NTIA Technical Report TR-11-473

# Case Study: Investigation of Interference into 5 GHz Weather Radars from Unlicensed National Information Infrastructure Devices, Part I

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*report series*

U.S. DEPARTMENT OF COMMERCE • National Telecommunications and Information Administration

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DEPARTMENT OF COMMERCE
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# ABBREVIATIONS/ACRONYMS

| | |
|---|---|
| **CW** | Carrier Wave |
| **dB** | decibel |
| **dBi** | decibels relative to isotropic |
| **dBm** | decibels relative to 1 milliwatt |
| **DFS** | Dynamic Frequency Selection |
| **DOC** | Department of Commerce |
| **EIRP** | Equivalent Isotropically Radiated Power |
| **FAA** | Federal Aviation Administration |
| **FCC** | Federal Communications Commission |
| **GHz** | gigahertz |
| **IF** | Intermediate Frequency |
| **I/N** | Interference-to-Noise Ratio |
| **ITS** | Institute for Telecommunication Sciences |
| **LNA** | Low Noise Amplifier |
| **MHz** | megahertz |
| **MSL** | Mean Sea Level |
| **mW** | milliwatt |
| **NTIA** | National Telecommunications and Information Administration |
| **OSM** | Office of Spectrum Management |
| **PPI** | Plan Position Indicator |
| **PRI** | Pulse Repetition Interval |
| **RF** | Radio Frequency |
| **RMS** | Root Mean Square |
| **TDWR** | Terminal Doppler Weather Radar |
| **U-NII** | Unlicensed National Information Infrastructure |
| **µs** | microsecond |
| **VSG** | Vector Signal Generator |
| **WISP** | Wireless Internet Service Provider |

# EXECUTIVE SUMMARY

In early 2009, the Federal Aviation Administration (FAA) became aware of interference to their Terminal Doppler Weather Radars (TDWR) that operate in the 5600–5650 MHz band, and provide quantitative measurements of gust fronts, windshear, microbursts, and other weather hazards for improving the safety of operations in and around major airports (45 airports at the time of this writing). Engineers from both the Institute for Telecommunication Sciences (ITS), part of the National Telecommunications and Information Administration (NTIA), and the FAA traveled to a site of reported TDWR interference in San Juan, Puerto Rico. They performed an extensive series of field measurements in the San Juan area to determine the cause of the interference.

When ITS engineers arrived, they noted ten TDWR azimuths experiencing performance degradation due to interference. With the assistance of FAA engineers, ITS engineers systematically measured and traced the interference through the various information processing stages of the TDWR for all ten interference azimuths and measured individual component specifications of the radar. Through these tests, it was determined that the interference sources were unlicensed national information infrastructure (U-NII) dynamic frequency selection (DFS) devices, from different manufacturers, operating in the same frequency band as these Federal radar systems. These devices employ technology that are supposed to detect the presence of nearby radar systems and change operating frequencies to prevent interference with an incumbent radar system.

After determining the interference source, ITS engineers, along with the local Federal Communication Commission (FCC) field agent, began locating the DFS devices on nearby towers and surrounding building rooftops with the intent of documenting device manufacturers, model numbers, FCC IDs, and, to the extent possible, software versions, responsible for causing interference. ITS then performed in situ (outdoor) and indoor performance tests of the devices identified as causing interference to characterize the device behavior and the signal environment they operate in. These field measurements and performance tests are described in this report. This report is Part I of a series of three reports covering this interference mitigation effort.

After obtaining the initial results reported here, ITS performed additional testing in controlled environments to better understand how to resolve the interference, beyond the immediate, ad-hoc solution of having operators manually move their U-NII devices' frequencies away from the TDWR frequency—a temporary solution that defeats the purpose of DFS.

Part II of this series will detail additional, follow-up testing performed at the ITS laboratory in Boulder, CO, and the FAA's Mike Monroney Aeronautical Center in Oklahoma City, to determine why some devices fail to detect TDWR signals, understand the interference mechanism into TDWRs, and explore at what interference levels the TDWR performance degrades. ITS obtained several U-NII devices from various manufacturers to test against an engineering TDWR system, with representatives from the respective manufacturers present to witness testing and provide engineering support.

Part III of this series will contain engineering solutions that may be used as part of a strategic plan to resolve interference to TDWRs.

