. So, that is a huge growth factor from where we were. Moreover, government needs are increasing and evolving over time. So, we've really got to get a lot smarter about how we are going to transition that 20th century table of allocations into the 21st century spectrum policy and use. I understand that you may be concerned that there is no R&D money coming to you in the next fiscal cycle. We need to keep talking about it and working the problem and defining the problem in order to feed ideas into the legislative process. The S.911 bill, for example, was the first attempt to pull some money in the direction of R&D—that is an important precedent.

What I really wanted to talk about was Cisco's perspective in working on the 5 GHz issues that have come up, particularly with the FAA weather radars. There is a panel on that tomorrow, so I'm not going to steal anybody's thunder; my industry colleague, Clem Fisher from Motorola, will be on that panel and talk from the industry's perspective. I wanted to pull it up from the nit and grit, however, and talk about the dimensions of sharing problems that I see. I see five dimensions to the sharing problem that we have to think about.

- **Technology** (whether DSA, DFS, geolocation database, or some other) is obviously an important dimension to understand how it might enable sharing.
- **Rules**: There have to be rules for the commercial people to follow. Those rules and the technology together have to be properly scoped to address the specific sharing problem. We didn't get all the problems scoped out when we started this project with weather radars at 5 GHz and that caused problems. We have to understand the full scale of the sharing problem if we are going to get it right, because the Federal mission should not be compromised.
- **Culture**: We need to develop a culture of spectrum responsibility where users are conscious of how their decisions affect what happens in the band.
- **Compliance and Enforcement**: This is associated with commercial equipment being properly constrained and correctly brought to market, as well as field enforcement to ensure

that bad actors are held accountable. One of the things we learned when working through the 5 GHz problem is the capacity constraints on enforcement at the FCC, NTIA, and FAA. These are real constraints, so if we want to share more and we are going to rely more on enforcement on the back end, or even with respect to equipment certification, we need to make an investment in that. We need to do a better job of funding the agencies so that they can do a better job of getting that job done.

- **Community**: We haven't gotten to a point where we're really engaged with each other on an ongoing basis so that we can learn what is really happening with the technology as it develops both on the commercial side and the government side. ISART and DySPAN are helpful, but we really need ongoing communications with all the stakeholders, particularly around the sharing problems. We are getting started on that but we haven't really achieved what I would consider nirvana yet.

So, briefly, in conclusion, those are the kinds of dimensions that we need to think about as a community. I would love feedback if you think that there are things that need to be added to the list. I am really trying to do a better job on the commercial side of addressing the concerns, and in the case of 5 GHz, I think there is room for improvement.

6.2.6 Joe Guerci, Guerci Consulting

So, as you heard, I was at the Defense Advanced Research Projects Agency (DARPA) for seven years and while I was there I spent tens of millions of dollars on advanced radar systems. And while DARPA is all about solving hard problems, it's not always obvious at the time that an emerging problem will really grow into a national security channel. A number of us in the radar community recognized the "coming storm" of the crowded spectrum some years ago, but could not convince senior leadership that something needed to be done about it at the time. Fortunately, I was able to "fly under the radar," an important quality in the government, and push a number of advanced radar projects forward that "indirectly" addressed the crowded spectrum problem. For example, we knew that there was a tremendous need for adaptive waveforms. But as Richard Reaser pointed out here, unless the warfighter program offices make it a requirement, when you bid for those radar systems, it's not going to happen. So, if you look at a lot of the work I did and funded, you really won't see, specifically, spectrum sharing. You will see things like advanced clutter mitigation, advanced jammer mitigation, and waveform diversity. All of these things luckily turned out to be very similar problems. So, let me just say that things are being done but they are being done in an indirect way.

I'm a part of that proverbial radar "ostrich" with its head in the sand, and in our defense, the radar R&D community really has kind of been seeing this coming, but certainly the acquisition community has not. The other very important thing, since I am representing the R&D panel, is to really understand the technical challenges. If you look at the bottom line, it really does come across that what has been developed for communications systems in general is not directly applicable. They may be indirectly applicable, and certainly the obvious one is dynamic spectrum access. But as you heard before, just because we are not transmitting doesn't mean we are not using that spectrum, which is a very different criteria than communications dynamic spectrum allocation. The other thing that is particularly of concern to me, since I am heavily involved in military and classified radar systems is security. Why don't you publish what you are doing and then everyone will get along? Well that is just out of the question, and will always be out of the question. So, please understand that while this word "collaborative" is used a lot, there are some real fundamental problems with that from a military perspective, and that includes when we operate overseas.

So, I guess the good news is that there really are a lot of things that we're working on from a technology perspective that could play a role. Now, I'm going to say there is no silver bullet and I encourage my fellow panelists this afternoon to challenge that if there is. But I think there are lots of nickel-plated bullets that together could get the job done. An example is something that has been around a long time, and that is passive radar. By the way, any time you introduce a new technology to take over the way radar typically operates, you may find yourself in a situation where you are losing some performance or you have to do things in a different way. You don't get something for nothing right? But passive radar certainly has been around a long time and ironically with the proliferation of wireless and all these other emitters out there, the number of opportunities for using passive radar has increased. So, if you kind of turn the problem around you might have an advantage there. And a closely related topic is bi- and multi-static radars. Multifunction radars—there is a talk from John Cho of Lincoln Labs later about the FAA's MPAR, trying to combine different radar functions for ATC into a single system. Clearly that is a good thing to do. Cognitive radar is an area that I have been heavily involved in for a number of years and again this is a classic case of a technology with a high degree of adaptivity on transmit and receive, and the only way that we have really been able to sell this and make use of this is in relation to problems other than spectrum sharing, but clearly it has a significant role there. You've heard Charles Baylis, and Larry Cohen, and the NRL folks on better spectral purity and hardware systems that will achieve that, and that's playing a huge role, especially digital front ends. And the other important area is that there is a lot of stuff going on in novel radar signal processing. There's lots of examples where, if you don't have contiguous spectrum, you only have pieces of it, you can kind of stitch it together and still get a decent SAR image or a reasonable detection capability. So, the good news is, lots of stuff going on. I guess the bad news is there is no silver bullet, so that means there is going to be a lot give and take and contention over exactly which techniques, or which combinations of techniques, are going to emerge.

Now, I'm going to offer up one concrete, quasi-political, program office suggestion as to how we might move forward in the radar community. Every military radar system has a requirement for electronic protection; anti-jam would be the word for that. I maintain that if we were to put electromagnetic compatibility in that category, then the program office exists, the lieutenant colonel or 06 whose job it is to do this already exists, there's a funding mechanism. Just add requirements to what already exists. And the second part of that would be, hey, if it's crisis mode or if it's war time, sorry, we're going to kick in our electronic protection techniques and if you can't connect to the Internet that's just going to be too bad. So, I offer that up as one possible quasi-political thing.

So, again, in summary, there are a lot differences between communications and radar. And the security issues are significant. There are a lot of promising technologies, but no silver bullet. We certainly need a higher degree of collaboration. But maybe if we take these pieces and try to figure out how we get them into the existing business model for radars, which I maintain is through electromagnetic protection, then we may be able to move forward on that.

6.2.7 Paul Kolodzy, Kolodzy Consulting

Thank you for this opportunity to talk. After all these presenters before me, it is difficult to say something new but I'm going to try. First of all, when you are operating in a stovepipe the only people who know what is happening between the stovepipes are the people from above. The people inside the stovepipes have a really tough time understanding what's going on between the stovepipes. I'm really actually anxious and really excited that this is one of the first opportunities where we are poking some holes in the stovepipes so the different organizations and researchers and the like can actually look at each other and try to understand a little bit about what's going on between the stovepipes. If you look at history and science of engineering endeavors, it's the poking of those holes in the stovepipes that people actually say, "Wow, is that how you solved that problem? Maybe that would work over here." Or we have joint problems, and that is a good idea that we need to start taking a look at that very carefully.

My second note that I want to start off with is: if it's not being used passively or actively and everywhere all the time, there is a possibility, an opportunity for sharing. I'm not going to say it's easy or that it's straightforward, but there's an opportunity. We should be thinking about that. Everybody keeps not talking about the same simple idea—if it doesn't get used everywhere and all the time, there is an opportunity there. The passive community, for example, is as vehement sometimes as the radar community at saying, "We need more spectrum! But people want to use our spectrum. How do we get to do this?" So, then you ask the question, "Do you need more spectrum, everywhere all time?" "No." "Does the other service need to use it everywhere, all the time?" "No." So there is in an opportunity to try to figure out how to actually use the spectrum between the two to give you more on both sides. So, it isn't just a one-sided discussion, it should be a two-sided discussion, in the sense of opportunities that exist.

When we talk about these opportunities in radar bands, there are basically two questions being discussed: (1) How can we use current radars that are deployed, without any changes, to share spectrum cooperatively or uncooperatively? (2) How can we modify radars to make them more amenable to sharing? And that is the end of the discussion. But in reality, there is more to it. First, there are a lot of different radar systems and usage scenarios, e.g., fixed long-range radars, mobile short-range radars, airborne, ground-to-air, air-to-ground, ground-to-ground, rotating, static systems. These are all very different systems and they have different opportunities and different issues associated with each one. Radar is bigger than just one system. Communications is bigger than just one system. There are short-range communication radios, long-range comms. Sharing over long ranges is always more difficult than sharing over short ranges. So we need to realize that there are different opportunities with the different system technologies, applications, and platforms. We need to break these up and see where the opportunities are. Sometimes there won't be an opportunity. Sometimes there will be a great opportunity. But we shouldn't just do the homunculus and say that there is just "an opportunity." …

We tend to push all these problems into one bucket and try to solve it. The incentives that Dale was talking about, for example, are really in the wrong direction if you think about it. It's almost like public safety, where Congress gives the community spectrum but no money for deployment. This results in a big-stick architecture, which is not easy to share. If you actually included deployment in the architecture design, that's when opportunities to share arise. We should look at the incentives, not just for technical research, but also for spectrum access and use. Then your architecture works with the system.

My final remarks are an attempt to move us away from sharing with current radars and radars that are modified a little bit to coexisting with radars designed to share. How should radars be designed? Things have changed and are changing still. There is more infrastructure now than we've ever had, and it's growing at an astronomical rate… Distributed radar designs and architectures utilizing this infrastructure should be considered. This will cost money. However, what is the trade space between the cost for deploying distributed radar systems and the value added from new spectrum available for sharing and increased broadband capacity?... Distributed radars, radar overlays, and use of out-of-band technology with radars—how do you combine out-of-band technology with radars? There are different designs that can go off into different uses. We need to be excited about that, and I would like to end with some thoughts on directions we should go in:

- Sharing on long-range systems is a hard problem. We can try and engineer the problem, or we can look at shorter-range architectures that will actually enable more sharing.
- Radar does not operate everywhere all the time. They have statistical problems just like other radio services. What are the statistics? How often does it transmit/receive? Does it TX/RX every microsecond, every millisecond, every second? Is there distribution?
- How much spectrum do the different radar systems need to meet their mission requirements? What are the tradeoffs between radar quality of service and excessive use of the spectrum? Communications people had to weigh these tradeoffs and move from a voice-centric to a data-centric architecture.

We keep thinking about things about 1970, we're actually in 2011 and we're going quickly to 2020 and the issue is the problems are changing and the implications are changing and how do we actually merge those together? Thank you.

6.3 Moderated Discussion

Calabrese: The first thing I'd like to bring up, which I think was implicit in what some of you said, but we heard a lot about it explicitly at last year's ISART, is this notion that trust is a big hurdle in making Federal users, especially those like radar with national security and public safety missions, willing to share unused capacity. I'd like to ask what technologies or techniques could satisfy this trust factor? For example, Dale mentioned that, along the lines of TV whitespace geolocation databases, connected devices could be required to call home to check an even potentially real time database that enables preemption devices to be disabled or de-authorized, firmware upgrades and so on. That is one area that we could think about, so I want to get some thoughts on how we address the trust issue with sharing radar bands?

Reaser: I think you have to go back to the traditional ways of building trust. I've negotiated a lot of agreements, and what you have to have is a written agreement that all the parties agree to or some sort of set of rules that people will agree to. It takes a long time to get those worked out. The EU/U.S. agreement on GPS spectrum sharing took four years to do, but I think it was a good agreement. The next thing you need is some sort of accountability or enforcement, either through public opinion or having people check… That is the ITU methodology: a written standard or requirement, and then people checking. A third party or the parties themselves could be responsible for accountability, but I think that is the way you build trust. That's a standard way of doing it, and it's worked very well in a number of areas that I've dealt with in the world of spectrum over the past couple decades.

Brown: I'm going to agree with Richard; one of the things that I talked about in my opening remarks is that this isn't a handshake. On one side there are really big expensive government systems, and on the commercial side these are really significant investments in equipment and in technology to build global market places. So, this is not a handshake deal. And the players need to understand the rules of the sharing agreement from both a technology and a rules perspective. It's going to be band-specific, and in some cases there are going to be bands where sharing is impossible. The other dimension worth mentioning is enforcement. How do we make sure that the contract is honored? And if it has to be adjusted in the future because "whoops, we didn't think of everything!" how does that work? Those are all aspects of the problem.

Kolodzy: I actually agree with the last two comments, because we saw this in D block when they were going to auction and combining with public safety. This was an effort to combine and share commercial and private public safety spectrum. However, there was a lack of specificity and getting down to what is meant by trust. The commercial carriers asked, "What do you mean you want to have access whenever you want it or overlay access or whatever?" And that is when everyone sort of backed off the table and said, "I don't understand the rules. I don't understand where we're going, so therefore I don't trust that this actually going to happen." So, the devil's in the details. When people actually started working it out and when two communities start talking, I think you can start understanding the specificity and start understanding what has to occur. Some things might not be solvable, but there may be some that are and let's find out where those points are.

Guerci: I'm going to sound like the hawk in the room; I'm the militant. For a lot of the places that we are going to operate and the adversaries that we are going to face, we're not going to have any kind of agreement with them. There is always going to be a need for technologies that can accomplish the mission and that can be tested to do so reliably without any cooperation from anybody. That is the way we are going to do things, and I am not sure what the implications are… Now within the contiguous U.S. we are going to do a lot of things differently, and what has been suggested here is very reasonable. But overseas, we just can't depend on that.

Calabrese: In the 5 GHz band we rely on DFS and sensing. Is that sort of thing going to be sufficient? In my opening, I mentioned how connected devices are and the database solution to sharing. Tom Power mentioned that as a possibility, but one challenge being classified information… Although I can easily imagine NTIA holding that information in a distributed database, which is a black box to the user and even to a company that is operating the database. It is a black box because NTIA holds the information and gives a real-time thumbs up or thumbs down based on what is in there from all the different agencies. In any case, would a database approach make a difference with certain bands and certain radars or is that really just another big expense for those rare situations like the terminal Doppler to change their waveforms or something?

Brown: Let me comment on the black box database approach. We already see that in the millimeter-wave database. If you want to establish a millimeter-wave link, you go to the database provider who queries NTIA for a green or red light. If you receive a red light, you have to go back and coordinate. I think databases are a very interesting technology to enhance sharing, there is going to be an application for these. Are they going to be the answer everywhere? I don't know, but I see promise with the FCC television whitespace decision that calls for devices to interact with databases for access. For Federal users, radar or other, one of the nice virtues of the database approach is that if a device is misbehaving or causing a problem, there is a way to tell it to stop. These ideas have tremendous merit, at least in Cisco's view, and we hope to see those ideas and more proliferate as we talk about how to use spectrum more efficiently.

Hatfield: If I'm going to lease my house and I'm a little unsure of the renter, what do I ask for? I ask for a security deposit. If I'm entering a contract to build a bridge and I'm worried about whether they're going to do it or not, I ask for a performance bond. If I'm a movie producer and I'm making a movie, I ask for a completion bond. If people are producing devices, they should be required to put up a $10 deposit that is lost if the device does not behave properly… That is how we handle this in the private sector, so maybe we ought to consider types of financial penalties for failure to perform on a contract.

Kolodzy: First following up on Joe's comment... Joe is absolutely right in how critical military systems operate internationally, so how do databases work internationally? How would systems operate domestically using databases, when they actually don't use databases outside? That is a challenge. I'm not saying it's impossible, but it is a definite challenge. A database solution for TV whitespaces is good, because it involves static transmitters. However, when you start looking at systems that move around physically or systems that are prone to be messed with, databases add a point of vulnerability and we have to be careful about that… Again, these are challenges and opportunities, not just reasons to not do it.

Nebbia: We started off the discussion with the question of trust. The biggest challenge in this process, as we begin to look for spectrum and we begin to look at radar spectrum, is that the decision timeframe is pretty fast. In our discussions with the Federal agencies, they are always asking, "If we put a band on the table for sharing, what's going to be the mechanism we're going to use to get there? We will want to see testing done ahead of time. We are going to want to see the modeling done before that to lead us to know what kinds of tests we have to do." So, one of the challenges that we're finding as we're looking at relocation of systems or ultimately sharing of systems, is that the relocation conclusions appear to be ones that you can reach faster, whereas sharing decisions, where people need to come together because the trust level isn't there, are much more difficult. Nobody wants to commit and say publicly (for example) "Yes, we are going to allow sharing in the 2.7–2.9 band" if it hasn't been demonstrated and shown that it is workable. So, I think key issues for us here are that we have to realize that trust is needed up front and that's only going to be created after we suggest certain bands and we begin the effort of proving and testing the systems in there.

Mokole: I'd like to follow on to Karl's comments a little bit. Trust is only going to be achieved in incremental steps with developing necessary technologies and testing them to minimize EMI. On the radar side, some of these technologies are spectrally cleaner power amplifiers, waveforms that reduce out of band emissions, and antennas that control when and where the RF energy is transmitted. Relative to the database question, regardless of the database, another challenge is that it needs to be continually updated. Viable database solutions will require real-time accurate sensing of the environment to make sure they are accurate. Secondly, although it is challenging, there are examples in other communities where multiple databases are put together at multiple security levels. There has to be a hierarchy all the way down. It is a lot of work, but I believe that they're doing it in the area of maritime domain awareness where they're having not just RF but multiple sensing modalities put together.

Calabrese: I would like to discuss active steps the government might take to promote sharing. Phil Weiser referenced Mike Marcus, who wrote a paper for New America Foundation that said that DOD has been the great sharer, e.g., 5 GHz, 900 MHz band. These examples, however, have all been on a completely passive basis. The mindset up until now has been, if we can continue doing exactly what we do and you can work around us and we don't notice you, then we'll put up with it. Joe's presentation brought it up as well. It talked about ways in which we might expect the government to go a little better than that, and maybe take some affirmative steps to enable sharing. Obviously, you run into questions of costs and incentives and we can come back to that, but I'm wondering what sort of affirmative steps could lead to more robust sharing of radar spectrum? Particularly, those bands that are not going to be cleared and auctioned for exclusive use, but that do have unused capacity for some use.

Guerci: If we can incorporate technologies that allow us to operate even though the spectrum is being shared, maybe at the same time, that is what electronic protection is all about. Electronic protection, which is anti-jam, there could be some intentional people that are trying to dominate your spectrum and we can still operate. It's one reason why I emphasize putting it under the electronic protection umbrella. If we can prove through testing that we can still operate just fine with some density of a certain type of emitter that are using the spectrum, then that is going to be the easiest way to go.

Calabrese: So that both opens the sharing window and enhances the national security simultaneously? And that will work overseas as well?

Guerci: Right, as often happens in the real world, there is always more than one reason to do something. And usually the reason that you did it wasn't the original reason that you started with. Someone mentioned NASA and going to the moon. We created NASA because we wanted spy satellites. We needed to have a robust rocket development program, which we could do out in the open in order to not draw suspicion. The real purpose was putting satellites up. You know the man on the moon was sort of a nice thing to do, but there was a pressing national security reason for NASA.

Reaser: What needs to happen is that the Federal government needs to make a real commitment with their pocket book and say this is important and put money up against real programs. There are a lot of great ideas out there that are not going to see light of day unless someone pays to have them developed and implemented and put on real programs… You've got to vote with your pocketbook if you are really serious about it. If it is really that important, it would be funded, because that is really how we set priorities. There are, of course, political things that get in the way, but if it is important politically, which I think it is important politically, then there ought to be money given to it so we can go off and do those kinds of things. I have one other comment.

There was comment made earlier about stovepipes. He can't be with us because he passed away, but Curtis Steadman, a former DHS technology guy, preferred the term "cylinders of excellence"!

Nebbia: One critical thing to recognize is the balance between long-term future plans and short-term immediate spectrum needs. One issue that we encountered when looking at the 3.5 GHz band and considering how it might be shared and made available was that moneys were being allotted for the next development of the Navy radar capability in those bands. At that point, we had three months to make a spectrum management decision and the Navy was investing millions of dollars for a 20–25 year aircraft carrier program that was moving out of port. We've got to be forward-thinking enough to advance our long-term spectrum management strategies and be real about our spectrum needs now… Another aspect is that there are a lot of capabilities within radar systems to deal with a jamming environment, but you have to realize from the radar users' perspective, dealing with jamming does alter the performance of the system. You don't get the same distance reach; you don't get the various performance aspects that you are looking for. Yes, you can survive: that's what the anti-jamming capability is for. The concern, however, is if you start eating up that margin (that they've applied for anti-jam) with thousands or millions of other types of communication devices, then the margin is reduced before the enemy starts hitting the jam button and then you have significant issues to work through.

Brown: I just had one other comment about what government could do to promote sharing; this is not intended to be a criticism of NTIA or any of the other Federal agencies. However, from a commercial manufacturer's view, on the executive branch side there is distributed decision making around spectrum policy. When we sit down to talk about a band, there are typically multiple stakeholders and multiple agencies in the room. We wonder if the right government people are in the room. Are these the government folks that really understand the sharing problem? Are we really getting the buy-in? I understand that that is the way it's been and maybe this is the way it is going to be for the foreseeable future. However, the distributed spectrum management decision-making process is a little unnerving from the other side of the table.

Calabrese: If we could come back to incentives. Karl was just saying that whether we are talking about the short term or the long term, clearly there are going to be costs for R&D, planning, retrofitting, perhaps even new techniques like electronic protection and so on, perhaps new systems that may or may not advance the DOD's mission. How can we pay for this? One example is the concept of expanding the spectrum reallocation fund. I would like to hear any thoughts about how we can pay for these things that need to be done, particularly in bands where there is not going to be an auction.

Kolodzy: I'm not going to answer your question directly, because I don't know where the money is going to come from. However, the technology development and the system procurement and the spectrum policy all tend to be in different cylinders of excellence. It is only the people at the top that can see it all, but it is down at the lower level that you have to deal with a lot of the issues. Therefore, when you are trying to get funding, who is actually bubbling up the funding requests or where is the top-down demand to do something in these areas? Further, even if the money is available, from whom and how will the appropriate guidance be provided to take advanced spectrum programs to the desired end point?

Reaser: It has to be a top-down mandate. What's going to have to happen is that OMB is going to have to say, okay DOT, DOD, DHS, DOC, you are each going to have to come up with X number of dollars and we are going to create a fund and it will be managed by Agency Y. We wanted NTIA to manage it, but they didn't want to take the job. Then have someone managing that fund and someone to allocate funds to make things happen… This is not going to happen on its own, it requires leadership, and it requires people to set up a management program and execute it. It will have to be top down, and it will come out of other things. I think you ought to let the agencies decide where the money comes out of the Federal side… The problem with most acquisition programs is that the money is needed now. It can't wait for an auction. It's already behind schedule, in fact, it was behind schedule before the requirement was received. The money needs to be put together now, and they need to get going on it because it takes a long time to get anything done in the world of acquisitions. So, it is going to have to be a top-down directive. You might be able to reimburse or come up with some kind of transfer mechanism if you have an auction, after you have some kind of auction in that band to replenish those funds. Congress will probably never go for that, because it violates the whole issue of single year appropriations and so forth. That is how the budget works; it is an annual fiesta.

Calabrese: I would like to come back to the concept of trying to turn the spectrum relocation fund into a revolving fund, so that Federal agencies can be reimbursed for the cost of clearing off a band. The current relocation fund is limited because agencies are not even compensated for the up-front costs. Reforms are in some of the bills, but agencies should also be reimbursed on a merit basis for investments they make for either sharing or spectrum efficiency and becoming more shareable with other Federal users (which has the ripple effect of opening up more spectrum). There has been a lot of interest, but no real determination on the Hill on this matter, I think in part because it does reduce the net auction proceeds. We need to get more creative, because there are ways on the back end to refill that fund. One could imagine a tiny device certification fee. Dale mentioned that as a security deposit, but imagine if every Wi-Fi device was paying a dime into a fund, it could really help agencies free up more spectrum.

Kolodzy: As you're talking about money and all of this, one of the questions I have for the panel is to flip around this idea of radars sharing with comms. You are trying to get money because you think you are going to have more money for auctions or whatever but what is the appetite in the commercial world right now? They want completely unencumbered bands. When one considers sharing, those are encumbered bands. How is that going to impact the Federal government's desire to fund large amounts of research if they don't see the commercial interest to pay for it? If it is a money-oriented process, is incentive money to be able to pay for research or is the incentive to actually utilize spectrum for more economic purposes and for defense purposes and for safety-of-life purposes? We haven't talked about that issue which is, how is encumberment on both sides actually viewed and how is it actually resolved?

Calabrese: I just want to raise a particular band, because I was somewhat surprised to see in the Senate Incentive Auctions bill that there was a mandate to auction the radar band at 3550–3650 MHz unless the President said that doesn't make sense in terms of national security… I wonder, with that as one example, how feasible is it to auction quickly that particular band and what are the implications for radar bands more generally? Regarding this push to get 500 MHz, which starts turning into a revenue-driven issue on the Hill, are we starting to get some bad policy?

Guerci: That's a classic Congressional approach. If they want to kill a program, they'll make some cuts and see what the reaction is. If the service chief falls on his sword for it, the funding is restored. However, if they cut and there is really no push back, guess what, cut some more and eventually it dies from a thousand cuts. You've got to expect that this kind of tactic is going to continue. Where they're going to say: "We want to auction this off, we want to do this." If there is no push back then they are going to get it.

Nebbia: Certainly, NTIA is already on record for having worked with Federal agencies to make the 3550–3650 MHz band available with a set of exclusionary controls. It was discussed earlier that most of those exclusion zones are based upon use off the coast, but there are other smaller exclusion zones to meet the needs of some Army land-based radars and some systems used for aircraft that fly in formation using radar devices. On the basis that we could auction the spectrum immediately, we've already sent our letter to the Commission saying that we've made that band available… Because our goal is more than just raising auction revenue, I've asked, are there technologies to make the bands more useful? Based on some recent CSMAC discussions, there concepts to look at. However, once again, we are going to have to look at the trust issue. The agencies, for instance, understand that those exclusion zones were created to protect the incoming wireless systems. The incoming wireless systems, however, may find that they don't want those protections or that they don't need that protection if they are going to get access into those higher population areas. Then we have to get past the circumstances where industry or users calls their congressman as soon as a DOD ship comes in and interferes with those systems.

6.4 Q&A

Pierre de Vries, Silicon Flatirons: This conference is doing a lot of really important work for people who need to work together in the trenches, but what I am struggling with is the disconnect I see at a more strategic level. I'll give you two examples and I'm hoping that maybe the panelists and the other people in the audience can re-educate me. The first disconnect is that this is going to cost money, this is going to cost real money. Now juxtapose that with what is going on in D.C. right now. It's not that we have a one-week problem; we have a ten-year problem with de-leveraging this country with a debt and a deficit. There is going to be no big money. That's the first disconnect. The second one is the issue of Federal/non-Federal sharing. On a small scale and a local level and if there is a lot of trust, then it can be done. Rick and Mary said, however, if you're going to do this for real and make big investments then you need real, long negotiations, and big contracts. How will you know it will be honored? You have to be able to go to some adjudicator, and the way that we have structured spectrum management in this country means that there is no adjudicator. There is nobody between or above FCC and NTIA that can adjudicate a dispute so how are we actually going to have Federal/non-Federal sharing that is enforceable?

Hatfield: I work with Pierre very closely, and I agree with his characterization of the problem. Much of it goes back to the fundamental way that we organize spectrum in the U.S.

Nebbia: I think I heard Rick and Mary vote already for NTIA being in charge, but it certainly provides a significant challenge… We had an initial challenge with the 5 GHz challenge, that I must say that for all the negative you hear, overall has been very positive and a tremendous step forward. I think as we work through these new goals, we are going to find ourselves more and more able to move them forward. There is going to be learning here in the beginning, and one of the challenges is bringing the right people together for a working mechanism that meets all the requirements under Federal and all these other legal requirements. The getting down and rolling up your sleeves is absolutely essential.

Brown: It is going to take a lot money, there are going to be a lot of bands that are particularly interesting to do some work in, and there are going to be some bands where we all going to decide it is not worth the candle. Just to give you an idea of the money sloshing around in the system, auctioning off over the next ten years 500 MHz of spectrum could potentially bring in between 60 and 80 billion dollars. That's a pool of money that is off the taxpayer nickel. One of the things that happened this year in spectrum legislation is the White House proposed and the Senate Commerce Committee accepted a plan to take some of that money and put it back into R&D. Those are the kinds of ideas that will help us get over that hump and we need to use whatever money we get responsibly and address the priorities. In terms of the adjudicator, I'm actually not worried that there be a traffic court to resolve disputes. I think within the engineering community you have a conversation about whether there's a real concern with interference. Certainly in the post hoc enforcement case, those issues can be resolved at a lower level.

Reaser: I'm not that worried about the adjudication issue. Once you have a written agreement, public opinion and a lot of other things play into that. I have written a number of agreements where there is no adjudicator… Principle negotiations are needed and should be put into a public document. If you get to an adjudicating place, we can go to the courts and sue over it.

Mokole: Just one comment on what Mary said about responsibly putting the R&D money aside. There was a similar process back in 2003–2004, perhaps not as important as this one, where there was a radar spectrum technology working group. Money was put aside to do R&D. I'm not convinced that it was responsibly spent, because from my own perspective I have no idea who was doing the work. We have been doing a lot of work on our own nickel. So, I think responsibly using it is important.

Bruce Naley, Naval Surface Warfare Center: First, just some agreement with the panel so far on incentives, particularly for radar program offices. From my position in my group, we directly support and advise some Naval program offices, and we have tried to push for greater spectrum efficiency and cleaner output requirements. Frankly, it comes down to cost, schedule, and performance. If it does not improve one of those three items, then they don't want to hear it. For very good reason the Navy has strong opinions about performance because they are trying to protect their people, their ships, and accomplish their mission. Unless there is some other aspect to create a requirement for spectral efficiency or those types of issues in the contract requirements it's not going to happen. On another topic of trust, particularly when you are talking about sharing bands, I was told this story before I came onboard the NSWC Dalgren. There was a case out in San Diego where a Naval aircraft was causing problems with garage door openers. Garage door openers are a Part 15 device and are supposed to accept interference. However, there are a lot of garage door openers and owners of garage door openers, and they all have a Congressman. In the end, the Navy had to change the way we operated the radar to accommodate the Part 15 devices. That factors into trust. We're asked to go sharing again, and we've got some issues of making sure that sharing will actually work before we agree to it. Perhaps a question for the panel involves enforcement. If a similar situation came up again, what happens when there is a problem? How is it resolved when the momentum is there, the inertia is there for the population to rely on these devices even though they are supposedly unprotected?

Calabrese: One thing that we discussed in the CSMAC meeting yesterday with respect to future shared and unlicensed bands. Most of the spectrum is from connected devices, and Kevin Kahn (Intel) articulated that we could require that devices ping a network or database and get upgrades or be disabled or whatever would fix the problem. There is also education to do as well, because manufacturers sell these things leading people to believe that they are always going to work, i.e., customers are not aware that they are contingent devices.

Mark Gibson, ComSearch: First, I would like to thank Pierre for his comments on cost. We are one of nine (maybe ten) companies operating a whitespaces database. We also administer the millimeter-wave database that Mary referred to. Lack of regulatory clarity is the thing that causes us consternation. It doesn't help me to make the case for R&D spending when there are articles in Fierce Wireless that the whitespace death knell may be near because they are going to start auctioning unlicensed spectrum. We've been developing the database for three years, and we are not sure what the feedback is going to be. I have to make the case to my management that for every dollar of R&D spending, there is at least more dollars in commercial opportunity. Hence, if I would leave anybody with one comment I might say this is one example of how not to do the regulatory effort. This is not a cut at anybody; we are breaking new ground here, and it is not easy. With whitespace this has simply been with the Commission. Also, there is a need to have better regulatory harmony with the international bodies, because what Ofcom is doing is very different from what the Commission is doing. If we are going to use databases to share spectrum with Federal and commercial users, then we all have to get to the table together and roll up our sleeves to get it done.

John Noter, Noter Research: In some ways the sharing we are talking about is sharing between military and DOD systems and systems that are opportunistic that operate under Part 15 or Part 90 rules. We're not talking about sharing with Verizon or AT&T or Sprint in their main wireless bands. They are not talking about sharing with DOD in those bands; they are expecting to have full access to any bands they purchase at auction and the right to use it without interference in normal circumstances. However, if you run a warship up the Potomac, you are going to take out cellular and all these other systems as well, and that's the price we pay when we are in that kind of environment. Hence, when we talk about sharing we are really talking about sharing with unlicensed systems and I would appreciate any comment on that.

Nebbia: We hope that is not true and that our wireless capabilities will expand. We understand that Part 15 devices have lived with this opportunistic sense. We are currently focused on spectrum below 3 GHz; even if we extend the scope up to 3.5 or 3.6, there is only so much there. Regarding radar systems, which occupy a significant portion of the spectrum, I've not heard anybody suggest from a knowledge base that we can really pack up the ATC radars and move them to 10 GHz… Hence, we are dealing with a spectrum-limited environment here, where a lot of these systems, particularly with their long-term acquisition cycles, are themselves probably not going to be moved. If the wireless industry is still looking for more spectrum, and I think they will be, they are going to have to look at this opportunistic capability as well, it's not going to just be Part 15.

Calabrese: And the increasing unlicensed offload that I think Phil mentioned earlier.

Beau Backus, Aeospace Corp: Often times, there are spectrum managers embedded in the field. On the Federal side, a lot of spectrum managers actually go between different systems and coordinate; a lot of time (I'm sorry Karl) without NTIA ever knowing about it. It's a method of working the resource at the field level, and it works. One of the things that has not been discussed is that we really don't know how to talk between non-Federal and Federal spectrum managers. There's no established guideline or methodology to talk to each other, or forums that really do this. The Satellite Interference Reduction Group, for example, is a whole bunch of satellite operators and I have never met a single person who formally coordinated that satellite spectrum. So, to that end, you have a lot operators that need to work among themselves. Do you have any comments for the need for this type of communicating?

Reasor: We already do that as you know, Beau, I'm talking Northrup and Boeing and then Edwards on a daily basis coordinating things… The first thing I did when I got to Raytheon was to try and figure out who all the local guys were. As contractors, I am not sure where we fall in the Federal/non-Federal world… I haven't really had a problem with non-Federal guys interfering with our stuff. We thought we did but it turned out that it wasn't true.

Brent Glass: There have been a lot of questions about money being tight, so I guess the obvious question to ask is: Why aren't we demanding that we get our money's worth? Certainly we should be able to expect our systems to be robust, otherwise why are we paying so much for them? I know, personally, I operate on unlicensed spectrum, and I have spent thousands of dollars of my own money making my systems more robust because of intentional interference from competitors. I've also encountered situations where there have been a number of people operating legally on the same tower and have created intermodulation products, where their signals mix together, and interfere with my licensed links. I've had to engineer them to get around that. Oh, by the way, there is another example and that is LightSquared. They would like to use their own spectrum, and they ought to be able to use it since it is legally licensed. GPS devices, however, were designed to be non-robust, and they can't handle interference from it. This may scuttle the whole deal. Why aren't we insisting on more robustness as engineers, and how can we make sure we are funding that?

Reaser: We need to start licensing receivers.

Kolodzy: There has been a lot going on about receiver standards. It is a sticky wicket in the sense of system longevity. When quick turnaround systems are considered, there is one way of dealing with it. Receiver standards on long-term systems is handled another way. Expensive systems add a whole different dimension to the problem. It should continue to be discussed.

Dave Lewberg, Raytheon: One thing that Mary said that intrigued me was similar to the model of investment, why can't the commercial community go directly, once priorities have been made, to fund independent R&D in the contractors that are working these long-term systems? We do that with the government with IRAD and CRADA money, I'm sure we could do that with someone else's money, it may not have to come from the government. That is point one. Point two is that empathy is needed between the parties. I would strongly suggest that groups go to the opposite conventions and panels on spectrum interests so that people could see some of the concerns of the radar community in the middle of the wireless convention and vice versa, because I think the hard sell here is there are lot of disparate groups and they do not appreciate the pressing need that the commercial industry has. Last but not least, Joe made an interesting point about how there are some things that can never be shared due to security. What's the converse of that on the commercial side? What are the things that require proprietary agreements that you don't want to share with your competitors but need to get out there to be successful? I think people don't understand that, and if they did they might be willing to move a little faster on this sharing business.

Peter Eckelson, Cisco: In 2002 when we talked about radar bands, we offered to put radar detectors in the Part 15 devices and after some consideration they decided that they thought it wasn't such a great idea to have them on the shelves in Baghdad. This is a different generation. If (1) regulators said we could have 500 MHz between 3.1 and 3.7 GHz, (2) we had radar detectors, (3) the FCC put up a testing regime, and (4) everyone was convinced that they could put out those signatures, then that is certainly something worth pursuing. The second comment is that in 2008 the TV whitespace rules had no security. There was nothing involved in it, and China came along and said, "We can't follow those rules, because we need to have some control over all those transmitters." Hence, the 2010 rules have control over all those transmitters with the database in the middle. We put up with something in the middle to get access to that spectrum. Regulators, however, need to think more about the partnership between what we will put in these Part 15 devices and what are the requirements needed to preserve access to the spectrum.

Nebbia: In the end, the agreements that we reached with Wi-Fi involved them receiving radar detectors. That was not our original goal. Ultimately, we went through a long negotiation process. We went through an international negotiation, where we essentially agreed that a DFS system would sense a certain signal level and move off. Immediately after reaching those agreements, the Wi-Fi came back and said "Oh we can't do that because then we'll be turning ourselves off." Then we got into asking the radar community to provide us with what exactly you look like. Obviously, in the long run, that is not a military solution, i.e., radars telling you what their signatures are. It certainly is a significant issue, but hopefully there will be other approaches besides just looking for individual signatures.

7 INTERNATIONAL RADAR COMPATIBILITY PANEL

The goal of the International Radar Compatibility panel was to provide an understanding of the regulatory regime and current interference issues facing the radar community. In the session overview, John Mettrop (UK Civil Aviation Authority) briefed the audience on the International Telecommunications Union (ITU) Radio Regulations and European requirements on unwanted emissions. Next, the individual panelists gave presentation on current compatibility issues with focus on types of interference, steps to resolve interference issues, and implications for users if issues are not resolved. Topics presented in the opening remarks included

1. Adjacent-Band Broadband Compatibility around 3 GHz—John Mettrop (UK CAA)
2. NBP Fast-Track Issues at 3 GHz—Joe Hersey (U.S. Coast Guard)
3. RNSS versus Radars at 1215–1300 MHz Band—Dr. David Choi (The MITRE Corporation)
4. Co-Channel RFI at 5 GHz—Chris Tourigny (FAA) and Frank Sanders (NTIA/ITS)
5. HF Ocean Graphic Radar and 5 GHz Band Radar Interference Issue—Dr. Jaewoo Lim (KCC/RRA)

7.1 Introduction by Session Chair John Mettrop

My name is John Mettrop from the UK Civil Aviation Authority. I have, in the UK, responsibility for all spectrum management issues on the technical side that affect aviation, i.e., comms, navigation radar, surveillance radar, radio altimeters, and RFI. To give you a clue at what we deal with, the UK is looking at a 500 MHz release. They are trying to identify bands for release by the end of the year. I've heard a lot of talk here about band sharing. From a safety of service point of view, it is important to avoid interference issues associated with sharing. The move in the UK is more towards re-planning for efficiency and clearing out bands. We are looking to develop actual radar-to-radar planning criteria and boundary conditions that are as efficient as possible. The proportions for the UK radar interference issues are different than the U.S. The UK is 90% the size of Colorado, and has 119 land-based radar systems. In the UK there are 19 solid state, 13 magnetron, and 11 TWT that cover 18 different civil radar types; 68 military; 8 maritime; and 1 rather large meteorological radar. In comparison, there are 400 S-band radars in the entire continental U.S.

The ITU Radio Regulations is an international treaty governing the use of radio spectrum and administered by the ITU, which is a United Nations (UN) body. ITU Radio Regulations were first published in 1906, so they thought about radio spectrum quite early on. At the moment it covers 9 kHz to 1000 GHz. There's over 1000 pages and 40 different radio services. It can only be changed by a World Radio Conference (WRC). Frequency bands are available for the various services, and it specifies those services as primary or secondary. The ITU Radio Regulations, formally, are about civil systems. There is one article in the constitution that talks about military and governmental systems abiding by civil rules where possible, but that is not mandatory.

There are restrictions on use and rules about how to coordinate those frequencies. This is all cross border stuff. The radio regulations attempt to answer questions like: What constitutes necessary bandwidth? What is the definition of an unwanted emission (which covers both out-of-band and spurious, but not adjacent band which corresponds to the nearest disparate radio service)? What level of an unwanted emission is harmful? ITU unwanted emissions for radar are shown in Figure 57. There has been an effort to improve the roll off of radars and hopefully their compatibility with other services. It started at 20 dB/decade and moved just recently for most radar systems to 30 dB/decade. There is still pressure to achieve 40 dB/decade. In Europe, the mask rolls off to the ITU level (-60 dB) at 20 dB/decade, but there is also a requirement to roll off to -100 dB for a single frequency radar in Europe.

Absolute limits are under consideration. Should absolute levels be used? Current roll-off limits are relative to the peak, but there is nothing stopping radar systems from increasing power. Consider a standard solid-state ATC operating at 60 kilowatts into the antenna with 32 dB gain compared to the Met Office radar operating at 600 kilowatts into a 56 dB gain antenna. For a given relative roll-off limit, out-of-band emissions are 10 times greater for the Met Office radar. Wouldn't absolute levels give a better understanding of unwanted emission levels? If so, should the absolute limits be defined at a single level or at multiple levels (e.g., one for harmonics and a second for quiescent noise)? The International Electrotechnical Commission (IEC) is a little ahead on some of this; they already have a maritime radar certification standard, which they are looking to update.

Article 3.3 is the only place in the ITU Radio Regulations that speaks toward receivers. It states, "Transmitting and receiving equipment intended to be used in a given part of the frequency spectrum should be designed to take into account the technical characteristics of transmitting and receiving equipment likely to be employed in neighboring and other parts of the spectrum…" I wonder how many people actually take that into account in designing their systems. I will come back around to that in a minute when I talk about adjacent band broadband compatibility.

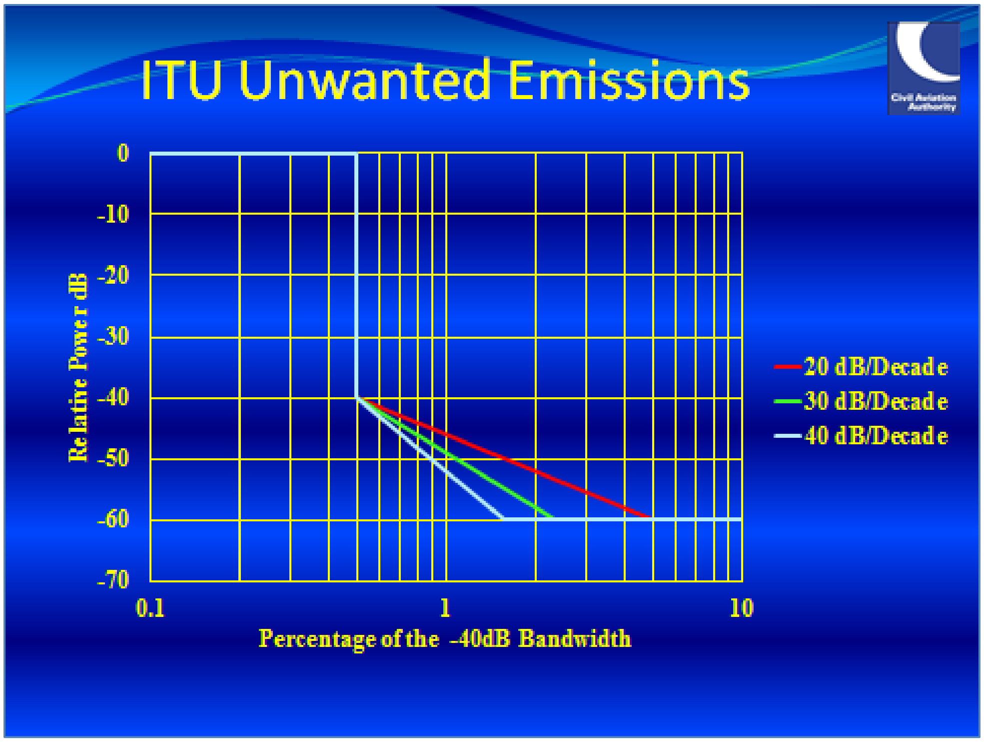


Figure 57. ITU radar emission limits.

7.2 Opening Remarks from Panelists

7.2.1 John Mettrop, UK CAA

Adjacent band broadband compatibility around 3 GHz is an important case study. How did it start? The band 2500–2690 MHz was allocated to the mobile service in 2000. In Europe, there was a decision for implementation. Ofcom drafted an invitation to tender for an auction in spring of 2008. CAA radar systems operate at 2690–2700 MHz, so we weren't worried. Ofcom, through due diligence, actually went out and tested a TWT Watchman radar in summer 2008. Their purpose was to measure the out-of-band spurious emissions in order to inform the mobile community what they will have to put up with coming from the radars. While they had the kit there, they tested the interference effects on radar… The radars turned out to be susceptible to interference at levels 21 dB lower than had been originally estimated. We informed Ofcom of the interference issue, and did some flight trials because Ofcom didn't believe us. Flight trial results are shown in Figure 58. We look for probability of detection P_d = 95%, but when WiMAX was operating at a sensible signal level (i.e., 15 dBm measured at the low-noise amplifier input) we measured P_d = 0% for the aircraft.

In general, the UK approach to spectrum resolution is to

- WiMAX/LTE: Delay roll-out.

- Aviation radar: Fund research to define the issue to be resolved, fund development of solutions, and fund implementation. Ofcom and the UK government are putting tens of millions into basically funding the first part of development down to a model and the roll out will be tailored to LTE and WiMAX.
- Maritime radar: Assess whether there is an issue.
- Military radar: Identify and resolve their issues. The military have phased array radars just coming into service, which will need to be redesigned.

I would like to bring a few points to the forefront regarding radar compatibility. First, adjacent band suppression by a radar receiver is insufficient, because there is approximately 40 dB of disparity between what we need and what we've got… Second, the 1 dB compression points (which are used as a reference point for radar susceptibility) were found to be -28 dBm for solid state radar and -42 dBm for older radar instead of the well-established -20 dBm. Third, the WiMAX/LTE regulatory limit of -30 dBm for unwanted emissions is enough to cause interference to radar. Finally, user equipment needs international standards work, and we need better-defined radar standards.

Calculations show that WiMAX/LTE base station power levels should be reduced by approximately 30 dB in order to avoid causing out-of-band interference (see Figure 59). Figure 60 shows the required limit plotted on top of a measured WiMAX/LTE unwanted emission. Observe that the WiMAX/LTE emission at the in-band/out-of-band boundary is more than 20 dB below the ITU level. Hence, our belief is the international standard probably could be changed without actually affecting the WiMAX/LTE equipment that's out there at the moment.

In summary, WiMAX/LTE can cause interference. We have done both theoretical and practical testing to show that. Additional radar receiver filters with 40–50 dBs of adjacent-band suppression are required, and the initial indication that we've gotten back from the radar manufacturers is that we are going to have to move our radars up 40 MHz from the bottom of the band to allow that filter to roll off, keeping phase and linearity. The unwanted specifications maybe need to be tightened. Finally, as far as the UK is concerned, we will continue to work with the international community on this issue and other issues. We will also share information where possible. I think information hidden away can cause us problems, and we need to sort it out.

Flight Trials Results

Interfering Signal	Equivalent Interference Level at the LNA Input	Probability of Detection	
		Normal Radar	Ground Clutter Filter
CW	Off	95%	90%
	-15 dBm	0%	19%
	-30 dBm	91%	82%
	-45 dBm	92%	76%
AWGN 10 MHz	-15 dBm	0%	
	-30 dBm	69%	65%
	-45 dBm	92%	
WiMAX 80%	-15 dBm	0%	
	-30 dBm	88%	
	-45 dBm	95.5%	

Figure 58. Field measurements results of ATC radar interference from WiMAX.

Example Out-of-Band Calculation

	LTE/WiMAX	
	Base Station	User Equipment
TX Power (dBm)	-30	-30
Antenna Gain (dBi)	17	0
Free Space Path Loss for 1km (dB)	101	
Multipath Gain (dB)	6	
IF Bandwidth Correction Factor (dB)	0.8	
Polarisation (dB)	3	
Radar Antenna Gain (dBi)	34	
Receiver Filter Rejection (dB)	0	
Received Signal at LNA (dBm)	-76.2	-93.2
Minimum Discernable Signal (dBm)	-112	
Indicative Interference Margin (dB)	-35.8	-18.8

Figure 59. WiMAX/LTE OOB interference margin calculation.

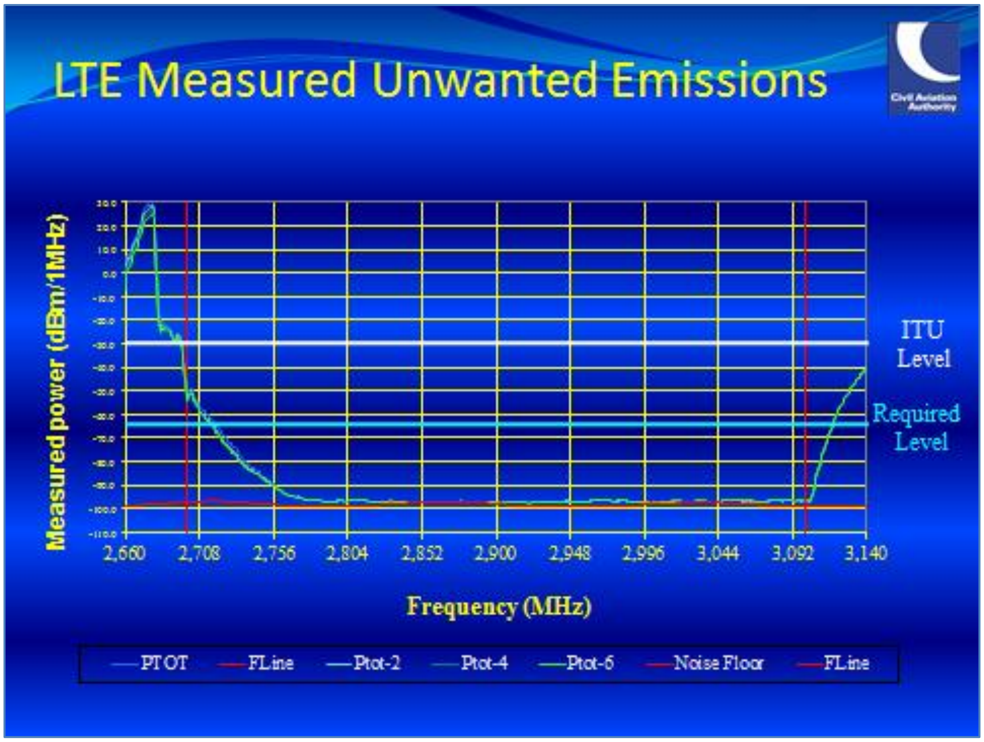


Figure 60. Measured WiMAX/LTE emissions with current ITU and CAA required OOB limits.

7.2.2 Joe Hersey, U.S. Coast Guard

Let me go back a little bit to the IEC and the radar standard that John mentioned earlier. About 50 or 60 years ago, the radar manufacturers in the maritime industry asked through their industry association for IEC to establish a technical committee to develop test standards in order to harmonize different countries' type approval requirements for getting their equipment approved. The International Maritime Organization (IMO) established after WWII was now requiring ships to carry radar of a type approved by Administrations for safety reasons. However, countries had varying rules as to what kind of radar could be approved. The IEC Technical Committee for Maritime Navigation and Radiocommunication Equipment and Systems shipborne radar performance requirements, methods of testing and required test results [35] is the outgrowth of that.

We are at a fortunate time with this particular standard on shipborne radar performance requirements and testing methods. It is in the process now of being updated, which happens every four or six years. We have asked ITS Boulder to develop interference protection criteria which could be included in that standard. Presently there is only three inches of text regarding interference susceptibility in the standard now, but it basically restates an IMO requirement that interference needs to be considered without requiring any interference susceptibility testing. Since IMO is primarily funded by countries having large numbers of flagged vessels, their interest is primarily in keeping costs to ship owners down rather than bringing new broadband spectrum into their communities. Anything that places an onerous test requirement on manufacturers that may affect their cost will likely get a negative reaction. Nevertheless we plan to pursue improving interference susceptibility requirements in this standard. Fortunately, this IEC Technical Committee also covers maritime GPS receiver certification standards, so we have an opportunity to address some of the interference susceptibility issues related to GPS—including interference from LightSquared.