# CASE STUDY: INVESTIGATION OF INTERFERENCE INTO 5 GHz WEATHER RADARS FROM UNLICENSED NATIONAL INFORMATION INFRASTRUCTURE DEVICES, PART I

John E. Carroll[1], Frank H. Sanders[1], Robert L. Sole[2] and Geoffrey Sanders[1]

In early 2009, the Federal Aviation Administration (FAA) became aware of interference to Terminal Doppler Weather Radars (TDWRs) that operate in the 5600–5650 MHz band and provide quantitative measurements of gust fronts, windshear, microbursts, and other weather hazards for improved safety of operations in and around major airports. This report describes field measurements and results from an examination of interference to a TDWR in San Juan, Puerto Rico from unlicensed national information infrastructure (U-NII) dynamic frequency selection (DFS) devices operating in the same frequency band. Several U-NII devices from different manufacturers were found to be causing interference into the TDWR. These devices operate in the same bands as these Federal radar systems, but employ DFS technology that is supposed to detect the presence of nearby radar systems and change operating frequencies to prevent interference with incumbent radar systems. This is the first of a three-part series of reports that describe research efforts by the Institute for Telecommunication Sciences (ITS) engineers, with assistance from FAA engineers, to determine the cause of the interference, understand why some devices fail to detect TDWR signals, and engineer solutions.

Key words: dynamic frequency selection; unlicensed national information infrastructure; spectrum sharing technology; radar interference; RF interference; radar performance degradation; terminal Doppler weather radar

## 1 INTRODUCTION

The Terminal Doppler Weather Radar (TDWR) system, introduced in 1993, operates in the 5600–5650 MHz band, and provides quantitative measurements of gust fronts, windshear, microbursts, and other weather hazards that are used to improve the safety of operations at major airports (45 airports at the time of this writing). “During the period from 1964 to 1986, at least 32 accidents and incidents have occurred in which windshear was identified as a contributing factor. These accidents resulted in over 600 fatalities and nearly 250 injuries. There is evidence to suggest that if undocumented “close calls” and general aviation statistics were included, these figures would be much higher.” [1] TDWRs improve the management of air traffic through forecasting of gust fronts and induced wind shifts, detection of precipitation, and detection of other hazardous weather phenomena including turbulence and tornados.

Beginning in early 2009, the Federal Aviation Administration (FAA) became aware of interference to TDWRs, including one in San Juan, Puerto Rico. An informal investigation by

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[1] Institute for Telecommunication Sciences, National Telecommunications and Information Administration (NTIA), U.S. Department of Commerce, Boulder, CO.

[2] Office of Spectrum Management (OSM), NTIA, Washington, DC.

the FAA concluded that Unlicensed National Information Infrastructure (U-NII) devices were responsible. U-NII systems can now operate in the 5250–5350 and 5470–5725 MHz bands, alongside many Federal radar systems, including the TDWR, but are required to employ dynamic frequency selection (DFS) technology to detect the presence of a nearby radar system and change operating frequencies to prevent interference to the radar. The Federal Communications Commission (FCC), the National Telecommunications and Information Administration (NTIA), other Federal agencies, and industry representatives collaborated to develop rules and compliance measurement procedures [2] for U-NII devices equipped with DFS technology. After three years of bench and field testing prototypes from many manufacturers, the DFS rules were finalized in March 2006 and the first DFS device certification was granted in August 2006. The U-NII devices are authorized to operate under the Part 15 rules for unlicensed devices, and as such they are not permitted to cause interference to allocated and protected systems.[3]

Interference sources cause interference strobes to appear on the San Juan TDWR plan position indicator (PPI) scopes. These strobes are sometimes referred to as “jam strobes” and appear as blacked-out zones on the PPI. Figure 1 shows an example of interference strobes, marked with white lines for graphical clarity.