You've been exposed to the S-band radar band in the Inventory Briefings. Patching together the whole of 2700–3650 MHz gets a little awkward. The maritime radio navigation portion that I've been concerned about for the Coast Guard is from 2900–3100 MHz. I think we've always assumed that being at the center of this band we were protected from broadband encroachment. Karl Nebbia has convinced me that we shouldn't be so complacent. As John had mentioned, the aeronautical navigation service in the lower S-Band had seen some WiMAX interference issues. Actually, we had as well, even though there is 200 MHz of separation with their band. Our interference issues, however, are not anywhere near as serious as those of the aeronautical service and the weather meteorological service.

One other thing that we are learning as this broadband initiative works out is whether the maritime navigation band can share more effectively with the military location band. They are being asked to "smoosh" (i.e. relocate downwards in frequency) to the left a little bit to try to open the 3500–3650 MHz band for broadband. That means that the maritime service will have to accommodate them somehow. Further, in the maritime service, mentioned yesterday, we are finding out even within our own service that solid state and magnetron don't necessarily coexist well. Relevant questions we are trying to sort out include: Can ATC, NEXRAD, marine, and military radar better share? Can solid state and magnetron radar systems better share? There are some interference issues that we need to sort out. We need to address not only our own services but military services as they move into this band.

It was mentioned earlier that 3500–3650 MHz is being allocated to broadband. This decision came from the NTIA report [4], which also recommended a geographic setback from coastlines to protect military ship radars operating 10 km or more offshore. The Coast Guard doesn't have equipment operating in this band but we are very much interested in it. The reason that we are interested in this band is because of the SPN 43 radar, i.e., an ATC radar of a type we can use to control air traffic around events similar to the Deepwater Horizon incident out in the Gulf of Mexico. Admiral Allen was the incident commander out there, and he felt that perhaps his greatest achievement was bringing air traffic control into that area and preventing a major accident. We're concerned that if operation of such radars are ever pushed beyond near coastal waters in the U.S. we would never be able to provide this type of capability in a similar incident in the future. Thank you.

7.2.3 David Choi, The MITRE Corporation

It is really a great honor for me to be here because the list of distinguished guests that spoke before me. I am Dave Choi, and I'm with The MITRE Corporation. I have deep roots in radar going back to my grad school days in the early 1980s. I have work experience in microwave remote sensing, HF over the horizon radar systems, UHF radar, and recently L-Band radar systems. More recently, I've been supporting the GPS Directorate on RNSS international and domestic spectrum management issues. I was hesitant when I was asked to come here and describe interference issues that are being considered at ITU-R. The issues are controversial in a way, but I felt that I could present what I believe is the technical truth, and you could make your own decision based on that.

By now, we know how important radars are to national defense and to the safety of navigation. The radar-RNSS interference issue that I will discuss here is in the 1215–1300 MHz band. RNSS includes systems such as GPS, Galileo. The L-Band radar being affected is the ARSR-4, i.e., ground-based short- and long-range air surveillance radar systems.

The radar system has been around for many years and operated in quiet environment for a long time. Sometime in the 1970s, an RNSS allocation in the band 1215–1240 MHz was granted by the ITU-R mainly to support satellite-based positioning, navigation, and timing (PNT). We now know this as GPS. That was followed by an allocation in1240–1260 MHz band to support GLONASS. Up to that point, there weren't many interference issues between radar and GPS because the RNSS allocation was predominately below 1260 MHz. At the conclusion of 2003 World Radiocommunication Conference (WRC-03), the RNSS community was given permission to use the 1260–1300 MHz band. The prospect of sharing 85 MHz of the 175 MHz radar allocation with RNSS caused concern in the radar community. They asked the ITU-R for continued study to look at whether this interference was going to be a real issue or not. The evaluation has been ongoing since 2003, and I will provide a summary here.

First, how does the RNSS signal interfere with the L Band radar systems? RNSS signals are transmitted from satellites, so by the time it reaches the surface of the earth it is a very small signal, i.e., approximately -155 dBW to -160 dBW. With a simple calculation, you can calculate noise floor for an L-band radar to be roughly -140 dBW. You might ask, "How can a signal that is 20–25 dB below the system noise of the radar actually interfere with it?" It turns out that most of the radars, especially the long-range radars, have high gain receive antennas, and when you point an antenna, with 40 dB gain, directly at the satellite it pulls the RNSS signal out of the noise by 10–15 dB, and that is the mechanism by which the RNSS signal interferes with the radar receiver.

In order for the radar to "pull" RNSS signals above the noise floor, the RNSS satellite must be in the radar main beam. A quick calculation shows how often this occurs. Assuming 30 satellites in an RNSS constellation, roughly half of those will be above the horizon, so that's about 15 satellites. L-band radar volume coverage is 25–30 degrees in elevation, or about a third of the coverage. So approximately five satellites per constellation intersect the radar main beam per scan. It is important to note that this is not a ubiquitous issue.

The second condition is that the radar must be operating at the same frequency channel as the RNSS.

Since 2003 the ITU-R Working Party 5B was responsible for this work, which resulted in a working document. The work is summarized in the following:

- Computer simulations that looked at time versus interference-to-noise ratio (INR) over a particular look angle. It also showed percentage of the time that the aggregate RNSS INR exceeds -6 dB. It concluded that the INR exceeded this level a significant period of time.

- Compatibility measurements were contributed by the U.S. and Germany, which confirmed that P_d is affected. It is reduced due to the fact that the noise floor rises, and the radar sensitivity is degraded.
- Statistical studies concluded that this kind of condition only happened 2–3% of the time.
- Assessment of interference mitigation possibilities considered that some of the radars have frequency agility/avoidance capabilities already built in, and that if there is at least one other set of frequencies then the radars could detect and avoid the RNSS interference. This is not an option for systems like ARSR-4, because of the compact frequency assignments for these radars. For fixed frequency radars, that is really not an option.
- Polarization diversity was also considered. A right-hand-circular polarized transmitted radar signal becomes a left-hand-circular polarized signal after it bounces off the target. All RNSS systems use right hand circular polarized waves, so polarization diversity might reduce the impact from the RNSS signal into your radar system.
- Adaptive data processing by the radar has also been considered in this report as well.
- Overlapping coverages, i.e., how the interference impacts the entire system of systems topology. I think that is something worth looking at.

So where are we? I think that under certain conditions—1) satellite is in the radar's mainbeam and 2) radar channel is near the RNSS carrier frequency—there is little doubt that the RNSS will cause the L-band radar noise floor to rise. The good news is that there are mitigation techniques available; the bad news is that funding is needed. Domestically, we are looking at the options and exploring ways to have these two systems share but really at this time there are no results available to be reported. Thank you.

7.2.4 Chris Tourigny (FAA) and Frank Sanders (NTIA/ITS)

Tourigny: Yesterday, I briefed on the TDWR and explained why we need the TDWR. Today, I'm going to expand the conversation a little bit into what the FAA uses and what we do. I'm going to keep it under the context of sharing the FAA's primary radar bands. We also have secondary radars that are dependent on 1030 and 1090 MHz and cover about 90% of what we do in surveillance. Not to imply that the primary radars are not important. All FAA systems are important; however, most of the work we do is in other bands. I'm going to start off today talking about the FAA's approach to aeronautical spectrum management, and I'm going to give you our game plan on how we approach change in the National Aerospace System. Then I'm going to talk about some of the bands that we actually share with other U.S. agencies and the public to provide safety, efficiency, regularity of flight, national defense, national security. Finally, with the help of Frank Sanders, we will talk about the TDWR interference issue. I do have the user perspective and I will begin that conversation from the perspective of the user of the data.

It's interesting to me that we, the engineers in this room, allowed the conversation to turn to an economic topic of incentives and somehow that was able to continue on for a while. In fact, it is important to note that we in the Federal government are not only engineers, but we are also responsible for making those tough decisions that involve human life. Our mission in the FAA is not necessarily driven by economics alone; it is a moral mission too. We need to continue to provide the safest and most efficient air space system in the world. That may seem kind of arrogant, because it is. We do want to be the best. We are accountable to the American public and our stakeholders include the aviation industry and commerce.

We're using Next Generation Air Transportation System (NextGen) as our vehicle for change. We are transforming the National Airspace System (NAS) from a system based on ground-based air traffic control to satellite-based air traffic management. The aeronautical surveillance systems (including radar) are critical safety tools in the air traffic management process used to protect in the U.S. and globally too. Our game plan for changing NAS involves the following three elements: policy, compatibility, and capacity.

- **Policy:** Regulations must be clear, enforceable, and always side in favor of protecting systems that protect lives, whether it be for homeland security, defense, or the safety of the NAS. We use FAA orders, radio regulations from NTIA, FCC, and ITU-R, standards and recommended practices (SARPs) from International Civil Aviation Organization (ICAO), and minimum operational performance standards (MOPS) from the Radio Technical Commission for Aeronautics (RTCA) and EUROCAE. These are collaborative groups that bring together industry, government regulators, and air service providers (public and private) to form consensus decisions on how to operate our electronic equipment. We have to be interoperable within national borders as well as internationally. We use policy to lay down a common set of standards and rules under which we can all operate and interact with each other.
- **Compatibility:** Systems sharing the aeronautical spectrum must ensure interference-free operation of the systems that operate for the safe operation of aircraft. This is a standard perspective from anyone responsible for the safety of human life—aviation, maritime, etc. We have an established process for compatibility assessment, which begins with a conceptual design through stakeholder collaboration. Next, modeling and simulation is performed to test how the system reacts to a perturbation. Bench and field testing are performed to demonstrate no unintended consequences for the avionics equipment or the aeronautical collision avoidance system. Finally, in-service performance monitoring is performed indefinitely.
- **Capacity** must be preserved for the expansion of the safety services. If you were to cap the growth of NAS at some number, existing safety margins might be sustainable in the long run. However, if the economy grows and air traffic subsequently grows, we cannot accept a reduced level of safety as a tradeoff for an increased level of economic performance. The level of safety must match the air traffic growth, and that might require more spectrum use.

The FAA manages a number of frequency bands that correspond to layers of safety to keep aircraft from colliding with each other and with the ground. The en-route ATC surveillance 1240–1370 MHz band is shared with DOD for air defense and DHS. The airport ATC surveillance band at 2700–2900 MHz is shared with DOD for ATC. The NEXRAD weather surveillance system operating at 2700–3100 MHz is a critical safety-of-life system used to benefit the public and provides weather forecasts for many news broadcasts. NEXRAD must coexist with the 400 or so radars that operate in the 2700–2900 MHz band. The international radio altimeter band at 4200–4400 MHz is used by the aviation industry to prevent collisions with ground.… The Microwave Landing System (MLS) band at 5030–5150 MHz is undergoing some change right now. In the U.S., we are exploring using airport local area networks in that band. The airborne weather radar band at 5350–5470 MHz and the two airborne Doppler weather radar bands at 8750–8850 MHz and 13.25–13.40 GHz were assigned in response to the 1985 aircraft accident in Dallas Fort Worth, where the Lockheed L1011 encountered a microburst which resulted in an aircraft accident. TDWR is a wind shear detection system to inform pilots of dangerous weather. It detects microbursts up to 16 nautical miles (29.6 kilometers), gust fronts up to 32.4 nautical miles (60 kilometers), and precipitation reflectivity. In addition, TDWR is used for air traffic planning and runway configuration changes when weather comes up. The airport surface detection (ASD) band and precision approach radar (PAR) band at 9–9.2 GHz is to prevent aircraft from colliding on the airport surface movement area, i.e., runways and taxi-ways, and for DOD to do precision approaches in foul weather. Finally, the ASDE band at 15.7–16.2 GHz band is used for the same purpose, airport surface surveillance.

In fall 2007, we started receiving reports from San Juan Puerto Rico TDWR that there were interference jam strobes being displayed on the weather products (see Figure 61). Local systems technicians and the Terminal Weather Surveillance Group eventually concluded that the noise that was interfering with the radar was external to the radar. It took quite a long time to figure that out. These systems are put in the field and the hope is that they work perfectly forever, but they don't always. That's why we have maintenance and system technicians. The interference was described as voids in the weather data, which concerns the FAA because the weather phenomena to be detected are relatively small and are easily masked by these jam strobes. The microburst that caused the Delta flight 181 in 1985 to crash was less than 2 nautical miles (3.7 kilometers) in diameter, so you need to have a good-resolution, interference-free product in order to detect these weather phenomena. The investigation expanded in early 2008 to confirm that the RFI was external to the radar, and we began to suspect that it was DFS 5 GHZ U-NII devices. The FAA, in conjunction with NTIA and FCC, went to Puerto Rico to continue the investigation. I'll let Frank Sanders talk about those tests.

Sanders: Along with John Carroll, Bob Sole of NTIA, FAA personnel, and the local FCC people in San Juan, we did a methodical study of the interference that was coming into the TDWR. The first thing that we needed to know was the types of signals that were causing the interference. The second thing we wanted to know was the location of the source transmitters. The third thing we needed to know was identity of the source transmitters.

The first problem was resolved by directing the radar beam to each azimuth where interference occurred and looking at the IF output in the time domain. Nine times out of ten, we found that the signals were either 802.11 or else were frame based. That was consistent with being from DFS capable 5 GHZ U-NII devices because those are the protocols that those devices use. The tenth case, by the way, turned out to be noise that was being transmitted by a cruise ship in the harbor and that was a completely different issue. Also, some of the azimuths had interference at lower levels where the blank out zones were not being created but weather data were being lost and nobody knew it. We established that by rotating around the horizon doing a preliminary survey. For each of the interference azimuths, we then moved up to the RF stage in front of the front end band pass filter and looked through the low noise amplifier at the interfering signals. We found that some of the signals were co-channel to the radar. Other signals were operating on channels that were adjacent to the radar's frequency, but the unwanted or spurious emissions from those signals were at a high enough amplitude to cause interference.

Following that, FCC personnel in San Juan moved out across San Juan and located places where the transmitters were in fact operating. We took advantage of the highly directional weather radar antenna and Google Earth to search azimuths from the radar site for high towers or rooftops. Those high buildings were good candidates for where interfering transmitters might be located. We did find a number of interfering transmitters in San Juan. We noted the model numbers and types of those transmitters and discovered a rogue device that had been illegally imported. Other devices we found were in fact legal, i.e., they were FCC certified. When this was discovered the FCC halted certification of 5 GHz DFS devices immediately.

We then moved our efforts from San Juan to the Mike Monroney Aeronautical Center in Oklahoma City where the FAA has an engineering TDWR that is not part of NAS to do testing of DFS devices under controlled conditions. Here, we performed a radiated experiment where a number of DFS devices were put on a rooftop two miles (3.2 kilometers) from the TDWR. Under controlled conditions, DFS detection was tested and interference levels that caused TDWR interference was measured. We discovered that:

- Five of the seven DFS devices tested detected the radar and moved off frequency as they were supposed to; two of the DFS devices did not. Since these field measurements ITS has worked to identify why they had passed FCC certification testing but were not in fact detecting actual TDWR signals in the field.
- DFS devices caused interference to the weather data when the interference was 8–10 dB below the radar's internal noise floor.
- 30 MHz of off tuning was needed to completely mitigate interference. DFS rules did not have an off-tuning requirement—they stated that off-tuning must occur but did not specify how many MHz. That's because devices had not been built when the rules had been written, so rulemakers did not know what the DFS spectrum would look like.
- A single DFS device can cause many wedges of interference all around the horizon because its energy couples into the antennas sidelobes in addition to the main beam. The good news being, resolution of one interfering source may clean up several interference wedges.

Tourigny: Thanks, Frank. In the interim the U-NII devices were halted, penalizing both DFS manufacturers doing the right thing in addition to the DFS manufacturers that had done the wrong thing. Obviously, that is not ideal. The FAA has an established process for introducing new equipment to NAS without causing interference, and I believe there is a way to go through that process to ensure that there aren't any unmitigated risks introduced to the safety of the NAS. If you want the FAA to change the NAS by moving equipment or using spectrum differently, I would recommend considering the FAA mission. Ask how that change would affect the FAA mission and service. It's not just a question of us changing, but what is the incentive for change? How does it make the NAS better? How does it make the efficiency and regularity of flight better? Thank you.

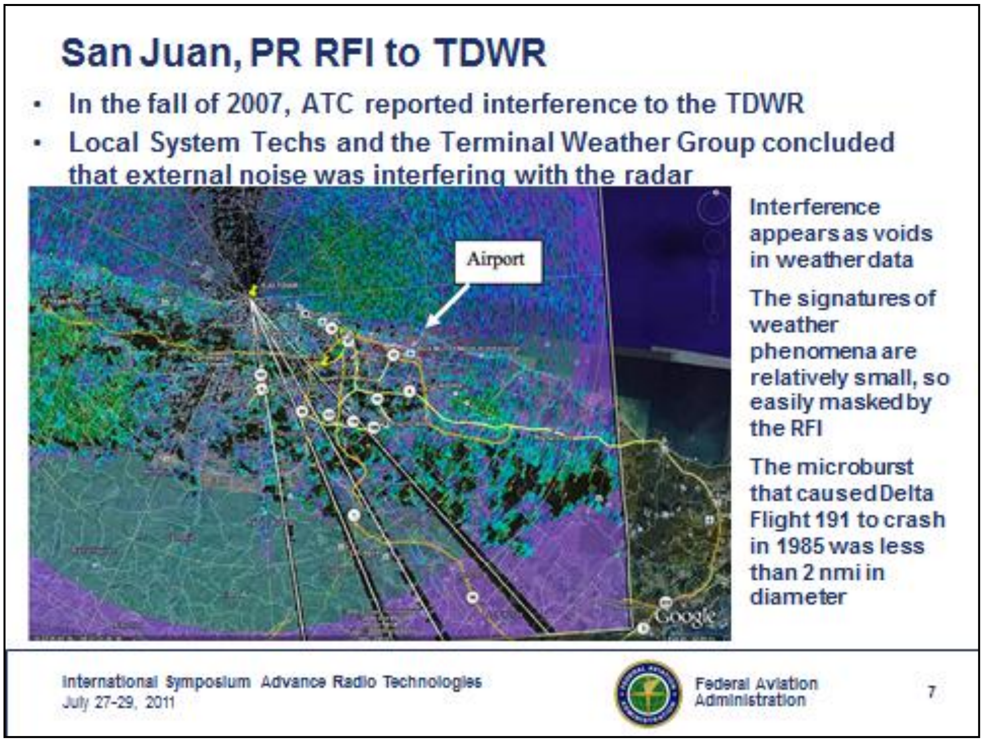


Figure 61. Example of RFI interference to TDWR from U-NII DFS devices.

7.2.5 Jaewoo Lim, Korea, KCC/RRA

My name is Jaewoo Lim, from Korea Radio Research Agency, and frankly speaking I am not a radar expert but I am a spectrum manager. For more than ten years, I have been involved in a number of projects dealing with spectrum-sharing policy and regulation, including for commercial and government radio services, including radar systems. Today, I'd like to talk about the 5 GHz radar interference issue and the HF Ocean Graphic Radar (OGR) issue.

The Korean Communication Commission (KCC) manages the radio spectrum in Korea. KCC is a single government body for the regulation and policy of spectrum in the commercial sector as well as the public sector. KCC's mission is to promote usage of spectrum for industry as well as manage the spectrum used for national defense. The Radio Research Agency (RRA) conducts research like NTIA/ITS in the U.S. Around 2000, RRA started developing an advanced radio management system, and today we use this system to solve interference issues in Korea.

With the popularity of the smartphone, Wi-Fi providers had to expand to satisfy their customer needs. Data traffic increased about 20 times over three months in certain Wi-Fi zones. The total number of access points has increased to around 600 million. The usage of the 2.4 GHz band is so congested that within five years it will be increased dramatically. WRC-03 allocated the bands 5150–5350 MHz and 5470–5725 MHz for RLAN. However, the band 5650–5725 MHz was not identified for RLAN in Korea due to concerns of broadcasters. With the rapidly increasing needs for RLAN, however, further considerations on this band were needed.

Sharing scenarios between radar and 5 GHz RLAN were analyzed experimentally and theoretically. We found that DFS was only one solution, and it had its problems. We must do further study for this coexistence issue. Moreover, I believe that the best solution would be to cultivate trust among users of different devices. Trust and sharing needs to work for both sides. Possible solutions to enable a spectrum sharing include:

- Guidelines for users who deploy Wi-Fi access points
- Update the regulation and the certification procedure
- Spectrum rearrangement
- New mitigation technology

HF oceanographic radar spectrum will be defined at WRC-12 next January. The oceanographic radar can monitor the sea environment, such as a tsunami or oil spill over. Figure 62 shows the 17 current OGR stations operating on the Korean peninsula on an experimental basis as well as the future deployment plan for 50 long-range and high resolution OGR stations by 2020. Spectrum occupancy measurements showed that frequencies above 20 MHz should provide sufficient quiet frequencies within existing allocations. However, below 20 MHz, careful design and site selection is required for stable radar operation without interference. Consideration of potential interference to and from neighboring countries is needed. Figure 63 gives analytical results for protection distances needed to share the 3–50 MHz band without interference. These separation distances might be less because the analysis was carried out in the worst-case scenario. We are planning further studies to find out the appropriate protection distance and will share those results with neighboring countries. Thank you.

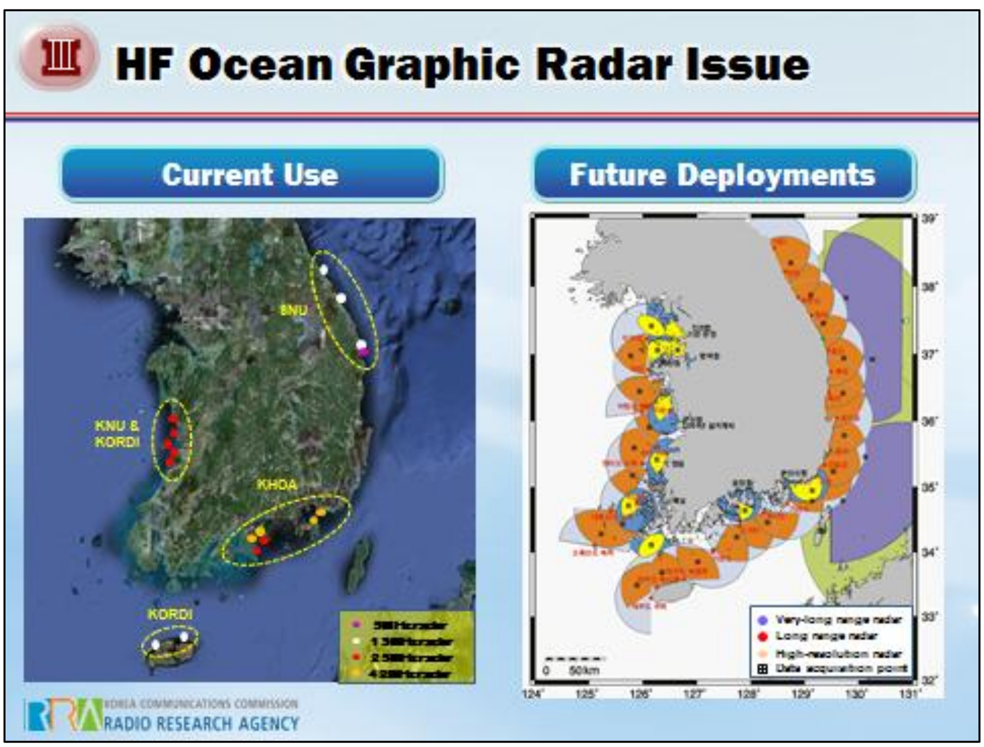
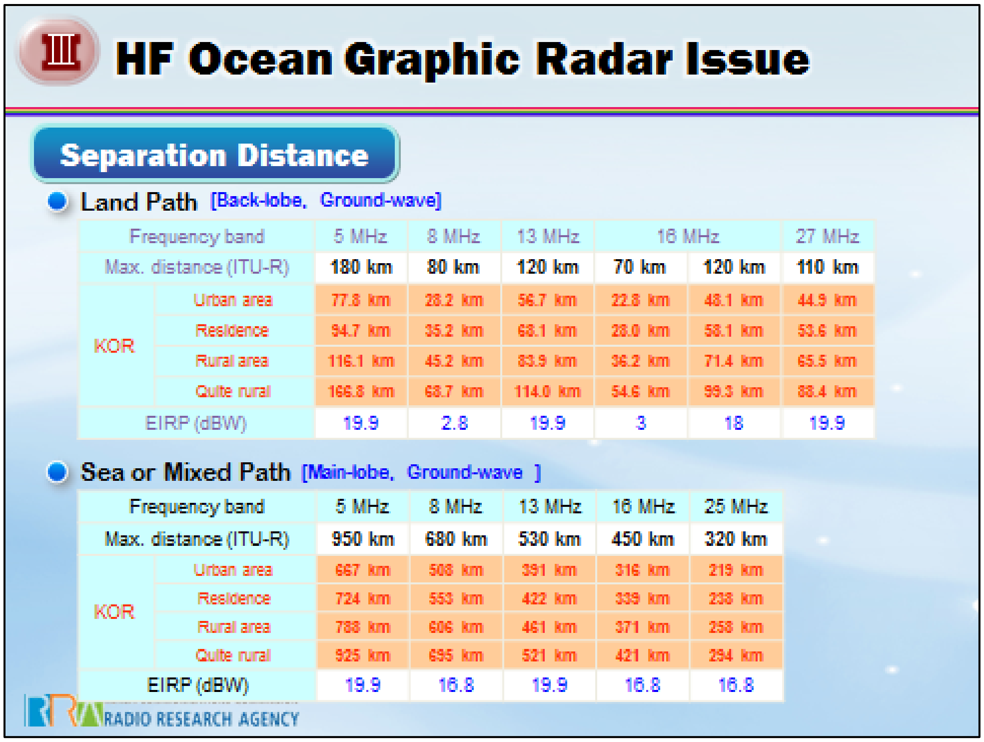


Figure 62. Current and future OGR stations in Korea.



HF Ocean Graphic Radar Issue

Separation Distance

Land Path [Back-lobe, Ground-wave]

Frequency band		5 MHz	8 MHz	13 MHz	16 MHz		27 MHz
Max. distance (ITU-R)		180 km	80 km	120 km	70 km	120 km	110 km
KOR	Urban area	77.8 km	28.2 km	56.7 km	22.8 km	48.1 km	44.9 km
	Residence	94.7 km	35.2 km	68.1 km	28.0 km	58.1 km	53.6 km
	Rural area	116.1 km	45.2 km	83.9 km	36.2 km	71.4 km	65.5 km
	Quite rural	166.8 km	68.7 km	114.0 km	54.6 km	99.3 km	88.4 km
EIRP (dBW)		19.9	2.8	19.9	3	18	19.9

Sea or Mixed Path [Main-lobe, Ground-wave]

Frequency band		5 MHz	8 MHz	13 MHz	16 MHz	25 MHz
Max. distance (ITU-R)		950 km	680 km	530 km	450 km	320 km
KOR	Urban area	667 km	508 km	391 km	316 km	219 km
	Residence	724 km	553 km	422 km	339 km	238 km
	Rural area	788 km	606 km	461 km	371 km	258 km
	Quite rural	925 km	695 km	521 km	421 km	294 km
EIRP (dBW)		19.9	16.8	19.9	16.8	16.8

RADIO RESEARCH AGENCY

Figure 63. HF OGR separation distances to avoid interference.

7.3 Moderated Discussion[9]

Mettrop: One point I forgot to make earlier regarding air traffic and aviation, in the U.S. these are Federal systems, or at least federally funded systems. In the UK, it's totally private. Effectively, the en-route surveillance is provided by one company, which is mainly owned by the airlines. It can be a little difficult to talk about government investment because in the UK there are 15 service providers for the airports and certain rules on governmental support of the private industry. In the 3 GHz situation, for instance, we are only looking to fund up to a prototype.

We've heard a number of issues against various radar bands and before opening up questions from the floor, I have two for the panel. First, with all of these issues, where does the responsibility for interference resolution lie and who should pay to put it right?

Sanders: With regard to the DFS U-NII devices at 5 GHz, I would emphasize that most of devices that have been fielded have properly detected and avoided the TDWRs. The residue of cases where interference has occurred, of course, has been troubling, and we've needed to get to a solution on that. We have been able to determine why the interference occurs and how to solve it. The interference occurs for several reasons.

- Sometimes the people who are operating the devices do not configure them properly. Although the U.S. regulation says that the devices may not have their DFS turned off by any control that a user can get to, there are country codes because the devices are sold

[9] Larry Cohen (NRL) joined the panel for moderated discussions and Q&A led by Mettrop.

internationally and some users have discovered that they can set the country code to not the United States and de facto turn off the functionality, even though they weren't nominally given a control over functionality. Sometimes that may be intentional and sometimes that maybe accidental. That is something that can be dealt with at the software level. It can also be dealt with by educating the users.

- We've also determined that in some cases, devices that did meet FCC certification protocols and were properly configured did cause interference. The problem in these cases has been that the certification process did not actually completely replicate a particular TDWR signal. That was intentional. That was done because, first of all, these devices are not just supposed to detect TDWR, they are supposed to detect any radar in the band and basically the U.S. government doesn't guarantee that the parameters of radar are going to remain fixed in time. That said, the take-home lesson has been that new certification protocols are being put in to place that do include some actual TDWR parameters mixed in with other radar type signals and we have a high level of confidence that devices that pass this future certification testing in fact will properly detect and avoid the radars.
- The third take-home lesson was that although detect-and-avoid had been written into the rules, nobody had ever been able to determine how much off tuning would be required when a device had been detected and avoided. The reason was that no hardware had been built when the rules were written and that is a chicken and egg problem, one or the other comes first. Now that we do know what the devices' emissions spectra look like, we now know how much they will need to off tune.

The good news is that all of these problems can be fixed at the software and hardware level. As for who pays for it, the U.S. government has sunk a lot of resources into understanding and rectifying the problems and this is what it costs to move new technologies forward in some cases. The manufacturers, for their part of course, have responded by doing some redesign work on their devices. Lastly, I would add that the Wireless Internet Service Providers Association does maintain a website that provides information to the wireless users as to the locations of the TDWRs and allows users to take additional steps to ensure that they don't accidentally tune onto those TDWR frequencies. In other words, a sort of geolocation-based and Internet solution, which I would also add, won't necessarily be possible to implement for other systems in other bands but it did work out for the TDWR.

Tourigny: I'll just make a quick comment on the burden. The taxpayer burden began on the day that we first saw the interference, and it continues to today. There are still emitters in San Juan and throughout the country that pop up here and there that interfere with the TDWR. Now, the taxpayer burden is in the form of FAA support and FCC enforcement; it is actually paid for by the wireless industry and every other industry in the United States through sales taxes, service taxes, and so on. So, I guess the burden is all of ours because we are all paying for it. Now, my mitigation to that is, if we spent more effort and time upfront, before devices are fielded, then TDWR would have actually been a very easy band to prevent this from happening. This is because you are only dealing with one system model. If you start looking in S band or L band, you are dealing with up to a 100 models of systems (each with its own mission). TDWR has one mission, well a couple of missions, but they are all using a similar technology to satisfy that. It seems that would have been the easier one to do, to put the burden up front to ensure that the interference wouldn't be present. Now, the industry people in this room are probably not the ones that caused the problem. It's probably those that are not listening to everyone else and collaborating that really caused the problem. So, with that said my message is, if we put the burden on everyone and we put it up front, the end result will be much better.

Cohen: If I look back over my career, 30 plus years, most of what I have done has been fixing problems after the fact. There have been very few occasions where way in advance I have prevented a problem, I can only think of a couple of cases. But everything has been due to the fact that somebody way higher up than me or people working in other DOD agencies have not been aware of what's coming down the line. And I think, just speaking for the DOD community, we've got to become more proactive in terms of getting more involved with the IEEE specs and standards committees of the various societies and become actively engaged and that is the only way that we are going to get a sense of what's before us.

Mettrop: After the 5 GHz issue, I've learned that what some people will call "the dumb public" are actually quite ingenious when they want to be and get around what we put in front of manufacturing to make sure they comply with rules. As far as the 2.7 GHz WiMAX issue, we've learned a number of lessons and a number of people, in all parties, have some part to play in it. The older type radars are probably the only ones that took into account what was in the adjacent band, and at the time of the design were actually working. The newer radars (installed in the UK after 2000), you could argue, have not been compliant because they didn't take into account the WiMAX/LTE that were coming in the adjacent band. Radar manufacturers have had some issues. Those who are actually procuring the radar systems should have worked more closely with their regulatory departments in order to pick up on the necessary requirements. If they had put it in the specification, then the manufacturer might have picked it up. Regarding the WiMAX/LTE community, after looking at the designs, they are pretty close to solving the spurious emission problem. Our interest is to make sure that we all learn the lessons and resolution of these issues is paid for once and not paid for multiple times. In this case, the UK will be picking up quite a bit of the cost. Whatever we do should be available to everyone else, and they shouldn't have to pay for the R&D.

Larry, perhaps in this area where we are moving on, I think there is a NATO project that you're involved in that you may want to say a little more about?

Cohen: Yes. A year ago around July 5th of 2010, I held the first NATO Sensors & Electronics Technology Panel on spectrum engineering and management. We did this over a video link with colleagues in France and the UK We defined an agenda, and I used that agenda to formulate a set of documents for NATO which summarized the activities of the panel. The expressed purpose is to meet twice a year with experts of the radar community from the different NATO countries (five members were present at the first meeting). Each participant was well versed in the radar-related disciplines of signal processing, waveform diversity, solid state and tube amplifier design, specs and standards, and measurements, as well as cognitive radar. I host this panel with Prof. Hugh Griffith who is a professor of Electrical Engineering at University College in London; Hugh is a world-wide expert in bi-static radar. We held our first meeting in Paris, June 16th and 17th this year, and we defined several areas with which to work. We are growing; for those that are interested in participating at future meetings, please email me or my boss Eric Mokole. We can provide the necessary information because there is a paper trail that you must complete and be accepted by the NATO committee. Next meeting is scheduled for November 2011 time frame at NRL.

Mettrop: Before opening it up to the floor, I want to make a couple of points. First, we need to cooperate, not just within states (both large and small). I think we need the whole community to work together, given that funding for R&D is at a premium at the moment because most governments are trying to cut back. Other than defense, it does in some ways come down to economics—even in aviation. We can turn it into an economic issue because spectrum management change has cost implications associated with bringing the system back to a safe state. For instance, Heathrow normally operates about at 48 movements per hour for landing and 48 for takeoff. If 33 movements per hour were lost (for safety precautions), the airlines estimate that to be worth about 3 million pounds. The value to the UK aviation industry is around 60 billion pounds per year. To give some context, Ofcom estimated the value of commercial spectrum use to be 40 billion… The main thrust in aviation is to maintain safety. We won't let that be compromised, otherwise I'm going to be the one in court answering the questions of why did I sign it off.

7.4 Q&A

John Atwood, MITRE: With regards to interference, can you suggest enforcement technologies, techniques, or methodologies against either accidental or rogue interferers across national boards? Internal to the country is one thing, but going outside, that's even more of a challenge.

Sanders: The U.S. has the luxury of only having two neighbors—Canada and Mexico. We do have special agreements that work along our borders for how we enforce spectrum regulations. The U.S. also has worldwide operations, e.g., U.S. Navy. In cases where interference occurs, there are existing protocols for communication between foreign administrations and the U.S. administration via, for example, the FCC's International Bureau. We at the NTIA lab here in Boulder have looked at data from foreign administrations and sent feedback on what we thought was going on. As far as actual enforcement actions go, I really wouldn't have anything that I could contribute from the NTIA perspective. It's more a matter, from our perspective, of looking at the engineering and trying to come up with engineering analysis and solutions.

Mettrop: Maybe I'm in the best position. Overall, we rely on the international regulation and on compliance with that regulation. Globalization, in way, helps us because makes wireless products more standardized and consistent. One big problem we face is someone buying a device on the Internet, bringing it into the country, and using it without necessarily knowing what the rules are. Home wireless surveillance cameras, for example, have caused problems in the UK in this way. It takes a lot of effort to chase the problem. For enforcement, there is good cooperation, at least within Europe. There are a number of listening stations that cooperate. In aviation, a cable television system in Germany was causing interference to France. That one got chased down and the cable system dealt with it. There is the cooperation out there, but we in Europe try to get the regulation right before it's fielded rather than actually chasing it down after it's been fielded. We put a lot of effort into the up front area.

Hal Grigsby, U.S. State Department: One of my primary responsibilities is what the U.S. and Mexico are doing in telecommunications. I'd like to add to what Frank just stated. The U.S. and Mexico have a set of bilateral agreements that were negotiated, led largely by the FAA and their Mexican counterparts, SENEAM, and put in place in the 1980s. They are online. They cover a number of the bands that you've been talking about—both radars and aeronautical communications and so on. The FAA and SENEAM coordinate frequently to conform to those. In the area of other types of cross border interference between the U.S. and Mexico, we have a joint commission on the resolution of radio interference. This is led, in the U.S., by the FCC's Enforcement Bureau and within that bureau the field offices along the common border on the U.S. They work directly with zone coordinators on the Mexican side all along the common border. That organization was put in place in 1982. They hold annual plenary meetings and meetings out in the border zones on a continuing basis. They have dealt with anywhere from 30–40 cases of interference per year to up to 150 cases per year (in the mid-90s). Those have included the aeronautical services. With Canada, we don't have a bilateral organization like we have with Mexico. It's much more localized but there is a similar amount of activity between Washington and Ottawa and with the agencies concerned.

Tourigny: When I was working with frequency assignments, we worked closely with Industry Canada and NAV CANADA. I don't know what the vehicle is that we were working under; I believe it was negotiated through NTIA/OSM. In addition to vehicles and processes, it is important to have people within the process be of adequate caliber to make those processes work. Agreements might be in place, but if the appropriate people (with connections across the border) are not involved, then the agreements are ineffective. When I was working frequency assignments, I had two numbers: one for NAV CANADA and one for Industry Canada. Industry Canada is their radio regulator and NAV CANADA is the air traffic provider. If we were to have an issue somewhere along the northern border, I knew who to call. In addition to the process, it is the people within the process that are important in spectrum management.

Robert Sole, NTIA/OSM: Another issue worth mentioning is wind turbine interference with radars. People are spending money to help fix that problem. My view is that the two groups, i.e., engineers evaluating wind turbine interference and engineers evaluating broadband interference, ought to get together to solve both problems together. I also wanted to mention that NTIA has two reports on the DFS problem in San Juan in the 5 GHz band. The second report was made available today.

Mettrop: Yes, I fully agree. Radar operators are responsible to pay for the WiMAX fix. They are already responsible for mitigating the wind farm interference. There is also some movement toward changing frequencies to clear some spectrum out. If we could get those programs together it might be a bit more acceptable.

Tom Kidd, Navy/Spectrum Policy, IRAC: In recent years, we've seen a trend to get away from worst-case scenario analysis, because it often leads to inefficiencies. It often leads to big margins. Except, here is a scenario where we didn't over-think it, and we didn't go to worst-case scenarios. We didn't look under every rock, and it came back to bite us. I would like to hear the panel's thoughts on this dichotomy of

- Do we try to solve the problems up front by engineering things out to the nth degree? Or

- Do we step back and set aside a little bit of funding or a little bit of time recognizing that we are not going to catch everything and so we then are ready to react and go and find it?

It would be interesting to know if we could (obviously, we probably can't), but if we would have been able to capture the cost of those two. How much money was spent actually tracking all of this down as opposed to how much it would have cost to prevent this upfront, if it even could have been prevented?

Sanders: It depends on the case. Consider trying to de-conflict systems in advance and reuse a frequency from one system to the next. Assume an ASR on a particular frequency, for example, how far away do we need to go before another ASR can reuse that frequency? There are a lot of really good propagation models to tell us what percentage of time interference thresholds will be exceeded for another radar located some distance away. The problem becomes, how many miles away is good enough? There is a tradeoff in terms of the safety that the radars are supporting versus the fact that we are going to use more spectrum. My bottom line thinking on that is, this is the kind of problem that computers do not do well on. It is the kind of problem that human beings have to think about a lot in trying to weigh the cost versus the risks and everybody does the best job that they can, in my experience. However, it doesn't always come out in the end with the result that people wanted and sometimes adjustments do have to be made after the fact. On the other hand, I can say that when people look at frequency assignments and say "Gee, you are not using a radar system for 500 miles. That just seems over conservative." However, if you dig down into the history, you will find that at some point they tried to not have such a large separation and learned that it didn't work well, so they backed it off. About a generation or so later is when the people with that historical knowledge went away and other people revisit the same problem. Hence, it's important to maintain as much historical, legacy knowledge as possible inside organizations. We try to do this in NTIA. Knowing that none of us are going to be here forever, we document as much as possible: how decisions were arrived at, what the decisions were, etc. With historical documentation, people in the future can see the material and hopefully conclude "Oh my gosh, we don't want to make that mistake again!"

Mettrop: In the CAA, at least in the spectrum area, we record the question asked, options considered, decisions, and why. Otherwise, corporate knowledge is lost. I would suggest a combination of theoretical analysis and field measurement. I've never seen a system where you don't learn something when you field it. Therefore, we've got to look at loading it with a little more practical testing. Be realistic about protection, and I think aviation may have been over conservative in the past, as it is a natural reaction, when someone is coming towards you in spectrum terms. Let's be realistic, not necessarily use the totally worst-cases. Then spend some money going out and actually testing with real systems. Once we're confident with it, then we deploy it. We spend too much time now doing straight theory and reacting to problems we never accounted for.

Beau Backus, Aerospace Corporation: I had a question that is follows on to what you were saying about field-tested equipment. There was a situation that occurred with the NEXRAD radar and Wi-Fi. Sort of a classic radar versus communications system interference problem. What are the panelists' thoughts on a resolution to the type of situation where both systems are appropriately fielded but there is interference? And how would you go about resolving it? Secondly, what kind of timeline would it take to resolve it?

Mettrop: We would see the NEXRAD situation being very similar to what we've seen against the ATC radars. The NEXRAD probably has some better adjacent band rejection. It comes down to both sides not considering the characteristics of the other system and taking them into account in their design. Let's not fool ourselves; UK, Belgian, and French studies predict that WiMAX/LTE will suffer from the radar as well. So, better cooperation might deal with it. In what time frame? Once we got past the blame game and got down to sensible engineering, we reckoned that it was a two year process, and that's with a full government push for solution installation. How long the solutions will take and in what order? We are trying to agree on that. Whoever wins the auction award for WiMAX/LTE will dictate installation priorities. If it is to roll-out in NEXRAD area, the NEXRAD solutions will be installed first. I emphasize, that's with government funding. If it were to the radar industry, we would be sitting in the UK court because those radars are owned by smaller companies who cannot afford to do that kind of work and put that sort of money into it. It just so happens there is pressure because the government feels that it can get money out of the auction.

Tourigny: We have members of the National Weather Service Radar Operations Center right in the room today. They are actually the ones who brought it to our attention, and they can talk about impact on NEXRAD. I'm representing the FAA. We partially paid for the product, and we use the product in the aviation industry. We did do a test in Jacksonville and in Grand Rapids that Frank might want to talk about.

Sanders: Given time constraints and other issues, I won't address the particulars. This audience is most interested in the overall view. The overall take-home lesson here is that when we are looking at reusing and reallocating spectrum, engineers and policy makers need to concern themselves not only with what is going on inside a band (co-channel issues), but also with adjacent band issues. Bands that have been historically and relatively quiet with sensitive receivers, and in which the introduction of higher-powered transmitters is being contemplated, need to be examined in terms of what is going on in adjacent bands. That analysis should be part of the process of looking at how spectrum is reallocated, refarmed, reused, whatever.

Mettrop: We need to get the spectrum back from the economists and back into the engineers' hands. (laughter, applause). Economists can show us what it is worth; they have nice narrow pencils that can draw the border line that allows high-power systems to operate adjacent to sensitive systems. Engineers understand the need for finesse. I want to close with a comment from the former head of the French Radio Regulator at a briefing in Europe about economic regulation of spectrum. He said, "I regret that I am too old to benefit from this because when you economists have messed up the spectrum, our spectrum engineers are going to be worth a fortune to put it right." For radar, I chair ITU Working Group 8B. We are always open to have these sort of the discussions, and I would encourage that. Thank you.

8 RADAR R&D PANEL

The goal of the Radar R&D Panel was to discuss a technological roadmap to next generation radar that achieves greater utilization and leveraging of emerging radio technologies. In the session overview, Joe Guerci established the challenges/constraints that currently exist for radar and listed a number of potential radar technology enablers. With that framework established, panelists drilled down into specific areas during opening remarks. Areas covered, and the panelists addressing each area, were:

1. Cognitive Radar—Dr. Joe Guerci (Guerci Consulting)
2. Spatio-temporal Waveform Agility and Adaptive Antennas—Dr. William Melvin (GTRI/SEAL)
3. Simultaneously Reconfigurable RF Circuitry and Optimizable Waveforms to Meet Spectral Mask Requirements and Maximize Power Efficiency—Dr. Charles Baylis (Baylor)
4. Multi-band, Multifunction Radar—Dr. John Cho (MIT Lincoln Laboratory)
5. Developing Radar to Share Spectrum—Dr. Preston Marshall (USC)
6. Radar/radio Cognition—Dr. Joseph Mitola III (Stevens Institute)
7. Building Green and White Radars—Dr. Marshall Greenspan (Northrop Grumman)

During the Q&A session, panelists drilled out to identify steps/technologies to solve the spectrum shortage/crowding problem.

8.1 Introduction by Session Chair Joe Guerci

You should enjoy this particular session, because I think you will walk away with a sense that there are a lot of technologies being worked on that could play a role in the spectrum crowding solution. As you've heard, one of the bigger problems is getting the funding to move these ideas and technologies forward as well as getting the "buyers," particularly in the military radar community, to require these technologies and require modes of operation. I'm going to reiterate some of the things I said earlier today about how we can move forward on that. I'm also going to spend a little bit more time on a particular technology, cognitive radar, and discuss how that differs from cognitive radios. The rest of the panel will dig down into other radar R&D topics that they are experts in.

The following is a list of constraints and challenges specific to radar systems:

- **Radar transmitters are more powerful than most communications systems** (often more than a gigawatt radiated power) making them a potentially greater source of interference.
- **Radar receivers are more sensitive than most communications systems** (e.g., receiving 1/100 picowatt of echo energy from targets at 80 miles range) making them more vulnerable to interference.

- **Airborne radars exacerbate the above given their panoramic view and line-of-sight range** exceeding 200 miles (322 kilometers) (covering 120,000 square miles (310,800 square kilometers) of area).
- **Radars require relatively long periods of useable spectrum.** Some SAR radars require many seconds of uninterrupted spectrum availability.
- **Current radars are highly restricted with regard to waveforms.** In general, radars use pulsed signals to localize objects in space and require high power to obtain detectable echoes. More modern, lower-power radars usually need to pulse but use phase or frequency modulation to compensate for low transmission power.
- **Security constraints associated with government radars.** Some are classified, and many unclassified radars cannot have their frequencies and locations made available in public listings.
- **Radar systems have long development times.** Modern communication systems (especially commercial wireless) have rapid development cycles (a couple of years at most) compared with radar (decades). This makes it difficult to modify and evolve radars in a timely fashion.
- **Changing radar bands can degrade capabilities.** Radars bands are selected to take advantage of atmospheric propagation effects for the accomplishment of specific missions.

Any list of differences between radar and comms is going to be incomplete, so don't get upset if you don't agree with the above list—it's just to provide a basic basis for comparison. So let's keep that context in mind. I think there are ways that military radars can be good for RF citizens. I think there are technologies that are dual-use that help in electronic protection and also help in the electromagnetic spectrum sharing, but this is a different world than FAA or civilian radar applications.

I'm going to spend a little time talking about the technology solutions presented in Table 4 to motivate the panelists.

Table 4. Potential Technology Enablers

<table>
<tr>
<td rowspan="2"><u>Novel radar architectures:</u>
• Passive radar using signals of opportunity (cooperative or not)
• Bi- and multi-static radar (transmitter can be separated from the receiver)
• Cognitive radar, e.g., novel control architectures, computational intelligence, cooperative architectures in which radar and other systems communicate
• Multifunction radars that integrate disparate radars into a single system</td>
<td><u>Novel radar hardware (H/W):</u>
• More agile (e.g., "digital") front-ends
• Wide- and multi-band antennas
• Greater spectral purity</td>
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<tr>
<td><u>Novel radar signal processing:</u>
• Adaptive waveforms (channel adaptive) & MIMO
• Compressive sensing and sparse signal reconstruction
• Space-time polarimetric coding</td>
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Passive radar has been around since the beginning of radar. Indeed, one of the first inventions in radar was brought on when it was noticed that radio waves were interfered with when ships traveled by. It's still around, there are deployed systems. Bill Melvin and Georgia Tech did a study for me when I was still at DARPA called Total RF Detection and Ranging (TORDAR). The idea was to use whatever emissions are available in an environment, passively, and only radiate to fill in emission holes. Those kinds of things are still out there. Multi- and bi-static radars are where the transmitter is significantly removed from the receiver. The separation can be many miles; in fact, the transmitter could be in space. The idea is that they are more cooperative, because the transmitted signals are known, it's not signals of opportunity. If you can arbitrarily place a transmitter in some judicious location that can significantly reduce interference problems, e.g., a mountain can be between you and the things you don't want to interfere with nor see. There are a lot of possibilities there. Multifunction radar is also a very hot topic in radar research these days; in fact, there are a lot of folks who ask, "Why don't we just do simultaneous communications and radar sensing?" Military radars are useless by themselves, because they have to share information. Combining the radar sensing and communications functions into one system is a significant area of research. A lot of these techniques are not mutually exclusive, i.e., they can be combined. Systems engineers trying to get the best solution to meet requirements at the lowest cost will take a little bit of this and a little bit of that, not just one silver bullet.

Hardware has been a big area in radar R&D. You've heard from Charles Baylis and Larry Cohen on spectral purity and adaptive waveforms trying to minimize a number of interfering effects. There are also advances in waveform generators and solid state amplifier devices, which allow for a wide diversity of transmit waveforms. If those hardware advances are coupled with the novel radar signal processing techniques, there is a whole new realm of possibilities. For example, instead of having a contiguous band of frequencies, snippets of bands can be combined to form a sparse frequency representation (or a sparse antenna representation, depending on the implementation) that produces meaningful data products, e.g., SAR images. Compressive sensing is a novel signal processing technique that has recently come to the fore, where if there is a priori knowledge that the signal or the object has a sparse representation then there are algorithms that can estimate or reconstruct the object from a sparse sampling. People have demonstrated this in the case of SAR imagery, where significant chunks of pulses have been eliminated from the SAR coherent processing interval and the missing data can be filled back in. Finally, space-time polarimetric coding is just a euphemism for any and all degrees of freedom (DOF) related to radar, e.g., time (fast and slow), space (polar and metric), code (e.g., CDMA).

There's no shortage of technologies out there that have the potential to help with the crowded spectrum problem. Starting back in the late 80s, my work in radar was focused on architectures and adaptive waveforms. Two decades of work in a variety of areas culminated into the concept of cognitive radar. As described in Figure 64, cognitive radar combines unprecedented sophisticated adaptivity of both receive and transmit functions. Adaptivity on the transmit side means the transmitted waveform is a function of the channel. This concept is new to the radar community. With these new DOFs available, we were able to go back to the drawing board and derive optimum transmit waveforms; design equations are given in [44]. Couple that kind of waveform adaptivity with real-time access to, and exploitation of, heterogeneous databases and functional models to estimate current position(s), locations of cell towers, geography, propagation effects. These are examples of knowledge-aided processing. Cognitive radar acts and looks a lot smarter than traditional radars, and that is a big area of activity these days. The spectrum-crowding problem is barely mentioned in [44]. This kind of architecture is really useful for complex cluttered environments and interference environments, which is good news because there are other reasons to be moving in this direction besides just spectrum crowding.

I'm going to return back to my practical side for a moment. We've got major military radar systems with program offices, line items, and budgets. To create a whole new program office to try to make radars more compatible with the electronic spectrum is an uphill battle, especially given the current budget situation. Military radars already have electronic protection (EP) requirements. I'm not going to say they are well-funded, but there is a mechanism there. I really would encourage people to think about the possibility of using the existing acquisitions structure, but putting into EP new criteria and new requirements that relate to this issue of sharing the spectrum. It would be easy to break that down into categories of operations, e.g., peacetime, overseas, quasi-cooperative, and war-time.

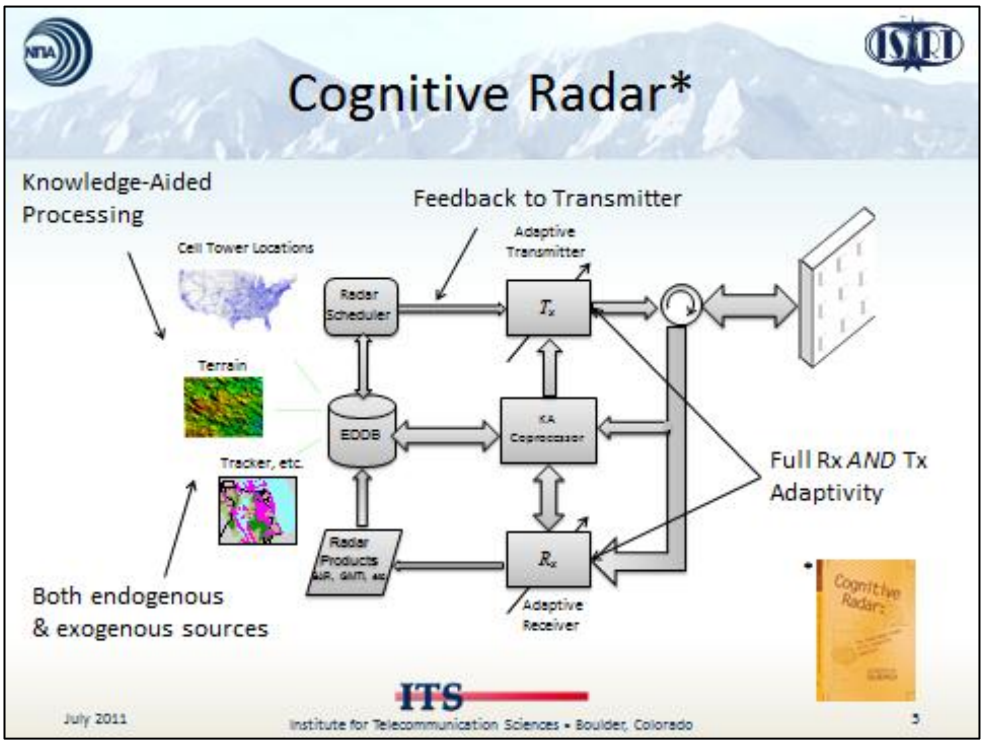

Figure 64. Cognitive radar.

8.2 Opening Remarks from Panelists

8.2.1 William Melvin, GTRI/SEAL

Joe asked me to give some thoughts about spatial, temporal, and waveform agility, and adaptive arrays. His guidance was to drill down and share some of my ideas and then maybe drill out and suggest some ways that we can go about pushing forward. Before I do that, though, I'd like to make a few comments about some things that I heard today. First of all, one of the things that came across was this issue of trust, which I found pretty interesting. Usually trust, or lack thereof, deals somehow with communication, and the way we can share information in this case is through technology. Technology is going to provide the solution.

It seems like we are really at the forefront where there is a lot of conjecture, and we really haven't dug in. Someone asked yesterday, "Why don't we just stick all the radars in one frequency block?" That might seem logical at first blush, but when a radar is designed there are a whole array of things that need to be considered. If we took that approach, most radars would not work properly. We have to be at low frequencies to go through materials. We have to be at high frequency, because we want fire-control quality and high resolution. We can't be too high in some cases because of propagation effects. We can't be too low in some cases because of propagation effects. There are a lot of considerations. But at the end of the day, technology will provide the solutions.

This is what I believe and of course I've been thwarted a few times already in my own pursuits in trying to fix some of these problems. I mentioned the ARSR-3 and ARSR-4 and the RNSS problem. I went to some meetings, and I had a few viewgraphs and a solution. I said "Gosh! This signal has structure we know. We can just estimate the unknown parameters. We can just subtract it out and we're good." And everyone said, "That's great!" But a guy took me aside and said, "Bill, that's great, but don't expect anything to happen." I pursued this for a few months and kept hearing, "This is good, but I've been told by this guy that we're not going to fund it. We need to talk to this guy… and this guy… and this guy…" And then it went around a few times, and I realized this wasn't going to happen yet. But I'm hopeful. That brings up the second point, which is that we are not going to solve anything until we really get serious about putting the resources behind it…

Technology may provide a solution for interference problems that occur, but it costs money. Clearly, acquisition will have to change. The radar community is performance driven. We start with an Initial Capabilities Document (ICD), and we build up what the system should look like. Next, we write up a System Requirements Document (SRD), which defines the functions and drives the cost of the system. ICDs and SRDs also evaluate technology readiness level, i.e., technology must be mature enough to support the capabilities and functions described in those documents. Radars are designed with DOFs, which are used to provide the best possible performance. If that doesn't work, then the Concept of Operations (CONOPS) is changed or data collection is tweaked.

In general, radar people don't want to deal with anti-jamming until there is a problem. Hence, we have something the military worries a lot about but doesn't always want to deal with, and we are layering on top of that RFI and spectral encroachment... It will be a challenge for the radar community to not think of spectrum sharing as an EP problem, and that's probably an impediment that we have to get over. There are also challenges in system deployment and security. Maybe there is a secure protocol so that the radar can collaborate…

Finally I want to talk about the real costs. Somebody said there was $60 billion of radar spectrum. I might ask, however, if we get $60 billion by selling off radar spectrum, what's it going to cost to redesign those 1,000 radars? Will it be more than $60 billion? Unfortunately, we live in a closed system.

I'm going to drill out quickly on radar measurements as a likely key in the overall solution.

- **Adaptive nulling** can be achieved by manipulating DOFs—if a target is in one location, and the source of interference is at a different angle, then it can be nulled.
- **Signal structure** can also be used to mitigate interference. If the interfering signal is known to be a BPSK or CDMA signal, signal parameters can be estimated and that signal can be cleaned out.
- **Multi-static configurations** can use less bandwidth by leveraging spatial diversity to better locate targets and better sense target characteristics. Tradeoffs: it costs money and there are deployment issues.
- **Non-cooperative sensing** and hosting off of somebody else's transmissions to detect targets.
- **Nulls** can be placed on the transmit antenna pattern to avoid causing interference… This would require well-calibrated arrays.
- An **electronic support system** could surveil to figure out where the electronic sources of transmissions are and what the transmit pattern should be. Tradeoff: performance.
- **Collection geometry** can be utilized to reduce bandwidth by integrating over a lot of angles. That would require time and probably new vehicles, because it takes a long time (flying at 200 miles per hour) to get through a lot of angles.
- There is **phenomenology** to exploit. For example, Joe was the creator of multipath exploitation for radar, where multi-hypothesis testing to locate targets in particular locations can be recognized because the signal will come back with a particular response given the geometry and corresponding multipath signature. The same is true in compression sensing.
- **Network architectures**.

Finally, I would like to emphasize, that if people are really serious about this then we need to quantify the real issues—no conjecture—model the systems in a representative environment (e.g., Poisson distributions), and really sort that out. The requirements then would flow down to requirements documents. We should consider building test beds, coming up with blue protocols, and eventually, for radar, because of the development times, focusing on open system architecture so we can quickly field new solutions.

8.2.2 Charles Baylis, Baylor

I direct the Wireless and Microwave Circuits and Systems (WMCS) program at Baylor University... At the WMCS advisory board meeting this spring, a research subcommittee member said, "You guys working with spectrum issues need to become problem solvers…" We are aware of the economic motivations from the wireless broadband industry that have created this spectrum crisis, which is a noble motivation that will help our governments come out of some tough times. I'm really looking at this with the sense that we have the opportunity to solve this problem by using our R&D effort in a multidisciplinary sense. We are looking at the difficult regulatory issues and working toward providing technical expertise to help resolve problems.

Radar designers normally look at optimizing the circuit and the waveform of radar systems separately. DSP guys work on the waveform, and the RF people work on the circuit. Technology and theory now exist to simultaneously optimize both at this point. We have built a test bed, and eventually, we want to put the test bed functionality, one piece at a time, onto an FPGA cognitive radar platform.

I talked yesterday about transmitters, but now I want to focus on our research in simultaneous waveform and low impedance optimization. The goal is to fit signals in spectral masks at as high efficiency as possible, i.e., maximum RF power out of our radar transmitter device under test (DUT) for the DC power that we put in. The test bed configuration, shown in Figure 65, is controlled by MATLAB®, which runs a vector signal generator, Maury ATS Load-Pull Software and Tuners, a spectrum analyzer, and a power meter. The signal generator inputs a signal into the source tuner and then onto the DUT. The tuners can change to any possible passive impedance on the load and source side of the DUT. The load tuner is tuned to get the maximum efficiency or best linearity possible (or combination of both) out of the DUT. The output is split between the spectrum analyzer and power meter, and the data collected is measured efficiency, linearity, or adjacent channel power ratio (ACPR) at all possible passive impedance points, and contours are fit to the data. This takes time.

Considering cognitive radar, we eventually want this platform to run in real time. If a cognitive radar system is shifting from one band to another, for instance, the RF matching network needs to facilitate that change quickly. We don’t want to measure all of these points and fit contours to them. We want an intelligent search algorithm that will change quickly. In January, we published some work on a fast load-impedance optimization algorithm [45] that estimates the optimal load impedance from relatively few measurements. Results converged for multiple simulations with different starting impedances.

We have also worked on chirp optimization [47], where we use a piecewise linear frequency modulation instead of a more conventional LFM to meet the spectral mask criteria and to maximize flatness in the band. With this approach, tighter spectral masks can be achieved.

Lastly, I want to discuss aiding optimization utilizing Wirtinger calculus. We can understand a nonlinear system through its nonlinear network perimeters. We assume a time invariant periodicity preservation (TIPP) non-linear system, where all currents and voltages are periodic with the same period, but harmonic levels can change. TIPP parameters give change in the m^{th} harmonic at the output due to a small input perturbation at the n^{th} harmonic. Given a system’s harmonic transfer characteristics, we can determine the input waveform to achieve the desired spectrally-confined characteristics at the output. TIPP parameters are also related to output power, so they can be used to understand the system efficiency and optimize the matching circuit with turners. Recall that we want to put the load tuners on a chip being controlled by a cognitive radar FPGA platform. Hence, the cognitive radar controls the RF load impedance and the waveform.

In conclusion:

- Spectral spreading from radar systems must be mitigated, but not at the cost of system efficiency.

- Several useful design approaches exist for linearity and efficiency improvement.
- An apparent solution is in joint waveform and circuit optimization with Wirtinger calculus.
- An approach and test platform for real-time load-pull and waveform optimization is under development at Baylor University.

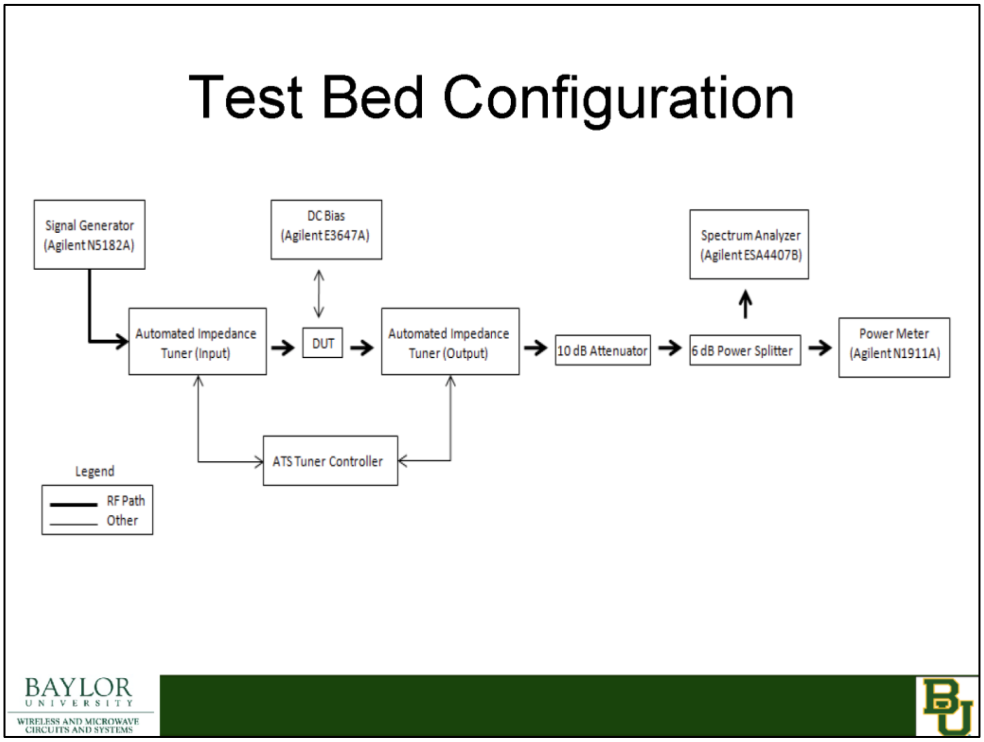

Figure 65. Waveform/Impedance optimization test bed configuration.

8.2.3 John Cho, Lincoln Laboratory

Today, I will talk about multifunction phased array radar (MPAR) [48]. My presentation is less about new radar technology, and more about a simple idea. You might recall from the inventory panel, in the continental U.S., NEXRAD and TDWR are weather surveillance radars, and ARSR-1, -2, -3, -4, -9, -8, -11 and FPS are government-owned aircraft surveillance radars. This is not a complete list but the set that the FAA (potentially together with the National Weather Service and the Air Force) is looking to replace, possibly, with the MPAR system. In some places they are densely spaced. For example, in the Washington, D.C., area you've got four TDWR, four ARSR-9, one NEXRAD, etc., and there is substantial overlap in coverage. Each system, however, has a different mission to accomplish, but that's how it is these days. Long-range air surveillance systems operate in L band, terminal air and National weather surveillance systems operate in S band, and TDWR is in C band. The simple idea is to replace all of them with one S-band multifunctional radar system, which would consolidate all the functions and eliminate 122 L-band radars and the 45 TDWR systems.

Just to be clear, there are a lot more commercial weather radars at C band. There are approximately 760 TV stations, and a little less than half of them now own their own weather radars. As an aside, TV stations typically require weather radars to have a peak power of one megawatt and dual polarization in order to claim that they have a super dual-pole megawatt system to compete with the other stations.

There are tradeoffs when moving from one wavelength to another. Long-range aircraft surveillance systems moving from L to S band experience increased atmospheric attenuation, which is compensated for by increasing power on target. In moving from C to S band, range velocity ambiguity is improved and there is less attenuation. Less angular resolution and more clutter is realized with the same size antenna, but the fact is that Lincoln Lab's original TDWR prototype operated at S band. One of the main reasons that TDWR was assigned to C band was potential conflict with existing terminal-area S-band radars.

There are a number of benefits in going to MPAR:

- Better overall coverage when MPAR is used to cover both aircraft surveillance and weather simultaneously (see Figure 66)
- Up to 36% fewer radar systems, depending on which types of radars are to be replaced.
- Streamlined operational and maintenance costs over the lifetime of the radar system.
- More graceful degradation of the phased array radar compared to the mechanically-scanned monolithic transmitter systems.
- Spectrum consolidation.

Multifunction radars already exist in the military. The main challenge is reducing cost for the initial procurement, otherwise the government won't go for it. Keep in mind that this is a high-volume production, i.e., hundreds of radars and thousands of transmit-receive modules per radar. Presumably within this sort of high production regime, economies of scale in manufacturing and test processes, developed for the wireless industry, can be leveraged.

Figure 67 illustrates a Lincoln Lab vision of what MPAR might be. More recently, we've been thinking about the spectral aspects of MPAR, and there are different issues compared to the legacy rotating dish system. Having multiple faces, for example, requires frequency isolation between adjacent faces and maybe for the front and back. To reduce cost, low peak power modules will be used, which forces long pulses and pulse compression. Fill pulses are required to cover the near-range that is not resolved by long pulses. Fill pulses will need to be separated from the long pulse, which is traditionally done by using a different frequency. There are strict Doppler-tolerant integrated side-lobe level requirements in the range for weather radar, which may require more pulse compression bandwidth. If the multifunction volume update rate cannot be met with one frequency band per face, multiple bands per face may be needed. During deployment, there will need to be a number of years when both the legacy radars and the new MPARs operate simultaneously. That is another spectrum issue. Finally, if DHS becomes an MPAR stakeholder and requires ultra-high bandwidth for target identification, spectral occupancy could explode.

There are a lot of issues in moving L- and C-band missions to S band, which will presumably increase crowdedness in the S band. The frequency space, as Joe was saying, is just another DOF, and we need to use that DOF to accomplish all required missions. Thank you.

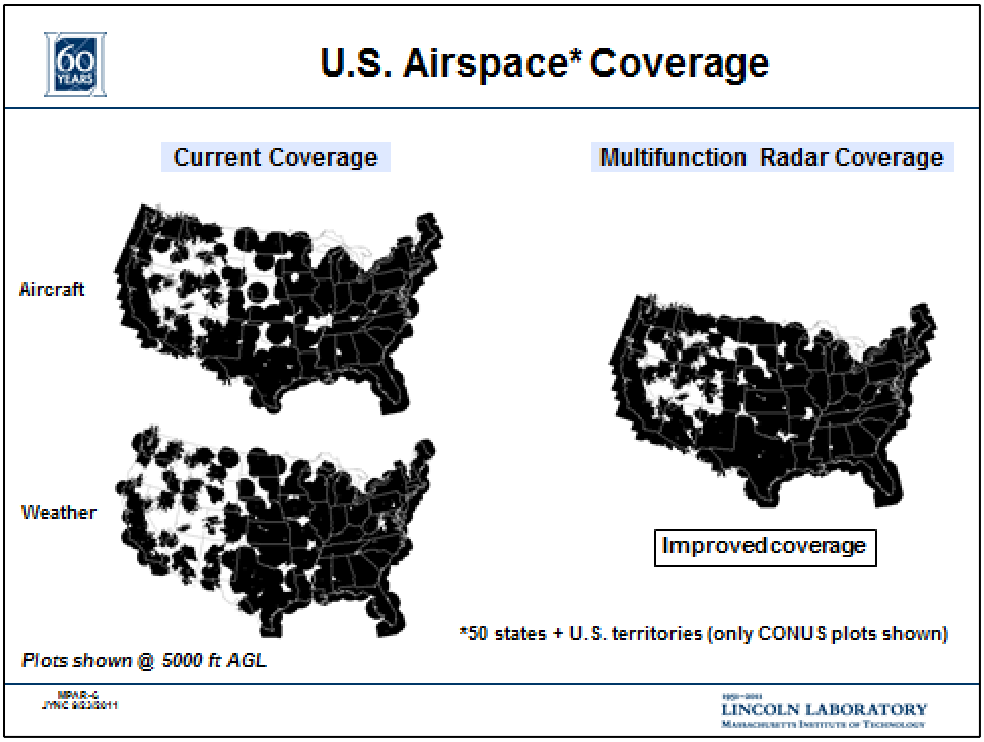

Figure 66. Improved overall coverage if MPAR replaced weather and aircraft surveillance radars.

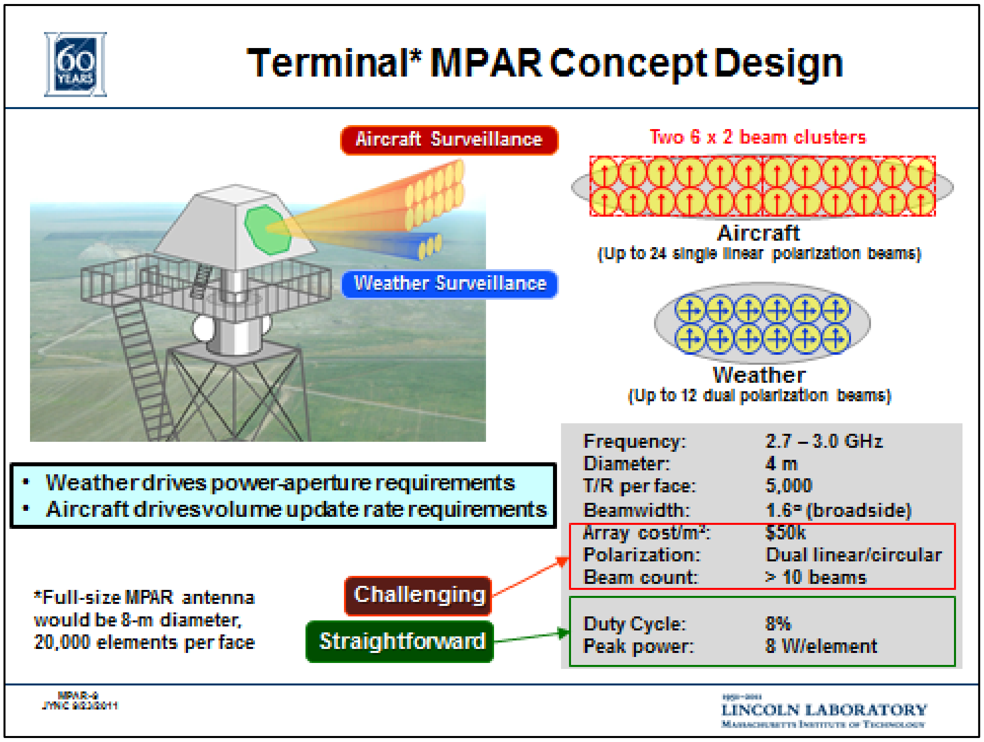

Figure 67. Terminal MPAR concept design.

8.2.4 Preston Marshall, USC

I'm not going to talk so much about a specific technology, but about a bundle of technologies that are really needed to put radar spectrum sharing on par with the kinds of spectrum sharing that we've contemplated for communications. Actually, I'm a radar guy, although I realize how bad I was. I spent years at Edwards Air Force Base, and I could never get a B-1 or an EA-6 radar to jam, and I come here and apparently anything, e.g., a light bulb, could jam a radar system. Live and learn! (laughter)

We have been somewhat successful at demonstrating that DSA is viable for some segment of the comms domain. It may not be viable in the radar domain. I want to talk about the many comparisons between communications and radar spectrum sharing and the reasons why those comparisons are invalid. Those reasons are insightful when prioritizing a package of technologies for radar R&D. I've come here and argued that if we accept a little bit of interference we can move out right now and start making meaningful spectrum sharing. I don't believe that is true in radar. I believe there is a whole set of enabling technologies, and that's really the bundle that I want to talk about.

Why is communications bandsharing unique from radar bandsharing? When we did DARPA XG, which was one of the most tremendously successful programs in DARPA's history, why did we leave radars out of it?

- **Radars are typically noise-limited, while most comms are interference-limited.** Steve Sharky (T-Mobile), at the WSRD meeting on Monday, said, "Our cellular systems are all interference tolerant by definition because their noise floor is all interference, it's ourselves." AT&T won't admit it, but they put 40% of their traffic on Wi-Fi, which is the most interfered with system in the world. Hence, comms have made this fundamental leap. We understand that we will never see Boltzman noise again. Radar guys have not made that leap, and until they do it does not make sense to start talking about DSA.
- **Radar antennas are too constraining to really do meaningful spectrum adaption.** Highly directional antennas have very limited bandwidth, e.g., 10-–20% for planar/dish/yagi antennas, whereas common omnidirectional comm antennas are multiple octaves. Similar constraints exist for amplifiers. Using comm antennas, 7,000 possible channels can be achieved for DSA. For a typical radar antenna there are 3–5 frequency choices.
- **Long lead for deployment.** No DARPA Director will fund a project that will take 15 years before the system can be tried out.
- **Highly non-symmetric relationship of comms and radars.** Comms, in general, can deal with a lot of the radar waveforms. Most radar systems, however, would have real problems dealing with comm waveforms.
- **Sensing radar signals is more complex that sensing typical comm signals.** Comms talk for a long time, radars typically don't.

Those issues lead to a set of technologies. I believe we should think about spectrum sharing not as finding 500 MHz right now to give away or share, but about a pipeline of investments that goes into technology development that gets put into fielded systems that ultimately then makes that spectrum available for sharing a decade or 15 years from now. This is a package of technologies that might go in:

- **Develop and validate waveforms optimized in the presence of various categories of comm signals.** We can no longer assume non-interference operation. The good thing about comm waveforms is that they are published, and we can build the necessary match filters to not only receive but to take out WiMAX, 4G, etc. Radar needs a toolkit not to eliminate but to live with the unwanted energy in the passband.
- **Develop out-of-band mechanisms and protocols to integrate with other band users collaboratively.** We may have to accept that the radar sharing solution is probably an out-of-band solution and de-stress sensing. We are doing that in TV white space. It's not as pretty as a symmetric sense-and-avoid, but in this case it is practical.
- **Expand signal processing repertoire as alternatives to power and bandwidth for range, resolution, P_d, and P_{fa}.** We need to think about how radar can use less spectrum, which is currently denied to the rest of the radio community.
- **Improve radar front-end performance.** Radar systems are an "easement" on adjacent bands due to poor performance of amplifiers and front ends. Assignments are means to protect poorly-designed radar receivers. The front-end filter of a typical radar system is its antenna. If wide-band antennas were used, the situation would be even worse, because high-powered radar transmitters use dirty class C amplifiers with poor out-of-band performance.

Hence, we need high-power filters to clean-up out-of-band emissions. Conversely low-power, low-loss receive filters need to be used to reduce susceptibility to adjacent band emissions. High dynamic range receive front-ends should be required to avoid unnecessary overload. Lastly, tunable filters should be used for dynamic frequency selection (same as comms).

- **Get spectrum-tolerance technology packaged into the acquisition pipeline.** We need to learn how to describe interference tolerance in order to make use of the electronic protection margin. We are probably not going to fight a war on top of a Wi-Fi station, so how do we specify that. The last thing we want is a new spectrum program office that no one will listen to. We need to get it into the acquisition programs. If we don't do the engineering work, learn how to specify spectrum tolerance, and get it into the pipeline, then in 20 years we will still be living with the stuff we bought without it. Thank you.

8.2.5 Joe Mitola, Stevens Institute of Technology

In the late 1990s, the Joint Tactical Radio System (JTRS) program, for voice and data radio used by U.S. military in field operations, had planned for 42 air interfaces—or "waveforms" in DOD terminology—in the radio. The complexity of these radios would require soldiers to go to signal school for "most of their careers" to learn how to use them completely, but would become irrelevant when used to help with an unpredictable event such as the Indonesian tsunami, for example. I complained about this at a MILCOM 97 and postulated a radio that had some computational intelligence built in... Proposing a self-aware radio to his doctoral committee, Mitola was reminded that it is impossible to build a self-referentially complete, consistent computing system according to Gödel's incompleteness theorem. I subsequently wrote a paper [51] that said that software radio is not general purpose computing and thus not subject to Gödel; rather, it is a hard, real-time finite state machine because during every millisecond, speech (or data) is going in and corresponding RF squiggles are going out and it is going to do the next frame and the next frame. Even with data, there are still hard real-time requirements… Based on that paper, a cognitive radio research prototype, CR-1, was built to observe the environment (including user actions), make immediate decisions if required and otherwise plan, decide, and learn in a self-referentially consistent way. Fortunately for me, Professor Simon Haykin got a copy of my paper and said, "Joe is right, but there is an easier way to deal with radio. Let's just sense the spectrum environment and essentially do dynamic spectrum access (DSA)." Hence, Haykin created great interest in DSA even though I wrote the seminal paper on DSA [52] and got a lot of credit for it because of cognitive radio.

There are a number of cognition technologies being researched and developed to improve spectrum utilization as a whole, e.g.:

- **Network self-configuration/-optimization/-awareness.** Computational intelligence in devices alone is not enough; it also needs to be in the network. If radar becomes interference tolerant, then architectures for self-configuration/-optimization/-awareness should be leveraged. Intelligence in the network includes consideration of technical band assets and characteristics, e.g., processing gain, duty cycle, antenna gain, etc. There are important research efforts in self-aware networks (mostly for communications), such as the E3 program (European community) and the Autonomic Network Challenge (IBM).

- **Fine structure sensing and control.** Radios can recognize and remember aspects about their environment as they move around. Consider the right side of Figure 68 which shows green pins where the Wi-Fi node could connect and the red pins where it couldn't. Historically, radio engineers have considered that kind of memory usage in a radio as being prohibitive. A megabyte would be plenty of characterization of this environment, and today my cell phone has two gigabytes for video. We should use a little bit of that memory to make radios smarter.
- **Machine learning.** In order for this to scale up, however, the radios have to learn. It is not enough to write rules, acquire data, and then optimize. Machine learning strategies range between supervised and unsupervised; we want these radios to be smart in an unsupervised way. Machines can learn numeric vectors and continuous variables or symbolic information. Hence, there are a wide variety of learning technologies that can make radios smarter.
- **Sensor-validated hi-fidelity RF modeling** is important, especially in the case of radar with its inherent sensing, surveillance, and imaging functions.
- **Policy reasoning within the device and network** can be used to predict and detect different operational circumstances, e.g., safety-of-life, low spectrum usage.
- **Semantic signal processing.** One other important thing to consider is the high cost of legacy radar and the huge tail of logistics that are surely associated with that high cost. At Stevens, we have developed technology to reverse-engineer existing systems and enable affordable transition to new RF platforms. The approach utilizes cognitive linguistics to build an abstract model and remap that abstract model to a target environment. We've done the easy part using formal languages, e.g., MATLAB®, C/C++, and VHDL. Going from a hardware platform to a different radio platform is a significant challenge because the coprocessors and the RF hardware capabilities are very different.

I'd like to conclude by saying that cognitive radio is a lot more than DSA, and the radio engineering community is heading in that direction. Communications systems need to know where things like buildings, people, vehicles, and multipath reflectors are located as well as the radars, but 4G communications systems are more dependent on the things that are on the ground, so it's more of an Army problem than an Air Force kind of problem. Computational intelligence is widely available. In order to get radio and radar leveraging off each other, we need to start thinking about information networks where the location, projected flight path, class, and parameters of this thing flying in the air is just another piece of information that can be provided by some data source (e.g., SatCom, GPS) and verified once in a while by a radar. Thanks a lot for your time and attention.

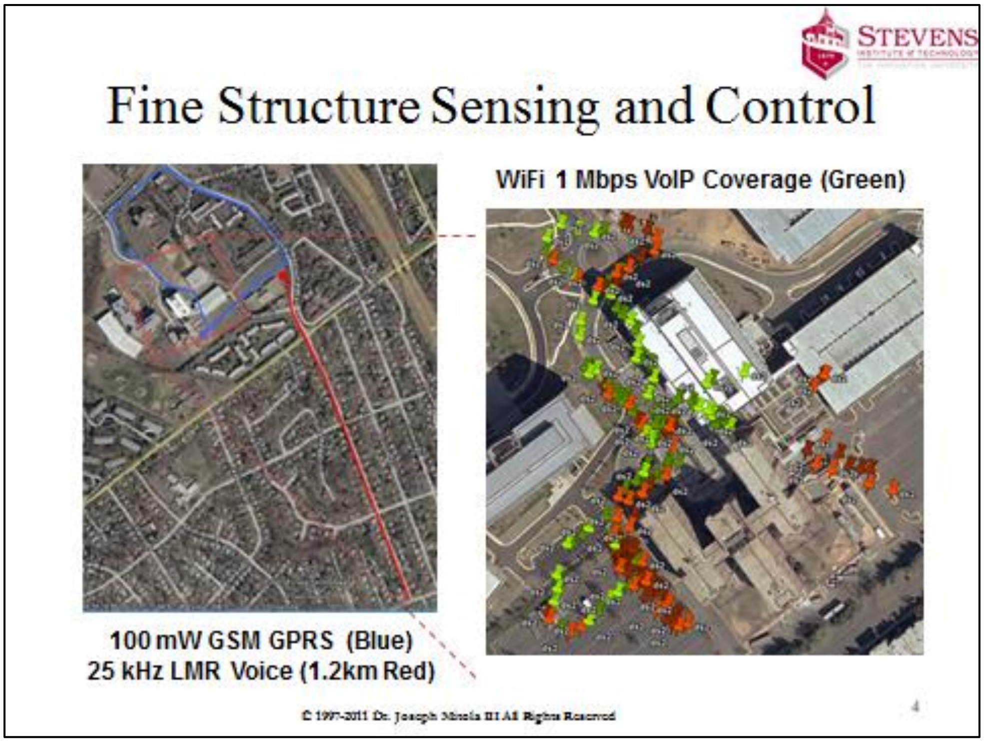

Figure 68. Fine structure sensing and control in smart radios.

8.2.6 Marshall Greenspan, Northrop Grumman

The title of my talk—Green and White Radar—is a little strange perhaps. My background is mostly in X- and Ku-band military airborne radars, so I don't have the 20–50 year lag in technology that we have heard about over the last couple of days in terms of the shipborne radars. I didn't know magnetrons and klystrons were still in use. Further, I was unaware of all the interference problems because there aren't a lot of users in the operational scenario that I typically consider. The only interference that occurs in flight comes from the fact that there are three aircraft on a strike and their radars can interfere with each other. Communications systems were always at a lower frequency band, and we didn't interfere with them except maybe via the power lines on the aircraft itself. We couldn't have done much about it anyway. Our waveforms are very structured, and the frequency could only be changed minimally. Pulse width, rise time, and fall time are all defined by hardware pulse forming networks. Pulse repetition rate, for example, is a function of how rapidly energy storage capacitors recharge. We actually had one of the more advanced radars at the time, because we had a tunable magnetron which had a servo that could change the size of the cavity. It would take several seconds to slew the radar from one end of its RF band to the other. There was also a little diaphragm inside that would dither, but it wasn't to avoid interference; rather, it was to decorrelate the target. In terms of the antenna beam, the mechanical dishes and feed horns we deployed were state of the art because the reflector could be moved up and down a little bit to change beam shape from a pencil beam to a cosecant squared ground beam. That was the extent of adaptation that we had to play with.

More recently, the situation has changed. There are many more comm users and comm equipment is moving up in frequency to accommodate the need for data capacity. Fortunately, key components have now become available to radar designers to address subsequent challenges.

- **Arbitrary programmable waveform generators** allow for spectrum to be shaped, e.g., place a notch at a specified frequency, decrease energy in one part and increase in another part, operate at frequencies not being jammed intentionally in order to improve SNR, etc.
- **High-power, wideband RF amplifiers**, e.g., TWT's initially and now 10,000 or more solid state amplifiers running in parallel, which don't necessarily have to use the same waveform as is the case for multi-input multi-output (MIMO) approaches that utilize waveform diversity arrays.
- **Adaptive beam forming** is enabled by high-speed A/Ds with ASICs and FPGAs operating behind them. Every radar system that I've worked on in the past 15–20 years has a minimum of three of four outputs and as many as ten simultaneous outputs. This allows an operator/designer to adaptively change transmit and receive beam width and shape the energy distribution in such a way to reduce energy to and from those areas where you might cause harm or be harmed. At some point later, when things have changed, the antenna beam can be readapted.
- **Cognitive radar** is the concept where the radar system is fully programmable and reacts to environmental conditions in frequency, time of arrival (fast and slow time), angle of arrival, and space.

What do I mean by green and white radar? Green radar is caring and considerate of others and takes pride in having a minimum impact on their neighborhood environment. It doesn't use any more resources than it needs to accomplish its mission. There are many cases, e.g.:

- **Multifunction radar** to consolidate the functionality of multiple systems into a single radar system.
- **Scaled radiated power according to the range being searched.** There have been some requirements for what used to be called low probability of intercept or low probability of track. In other words, just put out that amount of power needed to do the job. Now, many radar systems operate with excess power.
- **Radar network with intelligent tasking** can reduce maximum range, average power, and peak power requirements by assigning tasks to the radar in the best position to do that job. We have found that power can be reduced by 6–10 dB if intelligent tasking of a radar network is properly utilized.
- **Context awareness.** Radar systems should be aware of the potential vulnerabilities of friendly RF spectrum users, the dynamically changing the environment (based on the time of day, geographic location), and whatever other information is available. Real-time access to a global database sounds like a great idea. I don't know if that will be universally possible, especially in other parts of the world, but it might get you in the ballpark to start with. A radar system operating over water should have different characteristics (e.g., waveform, power) than when looking into high population density areas. In fact, radar systems should

not even bother radiating into areas where targets cannot be seen, e.g., a slow moving target in New York City will be shadowed by everything.

What's a white radar? That's the other side of the coin. Radar systems encounter adversaries that won't follow the rules and won't be good neighbors. When these encounters occur, radar systems should sense the interference and respond to it. Adaptable filters and polarization are example of ways to mitigate interference. Thank you.

8.3 Q&A

Greenspan: You talked about adaptive, cognitive radar. How does that fit into the regulatory game? We are having enough trouble going to the FCC and saying that we would like to put out this pulse or this waveform. I hate to see what would happen if I said that I don't know what I'm going to put out, it depends upon what I see.

Guerci: I think you need to define what interference means. If you are some Wi-Fi device, then you need to publish and indicate your interference criteria, and then FCC or ITU need to agree on that definition. Cognitive radar has a lot more tools available at its disposal in real time, to make sure that it meets those criteria. It is completely the opposite of a system that is hardwired ahead of time with some assumptions about how it's going to achieve noninterference, and then it gets into the real world and it's not quite perfect and there is no capability to adapt.

Greenspan: It sounds like more of a performance-based specification than a function-based specification.

Guerci: Is this a Socratic dialogue? Are you leading the witness?

Mitola: When you try to do what you just suggested, the regulators have a heck of a time with it. The cultural mindset and shift of the regulators is a challenge. Cognitive radio is working on it, but it is going to be a long time before it happens. The spectrum mask is a revered and honored approach, so as long as all the wild and wooly waveforms fit within the mask and do no harm then I think we may be okay.

Guerci: It sounds like maybe cognitive radio and radar need to come together and at least join forces on that.

Randy Jost, Ball Aerospace: We spent a lot time talking about legacy systems driving some of the problems here in terms of moving forward. It seems to me that more than that it is legacy thinking that is holding back some of the advances. We need to look at some kind of paradigm shift in the way we design things and meet requirements. It seems like a lot of the radar developers (present company excluded of course) are old school. They tweak the power, limit themselves to one waveform, and move forward in baby steps. Not many people are stepping back and asking: "What is it that I really want to accomplish?" I want to sense some object out there and get enough information to do some task associated with it. What is the best way of doing that (as opposed to cranking power up)? More importantly, how can we shift that thought process down to younger engineers and young regulators? I've given up on politicians because they are like generals that just want a number or a yes/no binary decision. How do we move forward as a community to do things in a different way instead of just the way we have been doing things?

Baylis: One thing that we are trying to do is look at the waveform and the circuit at the same time. I am an RF guy, and when I first attended a radar conference I noticed that not a lot of radar people were working RF problems. The focus was on signal processing. I have not worked a lot of waveform problems, but I am learning. The more we can learn about each other's disciplines and where they intersect, the better. One thing that I am working to learn more about is the detection part of radar. That is another piece of the puzzle. All aspects should be considered in an integrated fashion to design a system to accomplish a specified set of requirements.

P. Marshall: It goes beyond the radar designers. Since the FCC was established, the whole field we are in has tried to make everything independent: independent frequencies, non-interference, totally isolate people, thousands of little walled gardens. That paradigm has crashed and now we're starting to think of them all as one big vast ecosystem, where we don't try to block their interaction. In fact, the only way forward is to create and leverage that interaction… LTE designers are not trying to make their things not interfere, they are trying to live with radio resource management. We have not generalized that out across more heterogeneous things. Radar engineers shouldn't feel bad: spectrum managers are not appreciably better. Congress wants to auction off the spectrum free and clear, which is the 30 year old model. We have come along with this model of isolating things when we really know it's about how to create cohesive systems.

Guerci: You just made me think of an analogy. When the automobile first came about, there were no traffic lights, no stop signs, and no rules. People just drove anywhere they wanted to. Eventually, we had to share a finite resource which was the passable road ways. We had to start developing rules.

Marshall: But if you went to the FCC they would clear I-95 for you and only you until you got off of I-95 and then he could get on!

Guerci: Radar is worse than the sort of horse and buggy days.

Greenspan: Somebody came up to me yesterday and asked, "Why do you radar guys need so much bandwidth?" My first reaction was that we have to be able to see small targets, we want their shape, we want their characteristics, etc. I suddenly realized that another real benefit is non-susceptibility to interference. If a pulse comes in from another type of radar, then it spreads out in time. If a narrowband signal comes in through my spread spectrum match filter, then it spreads out into the noise. In either case, I don't see it as a target… I would gladly share our wideband radar spectrum on an energy-limited basis, because that is ultimately what is going into the energy noise density ratio and raise my noise floor.

Melvin: I will just make a quick comment which is that what Randy was saying is something I tried to bring up earlier that we really have to start asking what will the environment look like? What is a reasonable sharing of the spectrum? What are the spatial distributions of the radars and the interferers and then start to address these problems and ask through rigorous metrics, what does it do to the radar system, what does it do to the communication system?

Guerci: There are folks in the radar community that have ideas about how to design things better, but the acquisition cycles are killers. The military radar community has a very different outlook than most of the folks in this room, so that plays a role as well.

Howard McDonald, Defense Spectrum Organization: We are starting to see early implementation of cognitive radio with XG, WNAN, etc., and DSO is looking at the business processes associated with spectrum management and the automation needed to support these emerging radio technologies. When might we start seeing some of these cognitive radar capabilities? And, do you have any advice for the spectrum management community with respect to business processes and automation to support the integration of cognitive radio into the force?

P. Marshall: In a way we are better off in radar, because we have always hidden radar waveforms. In comms, we've always exposed them and that sets a high burden. Hopefully in radars, we can treat all of this adaption as just the war reserve mode and never document it. We ought to be using the comm stuff, which isn't as radical as the radar stuff, as the poster child to get rid of the Red Book that describes the waveform and replace it with something that describes the coexistence. The idea before was this: if it were cataloged then coexistence could be understood, because it was a static thing. Now that we are a temporal thing that is responsive to the environment, we really haven't thought at all about how to document that in a scalar fact sheet that describes the business process. We ought to use WNAN and XG as the first, and less complex than radar, example of that and come up with some new ground rules.

Mitola: When will we see it? If you think about the way that SDR and cognitive radio emerged through the Speakeasy 1 program (DARPA, 1990 or so), Speakeasy 2 and the SDR Forum getting going around 1995 was foundational. I think radar right now is in the position in evolution where software radio was in 1990… It was another decade to get to cognitive radio, where we are. That is going to be compressed for radar because of lessons learned in cognitive radio. Further, as radar systems become more able to communicate, and do lots of other nifty things, we will see an acceleration of that timeline. I believe that it will be about ten years, but that means we've really got to get going because it takes about a decade to get anything done in the Pentagon.

Guerci: It's interesting your analogy with your early days in SDR because it turns out that there were two programs at DARPA that picked up an element of cognitive radar, which is knowledge-aided processing. One is the multipath exploitation radar, where if you have an understanding of the layout of the city, you can predict where you should see multipath. If you get a signal you can hypothesize where it is coming from, and that program has been very successful. It has been a few years running, and it has worked, it's been proven with real data. Another related program that uses knowledge-aided processing is called Visibuilding, and this is the ability to have radar probe and detect objects inside of buildings. It starts with a model, and it builds up the model as it goes. That also has proven to be very successful. A little of the knowledge-aided stuff has filtered out into various terrain-aided C4 algorithms and some programs of record for radar. I think you are right. The way it gets adopted will be similar.

Mike Cotton, NTIA: Everyone has given some great ideas, and it's been a great panel. I am looking for starting points. We've heard some dialogue about the need for advancing spectrum management. Now, we went through a whole inventory of radar earlier in the conference. Give us a scenario or application where we start. Out of the opening remarks, John Cho gave us the only application-specific idea, i.e., MPAR for weather radar. So what else is there? Does anybody else have any ideas about how we can start utilizing some of these ideas on legacy radar to help us evolve more quickly?

Greenspan: One person mentioned 40 or 50 interference incidents. Another person claimed that there is no concern about radar interfering with the comms; comms interfering with radar is of more concern. I've never gotten a trouble report from the field or in fact from any user that said, this specific comm system is interfering with my radar. Comm waveforms are well-documented and public. As a radar designer, I would like to know those comm waveform details so we can model and design the next radar generation with anti-jam susceptibility blockers. Now, I can't protect against everything. Also, if there is an interference source in the field, there needs to be some mechanism to get those trouble reports back to radar manufacturers.

Guerci: There's a radar that has had this problem for 60 years now. It's called the E2C Hawkeye (formerly E2A). It is the Navy's AWACS plane that went operational around 1959. When it flew over the Middle East in particular, taxi cab radios operated in their band, so they had to learn to adapt and live with interference for decades. They were typically narrow band interferers, which is to your point about how sometimes wider bandwidth helps. Fortunately for the Navy, a lot of the communications has moved up in frequency so they just waited it out and life is getting better for them… Michael, when you asked where we are going to see developments, my short answer is that it is going to be in small radars. There is a burgeoning market in smaller radars that go on unmanned aircraft and vehicles. That is where the game is going to be won, because those radars will have to operate wherever, and in some complex environments they will need to be much nicer spectrum users. Those systems will be trying get a lot of information out of a small package… The proliferation and pace of innovation in wireless technologies is amazing. Our radar systems, the big ones, can't really take advantage of that kind of a pace, but the little ones can. Keep your eye on next generation mini-SAR out of Sandia for example, which heavily leverages COTS technologies. They go right directly to the commercial RF MMIC (monolithic microwave integrated circuit) houses and ask for transmit-receive modules, etc. There are a number of the commercial RF houses that are into these things. Microwave Associates, for example, partners with Lincoln Labs on the MPAR project; they want to commercialize and mass produce these. They are not high peak power, so they can run class A amplifiers and things like that. Does the panel have a response to this?

Greenspan: They've got much shorter development times than the military.

Melvin: The Navy is also trying to develop a whole class of digital array radars with waveform generators pushed right up to the aperture, so that opens up a whole realm of possibility.

Cho: In the weather radar community there is a program called Collaborative and Adaptive Sensing of the Atmosphere (CASA), and their idea is to go small. They want a dense network of X-band radars that are mounted on cell phone towers all over the country, or at least near urban areas, so that could be an area where this could be more applicable.

Eric Mokole, NRL: Our approach at the lab has been to go small. Our predominant effort over the last two decades has been with the large ship-based radar, even at the exclusion of the air radars. Now we're heading towards small distributed sensors which requires less SNR. On the other hand, we have also been looking at the large multifunction systems. One of the problems with these is the expense, which comes from the development and maintenance required for all the functions being integrated. Preceding the work that has been done by John (Cho), we had a multifunction test bed program at the Office of Naval Research that dedicated $150 million over a seven-year period from the mid-90s to 2002 or 2003. The program investigated simultaneous transmission and reception on two eleven hundred-element arrays separated by eleven feet with multiple beams in different directions. It's still under development, and I don't know if it will get into any systems. There is a cost/benefit debate going on over this concept. In summary, there is a lot of work going on, and I don't know whether the work is closed. The weather-radar MPAR is more appealing to me because it doesn't go over 4–18 GHz and that's what this system did.

Guerci: As Joe (Mitola) pointed out previously, things are going to happen in steps.

Eric Mokole, NRL: Exactly. Looking forward, the big area for us is the small distributed stuff.

Guerci: I'm hearing that a lot, and when you do that you almost always take advantage of commercial, state of the art technologies.

Eric Mokole, NRL: … which is why we are going in those directions. From our laboratory view, we can actually afford to build prototype systems. I cannot do R&D on a phased-array radar at NRL, that was a very unusual thing that ONR funded.

P. Marshall: There is one contrast with this panel and most of the others. Eighty percent of the panels in the last two days were all the reasons why we can't share spectrum with radars; this panel is about emerging opportunities. The challenge for NTIA and the regulators now is to not draw generalized conclusions from very old technologies. A lot of radar systems are the moral equivalent of AM broadcast (e.g., same technology base, same era). We run the risk of walking away from a great sharing opportunity (i.e., not investing in it and achieving it) if we draw overly generalized conclusions that we can't work with and share with large radar systems, and then the opportunity is precluded ten years from now or with the next generation. The challenge the regulatory community faces is arbitrating the promise of this kind of panel with the reality of legacy and not letting the legacy become too depressing. For the long-term, there are answers in the pipeline that money could bring about much faster. I know everyone here spends government money and they would all agree with that.

Mitola: A way to mechanize what Preston is talking about that we used in the Pentagon when we created Predator is a migration strategy. And we made the migration strategy be such that it was outside the Future Years Defense Program (FYDP). In 1993, we looked out and said that we will have Predator in 2010. And guess how long it took for Predator to come about? Way quicker because as we started chipping away at this migration strategy, we had to create money. This was the peace dividend era, and we did. We are in a similar situation now, so NTIA and government should develop a migration strategy because these radars are costing money, because of the logistics tail, and because they have to be replaced someday. If we identify and characterize how to do this over the next decade, then some of this stuff will show up way sooner.

Guerci: That's a brilliant strategy. I hope people really understood what he said, because inside the beltway and the Pentagon, male lions look for babies to kill all the time. A good way to get things done is to say "Look, I'm no threat. It's 10 years down the road!" But you know darn well that it will be done sooner, and when the need arises you are ready on the spot. Then you have four stars to back you up at that point… Let me add just one thing to what Preston said. I think, ironically, if the government and DOD was today to turn on a dime and start mandating that we stop using this antiquated technology and get on board with the kinds of technologies that we're talking about, then there is an enormous economic benefit to that. It would help our own indigenous industries in this country. People talk about stimulus programs in this country. There's a great one here.

Mike Cotton, NTIA: The conference was designed to capture the complexity of the entire spectrum management problem and to talk about the important aspects in moving forward. We talked about interference issues prior to you guys. We've got the ideas that you guys have. We've got to make sure that there is a business model that is out there. If we are going to share, if we are going to create the sandbox, there needs to be justification there. Finally, Eric Nelson's panel on regulatory reform will try to address the trust issue. You really hit it on the head where you basically said we need an advanced spectrum management scheme, and that's what we are really trying to build here, so I appreciate all the ideas.

Guerci: And there is economic benefit if we get out ahead of that. We had the Internet. We had micro processing. Why can't the next big thing be cognitive systems? If the U.S. was the leader in that technology and proliferated that it could be another boom for everyone. Thanks everyone.

9 SHARING RADAR BANDS WITH COMMERCIAL SYSTEMS PANEL

The goal of the Sharing Radar Bands with Commercial Systems panel was to explore the possibilities and make the case for sharing radar bands with commercial systems. In the session overview, Julius Knapp (FCC/OET) provided motivation for and an overview of traditional sharing concepts via geographic separation, frequency coordination, overlays, and time of use. Knapp also shared experiences thus far with advanced radio technologies toward sharing spectrum including sensing, unlicensed PCS, medical radio rules, unlicensed technologies, software-defined radio rule makings, U-NII DFS, 3650 MHz restricted/unrestricted bands, spectrum test beds, DSA Notice of Inquiry, and the television whitespace (TVWS) experiment. The panelists followed up with opening remarks on the following topics.

1. Cost/Benefits in Sharing Radar Bands?—Robert J. Matheson (retired NTIA/ITS)
2. WISPA Perspective on Radar Bandsharing at 5 GHz and 3.4 GHz—Jack Unger (Wireless Internet Service Provider's Association)
3. Operation of Wireless Broadband Services in the Band 3550-3650 MHz Identified Under the NTIA Fast-Track Evaluation—Clem Fisher (Motorola)
4. Opportunistic Primary-Secondary Sharing with a Rotating Radar [54]—Dr. Jon Peha (Carnegie Melon)
5. Medical Devices Coexisting with Radar in 420-450 MHz Band [55]—Glen Griffith (Alfred Mann Foundation)
6. Incumbent Spectrum Users' Dynamic Spectrum Access Requirements [56]—Dr. Mark McHenry (Shared Spectrum)

9.1 Introduction by Session Chair Julius Knapp

Good morning everybody. We've got a great panel for you this morning, and I thought I would do a handful of slides to set this up. Tom Powers talked a little bit why we are looking at these sorts of things. He mentioned some stats that I would like to repeat.

- 300 million mobile subscribers in the U.S., and 90% keep their device within arm's reach 24 hours a day.
- Smartphone sales have finally eclipsed personal computer sales.
- Mobile broadband is being adopted faster than any computing platform in history.
- Smartphones demand 24 times as much spectrum as an old feature phone, and tablets demand 120 times as much.
- Multiple experts expect that mobile demand for spectrum will increase more than 35 times in the next few years.

We often lose sight, because we are so focused on the technical part and the nitty gritty of spectrum sharing, but this is about what makes a difference in people's lives and the economy and jobs. One kind of opportunity includes increased video conferencing, even on our smart devices, so you can check on an elderly parent who is living at home alone. There are 18 million college students that won't answer their phone anymore; they will, however, answer a text or email, so you can keep in touch with them on the weekends. When your car breaks down you can consult with the mechanic. After an accident, you can use a video link to communicate directly with the doctor. The school buses can become mobile study halls. Farmers in the field can track weather and commodity prices in real time. Plumbers and electricians, when they get to the house, will have the information and technical diagrams right in the palm of their hands and be able to order a part right on the spot. The Telecommunications Industry Association (TIA) has estimated that there are 860 billion in productivity gains by 2016 from advanced mobile wireless.

What has the FCC's response been to the spectrum crunch? We published the NBP in March 2010, which I talked about that last year. We developed a comprehensive plan for spectrum policy reform. There are a number of other things that we've done; I won't go through them all. NTIA, of course, has been busy too. You've heard Karl and some of the other NTIA folks working from the presidential memo; they have issued a couple of important reports, one of which is the Fast-Track Report [4] that identified 115 MHz of spectrum for access. They've also been hard at work looking at the 1755–1850 MHz band and assessing what kind of access can be provided there. We've had a lot of discussion of that at the conference. Inside the Commission we've got a Spectrum Task Force, and one of our prime objectives is to make sure that things in the NBP are moving forward aggressively.