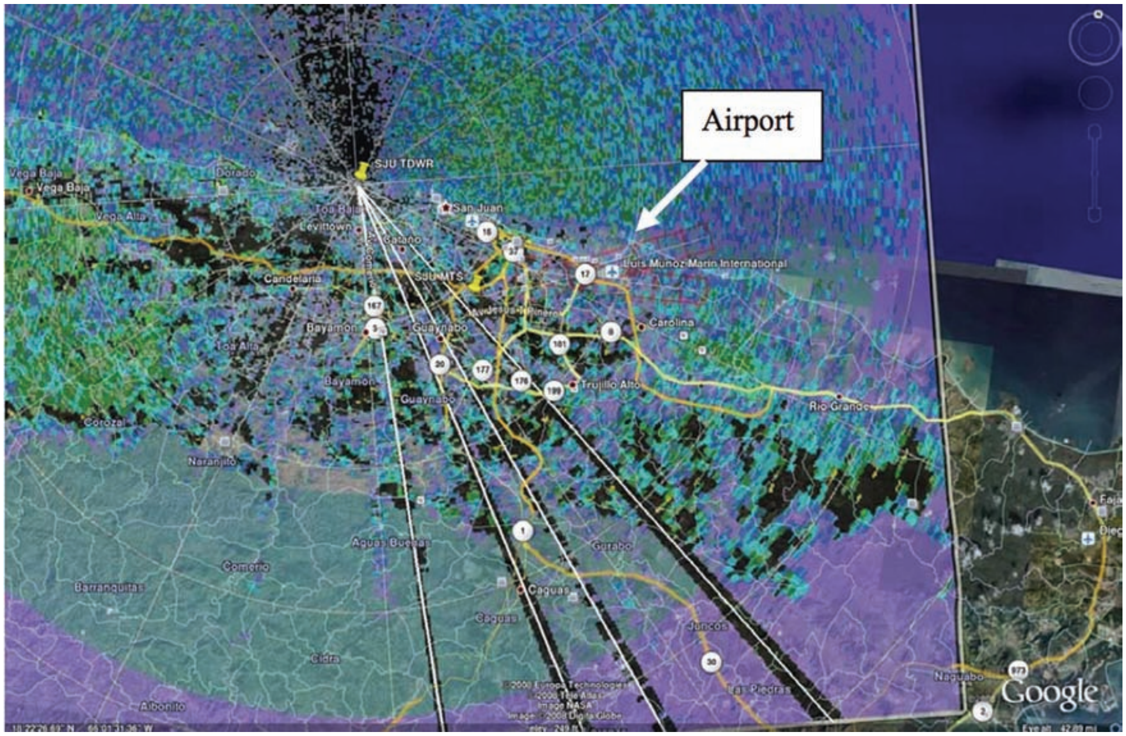

Figure 1. An example of interference artifacts on the San Juan TDWR display.[4]

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[3] “Operation of an intentional, unintentional, or incidental radiator is subject to the conditions that no harmful interference is caused and that interference must be accepted that may be caused by the operation of an authorized radio station, by another intentional or unintentional radiator, by industrial, scientific and medical (ISM) equipment, or by an incidental radiator.” 47 CFR § 15.5(b) (2009-2010).

[4] Map image © 2010 Google, Map Data © 2000 European Technologies, © 2000 TeleAtlas, NASA, © 2008 Digital Globe

At the request of the FAA, ITS and OSM engineers participated in a TDWR interference study in San Juan, Puerto Rico from March 9th through 20th, 2009 and performed a series of field measurements to determine the source of the interference. The results obtained are detailed in this report.

# 2 DYNAMIC FREQUENCY SELECTION OVERVIEW

In June 2006, the FCC released a Memorandum Opinion and Order [2] containing an Appendix specifying measurement procedures for certifying U-NII devices for compliance with the DFS requirements in the 5250–5350 MHz and 5470–5725 MHz frequency bands. U-NII devices operating in these bands do not have to follow any FCC guidelines for modulation or coding schemes, but must detect and avoid incumbent Federal radar systems.

The operational behavior of a U-NII device operating in the 5250–5350 MHz and 5470–5725 MHz frequency bands is:

1. U-NII devices must use DFS in order to detect nearby radar systems with received signal strength above the DFS Detection Threshold [2] of -62 or -64 dBm peak power[5]. The required Detection Bandwidth [2] is specified as a minimum of 80% of the device's 99% transmission power bandwidth.

2. Before a U-NII device can transmit on a channel, it must perform a Channel Availability Check [2] for 60 seconds to ensure no radar system is operating on the selected channel.