The traditional ways of finding spectrum for new services are

- **Improving efficiency** by packing more service in the same space. That has been achieved with technical rules, secondary markets, and so forth. Often people say "Why doesn't wireless just get more efficient?" If you look at the technology evolution from 3G to 4G, it has an evolutionary path of ongoing improvements in efficiency. We have to attack this on all fronts and efficiency is something we will continue to drive.
- **Sharing**, traditionally, is achieved via geographic separation, frequency coordination, overlay, and/or time-of-use coordination.
- **Reallocation** removes or reduces an allocation. It can occur with no compensation or with relocation of the incumbent being paid by the new licensee or auction proceeds. The first reallocation effort, called Emerging Technologies Policy, was with PCS (almost 20 years ago). Same sorts of discussions occurred regarding how we are to come up with more spectrum. In that effort, we moved fixed point-to-point services up to higher frequencies. We had done the technical work to make sure it was possible, and then the newcomers paid for the relocations. The process worked really well. Another example of reallocation was with Advanced Wireless Services (AWS-1), which was on the Federal side and paid for by auction proceeds. There were areas identified where it can be improved, but largely the process has worked.

Why are we focused on radar bands? Radar operates in lots of different bands. Oftentimes, the spectrum we consider for increased access involves sharing with radar (either co-channel or adjacent band). Radar systems are vital for national security, air traffic control, weather, etc. We can't do without them. Further, we can't just come along and say the band is not heavily utilized, so let's just put them someplace else. With a little consideration, one will realize that there aren't many relocation places. Hence, we're trying to be more clever. One emerging technique is opportunistic use of underutilized spectrum, and the technology has been evolving to give us tools to possibly enable us to do that.

Last November, we started a proceeding on Dynamic Spectrum Access (DSA) with a Notice of Inquiry (NOI), which asked a number of question, e.g.,

- Can the TVWS model be used for other bands?
- Should and how can sensing be used?
- Can FCC provisions for secondary market arrangements be enhanced to enable DSA?
- How can the FCC Spectrum Dashboard be improved?

We have received comments and replies, and we are going through the process of deciding what to do. Our goal is to put up something concrete before the end of the year. It is important that we develop DSA technologies, enable the private sector to use these tools to use spectrum more efficiently, and enable private parties to make arrangements through secondary markets.

Thus far in the conference, you have heard a lot about 5 GHz DFS. This is one of the first places that we used DSA. The concept of intelligent systems and access has been around much longer. In the cellular network, for example, every device is measuring the signals at that location and feeding that back into the network to make intelligent choices about the frequency assignments. Even back in 1997, when we were trying to find spectrum for medical devices, we required a listen-before-talk feature when sharing spectrum with weather balloons. It has been evolving.

I look at the whole 5 GHz DFS process as a great big win (see Figure 69). It brought all the players together to first figure out how it was going to work. We developed a plan going into the ITU WRC in 2003. Unlicensed spectrum is not typically discussed at the WRC, and everybody marched back feeling like we gained another 255 MHz in addition to the 300 MHz that we already had in the U.S. unlicensed service. After we first adopted the rules and the group started working on measurement procedures, this is when a little disconnect occurred. One group focused on sensing a level (-61 dBm or so), and the other group was focused on the need to detect radar signals. The challenge was that you won't detect radars at that level (confirm with Frank). People, a lot smarter than me, from DOD and NTIA and from industry, figured out a way to make all these pieces fit together. We have also encountered unexpected deployment scenarios, e.g., devices 1000 feet in the air and in direct line of sight to weather radars. Again, we brought all the players together to find solutions. I want to commend everyone involved from NTIA, FAA, and our staff for the way they approached this—diagnosing the problem and identifying ways to fix it. We are on a positive path to have this all resolved. DFS implementation has had its challenges, but the concept of DFS works.

Enforcement is a key piece. Jim Higgins from the FCC Enforcement Bureau is in the audience. We've spent a lot time in the field trying to locate the sources [of interference]. There have been enforcement actions taken and that process is continuing. You have to be sure that whatever rules you adopt, they are going to be enforced and the Commission is committed to doing that.

TVWS is a little different. Initially, the focus was all on spectrum sensing. For years, the discussions between broadcasters and DSA advocates discussed whether or not it could rely on sensing alone. In the end, we adopted rules that allowed for two techniques. One was a database technique where we take advantage of new technology to know where it is, access a database over the Internet to retrieve spectrum availability information, and operate in the permissible spaces. Second, we continue to provide for spectrum sensing techniques, although there is a high bar for those to demonstrate that they are going to work. The Commission is very supportive of this paradigm and considers it a tool in the DSA arsenal with a lot of promise for the future. We've had a lot of work going on in the last year to get this all up and running and we're pretty far along.

Lastly, I want to talk about the 3550–3650 MHz band where the NTIA Fast-Track Report [4] recommends exclusion zones along the coasts as a means for sharing with radar. NTIA and the Federal agencies are concerned about radar blasting into the wireless systems. However, there are lots of population areas along the coasts and opportunity for improved spectrum efficiency if we can figure out ways to use that spectrum through intelligent techniques.

The message I want to leave is the following regarding sharing spectrum between new services and radar: if you get the right people together (i.e., the people that really know the nitty gritty about how the wireless systems work and the people that really know the nitty gritty about how the radar systems work) to talk and put their minds to the relevant challenges, then you would be surprised about the solutions and the mutual benefits for everybody that can come of it.

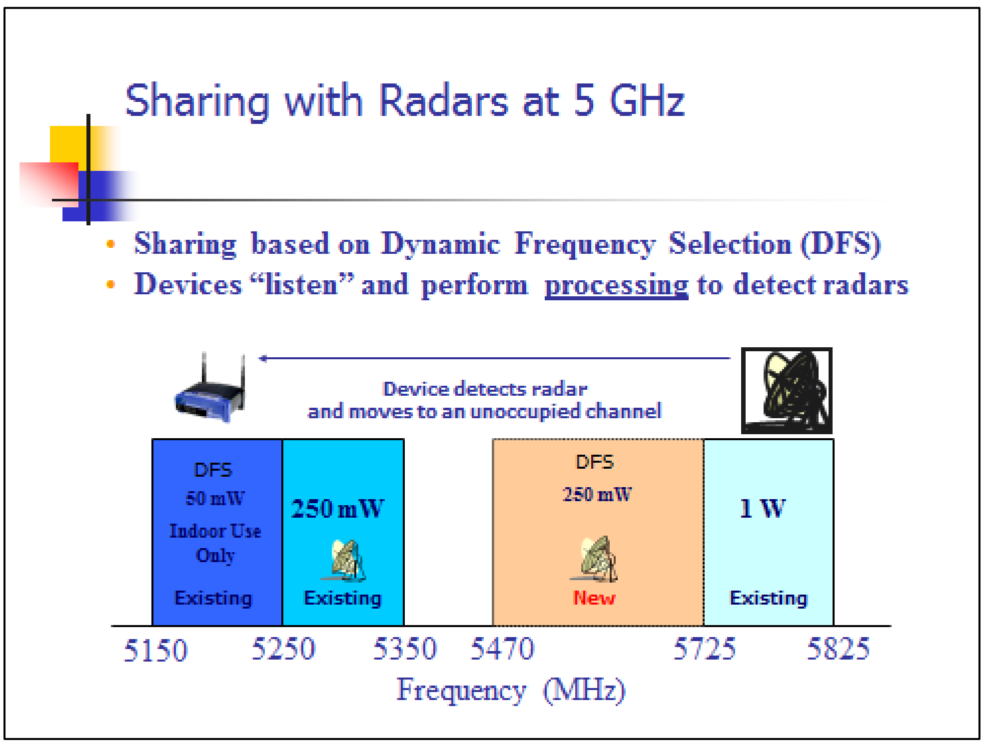

Figure 69. Sharing with Radars at 5 GHz.

9.2 Opening Remarks

9.2.1 Robert Matheson, retired NTIA/ITS

DFS or DSA proposes, for those many spectrum bands where typical usage is not 100% all of the time (and in many bands, the typical usage is 10% or less), to use some of these frequencies for new services without interfering with licensed operations currently going on in the band. If we can pull this off, it means that we will have more service in the band, but even more significantly, we get new services. The new services are the new kind of broadband data services that are in demand now, instead of the old services that were in the band before. We can do that without going through the expensive and tedious process of reallocating and clearing the existing bands. If we can pull this off, DSA has huge advantages.

There are all kinds of problems associated with DSA including:

- **Motivational problems** associated with who is really pushing for this to work and why should we spend a lot of effort on it.
- **Technical problems**—Does it actually work? How?
- **Regulatory ambiguities**—There is a lot of control and a lot databases to keep track of. When problems occur, how do we diagnose and who do we talk to?
- **Economic questions**—Is this a cheaper and better way to do things? Or, is this a more expensive and problematic way to do things?
- **Subtle questions—**If we've got to have 500 MHz for broadband and we can share, how shared does the band have to be before it becomes countable in the 500 MHz?
- **Future questions—**Where is DSA going? Will problems get better or worse?

DSA looks very different depending on whether you are in one of two different groups. First, we have the spectrum-envy group. Those are the people without spectrum who are envious of those who do have spectrum and they really trivialize the problems of the people you are borrowing the spectrum from. Then we have the spectrum-angst group. Those are the people who have already got spectrum, and they are really afraid that their licenses are going to be nibbled away and stolen from them bit by bit as things change in the band. Everyone starts these things out thinking that DSA really will be able to do all this stuff without interfering with the existing people, but sometimes that might not be the way it really works.

There's this slippery slope of DSA. I don't mean it in a bad way at all, but rules could allow spectrum use under one out of a number of possible conditions, e.g.:

1. No possible interference to the incumbent
2. Minimal possibility of interference to incumbent
3. Number 2, but incumbent must use high-performance receivers

4. Number 3, and incumbent must transmit detectable carrier tone or inform real-time database to protect current use
5. Number 4, and incumbent must allow time for DSA to move before transmitting

... etc…

N. All users are in a queue, and incumbent always has top priority.

Is there a reasonable and natural place to draw the line? Currently, there is no line. The lower we draw the line, the more rights are taken away from the incumbent and given to the DSA users. We might gain a good hunk of additional services, which may be very advantageous in economic terms. Recall, we have two very definite and opposed views even though everyone concerned may be trying to do the best thing for everyone. Finally, there may be a day when DSA services have grown to the point where the DSA users are the great majority in the band. When that time comes, whose band is it really? Who will control the band? Not just what the regulations say, but politically and economically. Who makes the decisions? How does that work out? Mind you, I don't have answers on any of this stuff.

There is a lot of regulatory ambiguity, because we aren't far enough into the process to really know what DSA devices are going to be. There is certainly an ideal situation, where DSA devices are unlicensed, smart, and adaptable. A user buys a DSA device, and that device drops into the band; maybe it signs up online or maybe it doesn't. It senses and gets pertinent information from a database and provides the desired service via frequency, modulation, or some other type of adaption. Maybe that will work out sometimes, but one of the lessons learned in the DFS situation is that we really need, at least in some critical situations, a database of where the users are so that we can do a better job of policing the band and sorting out interference problems and that kind of thing. We have not come to that yet. If incumbents spend a bunch of money to allow DSA to really work, is there going to be a way to recover some of that money? And is there going to be a licensing or use fee? If so, it starts to resemble a secondary license where the band is effectively reallocated in a sneaky back-door way. We haven't really done this before and in some cases we have to decide between opportunistic versus something that looks more like secondary licenses. Who owns the spectrum that is used by DSA? What are the user rights that attach to that? Do we end up auctioning those licenses also or some kind of payout to incumbents and what kinds of rights do particular users really have when they start providing really important services?

It is likely that different bands with different kinds of services will be regulated in different ways. Is DSA the best kind of bargain we can do in these bands? DSA systems are more complex because of the sensing and agility requirements. This may be a tough way to build equipment; on the other hand, economies of scale can result in higher efficiencies if mass production of DSA equipment occurs. Is DSA a stopgap measure that fills in but delays a more efficient band reallocation that would give better use? Or on the other hand, if DSA is an optimal means to provide a service via sharing an existing band, how do we optimize in the band to make it work well. Once we figure out how to make radars more efficient, would we do better by squeezing radars into a smaller part of a radar band and giving exclusive use of the leftover spectrum for broadband purposes?

In cases of elevated spectrum priority, e.g., emergencies when additional communications are needed immediately, regulators might deem that DSA is simply not going to be available because that service is lower priority. However, DSA could be the more efficient and capable infrastructure in response to an emergency. Is there a better way to use DSA than just turning it off when a big spectrum demand comes up by the primary user?

Toward the future, does DSA only work when lots of extra frequencies are available? Once the spectrum become more crowded, does it work anymore? Consumer radio use is becoming more nomadic, short-range, and varied. One minute we are texting, and then next minute we are receiving full-time video, and that happens all the time everywhere. Hence, an exclusive-use network-based constant traffic to a given location doesn't really match usage. On the other hand, DSA may not be able to count on frequencies being available, so can DSA guarantee anything better than a second-class opportunistic traffic? When 1000 people suddenly show up on a location that's coordinated by some kind of wireless Facebook message, how is the system supposed to adapt itself to make that work? Maybe that's an opportunity for DSA to work as part of the regular licensed network, as an auxiliary.

I have asked a bunch of questions here, and I have no idea what the answers are. It is clear, however, that DSA potentially offers a useful way to provide a large number of new services. In a lot of ways, DSA is much better than the old clear and reallocate cycle that causes a lot of problems for everyone and requires a lot of time. There are lots of questions about how we ought to proceed, including which DSA services can be mixed with which incumbent uses in which kinds of bands. I can just say that I wish you all huge amounts of good luck, and I can hardly wait to see what happens.

9.2.2 Jack Unger, WISPA

I'm going to touch briefly on the experiences we've had at WISPA, i.e., the Wireless Internet Service Provider (ISP) Association. We are the fixed, not mobile, wireless broadband providers. In my opening remarks, I would like to cover the following topics:

- TDWR spectrum sharing experience
- A successful spectrum sharing database model via extension of the TVWS database model and leveraging the 3650–3700 light-licensing model

There have been instances of outdoor wireless operation that have caused interference to some of the TDWR radars. The industry has worked on this for a couple of years. At WISPA, we first became aware of this at the beginning of last year and have been working with the 5 GHz Wireless Industry Group led by Mary Brown of Cisco. We've had a couple of meetings here at this conference to further address this issue, and I think we are making good progress. In July of last year, with the generous help of Spectrum Bridge, our TDWR database went live. Outdoor operators can now go to the database, put in their base station location, and determine if they within 35 km of an existing TDWR system. If they are, they are asked to exclude the single frequency that that TDWR system uses. If it is using 5610 MHz, they are asked to exclude that from their base station and stay 30 MHz away, below and above.

End-user education has been critical, because we had to get the word out: “Hey, there’s a problem... Hey, there’s a database, and it is easy to use. Please use it.” Hence, WISPA has done a lot of email announcements. We’ve publicized Julie Knapp’s memorandum from last year and created a flyer to hand out at shows. In the last couple weeks, Rashmi Doshi of the FCC did an online webinar on the topic of 5 GHz sharing and problem solving (about 120 people attended).

There were a couple of FCC enforcement actions over that last year, which had a positive effect. Prior to those enforcement actions, people used the TDWR database to see if they were within 35 km of a TDWR, but they wouldn’t register their base stations (which is optional). After the enforcement actions, suddenly, everyone started registering their base stations. By registering, providers are saying “Hey! I’m legal, I’m not the problem.” The point is that operators will look up and avoid TDWR radars once they know that they need to do that. There is a high level of cooperation once the word is out.

We did a survey of WISPA members and asked “Do you want to lose the TDWR spectrum plus 30 MHz above and below, i.e., 110 MHz of unlicensed spectrum, or do you want to use a database?” Eight-seven percent of the respondents said they would use a database to retain use of the 5570–5680 MHz band. A manual database or an automatic database, it doesn’t matter, we will use it. We worked for years to gain spectrum access. We don’t want to lose it. We need it.

A dynamic spectrum-sharing database (SSD) that coordinates in frequency and time is probably a good way to fully exploit spectrum resources. Let’s first look at a frequency band particularly well-suited for a SSD solution, i.e., 3550–3650 MHz band. This band is significant because it is 100 MHz of potential new spectrum and it is immediately adjacent to the existing 3650–3700 MHz band, which is not unlicensed (FCC Rules Part 15); it is light licensed (Part 90). Light-licensed means that a nationwide non-exclusive license is available for $200 and registration in the FCC database (with GPS coordinates, equipment description, etc.). Further, there are multiple equipment vendors that have worked in that band for a few years, so equipment is available. Hence, it is a low-cost, low-barrier entry. Adding another 100 MHz to the bottom of this band would be a huge advance and help WISPA operators deliver broadband to the U.S. residents that have no broadband option at home. We estimate that 15% of U.S. residents are beyond the range of cable and DSL. Satellite is not an equivalent substitute.

Second, consider the TVWS database model, which is almost online. The TVWS geo-location database model knows where the existing (licensed) TV coverage areas are and how much distance is needed to protect them from unlicensed interference. Outdoor fixed broadband devices operating in the TVWS must connect to one database (out of the nine) over the Internet to obtain an available-channels list. TVWS database software development is almost complete and security (user-to-database and data-to-database) is already built in.

A dynamic SSD model (shown in Figure 70) combines good things from the TVWS model and the 3650–3700 MHz soft-license model, plus one or two new things were added, i.e.:

- **Secure manual radar frequency inputs**—only designated government entities may enter frequency-in-use information
- **Secure dynamic near-real-time inputs**—sanctioned spectrum-sensing receivers can do full-time band scanning to detect radar operation.

- **Output a list of available frequencies**—to each fixed base station, depending on the station's geographic area.

Let's take Baltimore as an example because it is a harbor, the military are there, the commercial sector is there, ships come and go. 3550–3650 MHz is a maritime radar band, so along the coast is the only overlap between military and commercial use. When a ship comes into port using a radar system, it enters that information into the database and those frequencies will not be used by Part 90 users. If a Part 90 user is not in one of these coastal exclusion zones, the user doesn't need the database because there is no potential to cause interference to the incumbent. Further, sanctioned spectrum-sensing receivers linked to the SSD could be used to automatically detect radar exclude radar frequencies from use by the Part 90 users when a ship comes into harbor. In this model, there is no real need for manual entry. The output from the database, of course, would be for base stations to determine frequency availability.

The primary advantage of SSD is that it is proactive to avoid interference rather than reactive. Also, the model could be used with any band. There's no need to bear the costs of trying to build a new radar system and install it on ships. That is clearly not going to happen. Thank you.

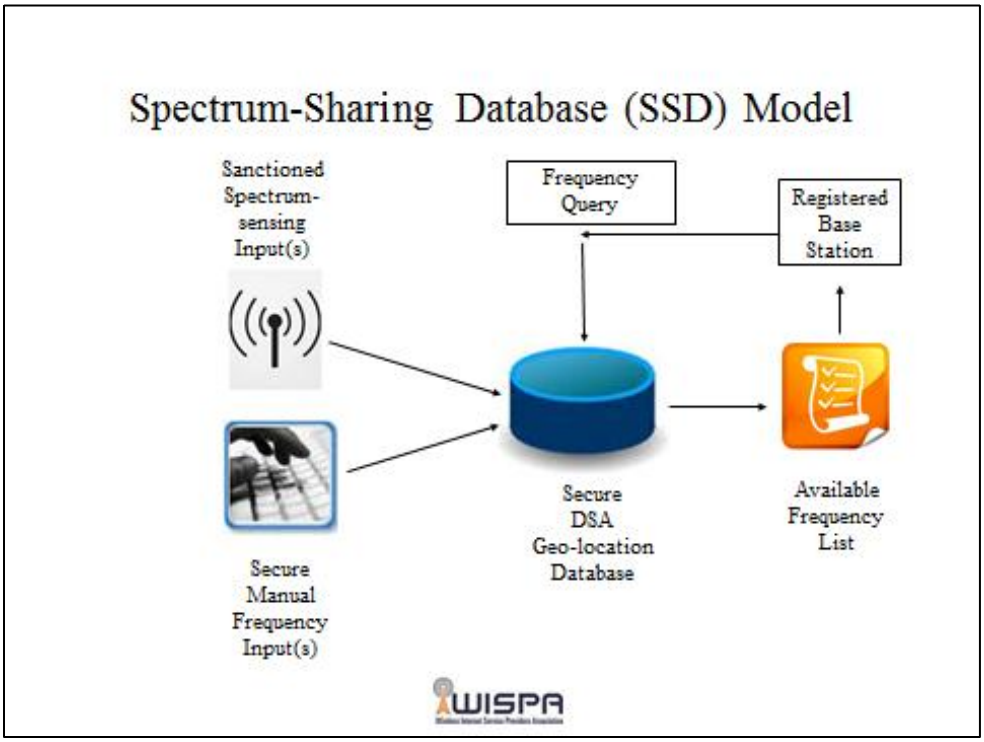

Figure 70. Spectrum-sharing database model.

9.2.3 Clem Fisher, Motorola

As a bit of background, I've been in the radio communication business for 40 odd years. I currently work for Motorola Solutions in the UK, and my main responsibility is to further the RF development of our point-to-point radios which operate anywhere from 2.5GHz to 38 GHz. As you are aware, NTIA has proposed making additional spectrum available in the 3550–3650 MHz band; Motorola has looked at these proposals and fully supports them. Further, we believe there is an opportunity to leverage existing rules (the light licensing approach) and the equipment ecosystems to quickly put this band into use and provide productive wireless broadband. We recommend that the rules get extended on the restricted contention basis that exists already at 3650–3700 MHz down to this extra 100 MHz. We believe this approach has benefits for both business and public interest. The rationale is that there is a clear need for additional spectrum for access and 100 MHz is a reasonable chunk of bandwidth to allow for workable systems that support multiple users in a given geographic area. NTIA has also identified in its report the need for exclusion zones. There are exclusion zones in the current 3650–3700 MHz band, so the concept is still the same. Motorola looked at the linked budget issues, and we propose the power levels in the 3650–3700 MHz band get moved down to minimize the size of the exclusion zones because they are something like 18 dB below the levels used by NTIA in their analysis.

What's important? First, any system that goes into a new band with incumbent users should try to avoid inference to the incumbent systems—that's got to be the major requirement. The original NTIA analysis on the 3550–3650 MHz band looked at mobile base station-type EIRP levels up to about 61 dBm. Mobile operators, however, have no plans for this band, so EIRP limits under the current 3650–3700 MHz rules (1 W/MHz or 43 dBm or 18 dB below NTIA analysis) would protect the incumbent systems from interference. Second, the NTIA Fast-Track report is more concerned about interference from the radar systems into the commercial broadband systems. These radars are rotating radars with very narrow beam widths; hence, the broadband system will see short pulses on a very low duty cycle. We don't think that would be a significant problem in designing radio systems to cope with that. Error correction should be perfectly capable of taking out those problems. If necessary, radios can be designed to sense what is going on in the whole band; we do that with our current products. Further, if the rules allow it, a user can select an operating channel with the least operating interference. This is good for two reasons: (1) avoiding interference with radar, and (2) sharing spectrum with other DSA users.

The NTIA Fast-Track report identifies three different types of radar: fixed ground, airborne, and shipborne. Fixed ground installations only operate up to 3500 MHz, so there is a clear 50 MHz guard band in existence and therefore NTIA proposed small exclusion zones to protect the radar from off channel emissions from the radio equipment. As we move forward, we ought to look at those exclusion zones again as the EIRP from the broadband systems is lower than indicated in the NTIA report. There is also a 50 MHz guard band, and the NTIA report concluded that there is not much point in putting in exclusion zones for the airborne case. The airborne radars tend to be limited by self-interference, because the systems are used when aircraft are flying close together. There is no guard band for shipborne radar because they operate up to 3550 MHz. Concentrating on protection for incumbents, the lower EIRP from broadband systems means smaller exclusion zones (approximately 73 km, down from 500 km recommended in the NTIA report). Obviously, size of exclusion zones would need to be discussed in any rulemaking.

From a business and economic point of view, there is already good take-up of the 3650–3700 MHz licenses (over 1600 to date). There is a clear demand from WISPs and other industrial users for medium power spectrum providing reasonably long reach and/or high data rates. Currently, there are more than 20 manufacturers of communications equipment in the 3650–3700 MHz band. Motorola is one of them. As this extra spectrum is adjacent to this band, it will be easy for manufacturers to modify the equipment and quickly make use of the extra 100 MHz of spectrum. Finally, existing rules and procedures from the 3650–3700 MHz band can be applied relatively easily to the new 100 MHz band.

In summary, we believe the best and most productive use of this band for broadband is to make it available under the current 3650–3700 MHz rules. We believe this approach promotes public and business interests and has the technical advantage of reducing the risk of interference to the incumbent users. Thank you very much.

9.2.4 Jon Peha, Carnegie Melon

I'm going to talk about cellular systems and rotating radar using the same spectrum. In a lot of the discussions about making more spectrum available, it is assumed that we are looking for unused spectrum, i.e., spectrum that, in time and space, nobody else has any use for. There are lots of cases, however, where systems can share in time and space without harmful interference. In the specific case of radar, there are systems that operate over part of the U.S. but not all of the U.S. We can take the parts of the geography where radar is operating and call them exclusion zones. Or, to pick up on Mike Calabrese's point in yesterday's CSMAC discussion, in some cases these exclusion zones should instead be considered sharing zones. Can we share used spectrum in frequency bands and geographic areas where radar systems operate? I think there is great potential for that and also some very real challenges. I'm going to talk about both.

First, consider the sharing model illustrated in Figure 71. We assume

- Fixed, ground-based LTE base station and mobile terminal located at the edge of the cell radius (0.8 km).
- LTE uses 2x2 MIMO in both directions
- Fixed, ground-based radar system rotating at a constant speed
- Shared spectrum at 2.8 GHz with 3 MHz bandwidth
- Site-specific path loss models: ITU-R P.1546 and COST 231 Walfisch-Ikegami
- Tolerable radar INR = -10 dB
- Radar transmit power: 0.45 megawatt
- Radar Antenna: Gain of main beam = 33.5 dBi, azimuthal beamwidth = 1.4˚, elevation beamwidth = 4.7˚, front-to-back ratio = 38 dB

In order to avoid causing interference, the transmit power of the LTE base station is adjusted in time. It knows exactly how much interference the radar system can tolerate, gain and orientation of the radar antenna, and propagation loss between the LTE base station and the radar. Subsequently, from an LTE system perspective, LTE cell capacity is fluctuating as the radar turns. It's fluctuating in part because the maximum transmit power is changing, and it's fluctuating in part because the interference from the radar itself is changing. Would you ever want such a thing if you are an LTE operator? Imagine a scenario where every once in while

LTE cell utilization exceeds the maximum capacity of the dedicated LTE spectrum. In this case, the LTE system spills over into the shared spectrum and utilizes shared spectrum as much as possible.

Under the given set of technical assumptions, Figure 72 illustrates simulated LTE performance as a function of LTE-radar separation. The y-axis is the average secondary LTE data rate; remember that there is fluctuation in throughput related to the time-varying LTE transmit power. The top curve is downstream, and the bottom curve is upstream. The vertical red line indicates that the systems need to be separated by more than 400 km in order for them to not affect the other (i.e., dedicated spectrum model). Achievable average LTE data rates are close to the dedicated spectrum limit at relatively small separations, especially in the downstream link.

From the LTE perspective, is the situation where data rate fluctuates versus time of any value? It turns out that LTE Quality of Service (QoS) will depend on time it takes for the pertinent data to transfer relative to the period of the fluctuation. If a large file is being transferred, the fluctuations won't matter at all because they will average out. If a relatively short file is being transferred, it matters a lot whether transmission occurs when the main lobe of the radar is pointing toward or away from the LTE system. In fact, numerical analysis show that for files a megabyte or larger, worst case QoS is close to average QoS, which is just fine. For files in kilobytes there may be a real problem, i.e., orders of magnitude difference between bad QoS and average QoS. We conclude that this is a nice arrangement for applications like streaming video and peer-to-peer file sharing. Web browsing works pretty well. Voice over IP, however, is not going to work at all, which means you better have dedicated spectrum that you can route those kinds of traffic over. We didn't pick those applications at random; those are the three dominant applications for Internet traffic. Hence, the vast majority of Internet traffic today would work pretty well over shared spectrum.

What are the challenges of sharing spectrum? First, disparate systems sharing spectrum are interdependent: (1) The secondary requires knowledge of the primary; (2) Upgrades to the primary system may require significant changes to the secondary; how does that happen? (3) Bugs in the secondary system are amplified by the risk and potentially harmful interference caused to the primary. Also, precertification is an increased challenge, because if something is missed in precertification there needs to be a way of shutting down that secondary system pretty fast. There are technical problems, but this shifts into a policy and governance problem. We need a primary user or some trusted third party with the ability and the authority to address these interference risks. I don't know that we have quite figured that out; I think that is a coming challenge. Thank you.

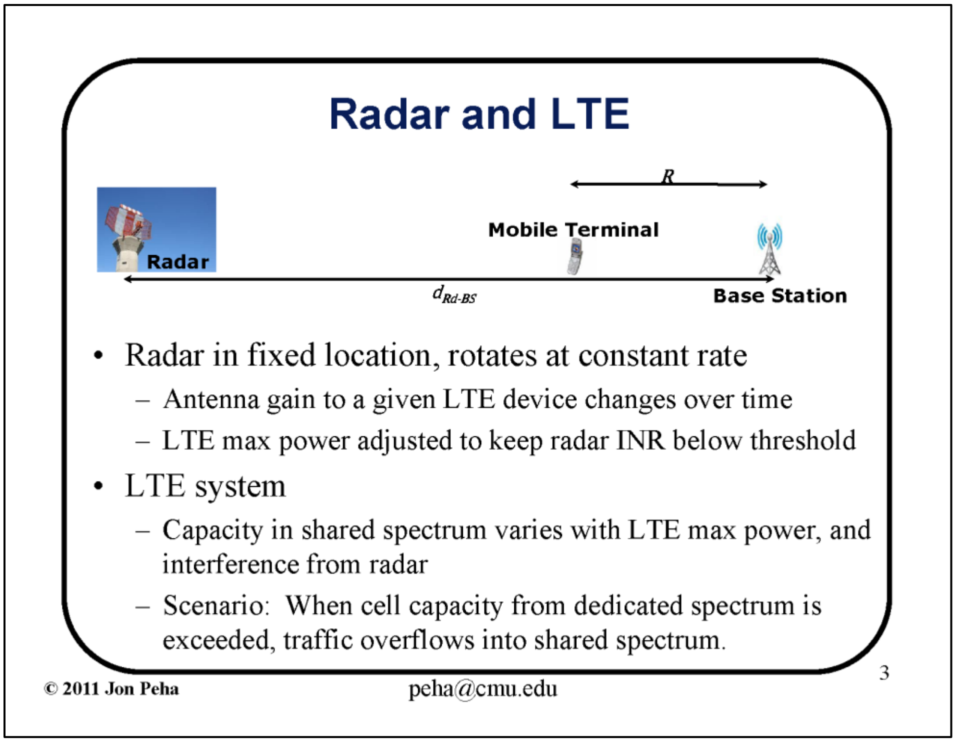

Figure 71. Radar-LTE sharing scenario.

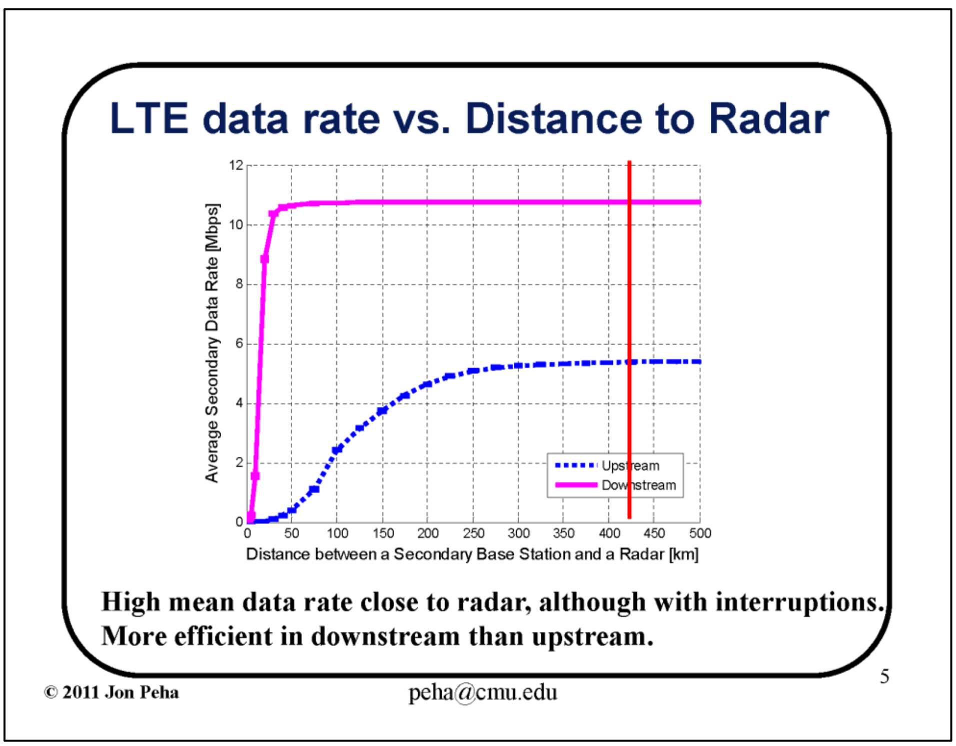

Figure 72. LTE performance versus radar-LTE separation.

9.2.5 Glenn Griffith, Alfred E. Mann Foundation

The Alfred E. Mann Foundation (AMF) has been involved with implanted medical electronic devices that enable treatments and prosthetics that were unimagined several years ago, e.g., cardiac pacemakers, cochlear implants, spinal cord stimulators for pain management, microstimulators for pain suppression, neurostimulation for stroke rehabilitation, myoelectric sensing for prosthetic control, and retinal implants. AMF has also developed near-field magnetic induction, short-range RF power, serial data channels optimized for specific medical applications. Wireless linkage provides a convenient and safe means of passing power and data through the skin without the risk of infection. Just as with conventional radio links, there are issues of co-site interference from other devices around the body and attenuation introduced by body tissues.

The medical micropower network (MMN) is a special application for microstimulators and sensors, where 2–12 implanted microstimulator devices (ISD's) are operated from an external master controller unit (MCU), which provides stimulus commands and monitors the state of health. As summarized in Table 5, MMN operates on four 6 MHz wide channels at approximately a 50 Hz rate (more specifically, 11 millisecond frame rate within which the MCU control signal and ISD response occurs) with a 0 dBm transmit level. The purpose of the four channels is to find an area of opportunity when balancing tradeoffs between antenna size and attenuation (which increases with frequency). QPSK modulation is utilized with raised cosine shaping to reduce emission adjacent to MMN channels. In terms of susceptibility, the 11 millisecond frame rate affords sufficient overhead that dropped frames ($\leq$ 5% error rate) can be tolerated. Signals from implanted devices experience 20 dB of attenuation from human tissue, which effectively provides shielding. Finally, MMN performs active frequency excision of narrowband interferers and channel monitoring to reduce the interference to and from radars.

Table 5 also presents required separation distances (RSD) to avoid causing interference to the radar operating in the 410–450 MHz frequency band. Calculations were based on interfering MMN signals being 6–10 dB below the thermal limit of the radar. For outdoor MMN operations, RSD are less than 0.4 m. For indoor MMN operations, RSD is even less. These RSDs are so small that an interference event is highly unlikely; hence, radar bandsharing is achievable.

In a second study, the MMN system was wired to an interference simulator to evaluate the frequency excision capability and evaluate MMN susceptibility to various anticipated interfering signals (i.e., ground and airborne radar, mobile voice and data, television, and enhanced position location reporting system). The testing verified that the MMN system performs to its specifications and is able to operate in the presence of incumbent users. It can spectrally excise narrowband users and is able to change channel without suspending clinical functions. It is able to gracefully shutdown in the presence of link service loss. Finally, it can sense incumbent users and select channels to avoid interference with them. Thank you very much.

Table 5. Required Separation Distances for Medical Micropower Networks to not Cause Interference to a Radar System Operating at 410–450 MHz.

AMF as TX Government C-E System as RX		RSD (Outdoor)				RSD (Indoor)			
		MCU PL(50%) (km)	ISD PL(50%) (km)	MCU PL(95%) (km)	ISD PL(95%) (km)	MCU & Bldg PL(50%) (km)	ISD & Bldg PL(50%) (km)	MCU & Bldg PL(95%) (km)	ISD & Bldg PL(95%) (km)
Land Mobile	Base	0.31	0.04	0.30	0.02	0.30	0.01	0.30	0.004
	Mobile	0.30	0.04	0.23	0.02	0.18	0.01	0.12	0.004
Mobile	Base	0.34	0.04	0.30	0.02	0.30	0.01	0.30	0.004
	Mobile	0.30	0.04	0.25	0.02	0.20	0.01	0.12	0.004
Aeronautical Mobile	Base	0.34	0.03	0.30	0.01	0.30	0.01	0.26	0.003
	Air	1.34	0.02	0.53	0.01	0.34	0.004	0.13	0.002
Maritime Mobile	Base	0.30	0.02	0.30	0.01	0.25	0.004	0.12	0.002
	Mobile	0.30	0.01	0.26	0.004	0.10	0.003	0.06	0.001
Radiolocatio n	Ground Station	0.70	0.12	0.41	0.05	0.32	0.03	0.30	0.01
	Mobile Air	5.98	0.08	2.38	0.03	1.50	0.02	0.60	0.01
	Mobile Ground	0.29	0.02	0.18	0.01	0.15	0.01	0.09	0.002
No Specific Service (Experimenta l)	Base	0.37	0.06	0.30	0.03	0.30	0.02	0.30	0.01
	Mobile	0.31	0.07	0.30	0.05	0.30	0.03	0.21	0.01
Fixed		0.52	0.09	0.31	0.04	0.30	0.02	0.30	0.01
Space Research (Space-to-Space)		No Records	No Records	No Records	No Records	No Records	No Records	No Records	No Records
50% to 95% difference of 8 dB									
Bldg – Suburban Building Loss of 12 dB used in analysis RX – Receiver TX – Transmit									

Source: Defense Information Systems Agency, Defense Spectrum Organization, Joint Spectrum Center, "Electromagnetic Compatibility Analysis of the Alfred Mann Foundation Medical Micropower Network," Consulting Report JSC-CR-10-058, Jan. 2011, Table 4-1, p. 20.

9.2.6 Mark McHenry, Shared Spectrum

We have been trying to identify the real requirements of a DSA system for both entrant and incumbent (as shown in Table 6) [56]. One thing that incumbents bring up over and over again is accommodating change in incumbent use. By letting a DSA entrant in, incumbents worry that they will be forever locked into what they are doing today.

Table 7 illustrates incumbent and entrant costs associated with each requirement. For each requirement, there is an approach specified. Hence, if spectrum sensing is the approach to do no harm, then the incumbent needs to tell the entrant what waveform is used. For some costs, the incumbent pays or the entrant pays or the costs are shared, e.g., database administration.

We are trying to see all the costs, from beginning to end; we are treating it as a whole system, and there are a lot of issues involved. I probably didn't hit on all of Bob's questions, but all you need is a few questions unanswered and everything stops. Ask T-Mobile or Verizon, "Do you want to do DSA?" Carriers don't see it as a system; they don't see a concrete answer. TVWS eventually got down to a system that everyone could see and agreed to use. That took a long time to get to that point. As we move into other bands, we are going to have to customize that system to all these other requirements because thing will vary band to band.

Table 8 focuses on the impact to accommodate changes in incumbent use, which was actually the trickiest one. Boxes in red identify changes that are difficult for the entrant to overcome. Consider a scenario where the incumbent made a deal with the entrant to provide within-the-hour position, but then realized that information is classified and cannot be provided. Under the agreement a geolocation system was developed which counts on position data. Withdrawing that information causes high cost to the entrant. Next, consider an incumbent changing transmitter mobility from fixed to mobile in a geolocation database arrangement. That is high cost to the entrant because update rates will need to be changed from hours to minutes. On a positive note, a combination of geolocation and sensing can accommodate any change.

Consider the lower class of changes that have little impact on the entrant's system but might chew up spectrum; for example, changing the incumbent's transmit power from 100 kilowatt to 5 megawatts, or changing location to the top of a hill or closer to a town. We are trying to put numbers to these.

When I started this a few years ago, I didn't know any of this. In fact, last year's ISART really helped us make this list. Nearly everything on this list I was hearing at the conference. All these requirements are being discovered, we've made a lot of progress and this 5 GHz thing has fleshed out a lot of stuff. It's a complicated problem, but there is nothing that blocks a solution. We are getting close to being able to define this as a system and come up with a solid answer.

Table 6. DSA requirements for entrants and incumbents.

Requirements of Entrant	Requirements of Incumbent
• *Do no harm to entrant*—unreasonable and time-changing incumbent interference protection criteria and equipment • *Safeguards* from unauthorized and accidental use • *Support current architecture* • *Minimal changes to standards*—to promote purchase of standardized, non-proprietary equipment from multiple vendors • *Low prime power* • *Minimal software integration costs* • *Capacity*—to support business model and justify investment • *High reliability and assured access* • *Reduced operator workload* • *Trust*—need assurance that agreement points will not change • *Fair-use policy* • *Security*—cannot reveal proprietary information	• *Do no harm to incumbent* • *Safeguards* from unauthorized and accidental spectrum use • *Accommodate changes in incumbent use*—mechanism to change incumbent equipment of parameters without impacting DSA entrant. • *Backup DSA operation band* to accommodate potential increase in incumbent spectrum use • *Enforcement*—means to identify DSA device causing interference • *Standardize DSA types and policy-based component* to simplify multitude of DSA systems and spectrum management workload • *Proven technology*—field tested in realistic environments before deployed • *Trust*—need assurance that agreement points will not change • *Security*—cannot reveal classified information

Table 7. Spectrum-sharing costs to incumbents and entrants.

Requirement	Approach Description	Cost		
		Incumbent	Entrant	Incumbent or Entrant
Do No Harm	Certain frequencies at certain locations/times are unavailable for entrant use.	None	Implement dynamic network management	None
Do No Harm	Implement sensing-based sharing approach	Provide waveform information and equipment description.	Modify equipment to implement sensing.	None
Do No Harm	Implement geographic-based sharing approach	Provide and update location information and equipment description.	Modify equipment to implement position location and connection to database.	Build and operate database system.
Do No Harm	Implement physical layer-based sharing approach	None	Reduced link distance performance.	None
Do No Harm	Implement cooperative time sharing-based sharing approach	Provide and update location and schedule information and equipment description.	Modification to equipment to implement position location and connection to database.	Build and operate database system.
Do No Harm	Implement opportunistic time sharing-based sharing approach	None	Modification to equipment to allow rapid sensing and response to avoid interference	None
Accommodate Changes in Incumbent Use	Entrant equipment connected to a database.	Provide information on usage (locations, waveform types, etc.)	All equipment must be periodically connected to a database.	Build and operate database system.
Accommodate Changes in Incumbent Use	Sensing-based approaches must have a programmable detector/classifier	Reduced flexibility in waveform design and must provide sensitive waveform information	Implement flexible, re-programmable detector/classifier.	None
Enforcement	Implement mechanism to detect and mitigate interference cause.	Provide information on interference event (locations, waveform types, etc.)	Centralized method to locate and control equipment	Operate interference management service.
Backup Band	Entrant hardware must cover multiple spectrum bands.	None	Additional hardware cost to cover additional spectrum bands.	None
Backup Band	Extra entrant spectrum must be provided by incumbent or entrant	Potentially need to provide additional spectrum to entrant.	Potentially need to acquire additional spectrum.	None
Safeguards / Security	Implement secure method to manage entrant spectrum.	None	Minimal cost, COTS solutions.	None

Table 8. Impact on geolocation- and sensing-based entrants to accommodate changes in incumbent use (1=easy, 3=hard).

Incumbent Change in Use	Impact to Geolocation-Based Entrant Only	Impact to Sensing-Based Entrant Only	Impact to Both Entrant Types	Method to Provide Certainty to Entrant
Waveform Type - modulation type, signal bandwidth or MAC	None	Must have enough waveform information to design classifier(3)	None	To enable sensing approach classifier design relative to entrant waveform, incumbent provides waveform information to limit waveform parameters.
Mix Waveform Types Within a Band(	Adjust exclusion zone(1)	Implement multi-detector/classifier system(2)	None	Incumbent provides waveform types in the band
Withhold Transceiver Location Information	Approach not feasible(3)	None	None	Incumbent agrees to not change Transceiver Location Information policy
Provide Entrant Advanced Warning of Transceiver Operation	Assume 100% duty cycle and reduces amount of available of spectrum, (2)	None	None	Incumbent agrees to not change advanced warning plan.
Mobility - Fixed to mobile to airborne transmitters	Obtain real-time transceiver location information, use large exclusion zones, or approach not feasible(3)	None	None	Incumbent agrees to not change mobility, or to provide transceivers info in real-time to enable geolocation approach.
Link Type—Duplex vs telemetry vs f1/f2)	Adjust exclusion zone size(1)	Telemetry links require lower detection thresholds. f1/f2 requires frequency plan information.(3)	None	Incumbent agrees to provide link type information.
Transmit Power Level	None	Change detection thresholds(1)	Decreases amount of available spectrum if sharing based on interference to entrant.	Incumbent agrees to limiting min and max transmit power level.
Transmit Mask Shape	Adjust exclusion zone if based on entrant interference(1)	Change detection thresholds(1)	Decreases amount of available spectrum if sharing based on interference to entrant.	Incumbent agrees to limiting min and max transmit mask.
Desired Interference To Noise Level	Adjust exclusion zone size(1)	Change detection thresholds (1)	Decreases amount of available spectrum.	Incumbent agrees to limiting interference level.
Number of transceivers or TX duty cycle	Provide waveform information and equipment description.(1)	None	Decreases amount of available spectrum	Incumbent agrees to limiting number of TX duty cycle within each operating area.
Receiver Selectivity	Adjust exclusion zone size(1)	Change detection thresholds(1)	Decreases amount of available spectrum	Incumbent agrees to limiting adjacent channel rejection level.
Antenna heights or antenna gain values	Adjust exclusion zone size(1)	None	Decreases amount of available spectrum	Incumbent agrees to limiting antenna height.

9.3 Moderated Discussion

Knapp: When we think about sharing with radars, what kinds of packages of techniques do you feel are most appropriate? What's different about sharing with radars than sharing with some of the other systems?

Unger: Well, I think lower duty cycle gives us some advantage in that they're on for only, at least transmitting, for short bursts, but of course receiving over a longer period of time, so that presents some interesting challenges and opportunities.

Griffith: Because of the rotation and the lower rate that they pulse at, for our systems, we are able to survive right through the pulses and our error rate tolerance is able to give us protection. Perhaps, that is unique to the applications that we're seeking.

Peha: The last couple of days have shown there are many flavors of radar, so it is going to depend. For the kinds that we are talking about, i.e., rotating radar systems that are fixed, predictability is helpful in a lot of ways. It is difficult, because we assume legacy and very little tolerance and of course the potential damage of getting it wrong can be very high. We can look at lot of other kinds of radar technologies that are maybe more tolerant or maybe more adaptive, but then at the same time become less predictable. So, there is a tradeoff.

McHenry: I think that sensing problem is the easiest in radar. In TVWS it was the hardest. Radar's got the high power and its co-frequency. There are no hidden nodes. However, their positions are going to be classified and that's going to create difficulties.

Knapp: One of the things that I think we struggle with at conferences like this is that communities come together and ideas are formed, but down the road when it is time to implement those ideas, suddenly we have the two different viewpoints at loggerheads. In each of your cases, we have some concrete ideas (e.g., 3550–3650 MHz and sharing with fixed rotating radars), what can we do better to bring the communities together to exchange information and not just focus on access but focus on the needs of the radar incumbents?

Unger: One thing that comes immediately to mind is test bed. If you could help implement a test bed, we could actually get our hands on some of this hardware and software and see what happens.

Peha: Actually, this conference is a great start. In the near-term, we've got to be thinking about living with legacy designs on both sides in some sense. I would like to see more work on creating systems that are designed to have radar and communications systems together, which is going to require the combined expertise. Forward-looking projects looking at those types of issues are where the real long-term wins will come from.

Griffith: For medical products, our authorization process is overseen by the FDA, and we could look to the FCC and NTIA for support on these particular types of products and issues. Within that context, we have an extensive risk and safety analysis requirement, because we are dealing directly with patients. For all the agencies we are involved with, patient safety is their first and foremost concern. Within that, agencies have been active in trying to build this new roadway toward accepting and tolerating experimentation and implementation related to medical products.

We're not the only one developing these types of techniques and things. There are other types of devices out there that haven't been described today. There is a lot of proactive work, and I commend it.

Fisher: Although there have been problems obviously with the TDWR systems, there has been good dialogue between industry, regulators, and the radar community (i.e., FAA, etc.). That is useful, and we need to build on that. One thing that is difficult is sorting out what kinds of rules to create from the wide variety of discussions that take place. Writing down the discussions, so that people who aren't actually involved in the process, e.g., manufacturers, are informed and know quite clearly what it is that they need to do. At the end of the day, a manufacturer in the Far East or in Europe will follow the rules, and rule-makers need to be careful that the rules are structured so that they say exactly what is really intended and needed.

Knapp: The list of radar bands was presented in yesterday's radar inventory briefings and was given in the NTIA Special Publication on Federal Radar Spectrum Requirements [65]. Clearly you can't tackle everything at once. Where do you see the opportunities? There are few that stand out to me. We've talked about 3550–3650 MHz. There has been some interest in trying to expand those techniques at 5.8 GHz. Karl Nebbia (NTIA) talked about a number of other radar bands identified for further study and consideration. What things stand out to you as the concrete areas that you would focus on?

Unger: Would I be repetitious if I would say 3550–3650 MHz?

Knapp: I've stumped the panel (laughter)… We have talked about spectrum-sharing ideas and techniques, but one of the challenges is figuring out how to move to the next step. What concrete things do we do to advance the ball?

McHenry: I think we need to agree on all requirements. We made the list, which needs to be vetted. FCC and NTIA need to say that these are the issues and requirements and provide a template for a particular band. As long as the requirements are not known, it's just swirling and thrashing.

Peha: I've just come off of two years in government service, and I saw all sorts of useful information that would help answer that question—information that I can't use. Sitting outside of government, I need to know an awful lot more about what is going on in specific bands to make an intelligent comment as to which of them is the most promising. I understand there are good reasons why some of that information is not widely shared, but if it were possible to share more of it then the community outside of government might be able to contribute more to this question.

Fisher: From a radio propagation point of view, most of the bands the radio industry would be interested are below 6 GHz; otherwise, the business cases for deploying products and selling products to people like WISPA are limited. From another perspective, one can always detect the presence of a radar signal. The problem is doing it in such a way that minimizes DFS false alarm rate. Consider the 5.4 GHz rules at the moment. If you detect radar, DFS devices are required to move off the channel and spend a minute looking for a clear channel. Perhaps we ought to think about ways of doing that in a background way, where perhaps DFS devices interfere with the radar for a short period of time before moving off rather than having to detect one radar burst. That potentially reduces DFS false alarm rate and system outage.

Matheson: There is a lot of S-band radar spectrum, i.e., 2700–3650 MHz. That's a lot of spectrum, and I suspect (although I don't know) there is quite a bit of flexibility in how that spectrum is used. It might be relatively easy to come to some agreement in the way it is used operationally, Perhaps, the commercial sector stays away from specified 200 MHz segments that are critical to military operations or avoids a particularly crowded area. It seems that there could be a huge amount of fairly easy payoff if one could get some buy-in from the radar side.

Knapp: I also wanted to take just a minute to recognize that Mike Marcus, who was originally going to be on this panel but couldn't make it in the end, also put together a paper that talks about some sophisticated techniques for sharing with radars. I was intrigued by the amount of capacity that Jon forecasted when sharing with rotational radar. When dealing with actual radars, there are antenna sidelobes and other complexities to deal with. Are there field studies going on right now to confirm your calculations and investigate the fine details?

Peha: No, I don't even know much analytic work other than the work that we are doing here, and don't know of any field test at this time. There are lots of reasons to want to try it though.

9.4 Q&A

Peter Tenhula, Shared Spectrum: I think it is right to put the 3550–3650 MHz band as a priority in light of the NTIA Fast-Track recommendation. Two questions for Clem and Jack about the potential barriers to that and the next steps. First, in Karl's letter to Julie saying go ahead and start the process on this, he said "If you change the parameters, we might have to revisit the protection criteria and the exclusion zones." What does that mean? Are we back to a new Fast-Track analysis? More than half the population is not available under the current exclusion zones. Can you potentially increase the value by reducing the exclusion zones? Our company presented a way in our comments to the FCC, but are there other ways? Second, pending legislation requires FCC to auction the 3550–3650 MHz band. Can a license-lite model be used in that case or do we need to tell Congress that it is not an auctionable set of frequencies?

Unger: Let me answer your last question first. Can we auction this spectrum and still have a licensed-lite approach? The answer is no. I don't see how that could be done. I think the notion of auctioning unlicensed spectrum is completely wrong headed. I also disagree with the notion of raising X billions of dollars one time and believing that that is going to be worth more than the ongoing economic value of using the spectrum in an unlicensed mode. We are lobbying heavily in Congress to get the legislation to be more beneficial. We are hearing that the focus in the House is on raising money; they've told us as much. Long-term benefit is not on their radar screen, literally.