3. The U-NII device then transmits Network Initiation [2] signals that allow other U-NII devices to associate.

4. During normal operation, the U-NII device monitors the channel (called In-Service Monitoring [2]) to ensure that there are no radar systems on the Operating Channel [2].

5. If the U-NII device detects radar systems during In-Service Monitoring, the Operating Channel must be vacated to prevent interference to nearby radar systems.

6. Once the U-NII device has detected radar systems on a given channel, it must not utilize that channel for a minimum of 30 minutes.

Sections 6 and 7 in the Appendix of [2] specify five sets of radar test waveform types and FCC certification procedures for U-NII devices requiring DFS. The waveforms were developed by ITS in coordination with several Federal agencies. The waveform sets simulate signals from various radars operating in the 5 GHz frequency band. All test waveforms are realized using a vector signal generator (VSG).

The "Short Pulse Radar Type 1 Waveform," hereafter referred to in this document as the "Bin 1 Waveform," was developed specifically to protect the TDWR. It consists of a pulse repetition interval (PRI) of 1428 microseconds (μs), a pulse width of 1 μs, and 18 pulses per burst [2].

For the purpose of the study documented in this report, in situ testing of U-NII devices in San Juan focused only on their Channel Availability Check and In-Service Monitoring modes.

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[5] A detection threshold of -62 dBm applies to devices with less than 200 mW equivalently isotropically radiated power (EIRP). For devices with 200 mW or greater EIRP, the -64 dBm threshold applies. These values assume a 0-dBi receive antenna.

# 3 TDWR MEASUREMENT RESULTS

The TDWR can operate in a fixed number of 1-MHz channels in the 5600–5650 MHz band. The measurements reported in this section apply only to the San Juan TDWR, which operates on 5610 MHz (at the time of this writing). The intermediate frequency (IF) of the TDWR is 30 MHz; that is, a signal at the radar operating frequency of 5610 MHz is downconverted to an IF of 30 MHz in the radar receiver.

First, the radar's PPI was used to locate the azimuths of interference. To determine the true characteristics of the interference and ultimately determine the interference source, it was necessary to understand the frequency response of various components of the radar system. This was done by disassembling the radar and performing measurements on various stages. ITS and OSM engineers measured the frequency response of the low-noise amplifier (LNA), radio frequency (RF) front-end bandpass filter, and the IF output (used to measure the IF filter response). On the radar azimuths where interference was occurring, measurements of signals in the ambient environment were then recorded at three different points in the radar system: at the antenna waveguide output, RF front-end bandpass filter output, and IF output. These measurement points are shown in Figure 2.

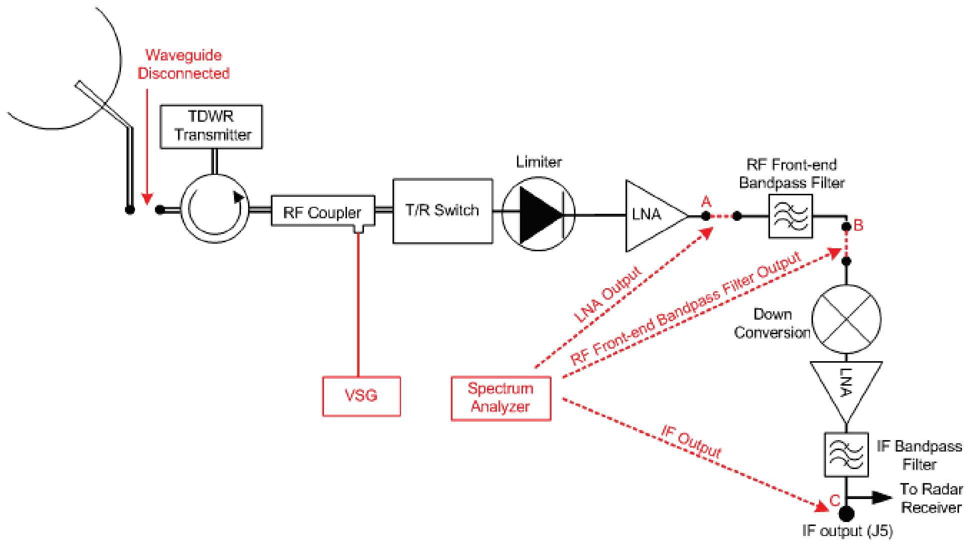

Figure 2. TDWR component frequency response measurement points.

Dashed lines indicate physical disconnections of waveguide. Waveguide to N-connector convertors were used to attach the test equipment to outputs A and B. Output C is bnc connectorized.

## 3.1 TDWR LNA, RF Front-end Bandpass Filter, and IF Output Frequency Response

ITS and OSM engineers measured the frequency response of the TDWR's LNA, RF front-end bandpass filter, and IF output by sweeping a carrier-wave (CW) signal in frequency and recording the results (Figures 3 through 5, respectively). The radar transmitter stage was disabled during these measurements. A signal generator, used to inject the CW signal, was directly attached to 30-dB directional coupler before the TDWR limiter stage.

The LNA frequency response presented in Figure 3 was recorded using a spectrum analyzer resolution bandwidth of 1 MHz with positive-peak detection at point A in Figure 2. During the measurement, a temporary malfunction of the signal generator caused three signal dropouts. These three data points do not reflect the actual response of the LNA.

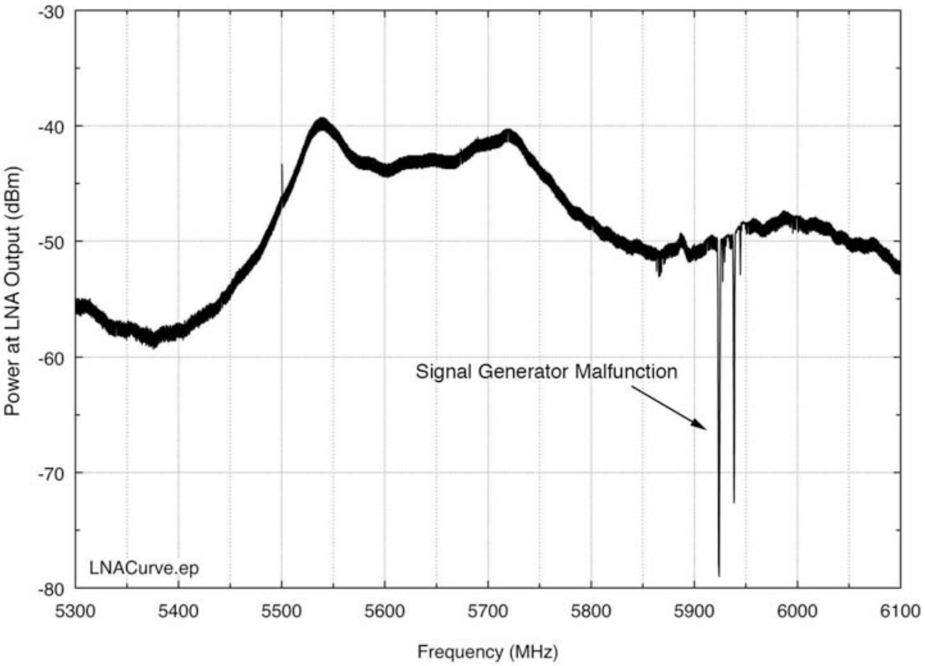

Figure 3. TDWR RF front-end LNA frequency response.

The data presented in Figures 4 and 5 were recorded using a spectrum analyzer resolution bandwidth of 300 kHz with positive-peak detection and were measured at points B and C, as shown in Figure 2. The frequency responses shown in Figures 4 and 5 have had their pass bands normalized to 0 dB for clarity. Figure 4 presents the TDWR RF front-end filter frequency response.