Chriss Hammerschmidt, NTIA/ITS: When we measure radars, we have to change the front end because the power is so high. Is that incorporated into your current systems? Also, a question for Glen and Jon: did you do actual measurements or did you simulate it and is there an opportunity for some type of simulation in this as an initial step forward?

Griffith: Table 5 showed required stand-off distances. A detailed record of that study is available from the Joint Spectrum Center. The second aspect where we were showing susceptibility was an actual wired measurement. We used synthesizers and actual equipment. The Aerospace Corporation did that study and the report is on record.

Peha: The results that I presented are based on lots of simulation. Some of the inputs to the simulation came from measurements, but the results are all simulation. Between that and Julie's last question I should use that as an opportunity to say that I would love to see more experimental work. This type of research starts with simulation. To go to the next step, one would need an environment to play with the real hardware (which is expensive) and do so without causing damage. This brings us back to the test bed idea. A test bed is too expensive for any one of us to put something together, but if we had a place to play then we could move research beyond simulation in new ways.

Knapp: I should add that we have an outstanding rulemaking to revamp our experimental licensing program, and we ask questions about test beds. As we look to the next steps in that proceeding it is certainly something we would like to provide for.

John Notor, Notor Research: One of the hats I wear is that I am vice-chair of IEEE 802.18, which is the radio tag of the IEEE 802. I've been involved in that since 2002, and I have my fingerprints on every submission that we've made to the FCC. Hence, I've bathed in the politics of this for nine years. I have a couple of observations that I would appreciate some comments on. First, I've come to believe (philosophically) that the way to think about spectrum is not in vertical slots, which is kind of how we think of it now, but rather as an ecosystem. In the spectral ecosystem we have low power devices (that transmit below a certain power level and will not cause interference with any system no matter how close you are to it) and high power systems (to be considered in a different light). I'd appreciate some comment on that. Second, one of the biggest issues is associated with each party in the discussion using worst-case scenarios to defend themselves. Every analysis uses free space models in range; however, for terrestrial systems, there are no free-space systems that are even worth talking about. Everybody uses noise submitted contours; however, in most cases, noise-limited contours are not the case. There is a certain amount on the industry side asking for things to be made simpler, when in fact, the cost of implementing complicated technical requirements are becoming less and less as time goes on.

Knapp: I've seen this when the parties themselves, after all the extremes have been filed, sit down together and try to come to an agreement. We had an outstanding rulemaking for the M band medical body area networks, and for the first couple of years there was contention between the advocates of the M bands networks and the users of the aeronautical telemetry systems (which were trying to pick up low-level signals from 200 miles away). One side said, "We're not going to cause a problem," and the other side said "Look at the extreme conditions under which we need to operate." It took a while, but when they sat down together and had a constructive dialogue, they ended up filing a joint proposal with the Commission. We need to find ways to get things moving down these sorts of paths, and this applies to everybody. The incumbent services need to realize that the spectrum resource is precious, and ideas are needed for accommodating additional use of the spectrum. On the other side, new entrants need have to be mindful of the needs of the incumbents. Sooner or later if you are fortunate, new entrants may become incumbents. Then you may have a different view.

Dan Lubar, Relay Services: I think it is a fantastic thing that a database is being used to create value in a spectrum management context and not just a Universal Licensing System (ULS) database. We are talking about a database that gets regulators out of the way and allows the incumbents, new entrants, and users to self-service. That is an important thing. Does auctioning spectrum coming from the Federal side create artificial restrictions and problems? Are there regulatory models that exist that don't have that requirement? Does the economics of the value of the spectrum trump that auction requirement? And when I say economics I mean economics in the U.S. economy, not in the Federal economy.

Unger: One small example to illustrate the value of not auctioning unlicensed spectrum is Wi-Fi—unlicensed spectrum that has created tremendous value to everybody.

Matheson: I think that some spectrum needs to be auctioned because some systems the user really does want complete control of it. Many of these dense cellular bands are that kind of thing, and maybe other bands as well. A much harder thing to decide is how much of each kind of spectrum we really need. If the Federal government need for revenue is the factor that decides in favor of auction in every case, that is surely a bad decision, because there is tremendous value in non-licensed spectrum as well.

Peha: I absolutely agree with Bob. There is value in licensed spectrum that is auctioned, and there is value in unlicensed. Partially, it is about balance. Also, when we are not talking about releasing entirely new bands, it matters what's in there. Whether you get more value with licensed or unlicensed depends, in part, on what you are going to do with it. Some purposes are just better in unlicensed and some aren't. It also depends on what you are going to share with. A broad, one-size-fits-all policy that doesn't allow an expert agency to think about those sorts of things would make me very nervous.

Michael Calabrese, New America Foundation: Peter Tenhula mentioned that 3550–3650 MHz would be required to be auctioned. The carrier industry has mentioned that they are not interested in that spectrum. Further, as Peter mentioned, NTIA calculated exclusion zones that blocked off half the country including the entire state of Florida and up and down the east coast. I believe the exclusion zones are so large because they calculated it for WiMAX power levels. I want to ask Jack, would that spectrum be more valuable at lower power levels (and correspondingly smaller exclusion zones)? And what power levels do you have in mind? Mark: have you calculated alternative exclusion zones corresponding to, say, Part 15 limits or on a light-licensed basis?

Unger: I would like to see, if possible, NTIA look beyond their initial analysis on exclusion zones needed if the spectrum were used for mobile verses exclusion zones needed if the spectrum were used for fixed and/or unlicensed. I think that's a perfect pitch to throw back to the NTIA given the budget availability.

Michael Calabrese: Yes, initially I thought they did it that way just to show people how stupid an idea it was, but they haven't done the alternative analysis. It is mystifying.

Unger: You're right. Sometimes it is very beneficial to show someone how poor an idea is because then everyone says "Ha! That's silly. Here is a much better use."

McHenry: The NTIA exclusion zones were damage to the entrant, which is a function of the antenna height, not transmission power. So if they run the same antenna heights as a carrier, it will be the same distance.

9.5 Paper Submissions

The following papers are associated with this panel:

- Incumbent Spectrum User's Dynamic Spectrum Access Requirements [56] - Mark McHenry
- Implanted Medical Devices Sharing the Radar Band [55]—Howard Stover and Glen Griffith
- Cellular Systems and Rotating Radar Using the Same Spectrum [54]—Jon Peha
- Thoughts on Radar/Communications Spectrum Sharing [57]– Michael Marcus

Incumbent Spectrum User's Dynamic Spectrum Access Requirements

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Abstract— **This paper discusses the Dynamic Spectrum Access wireless system requirements as viewed by incumbent spectrum users. Previously, DSA performance was primarily assumed to be based on the amount of interference the DSA system caused to incumbent radio systems. As DSA starts to mature, additional requirements have emerged. Incumbent stakeholders operate wireless systems that are critical to their operations and will only share spectrum when this basic goal is not threatened. Hence, the DSA entrant must develop a system to minimize the issues as viewed by the incumbent to facilitate spectrum sharing. They include the ability to accommodate changes in the incumbent's usage (amount and system types), enforcement and others.**

Keywords-Dynamic Spectrum Access, requirements, spectrum sharing

I. Introduction

This paper discusses the Dynamic Spectrum Access wireless system requirements as viewed by typical incumbent spectrum users. The requirements originated from conversations and meetings with multiple spectrum stakeholders including both commercial and incumbent groups. Additional insights were obtained from the DFS, AWS and TV white space spectrum rule proceedings.

Section II summarizes Dynamic Spectrum Access technology and provides a description of the "spectrum cube" vision where multiple types of wireless services efficiently share spectrum.

Section III describes the different DSA system requirements as viewed by the incumbent spectrum user. The goal of these requirements is to facilitate a "win-win" situation where the incumbent spectrum user will share spectrum and not enter into "life or death" struggles to prevent the entrant from using the spectrum. The different requirements focus on the incumbents' overall desire to be able to maintain and possible increase his spectrum use with high confidence. Many of these requirements are technical in nature. Some of the requirements are process orientated.

Section IV compares Shared Spectrum Company's DSA system to these requirements. While this system meets most of the requirements, there are some shortfalls that are currently being developed.

Section V provides a summary.

II. DSA Vision

Dynamic Spectrum Access (DSA) offers significant improvements in the amount of spectrum access compared to the present command and control, fixed spectrum access methods. DSA software technology dramatically improves spectrum efficiency, communications reliability, and deployment time. DSA software dynamically senses spectrum use and adapts to its radio frequency (RF) environment to maintain reliable communications with other DSA-software-enabled devices without causing interference to incumbent radios. The SSC DSA solution is a radio software solution comprising key radio software modules as depicted in Figure 1. DSA uses a variety of signal detectors and classifiers to characterize DSA signals from "Non-cooperative"/incumbent signals. When DSA signals are encountered, the DSA MAC determines the frequency selection strategy. When "Non-cooperative"/legacy signals are encountered, the DSA policy module follows FCC and NTIA rules to determine the operating frequency and power level. DSA technology was developed by SSC as part of the DARPA XG Program.

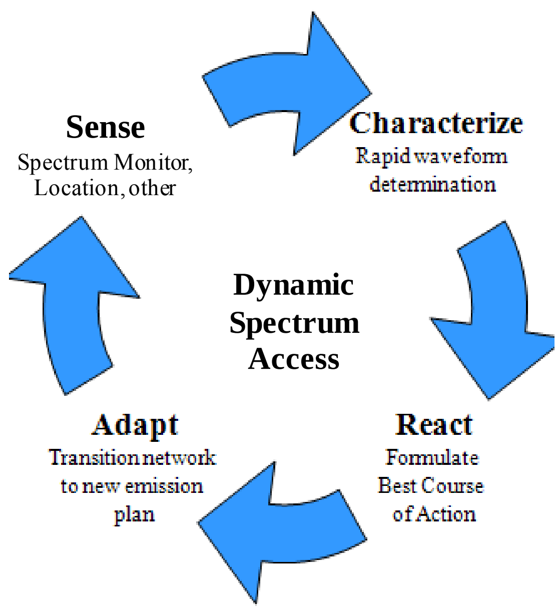

Figure 1. Dynamic Spectrum Access (DSA) Technology

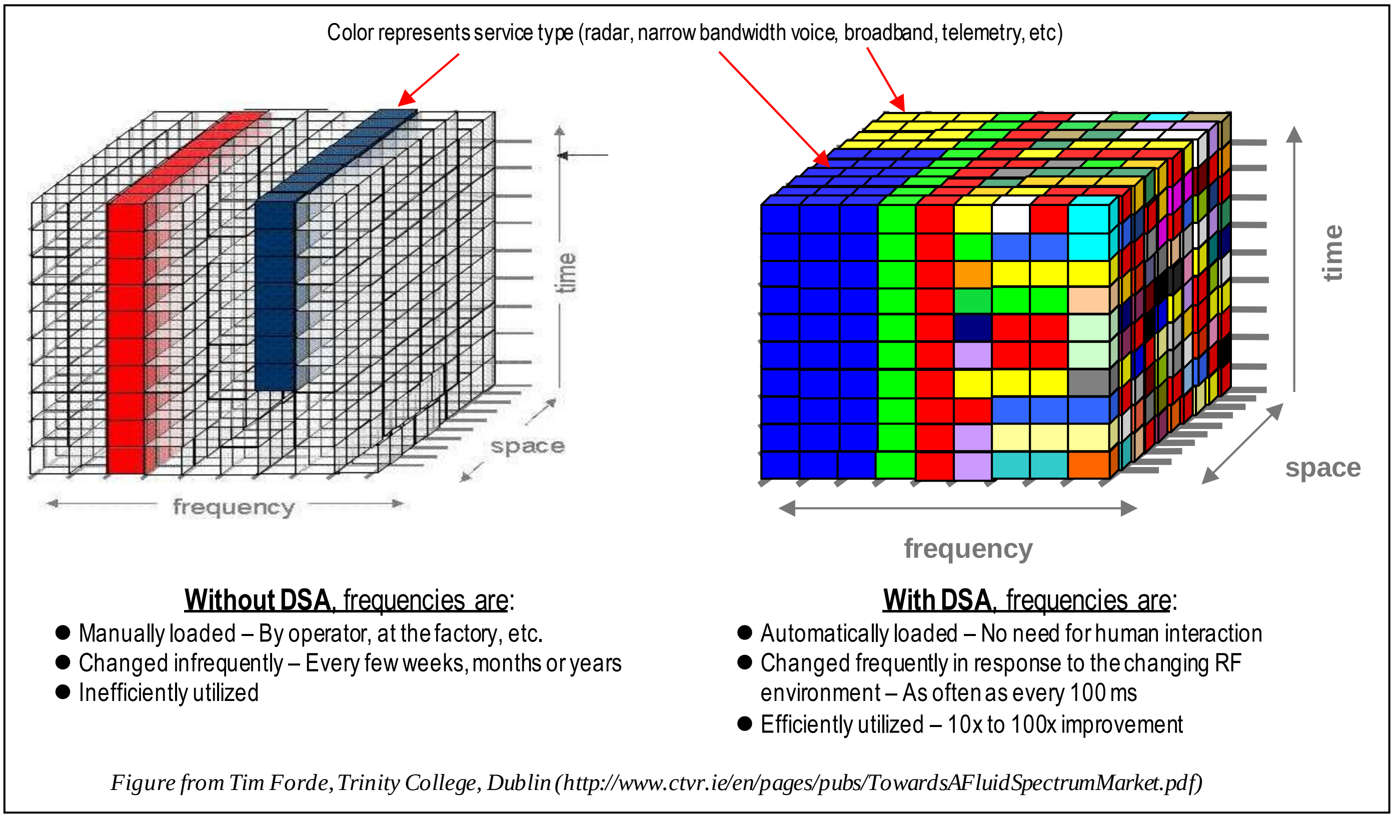

Figure 2. The "Spectrum Cube" vision is for a dense use spectrum use with diverse services sharing with minimal frequency, space and time spaces.

DSA improves spectrum efficiency by enabling efficient spectrum use as illustrated by the spectrum cube shown in Figure 2. Without DSA (left side of figure), there are large separations in frequency, space, and/or time between different users. These separations are used to minimize interference between the users with a minimal amount of coordination between the users. As the number of users has increased, the frequency, space and time separations represent a very large spectrum user inefficiency, which needs to be utilized if the wireless capacity is going to grow. With DSA (right side of figure), the amount of frequency, space, and time separation between users is minimized.

In the past, similar types of services were grouped in frequency bands to reduce coordination efforts. However, in the future, different services will share the frequency bands. Examples include the Dynamic Frequency Selection (DFS) rules which allow low power, unlicensed communication devices to share spectrum with high power radar systems, the TV white space (TVWS) rules which allow low power DSA devices to share spectrum with TV broadcast systems.

The question is what process will be used to develop rules and process that enable users to share spectrum. The DFS and the TVWS rules processes were protracted (5 to 10 years in length), adversarial approaches where a set of fixed rules were developed. The entrants and incumbents spent large sums on lawyers and lobbyists, conducted expensive (and inconclusive) tests, and finally resolved the rules through largely political means. If the entrant's top leadership had not personally contacted congressional and senior FCC leadership, the DFS and TVWS rules would still be pending in the government offices.

III. Incumbent DSA Requirements

This section describes the DSA system requirements related to satisfying incumbent spectrum stakeholder's concerns. Incumbent stakeholders operate wireless systems that are critical to their operations and will only share spectrum when this basic goal is not threatened. Hence, the DSA entrant must develop a system to minimize the issues as viewed by the incumbent to facilitate spectrum sharing.

A. Accomidate Changes in Incumbent Use

There needs to be a mechanism for the incumbent user to change their radio equipment types or parameters that doesn't significantly impact the entrant DSA user. An example is in the DFS band where a certain type of weather radars were not considered in the original DFS rules and the fielded DFS devices didn't detect these radars. It was very difficult for the government to go back to the commercial users to fix this problem.

DSA Implication – The DSA classifier and other spectrum access rules needed to be easily changed in fielded DSA radios. This software update must be done with the DSA radios that are in the field at an insignificant cost. DSA radios that don't get the update must cease operations after a certain time period.

B. Backup DSA Operation Bands

The entrant DSA user needs to have one or more backup spectrum bands to accommodate the incumbent user's potential increase spectrum use. The incumbent user might originally have a low spectrum use, but may later decide to increase their use. The incumbent user's fear is that the entrant DSA user's system will not function well when the incumbent user increases their usage, and then the entrant DSA user will go to the regulators to force the incumbent user to reduce its usage.

DSA Implication – DSA needs to be implemented on multi-band radios with at least three spectrum bands to enable robust "backup" secondary usage. The initial DSA radio operators need to seek two or more incumbent bands with dissimilar incumbent users in the initial pilot programs to demonstrate "backup" operation. Or, the entrant DSA spectrum band must augment the commercial system's existing spectrum bands. The DSA system should not solely operate in a single incumbent user's spectrum band(s).

C. *Enforcement*

If interference occurs, there needs to be a way for the incumbent user to easily identify which entrant DSA users are causing interference, and to then correct the problem or shut them down. For example, an interference issue occurred in the DFS band where the weather radars starting getting interference [1]. It occurred because the weather radars had a waveform that was not in the initial DFS rules. The incumbent users contacted the FCC and asked them to shut down the interfering DFS users. The FCC said that they would if the incumbent user told the FCC the owner's names and locations of the interfering radios, the FCC would shut them done. The incumbent user didn't have a method to do located the interfering the DFS users. Hence, the incumbents had to expand significant engineering resources to identify the source of the interference to correct the issue.

DSA Implication – The DSA system should implement a method to identify and shutdown suspected interfering DSA radios when the spectrum managers don't have information on the location and identity of the DSA radios in the field. This could be accomplished by transmitting new spectrum policies that shut down DSA radios in a certain geographic region and frequency band to isolate the DSA radios causing the problem. Then the DSA operators would incrementally change the policy parameters to determine the specific reason why the interference is occurring. The DSA system needs to include a function for the DSA radios to identify to the spectrum managers that the DSA radios are in the area being suspected of involved in an interference event.

To support enforcement, the DSA system needs to support a wide range of spectrum access rules as shown in Figure 3. These rules are needed to both localize what DSA radios are causing interference and to restrict use. For example, a sense-based (Listen-Before-Talk) DSA radio must also support spatial access rules to facilitate determining what DSA radio is the source of an interference complaint. Temporal type rules are required to enable rules to age out so that if a rule is changed, that this rule change is promulgated out to all users within a reasonable amount of time. Device based type rules are needed to support changes in incumbent radio types.

D. *Unauthorized and Accidental Use*

Incumbent users are concerned about unauthorized and accidental spectrum use by DSA systems. This includes both

Listen-Before-Talk based types
LBT – Same up and downlink frequencies
LBT – Different, but known, up and downlink frequencies
LBT – Different, but known, up and downlink frequencies, band plan known
Spatial types
Geographic border field strength limits
Database geographic/ Coverage area based
Temporal types
Time of Day restrictions
Authorization for finite time duration (with periodic renewals)
Device based types
Classifier Capability – Certified ability to detect specific incumbent signal type to a certain sensitivity level
Device Capability - Ability to measure second and third harmonic
Device Capability - DSA TX power spectrum density limit

Connectivity based types
Beacon reception required to use band
Connectivity requirement for any policy (can use certain bands only if connected to Spectrum Manager)
Group Behavior based types
Type 1 Group Behavior - Abandon channel if any node in your "group" detects Non-cooperative signal at above specified level
Type 2 Group Behavior - Determine DSA TX power based on estimated interference probability using "belief maps" of incumbent receiver locations
Control based types
Automated policy updates if feedback indicates that existing policy is insufficient for non-interference operations
Automated policy updates notification of policy revocation or update by policy authority
Node Identify restrictions (e.g., use while airborne prohibited, use only in fixed applications, Red Cross use only)

Figure 3. A wide range of DSA rules are needed to support interference mitigation and enforcement.

accidental and malicious situations.

DSA Implication – The DSA system needs to implement a policy software certificate security management feature that prevents unauthorized use [2]. This feature should include certificates installed in the radio software by the manufacturer that validates spectrum access polices in certain spectrum bands. Regulators also define regulatory policies, which are applicable to specific applications and which are certified by the regulators for use. In this operating mode, the DSA operator purchases an open, certified device from a manufacturer and specifies the type of application the radio is used for by providing the radio software through a secure link with appropriate certified policies. The device now consists of two certified objects – (i) a policy component, as part of the certified radio, which ensures that the radio conforms to policies, and (ii) the certified policies, which clearly define what the radio can do and what the radio must not do. Therefore, security threads caused by malicious users are still prevented through enforced security guards on the device and on the interface links; however, the security threads caused by malfunctioning or modifying a device are eliminated by dynamically avoiding them.

This approach addresses concerns raised by any stakeholder that is affected by smart software-defined radios. The approach allows regulators and other points of control to continue controlling where and how software-defined devices are allowed to transmit, yet at the same time this approach allows DSA operators and users take the full advantage of the software-defined radio technology.

E. *DSA System Diversity*

There will be a wide range of DSA entrant user system parameters (transmit power, mobile/fixed, directional/omni antennas, bandwidth, antenna height, etc) as shown in Figure 4. Each of these has a different potential to cause interference to incumbent users. The incumbent users are concerned about the complexity of this problem. For them to understand the technical details of the different DSA radio types and DSA spectrum access rules that are used is expensive and difficult for incumbent users. Incumbent users are also forced to determine the worst case scenario and/or force all of the DSA users to a common system type. Forcing all DSA system to be homogenous (as occurred in both the DFS and TVWS rules) is highly disadvantageous for the DSA operator since this is likely to cause significant unfavorable equipment tradeoffs.

DSA Implication – The DSA operators needs to derive simple "cheat sheet" equations and probabilistic simulation models that be used to determine the appropriate DSA spectrum access technique for each scenario. The DSA operators need to illustrate how a policy-based language approach can be used to reduce the spectrum management workload and complexity of managing the different types of DSA users.

F. *Proven Technology*

Incumbent spectrum users correctly require that DSA technology be proven before it is deployed in their spectrum bands. They believe that there have not been enough field tests in realistic environments showing interference avoidance and other DSA features.

DSA Implication – The DSA community needs to conduct more interference avoidance field tests. The demonstrations must have sufficient technical rigor and scope to facilitate the acceptance of DSA by the specific incumbent spectrum community. Third-party validation from disinterested parties (government, testing companies, or academic groups) is required. Scenarios, test plans, requirements and equipment parameters are developed with and corroborated by all interested parties.

G. *Incentives*

There is currently no "upside" for the incumbent user to participate in sharing schemes. They have no funding to participate in meetings or to conduct technical analysis to support spectrum sharing. Federal spectrum user incumbents can't directly accept money from the entrant DSA user; this

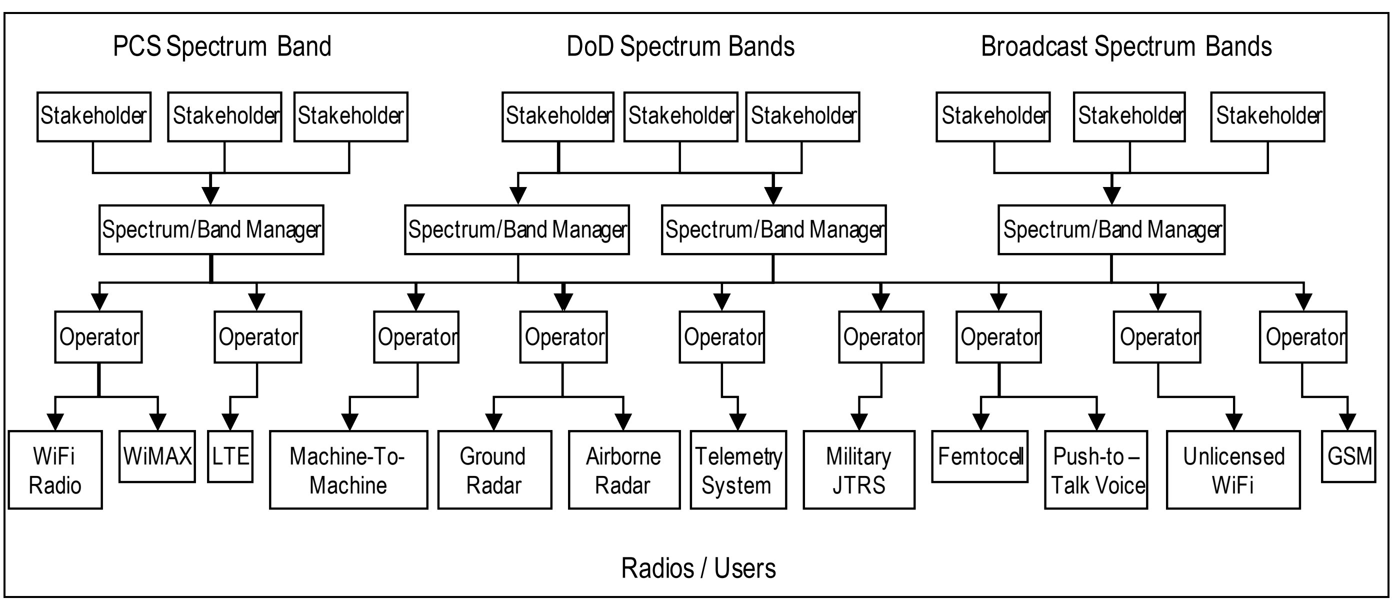

Figure 4. The wide range of DSA radio types and different types of DSA services creates undesirable complexity for the incument spectrum users.

money would go directly to the US Treasury. The incumbent user might be able to accept "in-kind" exchange.

DSA Implication – The entrant DSA operator needs to minimize the cost of the incumbent user in any spectrum sharing "deal". The entrant DSA operator needs to develop scenarios, legacy radio parameters, do field tests, etc with minimal input from the incumbent user. The entrant DSA operator needs to develop something to "give" to the incumbent user in exchange for use of the incumbent spectrum band. This could be incumbent use of commercial spectrum, free use of cellular networks, build out of cellular networks in remote DoD test ranges, free use of DSA radios operating in DoD spectrum bands for incumbent users, development of advanced DSA radios for DoD use, etc.

H. Keeping Commitments

The entrant DSA user needs to abide by its agreements with the incumbent user for a reasonable amount of time. Coming back several years to change "permanent" agreements is extremely upsetting to the incumbent users.

DSA Implication – DSA operators should avoid "challenging" the recent spectrum sharing agreements for in the initial DSA pilot programs. DSA operators should conduct pilot programs in bands where incumbent / entrant spectrum sharing is already going on. Examples are the TV band, 225-380 MHz band (for DoD-to-DOD DSA operations) and other spectrum bands.

IV. Example DSA System Capabilities Compared to the Requirements

Shared Spectrum Company (SSC) has developed and demonstrated a DSA radio system with most of the incumbent friendly features discussed in this paper [3], [4]. The SSC radio system spectrum access features are controlled by machine reasonable policy as shown in Figure 5. This radio system provides an existence tests that an "incumbent friendly" is feasible. The following describes the ability of this radio to meet the incumbent user DSA requirements.

- Accommodate Changes in Incumbent Use - The DSA spectrum access rules can be easily changed in fielded DSA radios by uploading a new policy file. The principal shortfall is the ability to easily change the DSA detector / classifier. At present, this requires a change of a portion of the radio's software.
- Backup DSA Operation Bands - The SSC radio operates over multiple spectrum bands depending on the RF card selected as shown in Table 1. This enables a DSA operator to use multiple spectrum bands and to avoid being dependent on a single incumbent spectrum stakeholder.

Table 1. The SSC DSA radio operates over multiple spectrum bands depending on the RF card selected.

DSA 1000 / DSA 2000 /DSA 2100			
DoD RF Board (MHz)	**Public Safety RF Board (MHz)**	**Wireless (TV) RF Board (MHz)**	**Commercial RF Board (MHz)**
225 – 512 1215 – 1390 1435 – 1525 1755 – 1850 2200 – 2290	138 – 174 220 – 512 764 – 869	174 – 216 516 – 806	698 – 941 1390 – 1435 1670 – 2680

- Enforcement – The SSC radio is policy controlled and can execute a complete set of sensing, geographic and other rules as shown in Figure 4. With a properly constructed set of policies within finite time duration, interference events can be tracked down and eliminated at low cost. An example would be to have all sense-based policies time limited to a few days and require a re-authorization for continued use. If an interference event to an incumbent device occurred at a specific location, the cause could be determined using a set of geographically limited sense-based policies with different parameters.
- Unauthorized and Accidental Use - The SSC radios use a certificated-based policy system that provides a high level of security.
- DSA System Diversity - The SSC radio uses a policy-based system that is designed to isolate the incumbent users from the entrants.
- Proven Technology – The SSC radio was used in interference to incumbent systems field tests as part of the DARPA XG Project [5]. These field tests indicated the ability of the system to meet low interference to noise ratio values and rapid channel abandonment time values. These tests were performed in an isolated region. Additional tests in more realistic environments are needed to further increase the incumbent's confidence in DSA technology.

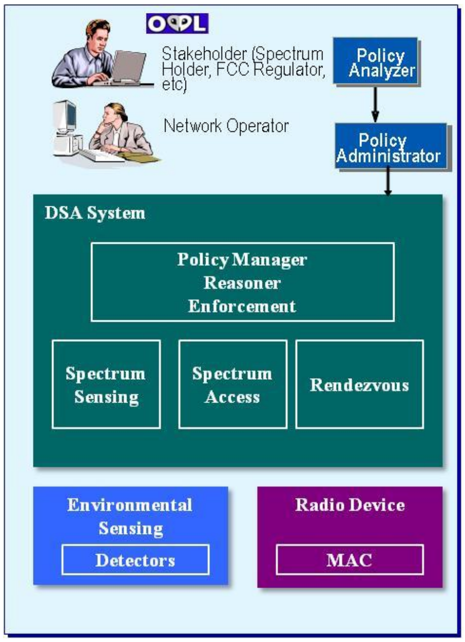

Figure 5. Shared Spectrum Company's DSA 2100 radio system is policy language controlled, which enables it to accomidate most of the incumbant DSA concerns.

V. CONCLUSIONS

To enable more rapid and less contentious deployment of DSA systems, the DSA system design needs to account for the valid incumbent spectrum users concerns. For example, the two DSA-related FCC rule proceedings (DFS and TVWS) were long difficult proceedings because they created significant perceived risks for the incumbent spectrum users. After fielding DFS devices, it was learned that certain incumbent devices types were not correctly accounted for during the rule making process, which led to interference events. Hence, the DSA devices needed to be "recalled" and modified. This caused significant expense for both the incumbent and the entrant entities.

Instead, we propose that DSA systems adopt incumbent friendly features. These include both technical and operational features. The specific entrant concerns and DSA features are as follows:

- Accommodate Changes in Incumbent Use - The DSA classifier and other spectrum access rules are easily changed in fielded DSA radios.
- Backup DSA Operation Bands - The entrant DSA user needs to have one or more backup spectrum bands to accommodate the incumbent user's potential increase spectrum use.
- Enforcement - If interference occurs, there needs to be a way for the incumbent user to easily identify which entrant DSA users are causing interference, and to then correct the problem or shut them down.
- Unauthorized and Accidental Use - The DSA system needs to implement a policy software certificate security management feature that prevents unauthorized use.
- DSA System Diversity - The DSA operators must take steps to isolate the incumbent from needing to understand the complexity of the many types of DSA systems. This includes developing simple representations of the DSA system interference performance and the use of policy language DSA command and control.
- Proven Technology - The DSA community needs to conduct more interference avoidance field tests. These tests need to be rigorous, well documented technical tests, and not "demonstrations".
- Incentives - The DSA operator needs to minimize the cost of the incumbent user in any spectrum sharing "deal". The DSA operator needs to provide funding, equipment exchanges or other compensation when possible.
- Keeping Commitments - DSA operators should avoid "challenging" the recent spectrum sharing agreements for in the initial DSA pilot programs. DSA operators should conduct pilot programs in bands where incumbent / entrant spectrum sharing is already going on.

SSC has developed a radio system that inherently meets most of these requirements because its spectrum access rules are policy language controlled using a certificate-based security policy. One shortfall is the ability to easily change the DSA detector / classifier. Presently this requires changing some of the software.

REFERENCES

[1] F. Sanders, " 5 GHz DFS Technology Development and Deployment: Challenges Met and Lessons Learned" , 11th International Symposium on Advanced Radio Technologies, (ISART), 2010.

[2] F. Perich, "Policy-based Network Management for NeXt Generation Spectrum Access Control", DySPAN 2007.

[3] "Shared Spectrum Company DySPAN 2008 Demonstration Overview", http://cms.comsoc.org/SiteGen/Uploads/Public/Docs_DYSPAN_2008/SSC_Demo_IEEEDySPAN2008.pdf

[4] M. McHenry, K. Steadman, A. Leu, E. Melick, "XG DSA Radio System", DySPAN 2008.

[5] M. McHenry, E. Livsics, T. Nguyen, and N. Majumdar, "XG Dynamic Spectrum Sharing Field Test Results", DySPAN 2007.

Implanted Medical Devices Sharing the Radar Band

Prosthetic and Diagnostic Implants Use Unconventional Communication Models

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***Abstract*—Medical applications of wireless and near-field inductive links are specific to the therapeutic application with unique constraints on power and co-site interference. The ability to share spectral regions previously reserved for radar systems, radio location, fixed and mobile communications, and amateur usage provides a critical solution to these constrained medical devices. Sharing of the 413-457 MHz band with the Medical Micropower Network (MMN) application is accomplished through a combination of mitigation measures, and its use of very low power transmission.**

Keywords-neurostimulation; microstimulator; radar; maritime mobile; aeronautical mobile; land mobile

I. INTRODUCTION

Implanted medical electronic devices are becoming more prevalent with a world-wide patient base. While cardiac pacemakers have been in use for several decades, many new applications for microelectronics and nanotechnology are enabling treatments and prosthetics that were unimagined several years ago. Cochlear implants have a world-wide patient base of over 220,000. Spinal cord stimulators for pain management are also prevalent. Microstimulators for pain suppression, neurostimulation for stroke rehabilitation and myoelectric sensing for prosthetic control are in development and various clinical trials. Retinal implant devices are available in Europe for partial alleviation of blindness. These devices are interactive with the world outside the body. Sensory replacement devices must be in continuous operation and this is generally achieved with some form of radio or induction link. The wireless linkage provides a convenient and safe means of passing power and data through the skin without the risk of infection. Just as with conventional radio links there are issues of co-site interference from other devices around the body, but there are added complexities of transferring power and the attenuation introduced by the tissues of the body. This has added to the pressure for spectral allocation for previously allocated spectral bands because of the unique transmission limitations the human body presents. As will be shown, the region in the area of 400 MHz allows useful signal transmission with modest antenna size and sufficient bandwidth for neuromodulation applications. The spectrum reserved for radar and other applications between 410-450 MHz is of course also useful for its present applications of long range radar and communication. The Medical Micropower Network (MMN) to be discussed limits its interference with the incumbent narrow-band co-channel systems by spectrally excising those signals from the receiver pass band. The reconstructed signal with interferers removed is subsequently demodulated to recover the short bursts transmitted by each implanted device. The MMN external controller monitors the available channels and can seamlessly change to an alternate channel if the current channel becomes too busy or too noisy to process. The excision also allows the MMN to maintain its own error-rate sufficiently high to avoid disruption. Additionally, as a secondary consequence of the need to conserve battery life, the low-power transmission limits the potential for interference for others users in an occupied channel.

In addition to an overview of different medical applications using wireless links, specific test results showing the compatibility of the MMN with the other formats used in this frequency domain will be presented.

II. CURRENT MEDICAL APPLICATIONS

A. External Medical Devices

The number of external electronic medical devices is staggering and seemingly without bound. The devices range from cardio recording devices, insulin pumps, glucose monitors, and functional electrical stimulation (FES) devices for the treatment of the effects of stroke, spinal cord injury and other movement disorders. These devices are external to the body, generally operate autonomously, and have a limited need to communicate except to receive infrequent control signals, clinician programming, or remote data reporting. The devices are predominantly battery powered and the modest average power consumption of a Bluetooth, WiFi, Zigbee, or MedRadio (MICS) style radio link is easily supported since the usage is overall very low duty cycle. Examples of some of these devices are illustrated in Fig. 1 below.

These types of devices often have an integral controller that is immediately accessible to patient and clinician. This eliminates the need for wireless controls; conventional switches and displays are adequate, although wireless connectivity provides additional features and convenience.

B. Implanted Sensorineural Devices

Implanted devices, other than temporary purely diagnostic devices require external power and signaling to be transmitted

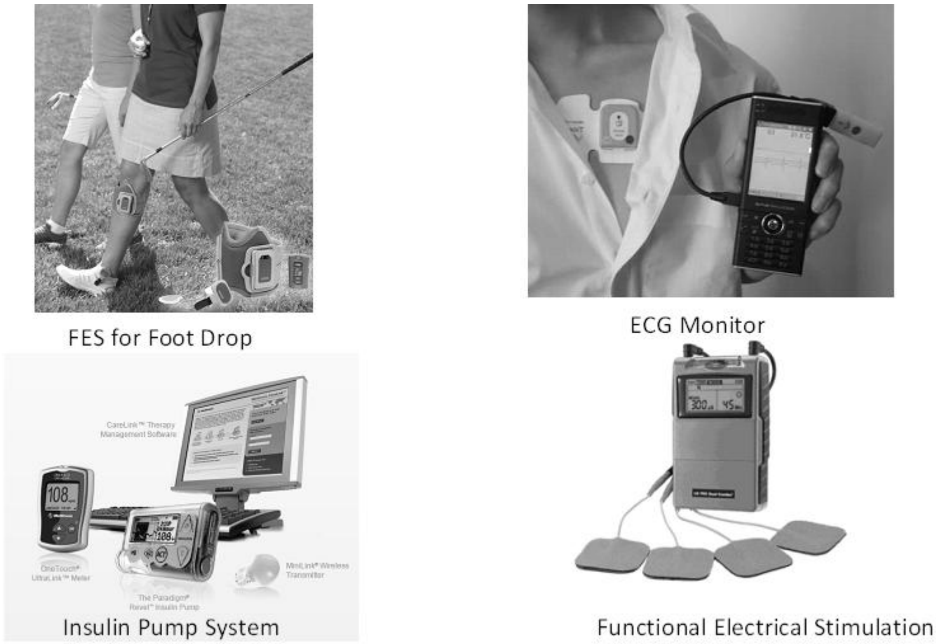

Figure 1. Examples of external medical devices.

to the device located inside the body. This is most often solved with some form of wireless channel. The development of percutaneous plugs has progressed, but the process is still developmental and presently presents risks of infection and the potential for injury.

One of the early implanted devices is the heart pacemaker. With the advances of microelectronics advanced programming capabilities were added as well as bi-directional telemetry control. Some early units utilized rechargeable batteries. The battery and electronics were contained inside a hermetic titanium enclosure, the use of low frequency magnetic induction could transfer the AC charging signal through the titanium case with moderate loss because of the rather low conductivity (and large skin depth) of the titanium. Although modern pacemakers use non-rechargeable primary batteries, the titanium case has been maintained and provides a somewhat transparent window for the communication channels as well as being a convenient hermetic enclosure. This is an example of the suitable choice of frequency for the specific application.

Devices that are currently in the market place, or just entering include cochlear implants for severe and profound deafness, retinal implants for the blind, and drug pumps for both insulin delivery and pain medication. These types of devices differ from the external applications because of the continuous data transfer that must occur and the general inefficiency of electrical sensorineural stimulation. With sensory devices, it is highly undesirable to remove the stimulation or sensing leads. Once the neuro-network and brain plasticity has accommodated the device disturbing the leads creates confusion and usually failure of the device to provide the functional therapy. For certain applications such as the cochlear implant the leads and implant package are inserted into the skull in proximity to the brain. It is desirable to create a fully implanted device with an internal rechargeable battery; however the safety aspects of having a battery in intimate contact with the brain have maintained the architecture using an inductive link external to the body that supplies the audio signals as well as the operating power for the implanted element. The implanted element and the external speech processor (that includes the battery and microphone elements) are shown in Fig. 2. Since the power is continuously transferred from the external device, the coupling link was chosen as a loosely coupled inductive link. The double-tuned network has a theoretical limit of 100% transfer, although usual component limitations, frequency multiplexing losses, and rectification losses reduce this transfer. This is distinctly different from spinal cord stimulator systems (for pain blocking) that resemble a pacemaker system. The spinal cord stimulator needs infrequent commands. A very high path loss can be tolerated to the implanted device since the communication draws on average a very low power level. The last example of the retinal implant is similar to the cochlear implant with added channels. The inductive link limits the present system to 60 channels, which are being expanded to 240 channels. This provides crude images compared to the resolution of an HD television, yet even perceiving edges is a tremendous aid to the blind.

III. THE MEDICAL MICROPOWER NETWORK

The medical micropower network (MMN) is a special application for wireless microstimulators and sensors. As microstimulators the devices are implanted within the muscle group, such as the arm as shown in Fig. 3. For this application it is necessary to have several devices operate in a coordinated

Figure 2. Cochlear implant and external speech processor.

fashion with direct continuous control from the patient through an unspecified sensory neural monitor system. The microstimulators are operated in a star network from a Master Controller Unit (MCU). The MCU continuously polls the implanted microstimulator devices (ISD) providing the stimulus commands and monitoring the state of health, or sensing information from the ISD's.

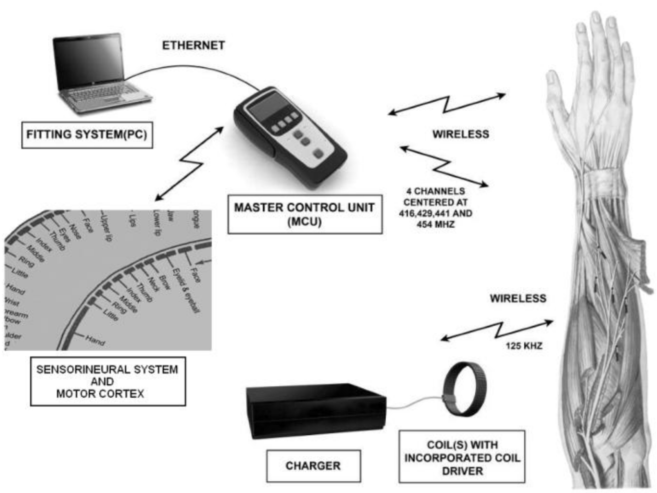

Figure 3. The MMN passes sensory information and stimulation to the ISD through the MCU.

The human response time is compatible with an update rate of about 50 Hz. The microstimulators must be physically small for insertion into the muscle. This limits the antenna size. The operating range needs to be 1-2 meters to allow for flexibility in the location of the MCU. The attenuation produced by the human tissue increases at higher frequencies as shown in Fig. 4. There is a range of compromise available in the 400 MHz region where the attainable antenna size and attenuation are more balanced.

The MMN system uses four bands (Fig. 5) of about 6 MHz width each to transmit in a half duplex format. The messages frame period is 11 msec. The modulation format is QPSK at a 5 MBPS raw data rate. Raised cosine shaping is used to minimize out of band interference. The MCU controls all timing. Fig. 6 shows the message format of the frame period. The MCU operates as the master unit in a star configuration with the ISD's, sequentially polling each unit. It is envisioned that the typical application will use between 2-12 ISD's.

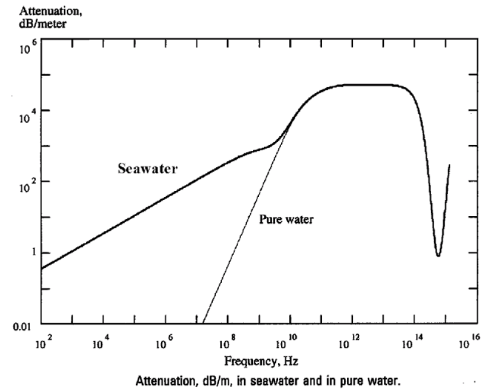

Figure 4. The attenuation of signals through the body increases with frequency while the antenna reduces in size.

MMN Channel Number (Frequency Range) (MHz)	Low Frequency Edge (MHz)	Center Frequency (MHz)	High Frequency Edge (MHz)
1 (413 – 419)	413.919	416.405	418.891
2 (426 – 432)	426.349	428.835	431.321
3 (438 – 444)	438.779	441.265	443.751
4 (451 – 457)	451.209	453.695	456.181
Guard Band 7.458 MHz		Bandwidth 4.972 MHz	

Figure 5. MMN Channels.

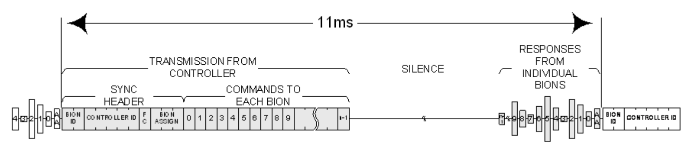

Figure 6. MMN Frame format.

A. *Interference Minimization Concepts*

To minimize the presence of the MMN to other users in the frequency band, several concepts were implemented. The transmit power is low, set at 0 dBm from the transmit elements. The implanted elements also have the additional path loss of the body attenuation that further reduces their emission. A modern digital modulation method with raised cosine shaping was chosen to reduce emissions adjacent to the MMN channels. The MMN also uses a process termed frequency excision and channel monitoring in this paper. Channels are assessed using a weighted function that factors in the number of co-channel users, ambient noise, signal levels on both ends of the link, and error corrector/detector performance. Once selected, a channel remains active until it is degraded to the extent that the error rate is likely to increase with further degradation. Under such circumstances, the master will move the system to the best available alternate channel. Channel change can be accomplished without loss of medical function. If no viable channel is available, the system will shut down by executing a pre-programmed safe shutdown sequence. The frequency excision also is a protection strategy to maintain the data integrity of the MMN system from outside interference. In the event that sufficient data error rate cannot be maintained, then a graceful shutdown algorithm is incorporated to insure that the patient does not continue to operate the system during unsafe conditions.

The physiological signals that the MMN is to replace occur at modest rates, and with the 11 msec frame rate there is sufficient overhead that dropped frames can be tolerated. The system is able to perform its designed functions with error rates in the region of 5%; thus it is inherently resistant to pulse interference such as that produced by radar transmissions, even at rather high pulse repetition rates. Occasionally during testing the MMN system would change channels when radar was detected. This is due to high pulse rate radar hitting two frames several frames apart; this very rare at pulse rates between 400 and 800 pps. There is no specific means to mitigate interference to radar systems due to the peculiar characteristics of this band which contains many more powerful uncontrolled incumbents.

B. *Evaluations and Test Results*

The MMN system has been evaluated for its impact on the existing allocated uses and in one study has shown that the MMN system produces the required separation distance (RSD) of less than 0.31 km. in the frequency band 410-420 MHz and less than 0.41 km in the frequency band 420-450 MHz with the MMN system operating out-of-doors. When the MMN is operated indoors, the distances are reduced. These predicted RSD's result from the MMN transmitters' low equivalent isotropic radiated power, duty cycle, and low antenna heights. These factors combined with the dynamic channel switching capability of the transmitter and the anticipated low number of MMN systems indicates that the MMN system should be compatible and not cause unacceptable interference with government communications and electronics systems currently in the 410-450 MHz band.

This study also concluded that the RSD for susceptibility of the MMN system to government equipment is less than 1.14 km in the 410-420 MHz band and 18.71 km in the 420-450 MHz band. However these numbers are mitigated by the frequency excision, low probability of simultaneous reception, and the forward error correction techniques used in the MMN. With these features, the MMN system can operate at substantially reduced RSD's.

In a second study the MMN system was wired to an interference simulator to evaluate the frequency excision capability and to evaluate the susceptibility of the MMN to various anticipated interference. The block figure is shown in Fig. 7.

The interference signals were synthesized from baseband files to provide the various formats with the associated data rates and modulation schemes. Twelve ISD's were connected in the test system. The test signals generated included FSK (both single and multiple simultaneous channels), analog FM, airborne radar (8 usec pulses at 2 KHz pulse repetition rate), ground radar, Enhanced Position Location Reporting System (EPLRS) (hopping 8 channels), and amateur TV. As a portion

TABLE 1. MMN SYSTEM SPECIFICATIONS.

Spurious Free Dynamic Range	68dB
Error Rate	Shall perform all functions with packet loss of up
Adjacent Channel Rejection	>40dB
Noise Bandwidth	2.486 MHz
MCU Noise Figure	11 dB
MDS at BER of 1E-3, Thermal Noise only, No Interferers	-88.7 dBm
Excision Loss Parameters	
FFT length	1024 bins
FFT bin width	4.85 KHz
# FFT Bins excised for CW intfr detected < -81dBm	7 FFT bins
# FFT Bins excised for CW intfr detected > -81dBm	9 FFT bins
SNR Loss per bin excised, worst case	0.029 dB/bin
Minimum Detectable CW Interferer	-99 dBm
Noise Floor Threshold Stepsize	6 dB
Typical Number of Interferers	10 (2dB SNR loss allowed)
Channel Change Parameters	
Channel change minimum time from command to execution	4 frames
Channel Change Trigger: Number of excised Bins	150 bins
Channel Change Trigger: Detected Interferer Narrowband Level	-60 dBm
Channel Change Trigger: Detected Integrated Noise Power	-79 dBm
Channel Change Trigger: Estimated Effective SNR	12 dB
Channel Change Trigger: Uplink Packet Errors detected on any 1 ISD	2 out of 7
Channel Change Trigger: Downlink Packet Errors detected on any 1 ISD	2 out of 50
Graceful Shutdown Parameters	
Trigger to shutdown is: At least one of the above channel change triggers occurring on all 4 channels	

of the testing the level at which the MMN dynamic channel changing activates was evaluated. The threshold for switching is generally in the range from -59 to -63 dBm.

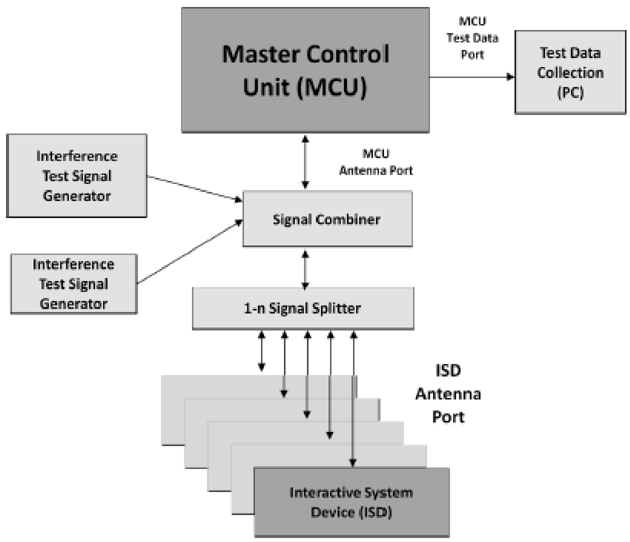

Figure 7. Test Set-Up.

The testing verified that the MMN system performs to its specifications and is able to operate in the presence of incumbent users. It can spectrally excise narrowband users and is able to change channels without suspending clinical functions. It is able to gracefully shutdown in the presence of link service-loss. It can sense incumbent users and select channels to avoid interference with them.

Cellular Systems and Rotating Radar Using the Same Spectrum

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***Abstract*—Spectrum-sharing with radar often means operating outside "exclusion zones" near the radar. However, it is technically possible for cellular systems to operate close to radar at data rates that are high on average without causing harmful interference simply by adjusting dynamically as the radar rotates. Despite fluctuations in data rate, cellular quality of service is sufficient for the applications that generate the vast majority of Internet traffic. This is an example of how "gray space sharing" can make more efficient use for spectrum; cellular devices operate on a secondary basis in spectrum that is *not* "unused." Although technically possible, this form of sharing poses new policy challenges. Particularly in cases where there are multiple entities operating primary systems and multiple entities operating secondary systems in the same spectrum, a new form of governance is needed to prevent, detect, and respond to harmful interference.**

Keywords: radar; cellular; spectrum sharing; primary-secondary sharing, gray space; white space; opportunistic

I. Introduction

There is growing pressure to support more and more communications within those spectrum bands that are most conducive to operating a cost-effective wireless system. A large part of that pressure will come from demand for cellular data services [1]. Many people assume that the only way to meet this need is to find an "unused" block of spectrum, and make it available for use. For example, a spectrum block within the frequencies allocated to television and within a geographic region that is far from any TV coverage area might be viewed as unused, and thus be made available for secondary use, as occurred in the TV "white space" rulings [2]. There is certainly great value in putting spectrum that is truly unused to work, but there are many ways to share spectrum and thus many ways to support more communications that go beyond simply finding unused spectrum [3, 4]. We refer to this as "gray space" sharing. For example, it has been shown that even in spectrum that is occupied by cellular systems with 100% utilization, there are ways in which other devices can operate on a secondary basis without having any impact on the cellular system's capacity or quality of service [5, 6, 7]. As this paper will discuss, it is similarly possible for radar to share spectrum with other systems without making the radar less effective.

There is good reason to consider spectrum sharing involving radar. Of the spectrum from 225 MHz to 3.7 GHz, roughly half (1.7 GHz) involves radar or radio-navigation infrastructure [8]. There are already proposals [9] to make some bands used by radar available for new uses in geographic regions where no radar systems are operating, while regions with radar would be "exclusion zones" that are only used for radar. Unfortunately, some of the areas with highest population density, and greatest spectrum scarcity, are likely to be within exclusion zones. There could be great value in opening up some of these exclusion zones for other uses, if it could be done without causing harmful interference to radar.

In this paper, we discuss the technical viability and policy implications of spectrum sharing between rotating radar and a 4G cellular system using OFDMA technology, both of which operate in the same area. OFDMA is used in Long Term Evolution (LTE) systems. (The underlying technical analysis can be found in [10].) Radar is considered the primary user, so the cellular system must be designed such that it never causes harmful interference to radar. We choose rotating radar operating from a fixed location, which is more conducive to sharing than other types of radar in some ways, although less in others. On the one hand, the radar system's behavior is more predictable than some other radar systems, which simplifies the sharing mechanisms. On the other hand, we assume that these are legacy systems that were not designed to operate in spectrum that is deliberately shared, whereas as future radar systems could (and should) be designed with sharing in mind.

II. Sharing Model

Sharing is based on the radar's rotation. From the perspective of a cellular device at a given location, rotation means that the radar's antenna gain fluctuates over time in a pattern that roughly repeats periodically. The cellular device uses dynamic power control to ensure that the interference it causes to the radar falls within the tolerable limit. Depending on the instantaneous value of antenna gain, as well as the cellular device's distance (or more precisely, path loss) to the radar, the device may be prohibited from transmitting, or allowed to transmit at full power, or allowed to transmit at a power below its maximum. Since cell radius is held constant, this reduced power has the effect of reducing cellular data rates.

Even though cell capacity fluctuates as the radar rotates, this shared spectrum can be of great use to a cellular provider. Consider the following scenario. A cellular provider serving a densely populated area where available spectrum is limited uses a combination of dedicated spectrum and spectrum shared with radar. Antennas are collocated, and cells cover roughly the same geographic areas in both the shared and dedicated bands. When capacity is sufficient, all traffic in a given cell is carried in the dedicated band. However, when instantaneous utilization exceeds the capacity of the dedicated band in that cell, some traffic is carried in the shared spectrum. The carrier may choose which traffic to shift to shared spectrum based on quality of service requirements. For example, as shown in [10] and discussed below, voice (telephone) traffic is better left in dedicated spectrum, while video streaming is better shifted to spectrum shared with radar.

III. PERFORMANCE

Even cells that are fairly close to the radar can support extensive communications on average, although with interruptions and fluctuations in data rate. To quantitatively assess the scheme, we have analyzed performance in [10] under the following specific conditions. The radar and cellular systems operate at 2.8 GHz in the same 3 MHz band. (The Federal Aviation Administration operates rotating radar in this band for air traffic control.) It is an urban area with fairly flat terrain, and this is reflected in the signal propagation assumptions [11, 12]. The radar rotates at a constant rate, and sends out pulses at a constant power. The radar's rotation period (4.7 seconds), transmit power (0.45 MW [13]), tolerable Interference-to-Noise Ratio (INR) (- 10 dB [14]), and peak antenna gain (33.5 dBi [13]), all of which are static parameters, are known to the secondary system. Background noise is -106 dBm [13]. The radar antenna is a uniformly-distributed aperture type with elevation, azimuthal 3-dB beamwidth, and front-to-back ratio of 4.7°, 1.4°, and 38 dB, respectively [13, 15]. The cellular system uses symmetric Time Division Duplex (TDD), Orthogonal Frequency Division Multiple Access (OFDMA), and 2×2 Multiple Input Multiple Output (MIMO) in both directions. At any given time, it employs the modulation (QPSK, 16QAM, or 64QAM) that maximizes data rate under current conditions. To suit an urban environment where demand is high and spectrum is limited, cell radius is 0.8 km. It is assumed that it is sufficiently unusual for a given cell's utilization to exceed capacity of its dedicated spectrum that this rarely happens in adjacent cells simultaneously, so radar is the primary source of interference rather than inter-cell interference. Mobile devices transmit at up to 23 dBm with omni-direction 0 dBi antennas, and basestations transmit at up to 46 dBm with sectorized 18 dBi antennas [16]. Background noise spectral density at a secondary receiver is -174 dBm/Hz [16].

Figure 1 shows the upstream and downstream data rates achievable in a cell averaged when over the entire rotation period of the radar, as derived in [10]. This is a worst-case scenario in which a single mobile cellular device is located at the edge of cell where path loss to the basestation is greatest, and at the point closest to the radar where interference between primary and secondary systems is greatest. Under these numerical assumptions, the radar and cellular basestation would have to be 425 km apart to avoid harmful interference to either system, i.e. to allow both the radar and cellular systems to perform as if they were in dedicated spectrum. Nevertheless, at a distance of just 40 km, the downstream rate of the cellular system is close to what could be achieved in dedicated spectrum on average, although data rate fluctuates. The impact of sharing with radar on the mean achievable upstream rate is somewhat greater, since data rate does not approach the maximum achievable until distance from the radar exceeds 200 km. Thus, this form of sharing can provide somewhat greater spectral efficiency for applications that involve greater downstream data rates. Nevertheless, the extent of communications upstream with relatively small distances to the radar is still impressive.

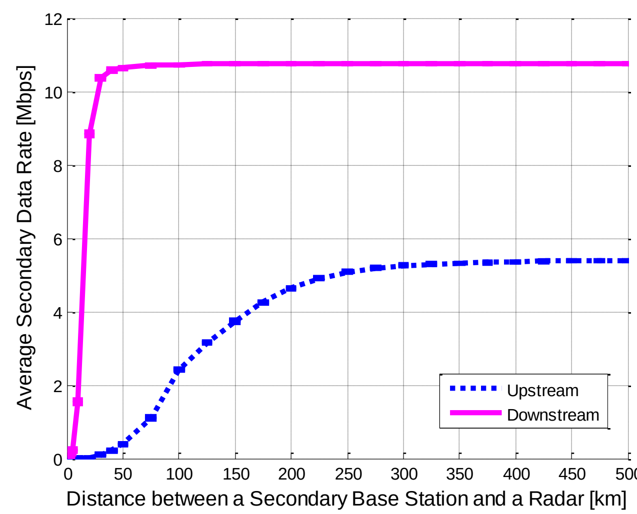

Figure 1. Mean upstream and downstream data rates of the cellular system

Whether a reasonably high but fluctuating data rate is desirable for a given packet stream depends on that quality-of-service requirements of the associated application. Indeed, whether the fluctuations are noticeable at all depends on the application as well. Consider any application that requires the transfer of a block of data which is useful only when the entire block has been received. If the transfer time equals the rotation time of the radar, or greatly exceeds it, then fluctuations will average out, and data rate as perceived by the application will equal the mean data rate. On the other hand, if transfer time is small compared to radar rotation time, then the time to transfer the file will greatly depend on when in the radar's cycle the transfer begins. Figure 2 shows the mean achievable downstream data rate for a file transfer, and the first percentile of perceived data rate[1] which represents near-worst-case performance, for files of different sizes. When transferring files of multiple MBs, performance will always be close to the average, but when transferring files of just 1 KB, an application can sometimes perceive data rate to be an order of magnitude below average. Thus, spectrum shared with radar can consistently offer perceived data rates close to those experienced in dedicated spectrum when transferring MBs of information, but not when transferring KBs of information.

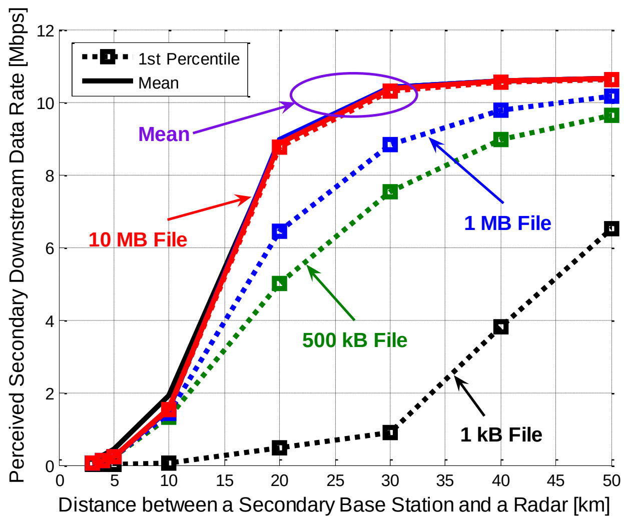

Figure 2. First Percentile and Mean Perceived Downstream Data Rate vs. Distance between Secondary Base Station and Radar.

Based on the above observation, and additional analysis shown in [10], we conclude that spectrum shared with radar is valuable for a number of common applications. For example, video streaming is a large and rapidly growing portion of Internet traffic [17]. It requires a high mean downstream data rate, but with reasonable buffering at the destination [10], the fluctuations in data rate inherent in this approach can easily be tolerated. Web browsing, peer-to-peer file sharing, meter reading, and image transfer can all be well supported in spectrum shared with radar [10]. Video, P2P, and web browsing combined are likely to constitute the vast majority of mobile Internet traffic [17]. However, any application that requires the transfer of small blocks of information in reliably short periods of time will not be well served in this spectrum. For example, interactive voice over IP (VOIP) is likely to experience unacceptable delays [10]; such traffic should be carried in dedicated spectrum.

IV. Policy Implications

As shown above, it is technically possible to deploy cellular systems that share spectrum directly with rotating radar, and to do so in a way that supports high mean data rates and meets the quality-of-service needs of the majority of traffic on the Internet today without harmful interference to the radar. Thus, there are great opportunities to relieve spectrum scarcity through efficient sharing.

However, there are additional challenges to meet before realizing this potential. In general, with sharing of this kind, the gains in spectral efficiency are achieved in ways that make the primary and secondary systems more interdependent. For example, it was assumed that the designers and/or operators of the secondary system had access to some technical characteristics of the primary system, such as its transmit power, and the level of interference it could tolerate. Such sharing of information when systems are deployed requires more coordination between primary and secondary spectrum users than often occurs. Moreover, systems are not static. An upgrade to the technology in the primary system could require changes to the secondary system as well. Some changes might be handled automatically through emerging cognitive techniques, but perhaps not all. If and when they prove necessary, jointly managing upgrades to systems that are owned and operated by different organizations is more complicated.

Dynamic sharing between radar and cellular systems also creates new risks of unintended harmful interference. Such risk is particularly problematic if radar is used for safety-critical purposes, such as air traffic control. For example, there may be situations in which a system bug causes a cellular basestation to incorrectly calculate the maximum power at which it can transmit without causing harmful interference to radar. As is generally true with cognitive radio, additional means are likely to be needed to pre-certify that a new product is sufficiently safe to deploy [3], compared to devices that do not share spectrum in complex ways. In addition, in case harmful interference is observed despite a thorough precertification process, mechanisms will be needed with which the secondary system can be forced to reconfigure or discontinue operation in the shared band. This may need to occur much more quickly than is typically possible through complaints to the regulator.

If all primary and secondary systems were under the same administrative control, coordination would be relatively easy. For example, this might occur if the Department of Defense deployed both radar and cellular in the same spectrum for its own use. If all radar systems are under the same administrative control, then giving this primary user authority to prevent dangerous technology from being deployed in secondary systems operating in the band, and authority to require secondary systems to terminate operations in the event of harmful interference, may solve many problems. This would occur if sharing occurred under the rules of real-time secondary markets [18]. However, in the case where multiple entities have deployed radar systems, and multiple entities have deployed cells, all within the same general region, a new form of governance will be needed that has both the capability and authority to address complex interference issues.

[1] Perceived data rate = (total file length) / [(the time when the file completes transmission) – (the time the file is first available for transmission, regardless of when transmission can actually begin)].

Finally, note that in the scenario addressed in this paper, a wireless Internet service provider should treat traffic differently depending on the associated application, e.g. transmitting video-on-demand over shared spectrum and VOIP over dedicated spectrum. This observation deserves consideration should network neutrality regulations be applied to wireless networks [19], although there are certainly traffic control approaches that would achieve this result and that are consistent with reasonable network neutrality principles [20].

ACKNOWLEDGMENT

My thanks to Rathapon Saruthirathanaworakun, a Carnegie Mellon University Ph.D. student who is first author and my co-author of the analysis in [10], which is heavily cited in this paper.

REFERENCES

[1] Federal Communications Commission, *The National Broadband Plan: Connecting America,* March 2010. www.ece.cmu.edu/~peha/policy.html

[2] Federal Communications Commission, In the matter of unlicensed operation in the TV broadcast bands, 2nd Report and Order and Memorandum Opinion and Order. ET Docket No. 04-186. Nov 14, 2008. www.wispa.org/wp-content/uploads/2008/11/FCC-08-260A1%282ndR0-111408%29.pdf

[3] J. M. Peha, "Sharing spectrum through spectrum policy reform and cognitive radio," *Proc. of the IEEE*, vol.97, no.4, Apr. 2009, pp.708-19. www.ece.cmu.edu/~peha/wireless.html

[4] M. J. Marcus, "Sharing government spectrum with private users: opportunities and challenges," *IEEE Wireless Communications Magazine*, vol.16, no.3, June 2009, pp. 4-5.

[5] J. M. Peha and S. Panichpapiboon, "Real-Time Secondary Markets for Spectrum," *Telecommunications Policy,* Vol. 28, No. 7-8, Aug. 2004, pp. 603-18. www.ece.cmu.edu/~peha/wireless.html

[6] S. Panichpapiboon and J. M. Peha, "Providing Secondary Access To Licensed Spectrum Through Coordination," *ACM/Baltzer Wireless Networks,* Vol. 14, No. 3, pp. 295-307, June 2008. www.ece.cmu.edu/~peha/wireless.html

[7] R. Saruthirathanaworakun, and J. M. Peha, "Dynamic primary-secondary spectrum sharing with cellular systems," *IEEE Int'l Conference on Cognitive Radio Oriented Wireless Networks (CrownCom),* June 2010. www.ece.cmu.edu/~peha/wireless.html

[8] K. Nebia, US National Telecommunications and Information Administration (NTIA), *Presentation: spectrum with significant federal commitments, 225 MHz - 3.7 GHz*, Dec. 2009. www.ntia.doc.gov/advisory/spectrum/csmac_2009_december_meeting_reports.html

[9] Federal Communications Commission, Spectrum Task Force Requests Information on Frequency Bands Identified by NTIA as Potential Broadband Spectrum, Public Notice, FCC DA 11-444, March 2011. http://transition.fcc.gov/Daily_Releases/Daily_Business/2011/db0308/DA-11-444A1.pdf

[10] R. Saruthirathanaworakun, J. M. Peha, and L. M. Correia, "Opportunistic Primary-Secondary Spectrum Sharing with a Rotating Radar,"*Proc. of 2012 IEEE International Conference on Computing, Networking and Communication (ICNC)*, in press. www.ece.cmu.edu/~peha/wireless.html

[11] ITU-R, *Recommendation P.1546-4: Method for point-to-area predictions for terestials services in the frequency range 30 MHz to 3 000 MHz,* 2009.

[12] T. Kurner, "Propagation Model for Macro-Cells," in E. Damosso, and L.M. Correia (ed.), *Digital Mobile Radio towards Future Generation Systems: COST 231 Final Report*, European Communities, Belgium, 1999.

[13] ITU-R, *Recommendation M.1464-1: Characteristics of radiolocation radars, and characteristics and protection criteria for sharing studies for aeronautical radionavigation and meteorological radars in the radiodetermination service operating in the frequency band 2 700-2 900 MHz*, 2003.

[14] B. Bedford and F. Sanders, "Spectrum sharing and potential interference to radars," *Proc. of the Int'l Symposium on Advanced Radio Technologies (ISART)*, Boulder, USA, Feb. 2007.

[15] M.I. Skolnik, *Introduction to Radar Systems*, International Ed., McGraw-Hill, Singapore, 1981.

[16] H. Holma, P. Kinnunen, I.Z. Kovács, K. Pajukoski, K. Pedersen, and J. Reunanen, "Performance," in H. Holma and A. Toskala (ed.), *LTE for UMTS: OFDMA and SC-FDMA Based Radio Access*, John Wiley & Sons, UK, 2009.

[17] Cisco, *Visual Networking Index: Global Mobile Data Traffic Forecast Update, 2010–2015*, White Paper, Cisco, USA, Feb. 2011. www.cisco.com/en/US/solutions/collateral/ns341/ns525/ns537/ns705/ns827/white_paper_c11-520862.pdf

[18] Federal Communications Commission, Promoting Efficient Use of Spectrum Through Elimination of Barriers to the Development of Secondary Markets, Second Report And Order, WT Docket No. 00-230, Sept.2004. http://hraunfoss.fcc.gov/edocs_public/attachmatch/FCC-04-167A1.PDF

[19] Federal Communications Commission, in the matter of Preserving the Open Internet and Broadband Internet Practices, Report And Order, GN Docket No. 09-191 and WC Docket No. 07-52, Dec.2010. http://transition.fcc.gov/Daily_Releases/Daily_Business/2010/db1223/FCC-10-201A1.pdf

[20] J. M. Peha, "The Benefits and Risks of Mandating Network Neutrality, and the Quest for a Balanced Policy," *International Journal of Communication*, 2007, pp. 644-68. www.ece.cmu.edu/~peha/policy.html

Thoughts on Radar/Communications Spectrum Sharing

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***Abstract*—This paper reviews a new approach to radar/communications spectrum sharing that is based upon parallel design of cochannel radar and communications systems with cost sharing between the two communities of users. Since the majority of the mobile wireless growth is not in symmetric voice connectivity but in asymmetric packetized information, the traditional full time access pair spectrum is not needed for the growth. Sharing with radar can lead to communications capacity to meet the needs of growth.**

Keywords-radar, spectrum policy, spectrum sharing

I. Introduction

Wireless communications is a key infrastructure in today's economies and societies. Spectrum is a key building for such wireless systems and is a key component for governmental[1] systems that are essential to security. Classically these two uses of spectrum have been mostly viewed as a "zero sum game", that is spectrum could be either used for nongovernmental communication uses or for governmental applications. There is sharing, but it generally is on a regional basis or a frequency by frequency basis, so the two classes of users are not on the same frequency at the same location.

But the need for spectrum is too great now to let this traditional viewpoint continue unchallenged. Economic security is also now recognized as a key aspect of national security.[2] Finally, the national security budget is now in the 3-5% of GDP range and any increases in national security spending will have to be tied to GDP growth under the current and foreseeable budgeting paradigms. Thus the national security community should consider with "what's good for the GDP, is good for national security".

The UK government has looked at the general spectrum problem and its counterpart of the US Executive Branch has declared,

> Spectrum is a valuable resource that enables growth and innovation by the private sector. Spectrum is also essential to the running of public services including defence, emergency services and transport. However, as part of the Government's drive to manage more effectively the nation's assets, we are committed to releasing surplus public sector spectrum to more productive private sector use.[3]

In the US, radar has been classically a major use of spectrum by federal government agencies. While there has been some very limited sharing on a geographical basis, the general view has been that such spectrum could not be shared with communications systems since the nature of the uses were so different. But new advances in communications technology and in the evolving nature of wireless communications mean that we should reexamine sharing options.

II. U-NII DFS Transparency Urgently Needed

On November 12, 2003 FCC approved the Report and Order in Docket 03-122[4] authorizing unlicensed device/radar

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[1] In this paper, I am using "government" in its generic usage, not the US spectrum management usage where it refers to federal government spectrum use.

[2] "To achieve the world we seek, the United States must apply our strategic approach in pursuit of four enduring national interests:

> • Security: The security of the United States, its citizens, and U.S. allies and partners.
> • <u>Prosperity: A strong, innovative, and growing U.S. economy in an open international economic system that promotes opportunity and prosperity.</u>
> • Values: Respect for universal values at home and around the world.
> • International Order: An international order advanced by U.S. leadership that promotes peace, security, and opportunity through stronger cooperation to meet global challenges." (emphasis added)

White House, National Security Strategy, May 2010, p. 17 (http://www.whitehouse.gov/sites/default/files/rss_viewer/national_security_strategy.pdf)

[3] "Enabling UK growth – Releasing public spectrum:Making 500 MHz of spectrum available by 2020", March 2011 http://www.culture.gov.uk/images/publications/Spectrum_Release.pdf

[4] http://hraunfoss.fcc.gov/edocs_public/attachmatch/FCC-03-287A1.pdf

sharing in the 5.25-5.35 GHz and 5.470-5.725 GHz bands. An earlier January 31, 2003 NTIA announcement stated

> The NTIA, FCC, NASA and Department of Defense (DoD), working closely with industry in detailed technical meetings, have agreed to modify the required Dynamic Frequency Selection (a listen-before-transmit mechanism) detection threshold characteristics contained in the U.S. proposal for WRC-03 Agenda Item 1.5.[5]

Since the adoption of these rules it has become clear that there have been recurring interference incidences, particularly involving the FAA's Terminal Doppler Weather Radar (TDWR) system. There appear to be three possible causes of this interference:

U-NII devices using the radar bands lack the dynamic frequency selection (DFS) capability required by 47 C.F.R. 15.407 either because it was not included in the design or because it was disabled through a software change after the design was approved.

U-NII devices with DFS capability but due to testing ambiguity they were not capable of the performance expected by those who drafted the agreement announced by NTIA on 1/31/03

U-NII devices met the capabilities expected in the agreement, but these DFS features were not adequate to prevent interference in specific circumstances

It is clear from both a November 2010 NTIA/ITS report[6] and from FCC enforcement cases that are on the public record that some cases[7] fall in the first category. It appears that some also fall in the third category where the standard adopted by FCC after consensus with industry and NTIA was not adequate to prevent interference. This is the clear conclusion of the July 27, 2010 memo from FCC's Office of Engineering and Technology and Enforcement Bureau [8] to "Enforcement Manufacturers and Operators of Unlicensed 5 GHz Outdoor Network Equipment". The memo states,

> "We have found that the interference at each location has generally been caused by a few fixed wireless transmitters used by wireless internet service providers (WISPs) and operating outdoors in the vicinity of airports at high elevations that are line-of-sight to the TDWR installations (5 GHz outdoor network equipment). In most instances, the interference is caused by operations in the same frequency band as TDWRs, but there are some instances where the interference is caused by adjacent band emissions."

The existence of cases in the third category is also seen in an NTIA presentation at last year's ISART.[9] However in both the case of the first category and the third category cases, these is no explanation on the public record as to the root causes of these problems. In order to develop future cognitive radio systems that share with radars on a noninterference basis, we need to learn from problems such as this one. As George Santaya wrote, "Those who cannot learn from history are doomed to repeat it."

The cognitive radio research community learned about the TDWR interference through cryptic FCC and NTIA statements, but there has been no technical information released to date on the specifics problems that arise from properly working DFS systems in high antennas near TDWR systems. The power budget modeling that was used in making the January 2003 agreement appears to have been wrong in the case of TDWR, yet there is no quantitative information on what we have learned on how to model these situations better. While some of the military radars involved in the 2003 analysis are classified, the TDWR appears to be an unclassified system so it is hard to believe that there is a valid national security justification for with holding information on the nature of the interference and why operational experience differs from the models used in 2003. While there is not a need to identify personal or organizational responsibility here, there is a need to understand the technical issues involved.

There have also been hints that some of the interference is due to first category – DFS systems that were disabled after they were tested and approved. In particular the AT&T/San Juan case[10] seems to be in this category. The original software defined radio (SDR) rules adopted in Docket 00-47 in September 2001 were relaxed in Docket 03-108 at the request of industry. The original rule[11] required protection against

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[5] http://www.ntia.doc.gov/ntiahome/press/2003/5ghzagreement.htm

[6] NTIA/ITS, Case Study: Investigation of Interference into 5 GHz Weather Radars from Unlicensed National Information Infrastructure Devices, Part I; NTIA Report TR-11-473, November 2010 (http://www.its.bldrdoc.gov/pub/ntia-rpt/11-473/)

[7] http://www.fcc.gov/Daily_Releases/Daily_Business/2011/db0217/DA-11-306A1.pdf

[8] http://www.wispa.org/wp-content/uploads/2010/05/FCC-Memorandum-on-UNII-Device-Operartion-July-27-2010-1.pdf (sic)

[9] Frank Sanders (NTIA), "5 GHz DFS Technology Devvelopment and Deployment: Challenges Met and lessons Learned", Presentation at ISART 2010(July 2010) http://www.its.bldrdoc.gov/isart/art10/slides_and_videos10/DFS%20development%20and%20lessons%20learned%20FHS.pdf

[10] http://www.marcus-spectrum.com/Blog/files/d7110e2482463dd2de998df926ceea1f-191.html

[11] "2.932(e) Manufacturers must take steps to ensure that only software that has been approved with a software defined radio can be loaded into such a radio. The software must not allow the user to operate the transmitter with frequencies, output power, modulation types or other parameters outside of those that were approved. Manufacturers may use authentication codes or any other means to meet these requirements, and

tampering, such as authentication codes, for *all* equipment where the software can change the unit's parameters. The current rules only require such protection if the unit is *marketed* as being changeable by the end user. FCC and NTIA should be more forthcoming as to whether some of the TDWR interference encountered was caused by software disabling of DFS function in units that are not subject to security requirements and testing in the former 2.932(e) as a result on the Docket 03-108 changes.

The author urges FCC and NTIA to use the occasion of ISART 2011 and the ensuing dialogue on communications/radar sharing to make a full technical disclosure on the nature and causes of the TDWR interference.

III. Design of New Radar and Communications Systems with Sharing as an Objective

The basic problem that the 5 GHz DFS system has is that the various radar systems it has to share with on a noninterference basis were not designed with sharing in mind. (The fact that the sponsors of these radar systems are basically the "judge and jury" for determining the risk of interference in any sharing scheme under today's spectrum policy arrangements also complicates things.) I explored this general issue in my 2007[12] and 2010[13] DySPAN papers.

The basic point on cooperative sharing vis-à-vis passive sensing is shown below:

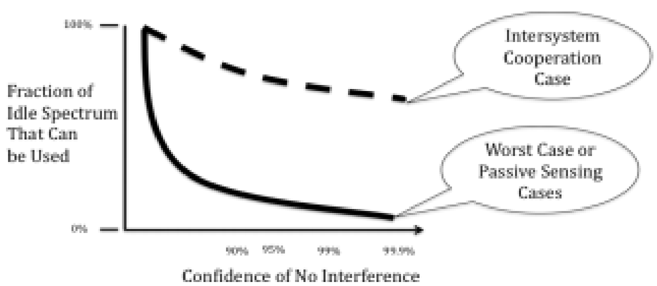

Figure 1. Postulated relationship between spectrum use and interference

In a cognitive radio or dynamic spectrum access system that depends solely on passive sensing of primary, e.g. radar, signal the only way to get a high confidence of noninterference is to use a small fraction of the idle spectrum. The probability of detection must be set so high that the probability of false alarm is very high – a false alarm meaning here that idle spectrum can not be used.

Designs with intersystem cooperation can potentially achieve much higher spectrum use with the same interference risk. This is because cooperative systems can effectively emulate nonrealizable systems, that it, systems that can predict the future based on other than past observations. The best DFS system can only make statements on past observations – if the primary system is about to turn on or change parameters it can not know that until after it happens. Allowing for such events requires more conservative sharing parameters as are seen in the 5 GHz DFS case.

But cooperative systems can share information about present and future transmissions and hence have more effective spectrum sharing while maintaining a low interference risk.

A. *Changes in Wireless Spectrum Use Today*

Before we get into cooperative radar/communications system design it is necessary to make an observation on trends in today's wireless spectrum use. Traditionally the wireless industry sought paired spectrum for full duplex operations. While the national Broadband Plan [14] does not state so explicitly, the 500 MHz of additional spectrum sought in Recommendation 5.8 is presumably full duplex spectrum. It is also unstated but presumed that this spectrum is full time availability spectrum - that is that it is available 24/7 **and** 1000 ms/1s.

When wireless use was predominantly 2 way voice these presumptions made sense. However, this is not the growth area in today's spectrum use. Total voice minutes may be actually declining. Today's growth in wireless communications is in packetized information and is generally asymmetric in its uplink/downlink ratio. Wireless spectrum users do not actually want spectrum, they want communications capacity![15]

Having asked for symmetric spectrum for 3G applications the wireless industry may be regretting that it got what it asked for. While carriers are secretive about the specific asymmetry of their present traffic load, it is clear that downlink traffic dominates and will continue to dominate. Furthermore, most of this packetized asymmetric traffic can be handled with more time delay flexibility than voice or 2 way video. While some user may want to pay a premium for very low latency communications, there may well be a market for latencies in the 0.5s – 2s range. Note also that the services offered by Sirius/XM have a latency resulting from time diversity used to control momentary path outages and few users have ever noticed it. Finally today's packet switching technology allows the design of systems that reroute packets on a real time basis as communications channels become available or unavailable.

must describe the methods in their application for equipment authorization."(Rules adopted in Docket 00-47)

[12] http://www.marcus-spectrum.com/resources/Marcus-DySPAN07a.pdf

[13] http://www.marcus-spectrum.com/documents/DySPAN10.pdf

[14] http://www.broadband.gov/download-plan/

[15] Note that radar users, by contrast, often *can* convert their requirements into bandwidth since radar performance in many cases is directly related to bandwidth since bandwidth is inversely proportional to ambiguity function width in the time domain.

B. Radar/Communications *Joint* Design

A key aspect of the development of the B-2 stealth bomber was that for the first time aeronautical engineers and electromagnetic engineers worked on an integrated team to design an innovative aircraft that could both fly well to perform its mission and have a negligible radar cross section. Similarly, there are tremendous benefits possible for joint design of communications and radar systems to share the same spectrum. The *ex post facto* approach used for 5 GHz DFS is doomed to have limited utilization of available spectrum.

Most noncombat radars rotate, most with mechanical rotation, a few with electronic rotation. Thus at a given moment the RF power is focused in one azimuth and that azimuth is changing with time. Similarly the radar receiver is focusing on one azimuth also. The antenna pattern governs how well focused the transmitter and receiver are and finite size antennas must inevitably have sidelobes and backlobes. But antenna design techniques exist to reduce such sidelobes and backlobes although designers of radars not subject to jamming and with access to plenty of spectrum have little incentive to use them. The antenna pattern for many federal radar systems are regulated by Chapter 5 of the *NTIA Manual of Regulations and Procedures for Federal Radio Frequency Management* ("Redbook").[16] Radar Spectrum Engineering Criteria (RSEC) C and D apply to many federal radar systems.[17] The main requirement for rotating antennas is a median gain of -10 dBi in the "principal horizontal plane". While this amount of sidelobe suppression might have been appropriate in the past when spectrum was less in demand, better suppression is likely available today and could be facilitated by cost sharing between radar users and spectrum sharing parties. Note that nonrotating radars are already subject to 26 dB suppression relative to the main beam.

While the specific performance details, including sidelobe levels, of operational military antennas are appropriately classified, a key question is whether the current "Redbook" limits are the best achievable with today's technology, or a historical goal. We note that level of sidelobe suppression is consistent with a 1958 open source article.[18] Any antenna of finite aperture *must* have sidelobes, although their levels are a function of antenna size, aperture illumination taper, aperture blockage, reflector surface errors and feed misalignment, and reflectivity of feed support.[19] For phased array antennas some of these factors disappear but new factors appear due to the discreteness of the current and phase shifts over the aperture. Radio telescope antennas share many characteristics of radar antennas and low sidelobe levels are useful for both. However, while radar operators can use regulatory tools to limit cochannel spectrum use, radio astronomers can not do so for observations of molecular resonances that are not in primary radio astronomy (RA) allocations. Thus the RA community has been aggressively pursuing novel antenna designs the suppress sidelobes.[20] One recent example is the Robert C. Byrd Green Bank Telescope which achieves 12 dB better suppression than a *similarly sized* conventional antenna.[21] Similar design techniques, as well as lessons learned from military antenna designs, could reduce the sidelobes of radar antennas to facilitate sharing.

Some of these reduction techniques involve increased antenna size which is practical within limits at a cost in many terrestrial radar systems but much less practical in airborne or naval systems. Other techniques increase the complexity and cost of antennas. If the communications and radar systems

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[16] http://www.ntia.doc.gov/osmhome/redbook/ed200801rev201009/5_9_10.pdf Note that unlike the FCC Rules, these requirements are not legally binding on federal users authorized by NTIA in that NTIA can give alternative limits in specific authorizations and the details need not be made public.

[17] Redbook 5.5.3.5 and 5.5.4.5 There is not stated general criteria for radars with rated peak power less than 100 kW. The present requirements are

> Since electromagnetic compatibility considerations involved phenomena which may occur at any angle, the allowable antenna patterns for many radars may be usefully described by "median gain" relative to an isotropic antenna. Antennas operated by their rotation through 360 degrees of the horizontal plane shall have a "median gain" of –10 dB or less, as measured on an antenna test range, in the principal horizontal plane. For other antennas, suppression of lobes other than the main antenna beam shall be provided to the following levels, referred to the main beam:
>
> first three sidelobes--17 dB;
> all other lobes--26 dB."

[18] McCoy, A.; Walsh, J.; Winter, C.; "A broadband, low sidelobe, radar antenna" *WESCON/58 Conference Record* Volume: *2* , Part: 1 (1958) , Page(s): 243 - 250

[19] Shahnaz Bibi ; Nadeem Faisal ; Xie ShuGuo ; "Analysis of Low Side Lobe Reflector Antenna", Multitopic Conference, 2006. IEEE INMIC '06, p. 383

[20] It is assumed that the military radar community has also been aggressive in this area, but since sidelobe performance affects jamming vulnerability there are valid national security reasons to be secretive about sidelobe levels of specific military radars. We note, for example, that the manufacturer of the AWACS radar system refers to its "Ultra-Low Sidelobe Array". (http://www.es.northropgrumman.com/solutions/awacs/assets/AWACS.pdf) No quantitative information on AWACS sidelobes is in the public domain, but a paper from the AWACS manufacturer states that "ultralow" means sidelobe levels "below -40 dB". (Hacker, P.; Schrank, H.; "Range distance requirements for measuring low and ultralow sidelobe antenna patterns"; *IEEE Transactions on Antennas and Propagation*, Volume: *30* Issue: 5 Page(s): 956 – 966, 1982) It is assumed that technology transfer of some of the features of this radar to other federal government radars is possible if key details were kept classified and the nonmilitary user compensated for the marginal cost of improved sidelobe performance through cost sharing with other spectrum users.

[21] http://www.gb.nrao.edu/gbt/gbtdesign.shtml

were designed jointly then cost sharing between the two classes of user could be considered and joint tradeoffs made. While such cost sharing is not possible under current legislation and present FCC and NTIA policies, it is not an inconceivable change either given the present demand for spectrum and the focus on economic growth for both societal reasons and national security reasons as outlines above.

If the communications users had cooperative real time information on the beam azimuth and rotation rate (or in the case of electronically steered beams the future azimuths in general) then the communications users could adjust their temporal and spatial use of the frequency to minimize impact on the radar system. For example, more power could be used when the radar azimuth is antipodal to the communications user and power could be reduced to zero or near zero when the radar azimuth overlaps the communications users. This makes no sense for full duplex voice systems[22], but as stated previously this is not the type of wireless use where there is significant growth is today and is unlikely to be in the future. Packetized communications systems can effectively use this type of intermittent availability spectrum.

Joint design radar and communications signals can also improve the D/U ratios needed for the interference free use of both systems both considering both signal design and antenna polarization. Such a change in D/U protection could increase the amount of communications that could be used on an interference free basis in the radars coverage area and within its bandwidth. When the two types of systems can never be made completely orthogonal in either signal space or electrical polarization, every few dB decrease in signal crosscorrelation and in cross polarization coupling translates into more effective spectrum use. Joint design would allow the tradeoffs and cost allocations to be made to maximize the public interest.

IV. CONCLUSIONS

It is in the public interest to maximize spectrum use by developing radar and communications systems designed from the beginning to share spectrum. Joint design would allow the marginal cost increases for the radar systems to be paid by the communications users that directly benefit from more sharing. Under present spectrum regulation, such spectrum sharing and cost sharing may be impractical, but pending legislation recommended by the National Broadband Plan would facilitate such sharing.

[22] Although it should be noted that VOIP-based voice systems could reroute packets to different physical channels during a call. However, voice telephone has time latency requirements that are much tighter than the other categories of mobile communications that are now dominating mobile use.

10 REGULATORY REFORM TO FACILITATE SPECTRUM SHARING PANEL

The goal of the Regulatory Reform Panel was to describe a roadmap for DSA deployment in general and in radar bands with practical first steps to advance both the development of new technology and new regulatory approaches. Session chair, Eric Nelson (NTIA/ITS), compiled a list of regulatory improvements that might help solve the problems encountered in the 5 GHz DFS band sharing scenario and facilitate DSA in general.

Panelists contributed with opening remarks on the following topics

1. FCC Perspective on DSA—Dr. Rashmi Doshi (FCC/OET)
2. Spectrum Sharing in the Radar Bands: An Economic Perspective—Dr. William Lehr (MIT)
3. Resilience Principles—Dr. Pierre de Vries (Silicon Flatirons)
4. Model-Based Spectrum Management—Dr. John Stine (The MITRE Corporation)
5. Building Trust in Software—Dr. Paul E. Black (NIST)
6. Federal Agency Perspective on DSA—Tom Kidd (Navy)

10.1 Introduction by Session Chair Eric Nelson

As discussed in previous panels there were a number of lessons learned from the recent interference events involving 5 GHz DFS devices and government TDWR systems. Assessments of that situation have underscored a number of principles that should be examined further to prevent future interference events of this nature.

- **Time limited leases** [66] have been proposed as a tool to provide a recall mechanism for new radio devices. This capability would also have been an invaluable troubleshooting tool for the TDWR interference problem.
- **Software assurance and conformity assessment** have gained greater attention with the modular design of modern software-defined radios permitting unapproved uses.
- **Improved monitoring of new technology rollouts** like that with DFS might enable regulators to recognize compatibility problems at an earlier stage before the new systems become widespread.
- **A robust enforcement capability** is required to deter so-called bad actors.
- **More resilient systems** should be fostered through diverse spectrum access schemes, holistic approaches to spectrum management, flexible spectrum policies, and delegated policy making.
- **Model-based spectrum management** holds great promise as a technique to capture, in machine-readable format, the technical parameters and policies derived from a delegated decision-making process.

Extrapolating from the DFS experience suggests some accommodations for DSA in a future regulatory regime. There are a number of institutional changes that would be necessary including:

- New spectrum management schemes
- Updated business processes
- Development of band migration strategies
- New approaches to enforcement
- Deployment of advanced new monitoring systems

There are a number of key decision points on the immediate horizon including consideration of responses to the FCC's recent notice of inquiry on DSA [67], an impending notice of proposed rulemaking on DFS, consideration of results of the Spectrum Sharing Innovation Test Bed, lessons learned as the TVWS database systems are deployed.

The general sentiment is that no single technology, but rather a multifaceted toolset, will be required to make DSA succeed. In light of the recent experience with DFS, there seemed to be agreement amongst panel members that DSA developers should seek modest victories and manageable failures. The objective of this panel is to describe a possible roadmap for DSA deployment and present possible next steps.

10.2 Opening Remarks

10.2.1 Rashmi Doshi, FCC/OET

I am in the FCC Office of Engineering and Technology managing the FCC equipment authorization program. We look at prospective issues on how equipment gets implemented and from a retrospective perspective if something goes wrong with compliance to our rules. There has been a lot of discussion about what has happened in the field. There are a number of listen-before-talk systems that have been approved. There is spectrum sharing in the 3650 MHz band, and then we have DFS. There is a significant demand for unlicensed devices in the 5 GHz U-NII band—much more so, an order of magnitude difference, than in the 3650 MHz band. It has become very popular and there are significantly more DFS devices than at 3650 MHz.

The population of DFS equipment is large, so when the FCC heard the first reports of interference in the U-NII band we were very concerned. Our first thought was that devices that had passed our tests weren't detecting radar properly. This was about 1½ years ago and since then we have been seriously investigating the issues. There were a number of TDWR sites having problems. We put investigation teams together and have been getting a better understanding of the situation since then. One thing that we've learned is that the device ecosystem is fairly complex. The systems are built from common RF chipsets layered with software drivers that are then put into larger complete packages. At about the same time that the DFS rules went into effect the FCC had another ruling that allowed for modular approvals. Parts of systems could be approved that could then be integrated into other end user systems. Also the use of software-based configuration has grown significantly.

There were two primary causes for the DFS interference problem. They were unrelated.

- **Unauthorized use of new broadband radio chipsets** common to multiple device types that permitted unfettered operation in multiple bands, including the U-NII band, by bypassing the software provided by the device manufacturer with non-OEM software. This was the most significant contributing factor. The FCC is researching this issue and is developing processes to address this broader trend in equipment development that might spawn similar issues in other bands. The FCC will focus on the implications of these types of hardware changes and on software assurance. The FCC has also worked with equipment manufacturers to develop schemes to push software changes out to fielded devices. We are looking at controls that can be implanted to prevent modification of device drivers. We are exploring controls on authentication, though we realize that we cannot stop a dedicated hacker. The idea is to focus on the simple exploits.
- **Technical flaws in DFS electromagnetic compatibility rules**, which were initially considered the primary contributor to DFS interference, actually played a lessor role. The NTIA and the FCC have identified corrective action in the form of new requirements for improved DFS device out-of-band spectrum monitoring and updates to the conformity assessment regimen to include additional radar waveforms. The recommended changes will be included in an upcoming notice of proposed rulemaking.

Some of these complex problems are being solved by learning from the field experience rather than just implementing a new set of sensor detection rules. If we had tried to come up with modified rules a year ago, we would probably still have problems in the field.

The FCC Enforcement Bureau has levied numerous penalties on U-NII device operators for unauthorized use of such equipment [68]. Subsequently, complaints of interference have effectively been reduced from approximately one half to just a couple of TDWR sites. The FCC will use the insights gained during its forensic analysis and corrective action activities to create a new set of guidelines for assessing software controls on general purpose broadband radio chipsets.

10.2.2 William Lehr, MIT

I am here to provide an economist's perspective and viewpoint. What are the economic goals? It should be to promote both the Federal agency mission and economic growth. The impetus of the National Broadband Plan is to garner additional spectrum for commercial wireless uses, so it makes perfect sense to focus on sharing with radar since it occupies an appreciable portion of the Federal spectrum. There is a subtext here. It is assumed that smart wireless to achieve mission goals and to grow the economy is more dynamic spectrum access oriented. That is an assumption that people should be aware of.

Government regulators have important roles and need to weigh several key considerations:

- **Set the agenda: balance missions (security vs. economy).** Regulators need to strike a balance between the security and safety mission of government systems and those of commerce. Do we assume the risk of less security that would go with lower taxes? Or do we seek security despite the higher costs? That needs to be considered, and the government mission needs to be defined. It is not an economic decision. It is a value judgment and ultimately a political decision that needs to be sorted out.

- **Establish rules/framework to enable sharing agreements.**
- **Police agreements, enforcement.** The government plays a critical role in its spectrum regulation enforcement capacity. Additional attention and resources need to be committed to this problem. This role could be delegated to private sector actors, but ultimately is the responsibility of the regulator.
- **Manage agencies.** Regulatory bodies need to keep in mind that the government is a major economic force in and of itself as a major consumer of radio spectrum. This is a problem for NTIA. It must simultaneously represent the interests of government agencies and their missions and at the same time try to manage the spectrum for better efficiency. It is a mixed mission.

Why is it a big economic problem? Consider why commercial spectrum sharing works. The risk-return models are different, commercial entities can be motivate by profit and scarcity. Liberalization of spectrum rules allows them more flexibility to make efficient tradeoffs. Also in the private sector we have competition which drives innovation and efficiency. There are situations where the commercial system doesn't always work. There are externalities and issues of the public good that show up even in the commercial space that demonstrate how spectrum sharing is not a trivial economic problem.

On the other hand, the government is non-profit and is mission driven. That is fundamentally different. It is not possible to make government agencies act like for-profit actors, since they are funded through an administrative budget process. Ultimately, they don't have competition.

There are a number of economic solutions. First, we should seek to lower the costs of sharing. New radar systems should be designed for sharing as was discussed at length in earlier conference panels, for example. Also, the government should choose opportunities for sharing carefully. The first candidates for sharing should include pooling of government agency spectrum and intra and interagency sharing. Public safety sharing is another example.

Eventually, sharing needs to be made a part of the budget. It must be explicitly embedded in the budget cost. The most obvious approach is procedurally—through the OMB A-11 process. There are issues, though, since there is no competition for spectrum like you have with energy markets, for instance. Spectrum fees are another possible approach, but there is a lot of work to be done there. Auctions are another possibility. I have papers you can download from my website if you would like to research this further.

10.2.3 Pierre de Vries, Silicon Flatirons

While evaluating the nature of complex systems such as the Internet, it is helpful to evaluate other complex systems that have undergone extensive study and interaction and attempt to borrow conclusions from analogous problems. Biological systems provide a wealth of information that can be exploited in this manner. We have gained decades of experience managing complex ecosystems such as forests and have a wealth of information on improved management methods. Research on ecosystems has exposed a set of so called “resilience principles” that govern enlightened management practices. These principles have been applied to regulatory issues surrounding the Internet [69]. Most recently, at the ISART chairman’s request, an attempt has been made to apply these principles to management of radio spectrum.

Much as Internet regulators have come to accept their limited control of that complex ecosystem, radio spectrum managers should adopt management principles for the wireless ecosystem rather than continue to seek to direct outcomes through direct controls.

The introduction of policy-based adaptive radios in the radio spectrum complicates an already complex wireless ecosystem. Such systems are inherently unstable systems and difficult to optimize. However, they are resilient and, with proper management principles, they can flourish. There is a set of resilience principles that apply to the management of the increasingly complex spectrum ecosystem that can adapt and still maintain their function. There are four principles:

- **Flexibility.** Spectrum managers should be flexible in their management of the spectrum and focus on the ends rather than the means. The end goal of radio management is to maximize the value of the use of the radio spectrum as opposed to the old paradigm of minimizing interference. This can be achieved by defining the operating rights clearly, making enforcement more efficient, and, finally, making it easy for the parties to conduct spectrum transactions.
- **Delegation.** Spectrum managers need to delegate control of the spectrum to the local agents, who understand the system best. This is facilitated by clear definitions of operating rights.
- **Big picture.** Regulators should take a big picture perspective, since you can’t isolate subsystems in complex environments. The manager must take a broad view of the problem or solution space. Compatibility problems don’t have to be solved through one technique or technology. A broad, system-wide collection of tools should be used to embrace the whole problem.
- **Diversity.** Finally, system diversity demands that managers not attempt to predict the best solutions. They should take a broad view and enable as many solutions as possible to be implemented. Also, they shouldn’t try to solve the hardest problem first. Federal/non-Federal sharing is the toughest problem to solve. The first step is to prove that military-to-military sharing works, and then move on to the problem of interagency sharing, etc. On the other hand, there is a notable lack of commercial-commercial sharing; regulators should not rush to implement Federal-to-non-Federal sharing until industry has shown that all possibilities for non-Fed-to-non-Fed sharing have been exhausted.

10.2.4 John Stine, The MITRE Corporation

Spectrum management tends to seek lasting or “persistent” solutions that produce static frequency assignments. There are two weaknesses to this approach. First, when a spectrum manager conducts a study, the knowledge gained during the analysis process is lost, because the only information captured and disseminated is the static frequency assignment. Second, using this approach with each new analysis is a duplication of effort and by its nature promotes static assignments.

The MITRE Corporation is developing Model-Based Spectrum Management (MBSM) [70] to address those shortcomings. MBSM seeks to capture the mental process followed by spectrum managers. It permits follow-on analysts to exploit the insights of previous studies. That promotes a more dynamic process.

MBSM uses "spectrum consumption" models. Spectrum consumption models have a modular design and are built using constructs that capture the different aspects of spectrum use. It should be noted that these models abstract a number of key elements or parameters such as power density, spectrum masks, and underlay masks to capture spectrum consumption. They do not use values such as radio model names or modulation types that can reveal the system mission or its vulnerability.

Given these generalized constructs, the spectrum manager in MBSM builds models of spectrum consumption. The spectrum manager models receivers and transmitters and can combine these into models of systems. System models and separate models of transmitters and receivers can subsequently be grouped into collections. The constructs and model hierarchy are defined in an XML schema. The model collections built using this schema can convey current spectrum use, spectrum that may be used, and constraints to spectrum use for interference prevention. The models can be shared between spectrum management systems to show their views of spectrum use. They can also be used to convey spectrum which is available for use by an RF system.

When a user builds a model that defines his use of the spectrum, he is in essence creating a policy that can be used by other users to understand the modeled system's interference protection criteria. The modeling and management process supported by MBSM inherently generates policy for DSA.

As illustrated in Figure 73, spectrum consumption modeling is a "loose coupler." Loose couplers are well defined interface specifications that capture the minimum set of shared data required for systems to function. A good example is the AC power specification that defines the plug types, voltage, and frequency. So long as they meet at this specification, many different power generation technologies can be combined into a power grid and many appliances can be designed to use the power. Another example is the Internet Protocol. There are many different ways to combine link layer technologies to form a network and to design systems above the IP layer. Loose couplers create conditions that allow for continuous innovation. In terms of the MBSM model, the loose coupler provides a bridge between the spectrum management functions at the top of the hierarchy and the users and spectrum devices at the bottom. Spectrum consumption models created by spectrum managers convey to devices or other spectrum managers what spectrum can be used. At the lower level, the devices themselves can collaborate with each other on spectrum use.

Considering radars, there are a series of constructs that can define the necessary rules to avoid interfering with them. It is important to note that there is no need to provide explicit descriptions of susceptibility. The models can be artfully constructed in a variety of ways to protect a radar system without divulging their sensitive operational characteristics. The constructs can also define explicit behaviors for other spectrum users to use to reduce the possibility of interference to a radar system. MBSM can also facilitate collaboration between devices.

MITRE has drafted a thorough description of these models [70] and is seeking comments on the draft. The intent is to update the draft and submit it to a standards development organization for further consideration. The draft is on the MITRE external site. Finally, an interesting extension of MBSM is the development of software algorithms to operate on the encompassed models to perform spectrum management tasks such as arbitrating compatible reuse and searching for unused spectrum. We are developing these algorithms and plan to make them freely available and hope the further development of algorithms becomes an open source activity.

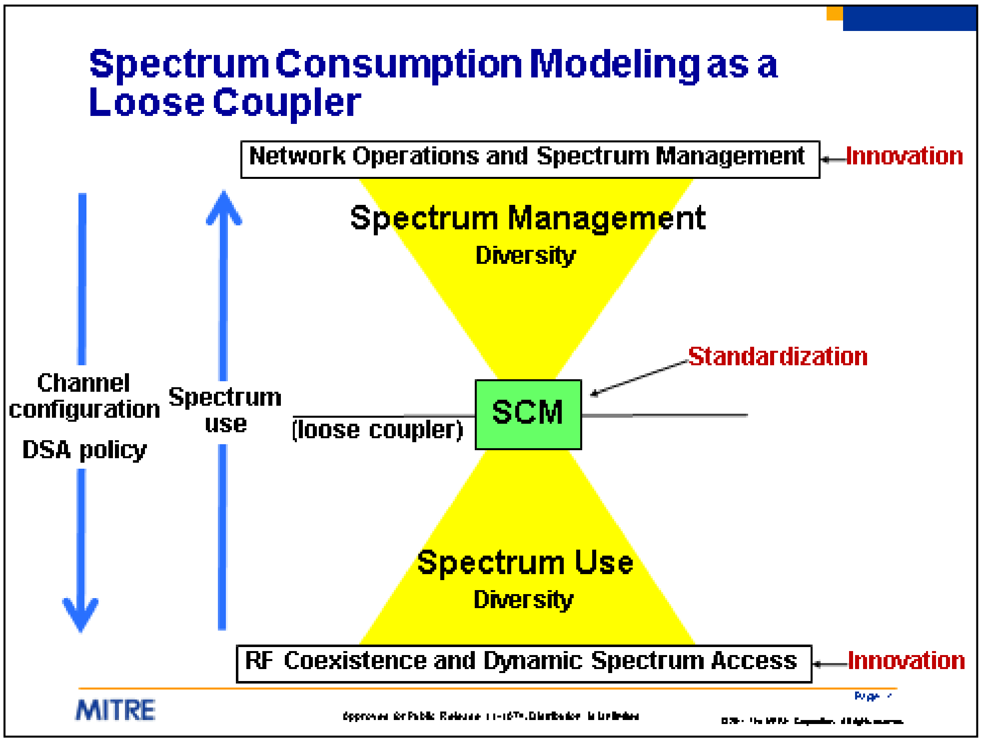

Figure 73. Spectrum consumption modeling as a loose coupler.

10.2.5 Paul E. Black, NIST/ITL

Software assurance is the process of building trust in a software-based system that it is going to do what you want it to do. Trust comes from three sources: the process by which it is built, analysis such as the conformity assessment process, and execution, which are the protections used to add to trust. Rashmi Doshi mentioned the unexpected uses of general purpose RF chipsets. That is an execution issue. It is exactly the same problem that Apple has trying to control application downloads on the iPhone. It is supposed to follow prescribed processes, but there still are many users who “jailbreak” their devices to gain greater control over them.

First, trust is fostered in systems where the design process is well understood and a rational framework is in place for development. Second, trust can be built through a system of analysis such as certification or acceptance testing. In this stage, the investigator seeks to determine whether the software-based system follows the expected rules. This is predicated, of course, on a clear articulation of expectations. There are two complementary types of analysis—static analysis or testing (dynamic analysis). Static analysis looks at how things are built. It evaluates the design at the code level. The model-based management system facilitates static analysis by allowing exploratory evaluations of hypothetical spectrum uses. Static analysis permits the investigation of what-if scenarios. A reliable certification has to include static analysis. It must include design review, and preferably, it includes source code review. It looks for such things as back doors and security flaws.