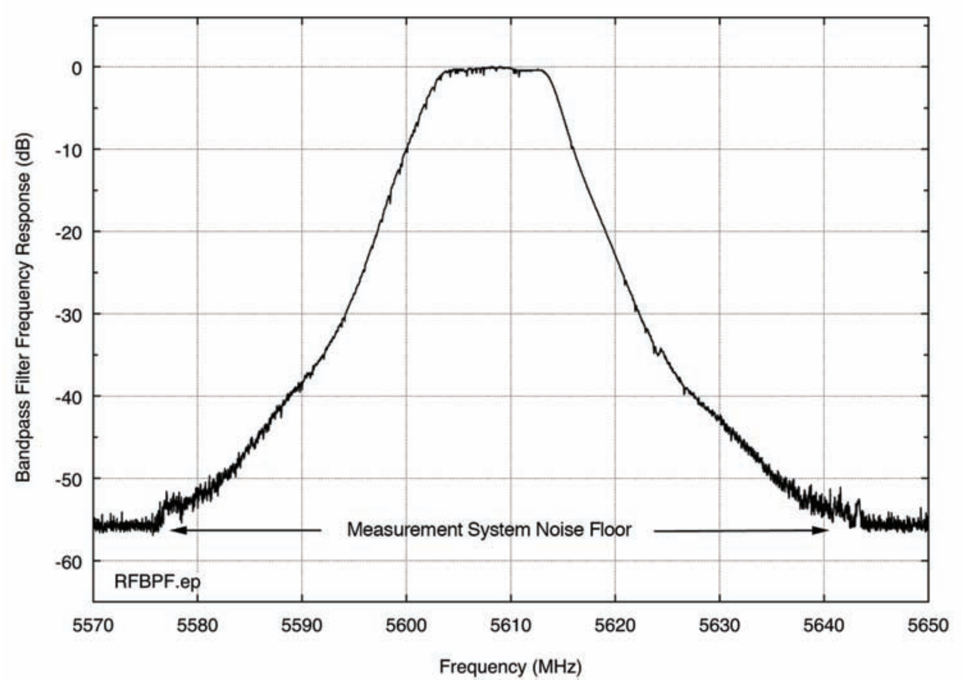

Figure 4. TDWR RF front-end bandpass filter frequency response; normalized to 0 dB.

Figure 5 presents the overall TDWR frequency response through the receiver. Figure 5 indicates that the IF filter in the receiver stage is about 1 MHz wide at the 3-dB points, which is consistent with radar design theory for the TDWR pulse width of about 1 μs.

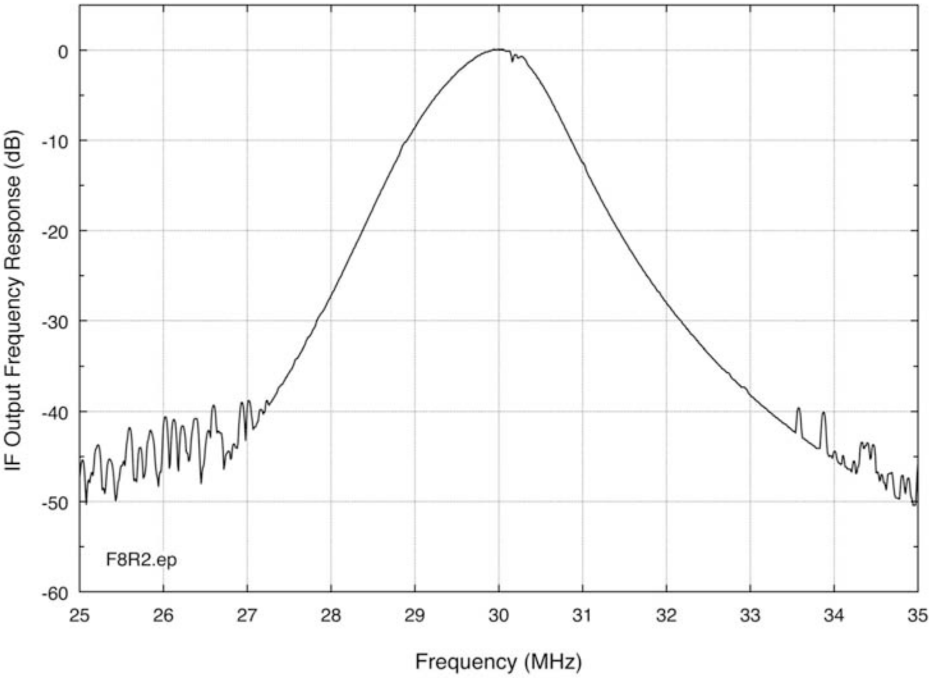

Figure 5. TDWR IF output frequency response; normalized to 0 dB.

ITS and OSM engineers also performed a measurement of the linearity of the LNA response as a function of input power, the results of which are shown in Figure 6. A CW signal was injected at the RF coupler with a peak power level of -50 dBm (a CW peak power level of -20 dBm minus 30 dB coupler loss). The CW was incremented by 10-dB steps through -10 dBm. The amplifier output was found to be linear at inputs up to -20 dBm. This was well above the peak-power levels that U-NII devices were later found to be coupling into the radar receiver. The data presented in Figure 6 were recorded using a spectrum analyzer resolution bandwidth of 1 MHz with positive-peak detection at point A in Figure 2.

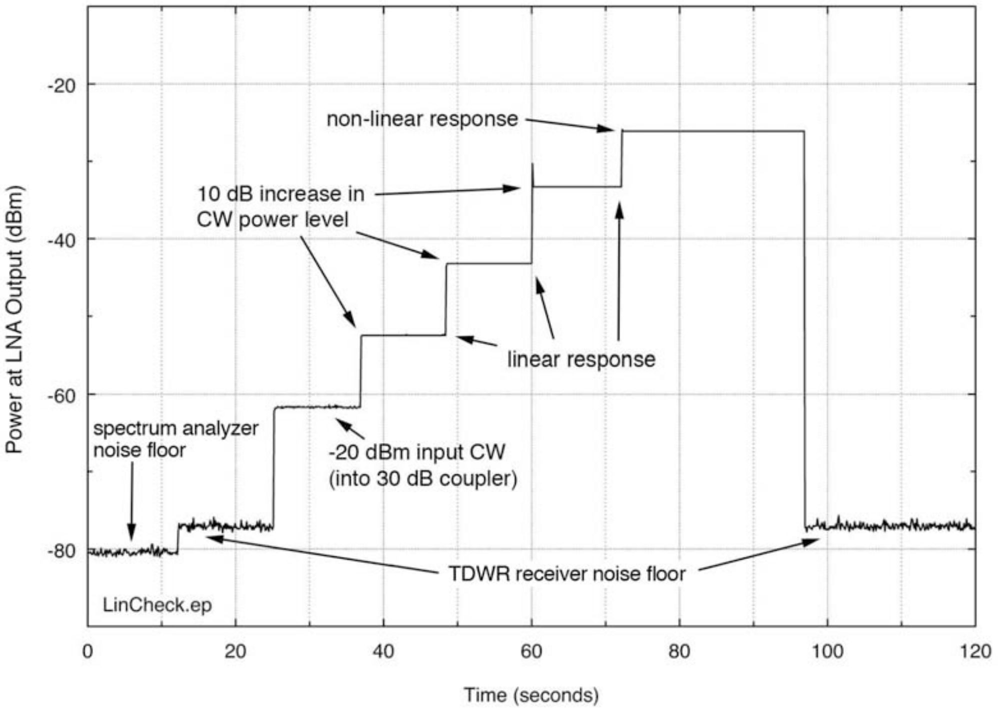

Figure 6. Linearity measurement result for the TDWR front-end LNA.

## 3.2 PPI Azimuths of Interference Strobes

The San Juan TDWR utilizes a parabolic antenna with a 0.55º 3-dB beamwidth and 50 dBi gain in its 3-dB beamwidth at its operational frequency of 5610 MHz. At the beginning of this effort, FAA engineers performed standard solar observation techniques. This allowed them to adjust and verify the accuracy of the TDWR beam-pointing angles.

Next, the radar was operated in its typical volume-scanning mode (a combination of rotating in azimuth and varying the antenna elevation) so as to catalog the set of all azimuths and corresponding elevation angles at each azimuth where the interference strobes were occurring. A total of ten azimuths experiencing interference were identified as shown in Table 1.

Table 1. Azimuths and Corresponding Elevation Angles where Interference was Identified

| Azimuth (Magnetic) | Azimuth (True)[6] | Elevation Angle(s) |
|---|---|---|
| 112º | 99º | +0.3 |
| 124º | 111º | +0.3, +1.0 |
| 131º | 118º | +0.3 |
| 143º | 130º | +0.3, +1.0 |
| 147º | 134º | +0.3 |
| 154º | 141º | +0.3, +1.0 |
| 161º | 148º | +0.3, +1.0 |
| 165º | 152º | +0.3, +1.0 |
| 175º | 162º | +0.3, +1.0 |
| 191º | 178º | +1.0 |

In addition to the azimuths listed in Table 1 where interference strobes were observed, measured, and recorded, a baseline azimuth of 0º magnetic was observed, measured, and recorded. This provided a reference against which effects on the interference azimuths could be compared.