On the other hand, dynamic testing looks at end-to-end testing under a comprehensive set of use cases. One complication of dynamic testing is the high number of test configurations created through a naive combination of all possible system states. NIST has developed techniques to reduce the problem space. The combinatorial testing technique developed at NIST dramatically reduces the number of test cases. The technique is based on the experience that software problems usually are predicated on no more than three or four unique inputs or interactions. By searching the total problem space for all of the possible three-way interactions, one discovers that the entire problem space is dramatically reduced. The example showed that a system with 10 different variables can be reduced from the 960 test cases required in a brute force testing approach down to only 13 unique test cases.

Finally, the triad of trust includes a thorough understanding of the execution of the software. This can be accomplished through techniques such as virtual machines or sandboxes. Experience with the software adds to trust. As the experience with DFS showed, powerful chipsets can be jail-broken just as the iPhone security system was compromised.

10.2.6 Tom Kidd, U.S. Navy

A recent quote captures the essence of a Federal government perspective on spectrum—"The future is just like today only better." A corollary to that is if the future gets worse then we're in trouble, especially when one considers the long lead times—often decades—that are required to procure critical government systems. Hence, the future has to be better, and if it can't get better then at least it better not change. The easiest perspective is to resist change unless it obviously leads to better outcomes.

Most sharing will take place within the construct of the current regulatory framework, i.e. the NTIA Redbook. There will be changes, but they will be of an evolutionary nature—not revolutionary. For example, one change that occurred recently involved sharing of Federal and non-Federal spectrum. This rule, captured in Section 8.2.47 of the NTIA Redbook, permits sharing of spectrum between Federal and non-Federal users. The original impetus for this provision was not necessarily for the purpose of interoperability but rather to address a need for additional spectrum to accommodate Federal land mobile radio users. However the legal description doesn't limit the application to LMR. This is an example of a small change to address a specific use that was generalized and can be used to facilitate other incremental changes.

There are little changes that can be accomplished within the constructs of the existing rules and the various stakeholders should exploit them. They should not just focus on revolutionary changes when evolutionary changes are possible. In fact, as Malcolm Gladwell has noted, there is a point at which enough small changes lead to a tipping point, where a set of small changes prompt a consolidation into more comprehensive changes or rules.

Consider the revolutionary perspective. The notion of eliminating the NTIA Redbook has been suggested. However, a number of spectrum managers involved who work at the ITU were once asked how long it would take to eliminate the existing spectrum management regime and convert to a completely dynamic system. The answer was sobering: probably 30 or 40 years longer than the lifespan of the youngest person present. Spectrum managers have almost a century of vested interest in the existing scheme and revolutionary change will not come easy.

It should be understood that there are many actors invested in the current regulatory process, so practically speaking the most productive efforts will focus on seeking incremental changes. The NTIA manual is continuously undergoing incremental changes. Perhaps enough small changes will lead to a tipping point that will result in revolutionary change.

10.3 Moderated Discussion

Nelson: Considering the notion of incremental change, perhaps we should not try to tackle what is perceived as the most difficult problem first. I would like your perspective on what would be a simpler problem. If we could break it down into its constituent parts and solve a simpler problem, what does that simpler problem look like? In particular, what are actions that the FCC and NTIA can take to address that?

Black: One simpler problem might be, rather than trying to create a new regulatory climate for brand new protocols, go back and look at DFS and ask what questions could have been asked and what actions could have been taken then. That would be a small step that might contribute to a solution. That might not solve all your future problems, but you have a concrete case study with lessons that can be applied to DSA.

Kidd: The simplest problem to solve is “like-to-like” sharing. It is easier to share when the users have similar requirements. Then you branch out from there. That change that I mentioned in the NTIA manual was originally conceived for LMR-to-LMR channel sharing. Then it branched out as policy developed. The LMR-specific references were removed to make the rule more general. The next step is then “similar-to-similar”. That is happening now. For example, Federal LMR users are sharing with state governments in Maine and Wyoming, so it is spiraling outward. There is no reason why at some point a commercial entity couldn’t come in and propose sharing. This is sharing in the sense that one party has an excess of the commodity while the other has a deficit. It is not just interoperability. Start with “like-to-like” then “like-to-similar” and spiral out. Build trust. Build use cases, examples, etc.

Lehr: That is along the lines of some of the ideas I’ve had. Part of what you want to do is move toward operational testing and demonstrations, so that the testing is not considered a purely technical matter. You are also trying to disseminate research results for consideration and debate to allow people to explore some of the non-technical issues associated with the adoption of spectrum sharing. Closely related to that, the NTIA needs to consider how spectrum use will become a part of the budget process. You probably do not necessarily want to consider Defense first, but start in those areas where the issues might be easier to assess and the analysis can be done in a more rigorous way.

De Vries: Just echoing what the other panelists have said, "like-to-like" sharing is the best place to start. I presume there is already a lot of this already going on in the day-to-day work that is done by the IRAC between agencies, such as military-to-military sharing. That is where more work needs to be done. Looking at the black box from the outside it seems to me as if the point of leverage is incentives. What is the incentive for more intensive sharing? At the moment the "stick" is that if you don't share more with commercial users, we'll just take it away. I don't know how effective that is. Perhaps there should be an incentive such as you don't get more assignments and you have to be more efficient. You have more missions such as operating UAVs. You have to perform those missions within your existing assignments. The other point of pressure is to be hard core about sharing among FCC-regulated users. There shouldn't be sharing with Federal users until you have exhausted all of the possibilities for commercial-to-commercial sharing. There is a lot of opportunity for that and it's not being used.

Doshi: In terms of small steps, the key message I take away from the conference is the need to build trust. Trust in many dimensions—in terms of compliance, in terms of sharing, and in making sure that the interactions between systems are as people expected.

Nelson: John [Stine], let me bring you into this question, but before you answer let me return to my opening remarks. NTIA is working on a "like-to-like" sharing test bed. One of the things that we are lacking right now is the ability to test the policy generator. Is there a way to take your policy creator and use it to construct a policy load for use in the test bed? And preferably in short-time, not long-time.

Stine: I haven't yet designed the radio that can respond to the policy, so that is sort of out of the question. The most logical way to start is to demonstrate the software and show that it can model systems. That is something that you can do right away. There is nothing that keeps you from doing that now. Then exercise the activity that searches for new spectrum sharing opportunities. That becomes your test. Use the tool to model a possible sharing scenario. Then use the output from the model and do the test to make sure that that answer is correct.

Black: In terms of testing policy, in software you not only test whether it does the right thing you also test whether it does not do the wrong thing. Another interesting test might be to come up with policies and then purposely break them or tweak them a little bit. Then the radios with these mutated policies should cause interference based on our rulemaking models. Break it and mutate it in different ways and then determine whether we have interference. If you find that you're never getting interference, then either you have a poorly designed test or an overly conservative algorithm.

Kidd: This is an interesting discussion and it's heading down the path which from a Federal IRAC perspective causes me to get nervous. What I mean by that is that the discussion begins to lean toward the notion that if we test it enough and design it enough, we can anticipate every problem, and it won't fail. And the reality is that everything fails. Version 1.0 of everything is awful. No matter what it is, when you roll out the first version we learn more the day we deploy it than we ever did in the labs and in the testing that preceded it. So not only do we have to think about how to prevent it from breaking, but you have to figure out what to do when it breaks, from both the technology and regulatory standpoints. There have to be built-in mechanisms. Back in the day when automobiles couldn't safely go more than a given speed we put governors in the vehicles to limit them. We need mechanisms built in [to govern DSA devices] and ways to find bad actors—maybe not at the level to thwart an ultra-hacker. The best hackers don't want to get caught, so they will move around the bands and won't cause persistent interference anyway. Perhaps if we're lucky we'll hear about what they did at Defcon and we'll be able to learn from it.

10.4 Q&A

Dan Lubar, Relay Services: John's MBSM framework is a one of number of different initiatives that exist. In an orbit around IEEE P1900 there is also an ontological framework. We saw Dr. Mitola's slide for those of you who were here the other day. The question I'm asking, there is a lot of opportunity here to start moving down the path, so who is the right convener for that piece of it? Is it a standards body? An international standards body? ITU-R? IEEE? A Federal agency? It is a very interesting problem because I'm not sure I see where the leadership will go given the wide array of applications that DSA will be used for. How do you partition it into the various FCC rules? So where is the leadership and where is the framework?

Stine: I've thought about the very same question. I don't know where the best place to create a framework would be. You often find when talking to people in government that they want to emulate the activities of commercial enterprises, but commercial enterprises are focused on their own problems, and they have a different problem. They are trying to obtain as much spectrum as they can for exclusive use. I thought about standards bodies. IEEE P1900 is international and is dedicated to DSA standards and so it seemed like the most appropriate to me, or perhaps the Wireless Innovation Forum.

Joe Hersey, U.S. Coast Guard: A question was asked earlier what incentives can be given the Federal agencies for sharing spectrum, one thought I had was to provide Federal agencies some sort of dynamic access to non-Federal spectrum—including auction spectrum. Just watching some of the legislation going through now on rearranging spectrum, there is no statutory process for Federal agencies to acquire spectrum once the spectrum is exhausted on the federally allocated side. One problem we have is the last of the internationally interoperable maritime communications spectrum was auctioned away to a spectrum speculator 10 years ago. When we have needs now, we're stuck. We have no process for getting spectrum even if it is available.

Lehr: In comment to that, I certainly think that Federal users ought to be able to use non-Federal spectrum. For example, when I go into Federal offices I see that they are using Wi-Fi access points. If they are compliant, they ought to be using the spectrum. Building that capability and that recognition for it is part of the process. I think it's a wonderful thing.

Kidd: Not just to support one of my fellow IRAC members, I think that as long there is recognition that there is a requirement for non-Federal exclusive spectrum and the argument can be made for reallocation for non-Federal exclusive use there has to be reciprocal discussion. There has to be discussion of those scenarios that occur where the best use of particular spectrum is going to be for Federal exclusive use. So I do agree with Joe, we need a similar and reciprocal mechanism for reallocation of non-Federal exclusive spectrum back to Federal. Perhaps we missed an opportunity with the DTV conversion, of [obtaining] some of that spectrum, I'm not sure, but we need to have some process that can be exercisable similar to this. I almost want to say, "bringing it back over," because it has definitely been a one-way process. We need to close the loop and bring it back.

John Notor, Notor Research: the thing I would say is that change is happening faster than the processes we are envisioning. For example, it has been about two years since the changeover from analog TV to digital TV over-the-air broadcasts, but arguably over-the-air broadcast is obsolete. So the fact that it's the greatest technology in HD broadcasting is completely irrelevant. Only 10% of the U.S. population watches over-the-air broadcasts. In my view, the mechanisms you are talking about are way too slow.

Kidd: You are correct. I have to be honest, I've had leadership come to me before and say that we have to change things quicker. There is a counter argument to that. One could argue that the current way that we distribute power may not be the most efficient way, but do we want that to change in 18 months? Sometimes these long timelines give the world a chance to change. It can be frustrating that it can take three ITU work cycles to get a change enacted. That is 12–16 years and then tack on a few extra years to implement it in the U.S. You are talking about two decades to really change something. In the Federal government we have systems with long lifetimes. I don't know that at the macro level, where we are talking about the foundational rules that a lot of these systems are built on, that the appropriate question is how fast do we want them to change? Do we want the international allocation to be changed in one work cycle? Which means that if enough pressure is put on the ITU in a four-year timeframe, that a major portion of spectrum could be reallocated, disrupting an entire industry or an entire worldwide operation. It is a balance. I'm not sure we want these processes to speed up too much.

De Vries: Perhaps it is a cheap shot, but when Tom Kidd was talking about power systems, I thought he was talking about political power. In that sense, there is a very efficient way to get government rules to change quickly: a dictatorship. Our system is designed to change slowly, and I don't think I want that to change.

Nelson: Rashmi [Doshi] you made the point about taking the necessary time to do a thorough analysis of the DFS interference problem. Please share with us your perspective, what if the FCC and NTIA hadn't taken the time to do a thorough root cause analysis?

Doshi: One of the findings as you go back through the chronology—back as far as Chris [Tourigny] mentioned as 2007—and also considering the work that Frank [Sanders] did in Puerto Rico, and some of the early experiments that we have done, I think if we had taken the steps that were recommended at that time, we would have changed the requirements but not have solved the problem in the field. One of the reasons we didn't move forward quickly is that we didn't quite understand some of the root causes. While the interference was very clear and observable, what was the mechanism by which the devices made it into the field? How was it that they were being deployed? What were the software changes behind the problems? It took some digging into it. Also, as Pierre mentioned, we have a due process issue. There is a stepwise investigation. We can't just declare guilt. In that case, it took a while, we had to assemble evidence, interview various parties, understand the uses. We had to understand what the manufacturers did. It was a learning process for the FCC. It was not like traditional FCC enforcement with users exceeding power limits or not operating in an authorized frequency. In this case, it was a new model of investigation where we needed to look at entire systems. Those are the kinds of issues that we have become a lot more aware of. The FCC enforcement bureau had to learn techniques. The old technique of directing finding wasn't good enough. They had to also use mapping and satellite views to find prospective interference sources. So now we have some more forensic tools to use in our enforcement cases. One of the issues we learned from working with ISPs, for example, was that we could use the SSID as a beacon.

Lehr: Obviously in the long term we're all dead, but there are plenty of reasons why it takes a long time to get anything done. That is one of the reasons why some amount of the new spectrum allocation in the NBP should be dedicated to unlicensed services. We need to create a playground where we can try new models because these other, more complex issues will take a long time to resolve.

Hal Grigsby, U.S. State Department: Tom Kidd stimulated a couple of thoughts regarding the situation with international agreements relevant to the 500 MHz issue. Both NTIA and FCC are aware of this, but the audience here should understand, that there are about 40 agreements with Mexico regarding spectrum coordination along the border. These are like-to-like uses. As we approach the 500 MHz issue there will be two scenarios—one where both parties want to move forward with technological changes and another where one party does not what to change in some bands and expects the other to still meet their international obligations or renegotiate the agreement. The like-to-like situations in the first scenario will be easier to deal with. In the second scenario, there is another concept that I wanted to comment on. Consider NTIA's fast track report that came out last October, where we see "exclusion zones" and some would say that those could be considered sharing zones along the coasts. If you are familiar with the situation, you will realize that we have similar zones along the two international borders and with some important U.S. cities on the border. I think that we will see some situations where those areas will turn into exclusion zones in some bands, and as we consider the repurposing of the various bands, we need to look at that. It is an important criterion and it hasn't been mentioned. NTIA and FCC are aware of this. The ten-year plan and timetable has a list of the 2200 MHz that Tom Powers mentioned in his presentation that is under consideration. Look at that list. Look at the footnote with the four asterisks. You will see the possibility that that band may be encumbered by existing international agreement. We'll see where it goes.

Kidd: Not just to echo what Hal said, I have experience with this. We have Yuma right on the Mexican border and in the 1710–1755 MHz band an exclusion zone was set up around the base to allow us to continue to operate. There were negotiations not just within the U.S. but with Mexico. The other side of this issue is that there is talk of reallocation throughout the world and the question is whether we should wait for the WRC activity or get ahead of it. Do we reallocate now and then in WRC-16, if the ITU reallocates differently, do we then reallocate again? Do we allow the two to diverge? This is another important issue, not to muddy the water.

Michael Calabrese, New America Foundation: I wanted to revisit a concept that we talked about on the overview panel, I would particularly be interested in Tom's perspective. In terms of the trust issue, would connected devices make a difference? Building on the concept that we have in the TVWS database where we have devices that know their location, check in periodically, can be remotely disabled, and can be forced to take firmware upgrades or de-authorized. They are required to be multi-band frequency hopping capable and presumably controlled by some sort of database governance system. Would that make a difference? And I ask John if his database would be implemented in a real time manner like that. I can see where having a “wild west” based on “fuzzy” parameters would be a scary thing, but if you have enforcement at the device level and it’s baked in, I’m wondering how much of a difference that makes?

Kidd: The type of technology you are talking about leans toward a system that helps to quickly build trust. It is a simple solution. We tend to trust simple solutions that are easier to understand. The database approach gives the impression of greater reliability. Psychology comes into play. Trust is gained slowly and lost quickly. A new technology like the one you are describing has a lower probability of failure. That is better than autonomous systems that are engineered and tested and released into the environment without any way to recall them. Another advantage to these types of [database] technologies is that when they fail, it is usually a softer failure—and it’s an understandable failure. It’s not like other technologies in which something goes wrong and no one knows why. That causes a huge crash in trust because you don’t know why it failed. Start with solutions that are simple, understandable, and reliable. Those are ones that are most likely to be embraced. When IRAC members are briefed on revolutionary technologies they tend to have reservations because it can be perceived as untested. Incremental changes are not perceived as untested, so there is more trust.

Black: Let me echo Tom’s point about complex systems. They tend to fail in complex ways. Consider the financial meltdown. It was just computers talking with each other, all of them were doing presumably reasonable things, and yet we had horrendous results. As far as I know, nobody quite knows what went wrong. Nobody has figured out the rule or algorithm that failed. I don’t know what the algorithm would be in a dynamic spectrum allocation system, but having seen complex systems and how they are very ingenious about failing, I don’t want to find out.

Stine: So since you mentioned MBSM, my intent is to create a management control system. The trust comes from the ability of the controller to do those oversight tasks. Clearly I’ve tried to create something that also allows human-to-human, human-to-machine, and machine-to-machine communications. Ultimately, you want to have that control in the system that can arbitrate those sorts of issues that might arise if you have a rogue operator.

Nelson: This is an issue that we have considered at ITS, if you have a situation where privileges can be revoked, is it incumbent upon the regulator to provide alternate means of spectrum access for the devices to make them more commercially viable. For example, a system shuts down in one band due to a major Air Force operation, is it incumbent upon us to provide more diverse means of access?

Lehr: The answer to that is yes. One of the things I took away from the CSMAC meeting is I kept thinking that the commercial users strike me as crybabies. It can’t be that they can only get perfect spectrum. That is not the situation with unlicensed spectrum. With Wi-Fi you don’t get guaranteed QoS and we’ve generated a lot of good [economic] activity in that market. If you can’t make a business model out of shared Federal spectrum with the assumption of possible interruptions, then get out of the way and let someone else do it. If there isn't any interest in that business model then perhaps this isn't something we need to worry about. Just because something's lifetime is limited or is contingent doesn't mean there isn't a lot of value. What we should try to do in terms of creating spectrum regimes is to make those opportunities so investors can choose which regimes they like—not the regulators dictating the regimes. Some mobile companies want exclusive licenses. Sure they should have that. Some want unlicensed. Sure they should have that. In the Federal bands they want to share. They should be able to do that. It is in the diversity of those options that you basically answer your own question.

De Vries: A quick comment about resilience... How do you make a system more resilient? You take the big picture. The consequence of that for regulation might be that operators should not operate in bands where they could be preempted if they don't have a fallback. This is a proposal of Mark McHenry's. That means that the regulator doesn't look at the system from an allocation by allocation basis, but they look more broadly.

Kidd: Spectrum managers are often viewed as naysayers. The job of a regulator is twofold. First to act as a filter—to suppress bad things from happening—and it's also to act as an enabler to permit good things to happen—and all good ideas, good or small. There might be a small good idea or a big one. It is not the regulator's job to suppress one idea over another. The purpose of regulation is to act as a filter. It is the job of the regulator to bend and tweak the filter, so if there is a good idea that can't get through that filter it is our obligation to adjust it so the good ideas get through without letting bad ideas through. That is the challenge. Does the regulator have the responsibility to enable alternates? Absolutely.

Doshi: From a slightly different perspective as a regulator, consider the Part 15 regulations: the user goes in with the understanding that they may be interfered with. It is very clear. In general the FCC encourages developers to consider alternatives in their business models. In fact, that reminds me, we had a case recently were the operator decided to use the 5 GHz band with DFS. Now they are complaining about the lack of availability due to radars which are present. That is the rule. We have to guide them to see that there are other bands they could use. The point is we're not there to protect their business model. We allow opportunities for business models that work around the contingencies.

11 REFERENCES

11.1 General

[1] Federal Communications Commission, *Connecting America: The National Broadband Plan* (Mar. 2010).

[2] The White House, *Presidential Memorandum: Unleashing the Wireless Broadband Revolution*, 75 Fed. Reg. 38387 (Jun. 2010).

[3] National Telecommunications and Information Administration, *Plan and Timetable to Make Available 500 Megahertz of Spectrum for Wireless Broadband* (Oct. 2010).

[4] National Telecommunications and Information Administration, *An Assessment of the Near-Term Viability of Accommodating Wireless Broadband Systems in the 1675–1710 MHz, 1755–1780 MHz, 3500–3650 MHz, and 4200–4220 MHz, 4380–4400 MHz Bands* (Oct. 2010).

[5] Senators Jay Rockefeller (D-WV) and Kay Hutchinson (TX), *Strengthening Public-safety and Enhancing Communications Through Reform, Utilization, and Modernization Act*, S. 911, 112th Congress (May 2011).

[6] Senators O. Snowe (R-Maine) and J. Kerry (D-Mass.), *Reforming Airwaves by Developing Incentives and Opportunistic Sharing Act*, S. 455, 112th Congress (Mar. 2011).

[7] M. Berejka, *Multi-Stakeholder-Ism: Making it Fly*, *The Digital Broadband Migration: The Dynamics of Disruptive Innovation*, Silicon Flatirons, Boulder, CO, Feb. 2011.

11.2 Tutorials

[8] M.I. Skolnik, *Introduction to Radar Systems (3rd Ed.)*, McGraw-Hill, Boston, MA, 2001.

[9] M.A. Richards, J.A. Scheer, and W.A. Holm, *Principles of Modern Radar*, SciTech, Rayleigh, NC, 2010.

[10] D.H. Johnson and D.E. Dudgeon, *Array Signal Processing: Concepts and Techniques*, Prentice-Hall, Englewood Cliffs, NJ, 1993.

[11] J.V. DiFranco and W.L. Rubin, *Radar Detection*, Artech-House, Dedham, MA, 1980.

[12] L.E. Brennan and I.S. Reed, "Theory of Adaptive Radar," *IEEE Transactions on Aerospace and Electronic Systems*, Vol. 9, No. 2, Mar. 1973, pp. 237–252.

[13] R. Klemm, *Space-Time Adaptive Processing: Principles and Applications, IEE Radar, Sonar, Navigation and Avionics 9*, IEE Press, 1998.

[14] J.R. Guerci, *Space-Time Adaptive Processing for Radar*, Artech House, Norwood, MA, 2003.

[15] W.L. Melvin, "A STAP Overview," *IEEE Aerospace and Electronic Systems Magazine*, vol. 19, no. 1, pp.19–35, Jan. 2004.

[16] J. Ward, "Space-Time Adaptive Processing for Airborne Radar," *Lincoln Laboratory Tech. Rept. ESC-TR-94-109*, Dec. 1994.

[17] A.G. Jaffer, M.H. Baker, W.P. Ballance, J.R. Staub, "Adaptive Space-Time Processing Techniques for Airborne Radars", *Rome Laboratory Technical Rept. TR-91-162*, Jul. 1991.

[18] S. Haykin, *Adaptive Filter Theory (2nd Ed.)*, Prentice-Hall, Upper Saddle River, NJ, 1996.

[19] I.S. Reed, J.D. Mallett, and L.E. Brennan, "Rapid Convergence Rate in Adaptive Arrays," *IEEE Transactions on Aerospace and Electronic Systems*, Vol. 10, No. 6, Nov. 1974, pp. 853–863.

[20] I.S. Reed, "A brief history of adaptive arrays," Sudbury/Wayland Lecture Series (Raytheon Div. Education) Notes, Oct. 1985.

[21] R. Klemm, "Doppler Properties of Airborne Clutter," *Proc. Research and Technology Org., North Atlantic Treaty Org. (RTO-NATO) Lecture Series 228—Military Applications of Space-Time Adaptive Processing, RTO-ENP-027*, Sep. 2002, pp. 2-1–2-24.

[22] L.J. Griffiths and C.W. Jim, "An Alternative Approach to Linearly Constrained Adaptive Beamforming," *IEEE Transaction on Antennas and Propagation*, Vol. AP-30, No. 1, Jan. 1982, pp. 27–34.

[23] I.P. Kirsteins and D.W. Tufts, "Adaptive Detection Using Low Rank Approximation to a Data Matrix," *IEEE Transaction on Aerospace and Electronic Systems*, Vol. 30, No. 1, Jan. 1994, pp. 55–67.

[24] W.F. Gabriel, "Using Spectral Estimation Techniques in Adaptive Processing Antenna Systems," *IEEE Transaction on Antennas and Propagation*, Vol. 34, No. 3, Mar. 1986, pp. 291–300.

[25] E.K.L. Hung and R.M. Turner, "A Fast Beamforming Algorithm for Large Arrays," *IEEE Transactions on Aerospace and Electronic Systems*, Vol. AES-19, No. 4, Jul. 1983, pp. 598–607.

[26] R.T. Compton, *Adaptive Antennas: Concepts and Performance*, Prentice-Hall, Englewood Cliffs, NJ, 1988.

[27] R.A. Monzingo and T.W. Miller, *Introduction to Adaptive Arrays*, John Wiley & Sons, New York, 1980.

[28] G.A. Showman, W.L. Melvin, M. Belen'kii, "Performance Evaluation of Two Polarimetric Space-Time Adaptive Processing (STAP) Architectures," *IEEE Radar Conference*, Huntsville, AL, 5–8 May 2003, pp. 59–65.

[29] F. Raab, P. Asbeck, S. Cripps, P. Kenington, Z. Popovic, N. Pothecary, J. Sevic, and N. Sokal, "RF and Microwave Power Amplifer and Transmitter Technologies, Parts 1–4," *High Frequency Electronics*, May–Nov. 2003, pp. 22–54.

[30] G. Wimpenny, "Improving Multi-Carrier PA Efficiency Using Envelope Tracking," *RF Engineer Network*, Apr. 2009, pp. 22–54.

[31] F. Raab, P. Asbeck, S. Cripps, P. Kenington, Z. Popovic, N. Pothecary, J. Sevic, and N. Sokal, "Power Amplifiers and Transmitters for RF and Microwave," *IEEE Microwave Theory and Techniques*, Vol. 50, No. 3, Mar. 2002, pp. 814–826.

11.3 Radar Inventory

[32] ITU-R, "Technical and Operational Characteristics and Protection Criteria of Radiodetermination Radars in the 2900-3100 MHz band," ITU-R M.1460-1, (Mar. 2006).

11.4 Overview

[33] National Telecommunications and Information Administration, Commerce Spectrum Management Advisory Committee (CSMAC), *Final Report of the Incentives Subcommittee* (Jan. 2011).

[34] Cisco, *New FCC guidelines for installation and operation of outdoor WLAN devices (U-NII devices) operating in the 5470–5725 MHz band* (Feb. 2011).

11.5 International Radar Compatibility

[35] International Electrotechnical Commission, "International Standard for Maritime Navigation and Radiocommunication Equipment and Systems," IEC 62388, 2007.

[36] J. Carroll, et al., Case Study: Investigation of Interference into 5 GHz Weather Radars from U-NII Devices, Part 1, *NTIA Report 11-473* (Nov. 2010).

[37] M. Ganley and Z. Wang, "Potential Impact of Out-of-Band Emissions from the 2.6 GHz Auction on S-Band Maritime Radar," *Cobham Technical Services*, Report Number 2009-0258 (Nov. 2010).

[38] UK Contribution to ITU Working Party 5B, "Radar Adjacent Band Selection," ITU-R, 5B/389-E (Nov. 2009).

[39] WD PDNR ITU-R M.[RNSS-RDS], “Compatibility of the Radionavigation-Satellite Service with the Radiolocation Service Receivers in the Band 1215–1300 MHz,” ITU-R, 5B/296 Annex 7, (Jun. 2009).

[40] M. Ganley, S. Munday, “Proof-of-Concept Radar Testing for Bandsharing: Watchman ATC Radar,” *ERA Technology*, Report 2008-0492 (Oct. 2008).

[41] EUMETNET, *Recommendation on C-Band Meteorological Radars Design to Ensure Global and Long-Term Coexistence with 5 GHz RLAN* (Apr. 2008).

[42] K.H. Teo, et al., “Standards in a Nutshell: The Mobile Broadband WiMAX Standard“, *IEEE Signal Processing Magazine*, Vol. 144 (Sep. 2007).

[43] F. Sanders, et al., “Effects of RF Interference on Radar Receivers,” *NTIA Report TR-06-444* (Sep. 2006).

11.6 Radar R&D

[44] J.R. Guerci, *Cognitive Radar: The Knowledge-Aided Fully Adaptive Approach*, Boston, MA: Artech House, 2010.

[45] J.R. Guerci and E.J. Baranoski, “Knowledge-Aided Adaptive Radar at DARPA: An Overview“, *IEEE Signal Processing Magazine*, vol. 23, no. 1 pp. 41–50, Jan. 2006.

[46] C. Baylis, L. Dunleavy, S. Lardizabal, R.J. Marks II, A. Rodriguez, “Efficient Optimization Using Experimental Queries: A Peak-Search Algorithm for Efficient Load-Pull Measurements,” *Journal of Advanced Computational Intelligence and Intelligent Informatics*, Vol. 15, No. 1, Jan. 2011.

[47] M. Moldovan, C. Baylis, M. Wicks, R.J. Marks II, “Chirp Optimization Using Piecewise Linear Approach,” submitted to *IEEE Waveform Diversity Conference*, Jun. 2011.

[48] J. Herd, et al, “Low Cost Multifunction Phased Array Radar Concept,” *2010 IEEE International Symposium on Phased Array Systems and Technology* (ARRAY), pp. 457–460, Oct. 2010.

[49] J. George, K.V. Mishra, C.M. Nguyen, V. Chandrasekar, “Implementation of Blind Zone and Range-Velocity Ambiguity Mitigation for Solid-state Weather Radar,” *IEEE Radar Conference*, Washington DC, May 10–14, 2010, pp. 1434–1438.

[50] P.F. Marshall, “A Potential Alliance for World-Wide Spectrum Access,” New America Foundation Issue Brief #25, Jun. 2009.

[51] J. Mitola III, “Software Radio Architecture: A Mathematical Perspective,” *IEEE Journal on Selected Areas in Communications*, Vol. 17, No. 4, Apr. 1999, pp. 514–538.

[52] J. Mitola III, “Cognitive Radio for Flexible Mobile Multimedia Communications,” *IEEE International Workshop on Mobile Multimedia Communications*, San Diego CA, Nov. 1999, pp. 3–10.

[53] J. Mitola III and G.Q. Maguire, Jr., “Cognitive Radio: Making Software Radios More Personal,” *IEEE Personal Communications*, vol. 6, no. 4, pp. 13–18, Aug. 1999.

11.7 Sharing Radar Bands with Commercial Systems

[54] J. Peha, “Cellular Systems and Rotating Radar Using the Same Spectrum,” *ISART 2011*, Boulder CO, Jul. 2011.

[55] H. Stover and G. Griffith, “Implanted Medical Devices Sharing the Radar Band: Prosthetic and Diagnostic Implants Use Unconventional Communication Models,” *ISART 2011*, Boulder CO, Jul. 2011.

[56] M. McHenry, “Incumbent Spectrum User’s Dynamic Spectrum Access Requirements,” *ISART 2011*, Boulder CO, Jul. 2011.

[57] M. Marcus, “Thoughts on Radar/Communications Spectrum Sharing,” *ISART 2011*, Boulder CO, Jul. 2011.

[58] I. Kash, et al., “Enabling Spectrum Sharing in Secondary Market Auctions,” *NetEcon’11*, San Jose CA, Jun. 2011.

[59] R. Murty, et al., “Senseless: A Database-Driven White Space Network,” *DySPAN 2011*, Aachen Germany, May 2011.

[60] Federal Communications Commission, “Spectrum Task Force Requests Information on Frequency Bands Identified by NTIA as Potential Broadband Spectrum,” *Public Notice*, 26 FCC Rcd 3486 (Mar. 2011).

[61] Aerospace, Alfred Mann Foundation (AMF) Medical Micropower Network (MMN) Wired Test Report, version 0.61 (Nov. 2010).

[62] Federal Communications Commission, Elimination of Interference to Terminal Doppler Weather Radar, (Jul. 2010).

[63] Federal Communications Commission, Office of Engineering and Technology, “Amendment of Parts 2 and 95 of the Commission’s Rules to Provide Additional Spectrum for the Medical Device Radiocommunication Service in the 413–457 MHz band,” *Notice Of Proposed Rulemaking*, 74 FR 22491 (Mar. 2009).

[64] E. Lee, et al., “A 400 MHz RF Transceiver for Implantable Biomedical Micro-Stimulators,” *IEEE Custom Integrated Circuits Conference*, San Jose, CA, Sep. 2007.

[65] J. Camacho, "Federal Radar Spectrum Requirements," NTIA Special Publication 00-40, (May 2000).

11.8 Regulatory Reform to Facilitate DSA

[66] J. M. Chapin and W. H. Lehr, "Time-limited Leases for Innovative Radios," *IEEE New Frontiers in Dynamic Spectrum Access Networks*, Dublin, Ireland, Apr. 2007, pp. 606–619.

[67] Federal Communications Commission, "Promoting More Efficient Use of Spectrum through Dynamic Spectrum Use Technologies," *Notice of Inquiry*, 25 FCC Rcd 16632 (Nov. 2010).

[68] Federal Communications Commission, "Weather Radar Interference Enforcement," Website, www.fcc.gov/encyclopedia/weather-radar-interference-enforcement.

[69] P. De Vries, "The Resilience Principles: A Framework for New ICT Governance," *Journal on Telecommunications and High Technology Law*, Vol. 9, Issue 1, Feb. 2011.

[70] J. Stine and S. Schmitz, "Model-Based Spectrum Management," *MITRE Technical Report 110131*, May 2011.

[71] National Telecommunications and Information Administration, Commerce Spectrum Management Advisory Committee (CSMAC), Interference and Dynamic Spectrum Access Subcommittee Final Report, Nov. 2010.

APPENDIX A: ISART 2011 AGENDA

<u>Day 1 (Wed 27 Jul)—Lectures and Inventory Briefings</u>

8:00 a.m. ***Welcome to ISART***—Michael Cotton (NTIA/ITS)

8:45 a.m. ***Lecture: Basic Radar Principles***—Greg Showman (GTRI/SEAL)

9:45 a.m. *15-minute break*

10:00 a.m. ***Lecture: Radar Frequencies and Waveforms***—Michael Davis (GTRI/SEAL)

11:00 a.m. ***Lecture: Radar Adaptive Interference Mitigation***—Bill Melvin (GTRI/SEAL)

12:00 p.m. *Lunch break*

1:00 p.m. ***Lecture: Radar Transmitter Technologies***—Larry Cohen (NRL) and Charles Baylis (Baylor)

1:45 p.m. ***Lecture: Key Differences between Radar and Comm Systems***—Michael Davis (GTRI/SEAL)

2:30 p.m. *15-minute break*

2:45 p.m. ***Inventory Briefings***

- Matthew Hussey (Senator Snowe)—moderator
- David DeBoer (UC Berkeley, NAS/CORF)
- Joe Hersey (U.S. Coast Guard)
- Frank Sanders (NTIA/ITS)
- Bob Sole (NTIA/OSM)
- Chris Tourigny (FAA)

<u>Day 2 (Thu 28 Jul)—Radar Compatibility and R&D</u>

8:00 a.m. ***Introductory Remarks***—Doug Sicker (FCC)

8:15 a.m. ***Keynote***—Thomas C. Power (DOC/NTIA)

9:00 a.m. ***Keynote***—Philip J. Weiser (CU/Silicon Flatirons)

9:45 a.m. *15-minute break*

10:00 a.m. ***Panel: Overview***

- Michael Calabrese (New America Foundation)—moderator
- Mary Brown (Cisco)
- Joe Guerci (Guerci Consulting)
- Dale Hatfield (CU/Silicon Flatirons)
- Paul Kolodzy (Kolodzy Consulting)
- Eric Mokole (NRL)
- Karl Nebbia (NTIA/OSM)
- Richard Reaser (Raytheon)

12:00 p.m. *Lunch break*

1:15 p.m. *Panel: International Radar Compatibility*

- *John Mettrop (UK CAA)—moderator*
- *Larry Cohen (NRL)*
- *Joe Hersey (U.S. Coast Guard)*
- *Frank Sanders (NTIA/ITS)*
- *Chris Tourigny (FAA)*
- *David Choi (Mitre)*
- *Jaewoo Lim (Korea KCC/RRA)*

3:00 p.m. *15-minute break*

3:15 p.m. *Panel: Radar R&D*

- *Joe Guerci (Guerci Consulting)—moderator*
- *Charles Baylis (Baylor)*
- *John Cho (Lincoln Lab)*
- *Marshall Greenspan (Northrop-Grumman)*
- *Preston Marshall (USC)*
- *Joe Mitola (Stevens)*
- *Bill Melvin (GTRI/SEAL)*

Day 3 (Fri 29 Jul)—Sharing Radar Spectrum

8:00 a.m. ***Panel: Sharing Radar Bands with Commercial Systems***

- Julius Knapp (FCC/OET)—moderator
- Clem Fisher (Motorola)
- Glen Griffith (Alfred Mann)
- Mark McHenry (Shared Spectrum)
- Robert Matheson (retired NTIA/ITS)
- Jon Peha (Carnegie Mellon)
- Jack Unger (WISPA)

10:00 a.m. *15-minute break*

10:15 a.m. ***Panel: Regulatory Reform to Facilitate Spectrum Sharing***

- Eric Nelson (NTIA/ITS)—moderator
- Paul Black (NIST/ITL)
- Pierre de Vries (Silicon Flatirons)
- Rashmi Doshi (FCC/OET)
- Tom Kidd (Navy)
- Bill Lehr (MIT)
- John Stine (Mitre)

APPENDIX B: SESSION PLANS

Session plans (provided in this appendix) were developed by the session chairs, in collaboration with conference chairs, and provided to panelists for preparation material.

B.1 Overview Panel

Goal: To provide high-level discussion amongst a diverse set of perspectives on the political pressure to find 500 MHz for fixed and mobile broadband and what the means for radar. This panel will discuss NTIA's plan to make the 500 MHz available, budgetary constraints, institutional obstacles, incentives, collaboration between the private and public sector, and sharing radar bands with the commercial sector.

Agenda:

10:00—10:10	*Session Overview*—Michael Calabrese (New America, moderator)
10:10—10:18	*Searching for 500 MHz Considering Radar Bands*—Karl Nebbia (NTIA)
10:18—10:26	*Naval Research Laboratory Perspective on Radar Spectrum and Usage*—Eric Mokole (NRL)
10:26—10:34	*Incentives to Promote more Efficient use of the Spectrum*—Dale Hatfield (Silicon Flatirons)
10:34—10:42	*Investment to Modernize Radar Technologies*—Richard Reaser (Raytheon)
10:42—10:50	*Sharing with Radar Bands*—Mary Brown (Cisco)
10:50—10:58	*Radar R&D*—Joe Guerci (Guerci Consulting)
10:58—11:06	*Active Accommodation of Radar Bandsharing*—Paul Kolodzy (Kolodzy Consulting)
11:06—11:45	*Moderated Panel Discussion*
11:45—12:00	*Audience Q&A*

Structure for Moderated Discussion/Examples Questions:

References: [1], [2], [3], [4], [5], [6], [7], [33], [34]

- There is mounting budgetary and political pressure to free up 500 MHz and auction as much as possible. For example, Senate Commerce recently reported out S.911, which requires that the radar band at 3550–3650 (minus exclusion zones) be auctioned within 3 years unless the President provides equally valuable Federal spectrum in its place. How feasible is this? What are the implications for radar bands more generally?
- NTIA's "fast track" analysis proposes reallocation of 3550–3650 subject to geographic exclusion zones. Is this generally the most efficient way to make unused radar band capacity available to the private sector? Private sector access to the 5 GHz radar bands is done very

differently—by means of dynamic frequency selection to avoid causing co-channel interference. Is this a viable model for radar bandsharing?

- What incentives can be used to improve radar spectrum efficiency, conservation and sharing? Clearly there are costs for R&D, planning, retrofitting—perhaps even new systems—that may or may not advance the DOD's mission. How can we pay for this?
- Last year at ISART we heard that "trust" was a big hurdle in making Federal users—especially those with national security and public safety missions—willing to share unused capacity. What technologies or techniques could satisfy the trust factor? What about real-time databases that enable preemption and firmware upgrades? What about sensing? Can that be sufficient by itself, or only in tandem with other safeguards? What types of regulatory changes or standard setting initiatives are needed to promote harmonious coexistence in radar bands?
- Radar is a critical element to defense and public safety with a voracious appetite for spectrum. They are expensive systems with relatively long life cycles; hence, future radar developments must address both long-term budget and spectrum constraints. Spectrum policy makers, in particular, need to understand the long-term cost/benefit analyses related to (1) sharing radar bands with the commercial sector, (2) radar upgrades to clean-up transmitted signals, and (3) transitions to more adaptable, cognitive, less susceptible, and consolidated radar systems. How can radar community prioritize R&D to address spectrum conservation and sharing? What incentives can be used to improve radar spectrum efficiency and conservation? Should radar spectrum be shared with the commercial sector? What types of regulatory reform are needed to promote harmonious coexistence in radar bands?

B.2 International Radar Compatibility Panel

Goal: To provide an understanding of the current interference issues facing the radar community.

Agenda:

13:15—13:20	*Session Overview*—John Mettrop (UK CAA)
13:20—13:25	*International Regulatory Framework*—John Mettrop (UK CAA)
13:25—13:32	*Adjacent-Band Broadband Compatibility around 3 GHz*—John Mettrop (UK CAA)
13:32—13:39	*NBP Fast Track Issues at 3 GHz*—Joe Hersey (U.S.CG)
13:39—13:46	*RNSS vs. Radars in 1215–1300 MHz Frequency Band*—David Choi (MITRE)
13:46—13:53	*Co-Channel DFS at 5 GHz*—Chris Tourigny (FAA)
13:53—14:00	*HF & 5 GHz Radar Compatibility Issues in Korea*—Jaewoo Lim (Korea KCC/RRA)
14:00—14:07	*NATO Technical Committee to Improve Radar Compatibility*—Larry Cohen (NRL)
14:07—14:45	*Moderated Panel Discussion*

14:45—15:00 *Audience Q&A*

Structure for Moderated Discussion/Examples Questions:

References: [35], [36], [37], [38], [39], [40], [41], [42]

- Overall the goal is to inform the audience of the regulatory regime, the current compatibility issues being faced and get them to think about how we can be smarter in the future to ensure that we face less of these problems in the future.
- Brief on the current compatibility issues focusing on:
  - The type of interference
  - What needs to be done to resolve the issue
  - Implications for users if it is not resolved
- Start the Debate with the a number of questions along the lines:
  - Why where the issues either not identified or mitigation techniques implemented prior to the deployment of the interfering systems?
  - Who is at fault and who should pay for the remediation work (Radar manufacturers, Government, Users, or the new service)?
  - How do we avoid similar situations in the future? Will better design or improved definition of performance help?

B.3 Radar R&D Panel

Goal: To discuss a technological roadmap to next generation radar that achieves greater utilization and leveraging of emerging radio technologies.

Agenda:

15:15—15:30 *Session Overview*—Joe Guerci (Guerci Consulting)

15:30—15:38 *Spatio-Temporal Waveform Agility and Adaptive Antennas*—William Melvin (GTRI/SEAL)

13:25—13:32 *Simultaneously Reconfigurable RF Circuitry and Optimizable Waveforms to Meet Spectral Mask Requirements and Maximize Power Efficiency*—Charles Baylis (Baylor)

13:32—13:39 *Multifunction Phased Array Radar (MPAR)*—John Cho (Lincoln Laboratory)

13:39—13:46 *Contrasts in Spectrum Sharing Between Radar and Communications Bands*—Preston Marshall (U.S.C)

13:46—13:53 *Cognition Technologies*—Joseph Mitola (Stevens)

14:07—14:45 *Moderated Panel Discussion*

14:45—15:00 *Audience Q&A*

Structure for Moderated Discussion/Examples Questions:

References: [43], [44], [45], [50], [45], [14]

- In the Overview, Joe will establish the challenges/constraints that currently exist for radar and an overview of relevant R&D areas.
- Panelist opening remarks will drill down into specific areas.
- Moderated discussion will drill out to identify steps/technologies to solve the spectrum shortage/crowding problem. Examples of questions from the moderator might include
    - In “peacekeeping” operations (which we are usually involved in for years), it seems perfectly reasonable that a “cooperative” approach could play a major role (as opposed to operating passively). How might radars be engineered in this “cooperative” environment?
    - Many recent advances in radar are due in large part to leveraging commercial RF markets, such as low cost T/R modules, and MMICs. How might the radar community increase this leverage in the future? How might the radar community “influence” the commercial RF market?
    - The pace of innovation seems greatest in “smaller” radars, such as those designed for UAV operations, etc. How might “large” radar systems benefit from the plurality of innovations occurring with smaller systems? Should the major radar primes have a more active role in “small” radars? Thereby facilitating transition?
    - If a more collaborative design environment is required in the future, how can military radars preserve essential security? Can this be accomplished with encryption and anti-tamper concepts alone?

B.4 Sharing Radar Bands with Commercial Systems Panel

Goal: To explore the possibilities and make the case for sharing radar bands with commercial systems.

Agenda:

8:00—8:15	*Session Overview*—Julius Knapp (FCC/OET)
8:15—8:23	*Cost/Benefits in Sharing Radar Bands?*—Robert Matheson (retired NTIA/ITS)
8:23—8:31	*WISPA Perspective on Sharing Radar Bands with Commercial Systems*—Jack Unger (WISPA)
8:31—8:39	*Operation of Wireless Broadband Services in the Band 3550–3650 MHz Identified Under the NTIA Fast-Track Evaluation*—Clem Fisher (Motorola Solutions)
8:47—8:55	*Transferring TV Whitespace Sharing Concepts to Radar*—Rohan Murty (Harvard/MIT)—could not attend due to last-minute health issue

8:55—9:03 *Implanted Medical Devices Sharing the Radar Band*—Glen Griffith (Alfred Mann)

9:03—9:11 *Incumbent Spectrum Users' Dynamic Spectrum Access Requirements*—Mark McHenry (Shared Spectrum)

9:11—9:45 *Moderated Panel Discussion*

9:45—10:00 *Audience Q&A*

Structure for Moderated Discussion/Examples Questions:

References: [54], [55], [56], [57], [58], [59], [60], [61], [62], [63], [64]

- When we think about sharing with radars, what package of techniques or approaches would be most appropriate?
- What radar bands look most promising for sharing and why?
- What do you feel are the greatest challenges to sharing with radars?
- Given that many radars seek to operate at the farthest possible range, what sorts of criteria would be appropriate for interference protection of radars?
- How might the sharing constrain future changes in the radar? Would there be a need to bound the extent to which the radar can change?
- What sorts of criteria should be considered when deciding whether a service that is sharing spectrum with radars should be licensed or unlicensed?
- How are the technologies and techniques developed for TV whitespaces potentially applicable to sharing spectrum with radars?
- What would you do differently from 5 GHz relative to sharing with radars generally?
- (Bob Matheson) Would the concept of a protected service area listed in a data base work for most radars?
- (Jack Unger) What concerns do users or network operators have relative to being listed in a data base?
- (Jack Unger) How can we assure that users would participate in the data base?
- (Clem Fisher) What is your sense of the utility of the 3550–3650 MHz spectrum (which was identified in the NTIA Fast Track report based on exclusion zones along most of the U.S. coast)?
- (Clem Fisher) Are there techniques that would allow wireless operations to continue in some fashion in the exclusions zones? Even when shipborne radars are present?
- (Jon Peha) Have any field studies been done using the techniques you describe?
- (Jon Peha) How would the rotational aspect of a radar affect potential throughput as compared to unencumbered spectrum?

- (Jon Peha) Would you need to know anything about the radar antenna characteristics such as backlobes and sidelobes to avoid causing harmful interference to the radar?
- (Rohan Murty) Is spectrum sensing a help or a hindrance to sharing?
- (Glen Griffith) What were the tradeoffs in determining the sensing levels for sharing at 420–450 MHz—or as Goldilocks would say, how did you decide what was too hot, too cold, or “just right”?
- (Mark McHenry) How would you approach sharing with radars any differently than sharing with other services?

B.5 Regulatory Reform to Facilitate Spectrum Sharing

Goal: Describe a roadmap for DSA deployment with practical first steps to advance both the development of new technology and new regulatory approaches.

Agenda:

10:15—10:20	*Session Overview*—Eric Nelson (NTIA/ITS)
10:20—10:30	*FCC Perspective on DSA Regulations*– Rashmi Doshi (FCC/OET)
10:30—10:35	*Spectrum Sharing in Radar Bands: An Economic Perspective*—William Lehr (MIT)
10:35—10:40	*Resilience Principles*—Pierre de Vries (Silicon Flatirons)
10:40—10:45	*Model-Based Spectrum Management*—John Stine (MITRE)
10:45—10:50	*Building Trust in Software*—Paul Black (NIST/ITL)
10:50—10:55	Federal Agency Perspective on DSA Regulations—Tom Kidd (Navy)
10:55—11:30	*Moderated Panel Discussion*
11:30—12:00	*Audience Q&A*

Structure for Moderated Discussion/Examples Questions:

References: [66], [69], [67], [71], [66]

- The dialog will follow this thread:
  - Explore lessons learned in the Sharing Radar Bands with Commercial Systems panel and identify needs of future technology and regulatory processes
  - Explore a set of tools (whitespaces, time-limited leases, model-based spectrum management) that can be applied to the problem. In particular, identify incremental steps that will build trust. Describe necessary first steps that we can act upon.

- Proactively address system management and enforcement requirements, i.e. the necessary technologies and processes to manage the DSA rollout.
- Discuss ways to bound the conformity assessment problem to converge upon the necessary and sufficient test requirements. Define a reasonable problem space working from broad expectations to component tests to critical use cases.

- Questions:
  - What would you say are the strengths and weaknesses of each other's proposals?
  - Think a few years ahead. DSA systems have been deployed and despite our best efforts harmful interference occurs. We've incorporated your various recommendations into the rules, our processes and the equipment itself, so were prepared for this eventuality. Describe for the audience how the various stakeholders: certification bodies, and enforcement agents, incumbents, DSA equipment manufacturers and operators would go about identifying and resolving interference? (How would this differ from the DFS experience?)
  - Our rules are based on incomplete models. For example, DFS models overlooked the need for out-of-band sensing to address the possibility of harmful OOBE. With the multitude of models encompassed in model based spectrum management, DFS-like oversights are inevitable. How do we proactively identify and correct these deficiencies before harmful interference occurs?
  - You are drafting the NPRM for DSA, assuming an incremental approach to DSA deployment, what overarching principles, features and characteristics would you incorporate in the first iteration of the rules?
  - Besides the NPRM, what recommendations would you give NTIA and the FCC to prepare for conformity assessment, product surveillance and enforcement? Please frame these as action items with specific recommendations. Who are the key stakeholders and what are the best mechanisms and venues to address these questions?
  - The FCC has done of lot of heavy lifting over the last several years serving as the sole authority for DFS device testing. This model is simply untenable in a DSA environment considering the anticipated number and complexity of new devices. How do we prepare for timely conformity assessment of DSA equipment? What principles and practices can we use to reduce the problem space?
  - Successful implementation of new spectrum sharing approaches is predicated on trust—in both the performance of the underlying technologies and the integrity of the governing regulatory processes. We can't innovate without risk, but improperly managed risk threatens trust. How can we progressively build trust and expand DSA capabilities while limiting risk to incumbent system operators?
  - When we encountered interference problems with DFS, the FCC curtailed all device certification. Similar interference issues with DSA are inevitable. Equipment manufacturers and service providers who extrapolate from the DFS experience see uncertainty about equipment certification. Similarly, incumbents worry about the lack of resources to address interference problems. How do we address both group's risk?

- In the previous panel we learned that about 70% of the reported incidents with UNII devices were caused by bad actors either defeating the DFS detect and avoid function or reprogramming non-UNII devices to operate in the TDWR band. We can't eliminate tampering, but what can we do to make it easier to control and police it?
- Model-Based Spectrum Management provides a formal construct for documenting equipment characteristics and automating compatibility studies, but we are years away from characterizing all of the necessary transmitter properties and interference protection criteria. How do we roll out this method?

APPENDIX C: SPEAKER BIOGRAPHIES

Charles Baylis (Assistant Professor, Baylor University, Electrical and Computer Engineering, WMCS) Dr. Baylis directs the Wireless and Microwave Circuits and Systems Program with Dr. Randall Jean. Baylis is presently performing research in the real-time optimization of radar waveforms and RF circuitry for linearity and efficiency in radar transmitters. He has authored several papers related to his areas of expertise. He received his B.S., M.S., and Ph.D. from the University of South Florida in 2002, 2004, and 2007, respectively.

Paul E. Black (Computer Scientist, NIST/ITL) Dr. Black has nearly 20 years of industrial experience in developing software for IC design and verification, assuring software quality, and managing business data processing. He is now a Computer Scientist for NIST in the Information Technology Laboratory. He has taught at Brigham Young University and Johns Hopkins University. Black has published in the areas of static analysis, software testing, software configuration control, networks and queuing analysis, formal methods, software verification, quantum computing, and computer forensics. He is a member of ACM, IEEE, and the IEEE Computer Society. He has a B.S. in Physics and Mathematics and an M.S. in Computer Science and earned a Ph.D. from Brigham Young University in 1998.

Mary L. Brown (Director Technology and Spectrum Policy, Cisco Systems, Inc., Government Affairs) Dr. Brown covers a wide range of issues for Cisco related to IP-based technologies, wireless and networking. During her career, she has worked as a consultant, as in-house regulatory counsel for a major carrier, and for approximately 10 years as a staff lawyer and manager at the FCC. In addition to telecommunications issues, she has substantial experience in Internet law and policy. Brown holds a J.D. with honors from the Syracuse College of Law, and an M.S. in Telecommunications from the S.I. Newhouse School of Public Communications at Syracuse. She is a Phi Beta Kappa graduate of the University of Massachusetts at Amherst.

Michael Calabrese (Senior Research Fellow, New America Foundation) As a Senior Research Fellow with New America's Open Technology Initiative, Calabrese focuses on developing and advocating policies to promote pervasive connectivity, including spectrum policy reform, wireless broadband deployment and IT investment and innovation more broadly. The founding director of New America's Wireless Future program, Calabrese also served as Vice President (2003–2010) and was instrumental in establishing the organization's programs in areas including retirement security, health policy and the Next Social Contract Initiative. Previously, Calabrese served as General Counsel of the Congressional Joint Economic Committee, as Director of Domestic Policy Programs at the Center for National Policy, and as pension and employee benefits counsel at the national AFL-CIO. An attorney and graduate of both Stanford Business and Law Schools, Calabrese speaks and writes frequently on issues related to spectrum, wireless broadband, and Internet policy, as well as on Next Social Contract issues related to improving retirement security and health coverage. He has co-authored three books and published opinion articles in The New York Times, The Washington Post, The Atlantic Monthly and other leading outlets.

John Cho (Technical Staff, MIT Lincoln Laboratory, Weather Sensing Group) Dr. Cho is the technical lead on meteorological radar projects at MIT Lincoln Laboratory. Before joining the Laboratory, he was a research scientist in the Department of Earth, Atmospheric, and Planetary Sciences at MIT, following a stint as a staff scientist at the National Astronomy and Ionosphere Center's Arecibo Observatory in Puerto Rico. He has also been a visiting scientist at the Leibniz Institute for Atmospheric Physics in Germany. Cho has 45 refereed publications in the fields of atmospheric radar, waves and turbulence, noctilucent clouds, meteors, and air traffic management. He received a 2011 R&D 100 Award for work on the Multifunction Phased Array Radar (MPAR), a 1996 Young Scientist Award from the International Union of Radio Science, and the 1993 CEDAR Prize from the National Science Foundation. He holds B.S. and M.S. degrees from Stanford University, and a Ph.D. from Cornell University, all in EE. He also served with the U.S. Peace Corps in Sierra Leone (1986–1988).

David S. Choi (Principal Sensors Systems Engineer, The MITRE Corporation, Spectrum/E3 Group) Dr. Choi joined MITRE in April 2006. Presently, Choi serves as the group leader for Spectrum/E3 group at MITRE C2C, and works on a number of domestic and international spectrum related projects. Before joining MITRE, he served for over 16 years as an Electronics Engineer at the Air Force Research Laboratory, where he worked on a number of R&D topics including Advanced OTH radar, UHF RCS characterization, and UHF DBF. Choi has a Ph.D. in EE from Tufts University, Medford, MA and B.S. and M.S. in EE from University of Massachusetts, Amherst, MA.

Lawrence Cohen (Naval Research Laboratory, Radar Division) Cohen has been involved in electromagnetic compatibility (EMC) engineering and management, shipboard antenna integration and radar system design for 32 years. In this capacity Cohen has worked in the areas of shipboard electromagnetic interference (EMI) problem identification, quantification and resolution, mode-stirred chamber research and radar absorption material (RAM) design, test and integration. For the past 23 years Cohen has been employed by the Naval Research Laboratory in Washington, DC. In 2007, Cohen was the Navy's Principal Investigator in the assessment of AN/SPY-1 radar emissions on a WiMAX network. Additionally, he has acted as the Principal Investigator for various radar programs, including the AN/SPQ-9B transmitter upgrade. Currently, Cohen is involved with identifying and solving spectrum conflicts between radar and wireless systems as well as research into spectrally cleaner power amplifier designs. He served as the Technical Program Chairman for the IEEE 2000 International Symposium on EMC and was elected to the IEEE EMC Society Board of Directors in 1999 and 2009. Cohen is also Secretary of the IEEE EMC Society Technical Committee 6 (TC-6) for Spectrum Management. He received a B.S in EE from The George Washington University in 1975 and an M.S. in EE from Virginia Tech in 1994, and is certified as an EMC engineer by the National Association of Radio and Telecommunications Engineers (NARTE).

Michael G. Cotton (Electronics Engineer, DOC/NTIA/ITS, Telecommunications Theory Division) Cotton joined NTIA/ITS in 1992. At ITS, he has been involved in a broad range of research topics including applied electromagnetics, radio channel measurement and theory, interference effects on digital receivers, and noise measurement. Cotton is a project leader and has authored or co–authored over twenty technical publications. In 2002, he earned the DOC Gold Medal Award for research and engineering achievement in the development of national policies for UWB technologies. Cotton received a B.S. degree in aerospace engineering in 1992 and an M.S. degree in EE with an emphasis on electromagnetics in 1999, both from the University of Colorado at Boulder.

Michael Davis (Georgia Tech Research Institute, Sensors and Electromagnetic Applications Laboratory) Biography not available.

Pierre de Vries (Senior Adjunct Fellow, Silicon Flatirons Center for Law, Technology, and Entrepreneurship, University of Colorado) Dr. De Vries works at the intersection of information technology and government policy, researching alternative models for wireless policy and new regulatory paradigms for the Internet/web. De Vries is a Research Fellow at the Economic Policy Research Center of the University of Washington and a Senior Adjunct Fellow of the Silicon Flatirons Center at CU Boulder. He is a former Chief of Incubation and Senior Director of Advanced Technology and Policy at Microsoft Corporation. Prior to his twelve years at Microsoft, De Vries worked for Korda & Co, a London seed capital company and consultancy. De Vries holds a DPhil in theoretical physics from the University of Oxford.

David DeBoer (UC Berkeley, Astronomy) Dr. DeBoer joined Berkeley in 2010 as part of the Radio Astronomy Laboratory to develop and manage radio astronomy systems. He is currently working on experiments that attempt to measure signals from the period of the very first stars, which formed in the first billion years of the Universe—so about 12 billion light years away. Prior to joining Berkeley, DeBoer was at the Australian Commonwealth Scientific and Industrial Research Organization (CSIRO) where he led the group building a new large radio facility in the radio-quiet Australian Outback. Prior to CSIRO, DeBoer managed the construction of the Allen Telescope Array in northern California and was a professor of Electrical and Computer Engineering at the Georgia Institute of Technology. DeBoer has a Bachelor's in Astronomy and Astrophysics from Harvard University and a Ph.D. in Electrical Engineering from the Georgia Institute of Technology.

Rashmi Doshi (Chief, FCC/OET, Laboratory Division) Dr. Doshi is responsible for managing the FCC's laboratory staff in leading the evaluation of new technologies and the development of measurement procedures for RF compliance in support of the major policy initiatives at the FCC. He also manages the FCC's Equipment Authorization program including the oversight of the Telecommunications Certification Bodies in the U.S. and related conformity assessment programs. Doshi has been involved in the communications industry for over 35 years and has worked as Executive Director for Verizon (Bell Atlantic, NYNEX) and held engineering positions at Bell-Northern Research and British Telecom Research Center. He has been involved in the development of network technologies for voice, data and multi-media services. Early on he was a Research Fellow at Imperial College, University of London (England).

Clem Fisher (Motorola Solutions) Biography not available.

Marshall Greenspan (Sr. Consulting Systems Engineer, Northrop Grumman Corporation; Electronic Systems) Dr. Greenspan has nearly 50 years of experience in the design, development, and testing of advanced technology military airborne radar systems. His key radar programs have included the AN/APQ-148/156 for the Navy A-6E, the RGWS for an enhanced A-6E, the AN/APQ-176 for the Navy A-6F, the AFRL/DARPA Pave Mover program, the U.S.AF Joint STARS radar, Israel's F-4E AN/APG-76 radar, the Discoverer-II/Space Based

Radar program and several other classified national and proposed civil/commercial satellite radar sensor systems. Most recently, Greenspan has focused his technical interests on radar concepts to optimally adapt the sensor to the dynamically-changing RF environment. Greenspan is a recipient of the UTC George Mead Gold Medal for Engineering Achievement, the IEEE AESS Warren D. White award for Excellence in Radar Engineering, the Northrop Grumman Lifetime Achievement Award, and the IEEE Waveform Diversity and Design Conference Person of the Year Award. He is a Senior Member of the IEEE and a member of the AESS Radar Systems Panel, as well as a frequent author, presenter, and conference session chair at numerous national and international radar conferences. He also holds eight U.S. Patents and has been a member of several industrial, academic and government advisory boards. He received BSEE and MSEE degrees from MIT in 1962 and a Ph.D. in EE from the University of Connecticut in 1969.

Glen Griffith (Principle RF Communications Engineer, Alfred E. Mann Foundation) Griffith is currently with the Alfred Mann Foundation developing inductive coupled communication systems for implanted medical devices. Previously with the Advanced Bionics Corporation he developed similar systems for their cochlear implant devices and holds several patents in that field. He has also developed receivers and transmitters as well as digital demodulation devices for IFF (secondary surveillance radar) interrogators and transponders while with Teledyne Electronics and Litton Guidance and Controls. As Technical Director at Teledyne Electronics he was responsible for the technical oversight of the the IFF transponder developed for the B2. He was a Hughes Aircraft Master Fellow and developed several laser radar and laser target designator subsystems.

Joseph Guerci (Independent Consultant, Guerci Consulting) Dr. Guerci has over 23 years of experience in advanced technology R&D in government, industrial, and academic settings. His government service included a recent seven-year term with the Defense Advanced Research Projects Agency (DARPA) in which he held the positions of Program Manager, Deputy Office Director, and finally Office Director of the Special Projects Office. In these capacities, Guerci was involved in the inception, research, development, execution, and ultimately transition of next generation multidisciplinary defense technologies. Guerci is a recognized R&D leader in next generation sensor systems and adaptive signal processing. In particular, he has pioneered several major radar technologies including robust and knowledge-aided space-time adaptive processing (STAP), and optimal MIMO waveform design. In addition to authoring over 80 peer reviewed articles, he has two book chapters and is the author of Space-Time Adaptive Processing for Radar (Artech House, 2003). Guerci also recently received the 2007 IEEE Warren D. White Award for "Excellence in Radar Adaptive Processing and Waveform Diversity." Guerci received his B.S. in Engineering Science from City University of New York and earned M.S. and Ph.D. degrees in Systems Engineering from the Polytechnic University, NY.

Dale N. Hatfield (Senior Fellow/Adjunct Professor, University of Colorado at Boulder, Silicon Flatirons Center for Law, Technology, and Entrepreneurship, Adjunct Professor/Interdisciplinary Telecommunications Program) Prior to joining the University of Colorado, Hatfield was the Chief of the Office of Engineering and Technology at the Federal Communications Commission (FCC) and, immediately before that, he was Chief Technologist at the Agency. He retired from the FCC and government service in December 2000. Before joining the FCC in December 1997, he was Chief Executive Officer of Hatfield Associates, Inc., a Boulder, Colorado based multidisciplinary telecommunications consulting firm. Before founding the consulting firm in 1982, Hatfield was Acting Assistant Secretary of Commerce for Communications and Information and Acting Administrator of the National Telecommunications and Information Administration (NTIA). Before moving to NTIA, Hatfield was Chief of the Office of Plans and Policy at the FCC. Hatfield has nearly fifty years of experience in telecommunications policy and regulation, spectrum management and related areas. Hatfield holds a B.S. in EE from Case Institute of Technology and an M.S. in Industrial Management from Purdue University. In May, 2008, Hatfield was awarded an Honorary Doctor of Science degree by the University of Colorado for his commitment to the development of interdisciplinary telecommunications studies. Hatfield is also the Executive Director of the Broadband Internet Technical Advisory Group (BITAG) and is currently serving on the FCC's Technology Advisory Council (TAC) and on the Commerce Department's Spectrum Management Advisory Committee (CSMAC).

Joseph Hersey (U.S. Coast Guard, Spectrum Management Division) Biography not available.

Matthew Hussey (Legislative Assistant, Senator Olympia Snowe (R-Maine)) Hussey is telecommunications, commerce, science, and education advisor to Senator Snowe (R–Maine). Hussey deals with a wide range of telecommunications and media issues including the DTV transition, cyber security, Internet governance, media ownership, Universal Service, spectrum policy, and network neutrality. Prior to working in the Senate, Hussey was the Telecommunications & IT Task Force Director for the American Legislative Exchange Council (ALEC), a nonpartisan membership organization of state legislators. There he was responsible for educating and advising state legislators and private sector leaders on telecommunications and IT issues as well as working with members to develop model legislation. Before joining ALEC, Hussey worked for over eight years in the telecommunications industry, most recently for Verizon Communications. There he worked in network architecture and planning, sales & marketing, and business development. Prior to that, he spent several years in the cable industry where he held product development and engineering positions for broadband services. Hussey has a B.S. in EE from Georgia Tech, and an M.B.A. from the University of Maryland.

Tom Kidd (Director of Strategic Spectrum Policy, Department of the Navy) Kidd develops strategic policies for using electromagnetic spectrum to ensure that the Navy and Marine Corps can access wireless communications at sea and on missions worldwide. He is a representative to the IRAC and served as a delegate to the ITU World Radiocommunication Conference in 2007. Kidd entered the Air Force in 1978 at Ellsworth Air Force Base in South Dakota, and is a 1991 graduate of the Interservice Radio Frequency Management School at Keesler AFB, Mississippi. He has worked exclusively in Communications Electronics since 1985 and served as Contingency/War Planner Radio Frequency Spectrum Manager for Headquarters 12th Air Force, Headquarters U.S. Air Forces Korea, and the Air Force Frequency Management Agency (AFFMA). After retiring from active duty in 1998, he served with the Naval Electromagnetic Spectrum Center (NAVEMSCEN) and Naval Base Ventura County (NBVC). In 2005 he returned to Washington D.C. to serve as senior advisor to the Department of the Navy Chief Information Officer (DONCIO) on matters related to the electromagnetic spectrum. Kidd serves as the DON representative to the IRAC and DON member of the DOD Spectrum Management Review Group (SMRG). In 2007, he was a United Nations Delegate to the International Telecommunications Union (ITU) World Radiocommunication Conference (WRC). He is also a regular contributor to Chips Magazine, author of the recurring column "Full Spectrum," and a winner of Federal Computer Week's 2010 Federal 100 award.

Julius Knapp (Chief, FCC/OET) Knapp has been with the FCC for 35 years. He became Chief of OET in 2006, having previously served as the Deputy Chief since 2002. OET is the FCC's primary resource for engineering expertise, provides technical support to the Chairman, Commissioners and FCC Bureaus and Offices, and serves as the FCC's lead office for coordinating FCC spectrum management matters with the Federal government and the IRAC. OET is also responsible for spectrum allocations, technical rules for radio equipment and unlicensed devices, experimental licensing, equipment authorization and technical analyses. Prior to 2002, Knapp was Chief of the Policy and Rules Division where he was responsible for FCC frequency allocation proceedings and for proceedings amending the FCC rules for radio frequency devices. From 1994 to 1997, he was Chief of the FCC Laboratory, where he was responsible for the FCC's equipment authorization program and technical analyses. Knapp received a B.S. in EE from the City College of New York in 1974. He is a member of the IEEE EMC Society and a Fellow of the Radio Club of America. He was the 2001 recipient of the Eugene C. Bowler award for exceptional professionalism and dedication to public service and has received the FCC's Silver and Gold medal awards for distinguished service.

Paul Kolodzy (Wireless Consultant, Kolodzy Consulting) Dr. Kolodzy has 25 years of experience in technology development for advanced communications, networking, electronic warfare, and spectrum policy for government, commercial, and academic clients. He is currently a communications technology consultant in advanced wireless and networking technology based near Washington DC. Current areas include advanced technology development for communications, electronic warfare, and ISR with DARPA; the radio and policy for broadband radio access; 700 MHz commercial and public safety spectrum policy and interference mitigation technology; Advanced Wireless Service (AWS); TDD/FDD Coexistence; Fourth Generation (4G) radio technology inclusive of intelligent antenna; and adaptive spectrum resource allocation. He is active in technology development for wireless components and new wireless networks and architectures as well as spectrum policy as impacted by new technology. Prior to being a consultant, Kolodzy has been: at Stevens Institute of Technology; during 2002, the Senior Spectrum Policy Advisor at the Federal Communications Commission (FCC) and Director of Spectrum Policy Task Force; Program Manager at the Defense Advanced Projects Agency (DARPA); Director at Sanders, A Lockheed Martin Company; and a Group Leader/Staff Member at MIT Lincoln Laboratory.

William Lehr (Economist/Professor, Massachusetts Institute of Technology, Communications Futures Program) Dr. Lehr is a research associate in the Computer Science and Artificial Intelligence Laboratory (CSAIL) at MIT, currently working with the Communications Futures Program, an industry–academic multidisciplinary research effort focused on road-mapping the communications value chain. Previously, Lehr was the associate director of the MIT Research Program on Internet & Telecoms Convergence, and an associate research scholar and assistant professor on the faculty of Columbia University's Graduate School of Business. Lehr's research focuses on the economics and regulatory policy of the Internet infrastructure industries. He teaches courses on the economics, business strategy, and public policy issues facing telecommunications, Internet, and eCommerce companies, and is a frequent speaker at international industry and academic conferences. He has published articles on such topics as the impact of the Internet on the structure of the communications infrastructure industries, telecommunications regulation, and the pricing of Internet services. He is currently engaged in research on the convergence of the Internet and telecommunication services and the implications for corporate strategy and public policy. In addition to his academic research, Lehr provides litigation, economic, and business strategy consulting services for firms in the information technology industries. Lehr has advised information technology companies on strategic marketing, pricing, financial planning, and competitive strategy; and government agencies in the U.S. and abroad on telecommunications policy matters. Lehr has prepared expert witness testimony both for private litigation and for regulatory proceedings before the FCC and numerous state commissions. Lehr holds a Ph.D. in Economics from Stanford (1992), an M.B.A. from the Wharton Graduate School (1985), and M.S.E. (1984), B.S. (1979) and B.A. (1979) degrees from the University of Pennsylvania.

Jaewoo Lim (Korean Communications Commission, Radio Research Agency) Jaewoo Lim joined the Radio Research Agency/Korea Communication Commission in 1997. He has served for 14 years as a researcher in the Radio Resource Developmant Division, developing IMT-2000, 5GHz RLAN and 2.3GHz mobile WiMax spectrum technology and regulations, including work on interference issues. Lim works on a number of international spectrum issues and participates in the World Radio Conference of ITU. He also works on a number of domestic interference issues with regard to the terrestrial radio service. Presently, he serves in the Regulation Research Division and develops technical regulations for approval of radio equipment in Korea. Lim has a Ph.D. in EE from Yonsei University, Seoul, Korea.

Preston Marshall (Director, University of Southern California, Information Science Institute) At USC's Viterbi School of Engineering, Dr. Marshall leads research programs in wireless, networking, cognitive radio, alternative computing, and related technology research. Marshall has thirty years of experience in networking, communications, and related hardware and software research and development. For most of the last decade, he has been at the center of cognitive radio research, including seven years as a Program Manager for DARPA, where he led key cognitive radio and networking programs, including the neXt Generation Communications (XG) program, Disruption and Delay Tolerant Networking (DTN), Sensor Networking, Analog Logic, and the Wireless Network After Next (WNaN) program. These programs demonstrated the viability of key aspects of cognitive radio technology, including DSA, adaptive wireless networking, content–based networks, and low cost, multi–transceiver adaptive networking, and probabilistic models of signal processing. He has numerous published works, and has many appearances as invited or keynote speaker at major technical conferences related to wireless communications. He is the author of Quantitative Analysis of Cognitive Radio and Network Performance (Artech House, 2010). He was awarded the SDR Forum's 2007 Annual Achievement award, the Defense Superior Service Award in 2008, has been a guest editor for IEEE Proceedings, and chairs the Steering Committee for the IEEE DYSPAN Conference. Marshall holds a Ph.D. in EE from Trinity College, Dublin, and a B.S. in EE and M.S. in Information Sciences from Lehigh University, PA.

Robert J. Matheson (Retired Electronics Engineer, DOC/NTIA/ITS) Matheson served with the NTIA/ITS and its predecessor agencies within the DOC from 1957 to 2008, and was the lead engineer when NTIA began to monitor the Federal use of the radio spectrum in 1972. He was instrumental in developing the highly automated mobile Radio Spectrum Measurement System

(RSMS), which made extensive measurements of aggregate signals in Federal radio bands, as well as detailed technical measurements on a wide variety of Federal systems, and resolved numerous EMC/interference problems. He was awarded a 1986 DOC Silver Medal for his work with the RSMS. From 1988 to 1991, Matheson served as deputy director of ITS and directed the work of the Spectrum Division. Since 1991, he has been working on technical spectrum use issues, and has published papers on spectrum efficiency, projections of spectrum requirements, technology forecasting, and spectrum property rights. A recent internal paper examined spectrum property rights with respect to prospective rules needed to permit very flexible use of radio frequencies. His most recent report, "Spectrum Usage for the Fixed Services," details the present U.S. use of some 30 fixed services microwave bands and predicts their future growth rates. Matheson attended the University of Colorado and received a B.A. in physics in 1961 and an M.S. in EE in 1968.

Mark McHenry (President and CTO, Shared Spectrum Company) Dr. McHenry founded Shared Spectrum Company in 2000 and is the President and CTO. He has 22 years of experience as an innovative engineer. McHenry was awarded the 2006 Engineer of the Year Award by the D.C. Area Council of Engineering and Architectural Studies and is a member of the DOC Spectrum Management Advisory Committee. McHenry has extensive experience in military and commercial communication systems design, and was a co–founder of San Diego Research Center, Inc., a wireless research and development company. Previously he was a Program Manager at DARPA, where he managed multiple programs. He has worked as an Engineer at SRI International, Northrop Advanced Systems, McDonnell Douglas Astronautics, Hughes Aircraft and Ford Aerospace. He received the Office of Secretary of Defense Award for Outstanding Achievement in 1997 and the Office of Secretary of Defense Award for Exceptional Public Service Award in 2000. He has multiple RF technology related patents.

William Melvin (Director, Georgia Tech Research Institute, Sensors and Electromagnetic Applications Laboratory) Dr. Melvin joined the research staff of the Georgia Tech Research Institute (GTRI) in 1998 as a Research Engineer II and is presently director of the Sensors and Electromagnetic Applications Laboratory (SEAL). Prior to joining the staff at GTRI, he served as Captain in the U.S. Air Force at the Rome Laboratory, currently reorganized under the Air Force Research Laboratory (AFRL). His work within the Signal Processing Branch of the U.S.AF Rome Laboratory involved space-time adaptive filtering and detection methods for improved performance of airborne surveillance radar. This work included extensive analysis of measured multichannel airborne radar data, as well as analysis of Airborne Warning and Control System (AWACS) data and the development of adaptive filtering methods for Airborne Early Warning radar. He remains a reserve captain in the U.S.AF through the Individual Mobilization Augmentee (IMA) program, attached to the AFRL, Sensors Directorate, Wright-Patterson Air Force Base. Melvin earned B.S., M.S., and Ph.D. degrees in EE from Lehigh University.

John Mettrop (Spectrum Manager, Civil Aviation Authority) Mettrop is a chartered Engineer with over 23 years of experience in the field of civil aviation, having joined the UK Civil Aviation Authority directly from University. Having initially worked on a new military operations room at the London ATC Centre and then in the communications department as the microwave radio link design authority, he has now worked for over 19 years in the Surveillance and Spectrum Management section as the technical manager. His responsibilities cover technical policy and spectrum management issues both nationally and internationally, providing aeronautical support to UK delegations at international spectrum related meetings on issues related to aeronautical communication, navigation and surveillance systems. Through his pro-active participation he has been asked to chair various groups within International Civil Aviation Organization, currently is the chairman on Working Party 5B in the ITU (the group responsible for aeronautical, maritime and radio-determination systems and will be a Committee chair at the forthcoming World Radiocommunication Conference.

Joseph Mitola III (Distinguished Professor and Vice President for the Research Enterprise; Stevens Institute of Technology, Systems and Enterprises) Recognized globally as the father of software radio and cognitive radio, Dr. Mitola's research interests focus on trustable, teachable cognitive systems including socio-technical systems, nano-enabled medical systems, multifunction trustable agile RF systems, and mathematically secure computing and communications. Previously, he was the Chief Scientist of the DOD Federally Funded Research and Development Center for The MITRE Corporation; Joint Special Assistant to the Director of the U.S. Defense Advanced Research Projects Agency (DARPA) and to the Deputy Director of the U.S. National Security Agency (NSA) for trustable cognitive systems; DARPA Program Manager; Technical Advisor to the Executive Office of the President of the United States; and Technical Director of Modeling and Simulation for DOD. He has also held positions of technical leadership with E-Systems, Harris Corporation, Advanced Decision Systems, and ITT Corporation. Mitola began his career as an engineering student assistant with DOD in 1967. His graduate text books include Software Radio Architecture (Wiley 2000) and Cognitive Radio Architecture (Wiley, 2006). Mitola received the B.S. degree in EE from Northeastern University, Boston, MA, in 1971, the M.S.E. degree from The Johns Hopkins University, Baltimore, MD, in 1974, and the Licentiate (1999) and doctorate degrees in teleinformatics from KTH, The Royal Institute of Technology, Stockholm, Sweden, in 1999 and 2000, respectively. Mitola is a Fellow of the IEEE.

Eric Mokole (Supervisory Electronics Engineer, Naval Research Laboratory, Radar Division, Surveillance Technology Branch) Dr. Mokole has nearly 30 years of experience in conducting and leading radar-related research and development. Since 1986, he has been employed in various roles by the Radar Division of the Naval Research Laboratory. He has directed and conducted system analyses and basic/applied research on space, shipboard, and ultrawideband radars. These efforts have involved radar waveform design, radar spectrum use, system simulation/modeling, RF propagation aboard naval ships, tropospheric/ionospheric propagation, pulsed propagation for dispersive media, RF scattering from sea and land, and antenna theory. He has over 70 conference/journal articles, book chapters, and reports and is co-editor/co-author of four books (Ultra-Wideband, Short-Pulse Electromagnetics 6,7; Physics of Multiantenna Systems and Broadband Processing; and Principles of Waveform Diversity and Design). Professional activities include: Fellow IEEE; IEEE AES Radar Systems Panel (2006–present); Government Liaison to U.S.NC-URSI (2009–2011); Committee Member of MSS National Symposia (2007–present); U.S. Member (2006–present), Vice Chair (2009–2011), and Chair (2011–2013) of NATO's Sensors and Electronics Technology Panel; U.S. Navy Lead for MSS Tri-Service Radar Symposia (2005–present); Panel Member and Subject Matter Expert of OSD's Radar Spectrum and Technology Working Group (2004–2005); Founding Member of Tri-Service Waveform Diversity Working Group (2002–present); AMEREM/EUROEM High-Power Electromagnetics Committee (2002–present). Mokole received a Ph.D. in mathematics from the Georgia Institute of Technology in 1982.

Karl Nebbia (Associate Administrator, DOC/NTIA/OSM) Nebbia leads spectrum management for the executive branch agencies and manages engineering, frequency assignment, IT, policy, emergency planning and, strategic planning functions. Recent efforts have focused on President Obama's call to identify within 10 years 500 megahertz for wireless broadband. Previously, he served as the Deputy Associate Administrator for Domestic Spectrum Management, acting as the focal point for development of domestic policy and coordination of spectrum issues with the FCC. In this capacity, he also chaired the Interdepartment Radio Advisory Committee (IRAC), an advisory committee with radio spectrum managers from 19 executive branch agencies. The longest standing Federal advisory committee in the United States, the IRAC serves as the primary mechanism for frequency coordination among U.S. government users. Nebbia also has extensive international experience as the program manager coordinating the participation of NTIA staff and the U.S. Federal agencies in international spectrum management fora, particularly International Telecommunication Union (ITU) activities such as the ITU Plenipotentiary and Council, the ITU-R study groups, the Radio Advisory Group, the Radiocommunication Assembly, World Radiocommunication Conference (WRC), and ITU Development Sector regarding spectrum management. A 1974 graduate of the U.S. Naval Academy, Nebbia joined NTIA in 1983.

Eric Nelson (Supervisory Electronics Engineer, Spectrum and Propagation Measurements Division, DOC/NTIA/ITS) Nelson has held systems engineering and supervisory positions in metropolitan, rural, and airborne cellular companies. He joined ITS in 2002 and became involved in Project 25 digital land mobile radio (LMR) standards development with TIA. He helped develop the Public Safety Communications Research laboratory's LMR testing capability and spearheaded the formation of a conformity assessment program to evaluate conformance, performance, and interoperability of Project 25 equipment. He currently leads the Spectrum and Propagation Measurements Division at the Institute and oversees testing for NTIA's Spectrum Sharing Innovation Test Bed pilot program, which is evaluating dynamic spectrum access devices' ability to opportunistically share vacant spectrum in the UHF LMR bands. Nelson received his M.S. in EE from the University of Washington in 1993.

Jon Peha (Full Professor, Carnegie Mellon University) Dr. Peha has been on leave from 2008 to 2011 to serve in government, first as Chief Technologist of the Federal Communications Commission, and then Assistant Director of the White House Office of Science & Technology Policy where he focused on Communications and Research (including creation of the Wireless Spectrum Research & Development Committee). At Carnegie Mellon, he was a Professor in the Dept. of Engineering & Public Policy and the Dept. of Electrical & Computer Engineering, and Associate Director of the Center for Wireless & Broadband Networking. He has been Chief Technical Officer of three high-tech start-ups, and a member of technical staff at SRI International, AT&T Bell Laboratories, and Microsoft. He has addressed telecom and e-commerce on legislative staff in the House Energy & Commerce Committee and the Senate, and helped launch and lead a U.S. Government interagency program to assist developing countries with information infrastructure. Peha consults for industry and government agencies around the world. His research spans technical and policy issues of information networks, including spectrum management, broadband, wireless, video and voice over IP, communications for emergency responders, universal service, dissemination of copyrighted material, e-commerce, and network security.

Thomas C. Power (Chief of Staff, DOC/NTIA) Power joined NTIA in April 2009 after serving for nine years as General Counsel of Fiberlink Communications in Blue Bell, PA. From 1994 to 2000, he worked at the Federal Communications Commission in Washington, D.C. At the FCC, Power initially served in supervisory roles in both the Cable Services Bureau and the Common Carrier Bureau. In 1997, FCC Chairman William Kennard selected Power to serve as his Legal Adviser, advising the chairman on broadband, common carrier, and mass media matters. Before joining the FCC, Power was a telecommunications and litigation partner at the law firm of Winston & Strawn in Washington. He received his undergraduate and law degrees from the University of Virginia.

Richard Reaser (Raytheon) Biography not available.

Frank H. Sanders (Supervisory Electronics Engineer, Telecommunications Theory Division; DOC/NTIA/ITS) From 1979 to 1987, Sanders was a Junior Fellow with the Institute for Telecommunication Sciences (ITS) at the U.S. Department of Commerce in Boulder, CO. Since 1987 he has been an electronics engineer at ITS. He currently leads the Telecommunications Theory Division at the Institute. His research areas include advanced radio spectrum measurement techniques, radar emission measurement techniques, and effects of interference on radio receivers in general and radar receivers in particular. Sanders is a Colorado native who received a B.A in physics from the University of Colorado in 1987.

Gregory Showman (Director/Senior Research Engineer, Georgia Tech Research Institute, Sensors and Electromagnetic Applications Laboratory, Adaptive Sensor Technology Branch) Dr. Showman has 25 years of experience in advanced RF sensor research and development, with an emphasis on the design and implementation of innovative signal processing techniques for radar imaging, electronic protection, and multi-dimensional adaptive filtering. Showman's accomplishments include development of novel techniques for ultrawideband synthetic aperture radar (SAR) and high-precision turntable inverse SAR (ISAR) image formation, methods for polarimetric SAR calibration, electronic protection against coherent jamming, and space-time adaptive processing (STAP) algorithms and architectures for airborne and space-based ground moving target indication (GMTI) radar systems. Showman is currently involved in the development of robust algorithms and architectures for STAP radar and problems related to electronic warfare for SAR and STAP systems. Specific applications include airborne and space-based radar signal processing for imaging and moving target detection, and electronic protection methods to counter advanced interference techniques. From 1985 to 1992 he worked as an anti-air warfare analyst at the Naval Air Warfare Center, China Lake, and from 1992 to 2000 he was a full-time graduate research assistant at Georgia Tech. Additionally, Showman is a Senior Member of the IEEE, has served as Treasurer and Chair of the Atlanta joint chapter of the Aerospace and Electronic Systems and Geoscience and Remote Sensing societies of the IEEE, and is actively involved in the peer-review process for IEEE and IET conference papers and journal articles. He received the B.S. degree in Applied Physics from the University of California at Davis in 1985, and the M.S. and Ph.D. degrees in EE from the Georgia Institute of Technology in 1994 and 2000, respectively.

Douglas C. Sicker (Chief Technology Officer, FCC) Dr. Sicker has held various positions in academia, industry and government. In addition to his current position at the FCC, Sicker is also the DBC Endowed Associate Professor in the Department of Computer Science at the University of Colorado at Boulder with a joint appointment in the Interdisciplinary Telecommunications Program. Prior to this he served as a senior advisor on the FCC National Broadband Plan. Prior to this he was Director of Global Architecture at Level 3 Communications, Inc. In the late 1990's Sicker served as Chief of the Network Technology Division at the FCC. He has also held faculty and industry positions in the field of medical sciences and is a senior member of the IEEE, as well as a member of the ACM and the Internet Society. He has served as an advisory to the Department of Justice National Institute of Justice. He was also the Chair of the Network Reliability and Interoperability Council steering committee and served on the Technical Advisory Council of the FCC. His research and teaching interests include network security, wireless systems and telecommunications policy.

Robert Sole (Supervisory Electronics Engineer, DOC/NTIA/OSM, Spectrum Engineering Branch) Sole has been employed by DOC since 1993 working for the NTIA/OSM as a radio spectrum engineer and a branch manager. His primary work involves tests and measurements of radar and communication systems. Sole has published ITU–R reports and recommendations, and numerous NTIA publications. He attended college in West Virginia earning a B.S. in EE and has pursued graduate studies in engineering at John Hopkins University and George Washington University.

John A. Stine (Chief Technology Advisor, The MITRE Corporation, Operations Research and Systems Analysis) Prior to joining MITRE, Dr. Stine served 20 years as an engineer and as an ORSA in the U.S. Army. He served in all company-level leadership positions and in battalion, brigade, and division staff positions. He taught electrical engineering at the U.S. Military Academy. He was the coordinating analyst in the Army's first tactical networking experiments. In his ten years at MITRE, he has led internally funded research in mobile ad hoc networking, consulted with the DOD on spectrum management issues, authored"Spectrum Management 101" consulted with Army analysis agencies on modeling and analysis of tactical networks specializing on operational effectiveness, and is currently leading a research project to enable more dynamic spectrum management by exploiting models of spectrum consumption. Stine has authored numerous papers on wireless networking, spectrum management, dynamic spectrum access and network modeling and evaluation and has patents and patents pending in wireless mobile ad hoc networking and spectrum management. He received the best paper award at the 2007 IEEE DySPAN Conference and received the International Test and Evaluation Association's publication award for 2007. Stine holds a B.S. in General Engineering from the U.S. Military Academy at West Point, M.S. degrees in EE and Manufacturing Systems Engineering from the University of Texas at Austin and a Ph.D. in EE from the University of Texas at Austin. He is a senior member of the IEEE and is registered as a professional engineer in the State of Virginia.

Chris Tourigny (Electronics Engineer, Spectrum Engineering Services, FAA) Tourigny's concentration is in aeronautical surveillance spectrum management on the Spectrum Planning and International Team. He serves as the spectrum advisor to the U.S. Member of the International Civil Aviation Organization (ICAO) Aeronautical Surveillance Panel (ASP); participates in aeronautical surveillance and collision avoidance policy and systems standards development within the FAA, ICAO and RTCA, Inc.; applies safety risk management practices within the FAA safety culture; and helps develop mitigations to aeronautical spectrum congestion and system compatibility challenges. After graduating with a B.S. in Physics, Tourigny earned an M.S. in Applied and Engineering Physics under Graduate Research and Teaching Assistantships at George Mason University in Fairfax, Virginia.

Jack Unger (FCC Committee Chair, WISPA) Unger is sometimes called the "grandfather of the wireless ISP industry". After founding Wireless InfoNet (now Ask-Wi.com) in 1993, he deployed one of the first fixed wireless ISPs in 1995. He has trained over 3500 wireless industry personnel, served over 3000 client companies, and he wrote the first fixed wireless broadband handbook, Deploying License-Free Wireless Wide-Area Networks (Cisco Press, 2003). Today, Unger continues to provide consulting and training services for the wireless broadband industry. He also serves on the Board of WISPA, the Wireless ISP Association (U.S.) and as WISPA's FCC Committee Chair. The FCC Committee directs WISPA's FCC work which includes advocating for more licensed and unlicensed WISP spectrum and for more practical operating rules. Unger's work includes anticipating, addressing and helping to solve spectrum-sharing issues.

Phil Weiser (Dean; Thompson Professor, University of Colorado Law School) Prior to re-joining Colorado Law, Dr. Weiser served as the Senior Advisor for Technology and Innovation to the National Economic Council Director at the White House. Prior to that post, he served as the Deputy Assistant Attorney General for International, Policy, and Appellate Matters in the United States Justice Department's Antitrust Division. Before joining the Obama Administration, Weiser was a professor of law and telecommunications at the University of Colorado, where he also served as an Associate Dean. At CU, Weiser established a national center of excellence in telecommunications and technology law, founding the Journal on Telecommunications & High Technology Law and the Silicon Flatirons Center for Law, Technology, and Entrepreneurship. Over the last decade, Weiser has written and taught in the areas of technology, innovation, and competition policy. In particular, Weiser has co-authored two books—Digital Crossroads: American Telecommunications Policy in the Internet Age (MIT Press 2005) and Telecommunications Law and Policy (Carolina Academic Press 2006)—and numerous articles (in both law journals and publications such as The Washington Post and Foreign Affairs), and has testified before both houses of Congress. While a professor at CU, Weiser was active in a number of public service activities, briefing and arguing a number of pro bono cases before the Tenth Circuit Court of Appeals, co-chairing the Colorado Innovation Council, and serving as the lead agency reviewer for the Federal Trade Commission as part of the 2008 Presidential Transition. Prior to joining the CU faculty, Professor Weiser served as senior counsel to the Assistant Attorney General in charge of the Antitrust Division at the United States Department of Justice, advising him primarily on telecommunications matters. Before his appointment at the Justice Department, Weiser served as a law clerk to Justices Byron R. White and Ruth Bader Ginsburg at the United States Supreme Court and to Judge David Ebel at the Tenth Circuit Court of Appeals. Weiser graduated with high honors from both the New York University School of Law and Swarthmore College.

APPENDIX D: GLOSSARY

δ_R	range resolution
λ	wavelength
σ	radar cross section
τ	pulse duration
1-D	one dimensional
2-D	two dimensional
3-D	three dimensional
A/D	analog-to-digital converter
AAW	anti-air warfare
ACF	autocorrelation function
ACPR	adjacent channel power ratio
ADIT	automatic detection and integrated tracking
A-DPCA	adaptive displaced phase center antenna
ADT	automatic detection and track
AESA	active electronically scanned array
AEW	airborne early warning
AF	array factor
AFB	air force base
AGC	automatic gain control
AGL	above ground level
AIS	automatic identification system (for ships)
AMTI	airborne moving target indication
ANSI	American National Standards Institute
AOA	angle of arrival
ARMA	autoregressive moving average
ARSR	air-route surveillance radar
ARSS	Advanced Radar Surveillance System
ASDE	airport surface detection equipment
ASR	airport surveillance radar
ATC	air traffic control
AWACS	airborne warning and control system
AWG	arbitrary waveform generator
B	bandwidth
B.Eng.	Bachelor of Engineering (UK)
BPF	bandpass filter
BMD	ballistic missile defense
BMEWS	ballistic missile early warning system
B.S.	Bachelor of Science
c	speed of light
CA	cell averaging
CA-CFAR	cell averaging constant false alarm rate
CDL	common data link
CDMA	code-division multiple access
CFA	crossed field amplifier
CFAR	constant false alarm rate

CNR	clutter-to-noise ratio
COHO	coherent oscillator
CONOPS	concept of operations
CONUS	contiguous United States
CORF	Committee on Radio Frequencies (The National Academies)
COTS	commercial off-the-shelf
CPI	coherent processing interval
CRFS	Cambridge Radio Frequency Services
CRT	cathode-ray tube
CS	computer science
CSMAC	Commerce Spectrum Management Advisory Committee
CTO	Chief Technology Officer
CU	University of Colorado
CW	continuous wave, carrier wave (sine wave) signal modulation
DAC	digital-to-analog converter
DARPA	Defense Advanced Research Projects Agency
dB	decibel
dbc	decibels relative to the carrier
DBF	digital beam-forming
DBS	Doppler beam sharpening
DDS	direct digital synthesis (synthesizer)
DFS	dynamic frequency selection
DHS	Department of Homeland Security
DISA	Defense Information Agency
DOA	direction of arrival
DOC	Department of Commerce
DOD	Department of Defense
DOE	Department of Energy
DOF	degrees of freedom
DOJ	Department of Justice
DOT	Department of Transportation
DPCA	displaced phase center antenna
DSA	dynamic spectrum access
DSO	Defense Spectrum Organization
DSP	digital signal processing
DSX	direct synthesizer
DTE	digital target extractor
DTV	digital television
DUT	device under test
DySPAN	International Symposium on Dynamic Spectrum Access Networks
E^3	electromagnetic environmental effects (DOD)
EA	electronic attack
ECCM	electronic counter-countermeasures
ECM	electronic countermeasures
EE	electrical engineering
EESS	Earth Exploration Satellite Service

EIO	extended interaction (klystron) oscillator
EIRP	effective isotropic radiated power
EKF	extended Kalman filter
EM	electromagnetic
EMI	electromagnetic interference
EMC	electromagnetic compatibility
EP	electronic protection
ESA	electronically scanned array
ESNL	estimated system noise level
EW	electronic warfare
F	receiver noise factor
f	frequency
f_D	Doppler frequency shift
f/D	focal length to diameter ratio
FAA	Federal Aviation Administration (DOT)
FAR	false alarm rate
FASR	fixed array surveillance radar
FCC	Federal Communications Commission
FCR	fire control radar
FDS	fractional Doppler shift
FFT	fast Fourier transform
FM	frequency modulation
FMCW	frequency-modulated continuous wave
FOPEN	foliage penetration
FOV	field of view
FPGA	field programmable gate array
FTC	fast time constant radar receiver processing, Federal Trade Commission
FWHM	full width at half maximum
FYDP	Future Years Defense Program (DOD)
G	gain
GCA	ground controlled approach
GCMLD	generalized censored mean level detector
GMTI	ground moving target indication
GOCA-CFAR	greatest-of cell averaging constant false alarm rate
GPEN	ground penetration
GPR	ground penetrating radar
GPS	global positioning system
GSLC	generalized sidelobe canceller
GTRI	Georgia Tech Research Institute
H	horizontal polarization
HCE	heterogeneous clutter estimation
HF	high frequency; frequency band designation for 3–30 MHz
HRR	high range resolution
I	in-phase channel or signal
I/N	interference-to-noise ratio
I/Q	in-phase/quadrature

IADT	integrated automatic detection and tracking
IAGC	instantaneous automatic gain control
ICAO	International Civil Aviation Organization
ICBM	intercontinental ballistic missile
ICD	initial capabilities document
IDA	Infocomm Development Authority (Singapore)
IEC	International Electrotechnical Commission
IEEE	Institute of Electrical and Electronic Engineers
IF	intermediate frequency
IFF	identification friend or foe
IFM	instantaneous frequency measurement
IFSAR	interferometric synthetic aperture radar
IIT	Illinois Institute of Technology
IMO	International Maritime Organization
IMP	intermodulation product
iNet	Institute for Networked Systems (RWTH Aachen University)
IOT	inductive output tube
IPP	interpulse period
IR	interference rejection
IRAC	Interdepartmental Radio Advisory Committee
ISAR	inverse synthetic aperture radar
ISART	International Symposium on Advanced Radio Technologies
ISM	industrial, scientific, and medical
ISP	Internet service provider
ISR	integrated sidelobe ratio
ITS	Institute for Telecommunication Sciences
ITU	International Telecommunications Union
ITU-R	International Telecommunications Union, Radiocommunication Sector
JSC	Joint Spectrum Center (DOD/DSO)
JSTARS	joint surveillance and target radar system
JTRS	Joint Tactical Radio System
LFM	linear frequency modulation
LHC	left-hand circular
LINC	linear amplification with nonlinear components
LLWAS	Low-Level Wind-shear Alert System
LNA	low-noise amplifier
LO	local oscillator
Log FTC	logarithmic fast time constant radar receiver processing
LOS	line of sight
L_s	system loss
M.A.	Master of Arts
MAC	medium access control
MLE	maximum likelihood estimate
M.B.A.	Masters of Business Administration
MDD	minimum detectable Doppler
MDS	minimum detectable signal

MDV	minimum detectable velocity
MHz	megahertz
MIMO	multi-input multi-output
MLC	mainlobe clutter
MLS	Microwave Landing System
MMW	millimeter wave
MOPA	master oscillator power amplifier
MOPS	minimum operational performance standard
MOTR	multiple-object tracking radar
MPAR	multifunction phased-array radar
MP-RTIP	Multi-Platform Radar Technology Insertion Program
MPI	message passing interface
MPM	microwave power module
MPS	minimum peak sidelobe
M.S.	Master of Science
MSLC	multiple sidelobe canceller
MSTV	Association for Maximum Service Television, Inc.
MTBF	mean time between failures
MTD	moving target detector
MTI	moving target indicator
MTT	multi-target tracking
MVDR	minimum variance distortionless response
NARTE	National Association of Radio and Telecommunications Engineers
NAS	National Airspace System
NASA	National Aeronautics and Space Administration
NATO	North Atlantic Treaty Organization
NCA	nearly constant acceleration
NCTR	non-cooperative target recognition
NCV	nearly constant velocity
NextGen	Next Generation Air Transportation System (FAA)
NIJ	National Institute of Justice
NIST	National Institute of Standards and Technology
NLFM	nonlinear frequency modulation
N_0	thermal noise power density
NOAA	National Oceanic and Atmospheric Administration
NOI	Notice of Inquiry (FCC)
NRA	no return area
NRL	Naval Research Laboratory (U.S.)
NSF	National Science Foundation
NTIA	National Telecommunications and Information Administration (DOC)
NTSB	National Transportation Safety Board
NWS	National Weather Service (DOC/NOAA)
OET	Office of Engineering and Technology (FCC)
OGR	ocean graphic radar
OSM	Office of Spectrum Management (NTIA)
OTHR	over the horizon radar

OTR	on-tuned rejection factor
PA	power amplifier, power-aperture
PAG	power-aperture-gain
PAR	precision approach radar
PCS	personal communications services
P_d	probability of detection
pdf	probability density function
PDR	phase-derived range
PDRO	phase-locked dielectric resonant oscillator
P_{fa}	probability of false alarm
PFA	polar formatting algorithm
PFD	power flux density
PFN	pulse-forming network
Ph.D.	Doctor of Philosophy
PHY	physical layer
PLL	phase-locked loop
PLO	phase-locked oscillator
PNT	positioning, navigation, and timing
PPI	plan position indicator
PPSG	Policy and Plans Steering Group (NTIA)
P_r	received power
PRF	pulse repetition frequency
PRI	pulse repetition interval
PSR	primary surveillance radar
P_t	transmitted power
Q	quadrature phase channel or signal
R	Range
R&D	research and development
RAC	reflective-array compressor
RACONS	radar beacons
Radar	radio detection and ranging, paired receiver and transmitter
RAM	radar absorbing material
RAPCON	radar approach control
RBGM	real beam ground mapping
RBW	resolution bandwidth of a spectrum analyzer
RCS	radar cross section
REX	receiver/exciter
RF	radio frequency, radar frequency
RFI	radio frequency interference
RHC	right hand circular
RHI	range-height indicator
RMA	range migration algorithm
rms	root mean square
ROC	receiver operating curve, receiver operating characteristic
ROTHR	relocatable over the horizon radar
RNSS	radionavigation satellite service

RRE	radar range equation
RSEC	radar spectrum engineering criteria
RTCA	Radio Technical Commission for Aeronautics
RWTH	Rheinisch-Westfälische Technische Hochsghule
RX	receive, receiver
s	second
SAR	synthetic aperture radar
SARP	standard and recommended practice
SAW	surface acoustic wave
SBR	space-based radar
SDR	software defined radio
SEAL	Sensor and Electromagnetic Applications Laboratory (GTRI)
SFDR	spurious-free dynamic range
SINR	signal-to-interference-plus-noise ratio
SIR	signal-to-interference ratio
SIR-C	shuttle imaging radar-c
SLAR	side-looking airborne radar
SLC	sidelobe clutter
SMI	sample matrix inversion
SMIT	Studies on Media, Information, and Telecommunications
SMRi	improved surface movement radar
SNR	signal-to-noise ratio
SOCA-CFAR	smallest-of cell-averaging constant false alarm rate
SOLAS	safety of life at sea
SPEC	Standard Performance Evaluation Corporation
SPTF	Spectrum Policy Task Force (FCC)
SRD	system requirements document
STALO	stable local oscillator
STAP	space-time adaptive processing
STC	sensitivity time control
t	time
T/R	transmit/receive
TAC	Technology Advisory Committee (FCC)
TACCAR	time-averaged-clutter coherent airborne radar
TAR	tethered aerostat radar
TBM	threshold bias map
T_D	time delay between transmission and reception of target echo
TDU	time delay unit
TDWR	terminal Doppler weather radar
TESS	tactical electronic support system
TI	Texas Instrument
TIPP	time invariant periodicity preservation
TORDAR	total RF detection and ranging
TRF	tuned radio frequency
TVWS	television whitespace
TWS	track while scan

TWT	traveling wave tube
TX	transmit
TX/RX	transmitter-receiver combination
U-NII	Unlicensed National Information Infrastructure
UAV	unmanned aerial vehicle
UC	University of California
UDSF	usable Doppler space fraction
UHF	ultra-high frequency; frequency band designation for 300–3000 MHz
ULA	uniform linear array
UMOP	unintentional modulation of pulse
UN	United Nations
USAF	U.S. Air Force
USCG	U.S. Coast Guard
UWB	ultrawideband
V	vertical polarization
VHF	very high frequency; frequency band designation for 30–300 MHz
v_r	radial velocity
VSWR	voltage standing wave ratio
WiMAX	Worldwide Interoperability for Microwave Access
WPAN	wireless personal area network
WRC	World Radio Conference (ITU)

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15. ABSTRACT (A 200-word or less factual summary of most significant information. If document includes a significant bibliography or literature survey, mention it here.)

These are the proceedings for the 2011 International Symposium on Advanced Radio Technologies hosted by the National Telecommunications and Information Administration's Institute for Telecommunication Sciences in Boulder, Colorado. The conference focused on radar spectrum usage and management. It included radar tutorials; spectrum inventory briefings; and moderated discussions about radar policy, spectrum management, research and technology, and regulatory issues related to sharing radar spectrum. Overall, ISART 2011 successfully brought together the radar and communications communities to identify spectrum issues and discuss ways to make radar systems and spectrum more efficient. Conclusions drawn at this year's conference were that better spectrum management in radar bands is a multi-faceted problem spanning economic, regulatory, and technical issues. Technical concepts and solutions were identified that could improve radar spectrum efficiency. Examples include radar transmitter upgrades to improve out-of-band emissions; using adaptive and cognitive antennas and signal processing to avoid, mitigate, and prevent interference; and consolidation of multiple radar systems, functions, and/or operational bands into a single platform. In regards to sharing radar spectrum as a means to increase spectrum utilization, radar usage models that offer whitespace opportunities were identified. Radar spectrum improvement projects, however, have technical challenges and tend to be large and expensive. Further, current funding models do not support wide scale development for the sake of spectrum efficiency. The path forward involves the development of a cohesive long-term radar spectrum strategy that reduces large radar projects into incremental and manageable steps with limited risk. Similarly, incremental regulatory reform is needed to enable spectrum sharing rules to be implemented in manageable increments with a "crawl-walk-run" approach.

16. Key Words (Alphabetical order, separated by semicolons)

adaptive radio; cognitive radio; International Symposium on Advanced Radio Technologies; ISART; radar policy; radar spectrum management; radar spectrum usage; RF interference; signal processing; spectrum efficiency; spectrum inventory; spectrum management

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