### 3.3 U-NII Signals at Antenna Waveguide Output, Bandpass Filter Output, and IF Output

All measurements were performed in a 1-MHz bandwidth so as to replicate the TDWR's processing bandwidth and provide assurance that the peak power levels measured would replicate peak power levels as processed by the TDWR receiver stage. The radar transmitter stage was disabled during these measurements, except during the IF output measurements. The TDWR receiver expects a series of calibration pulses from the transmitter stage; without them, the radar will disable itself as the lack of calibration pulses indicates a system fault has occurred.

ITS and OSM engineers measured the U-NII signals at various test points of the TDWR in the frequency and time domain at each of the azimuths that were receiving interference. These test points are shown in Figure 7. Dotted lines indicate physical disconnections of the radar waveguide.

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[6] TDWR azimuths are reported in magnetic terms to maintain consistency with air traffic control operations, which use magnetic azimuths because pilots always fly on magnetic headings. For Puerto Rico, the conversion from magnetic to true azimuths is (True = Magnetic – 12.75º); a TDWR interference azimuth of 112º is 99.25º true. Listed azimuths are only reported to the nearest degree.

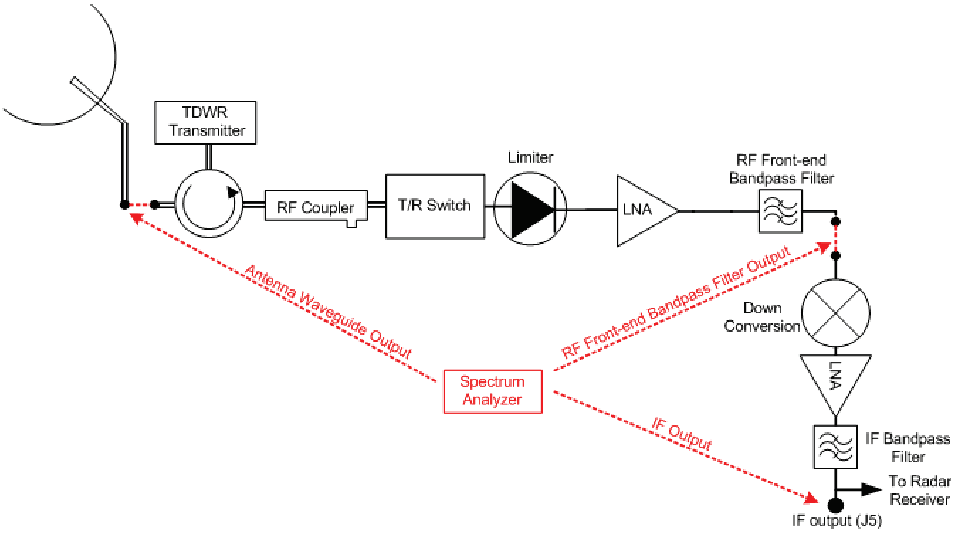

Figure 7. TDWR measurement point configuration.

Figures 8 through 11 show the measured signal at an azimuth of 154 degrees from the radar location at each of the three test points of the TDWR. The frequency and time-domain measurement results yielded signal structures consistent with “frame-based” U-NII devices. Frame-based devices transmit data for a fixed period of time, followed by a fixed period of time during which they receive data. An example of this behavior is shown in Figure 10. A similar signal structure was observed on all but one of the azimuths listed in Table 1 (the exception was one azimuth experiencing broadband noise emanating from a cruise ship).

Each frequency-domain measurement at each point in the TDWR was performed across two frequency ranges: 5000–6000 MHz and 5595–5625 MHz. Examples of the two frequency range measurements are shown in Figures 8 and 9. This pairing provided a broad look at the spectrum on each azimuth, as well as a detailed examination of the spectrum near the radar center frequency of 5610 MHz. Each of these spectra was repeated with two spectrum analyzer detection modes: positive peak and Root Mean Square (RMS) average. This allowed the effect of the duty cycle of the interference signals to be observed, as high-duty-cycle signals would be observed with both detectors, while low-duty-cycle signals would be observed well with positive-peak detection but not with RMS average detection. The spectrum measurements allowed both the tuned frequencies and the transmitted spectrum shapes (spectrum width and roll-off) of the interference signals to be observed and recorded.

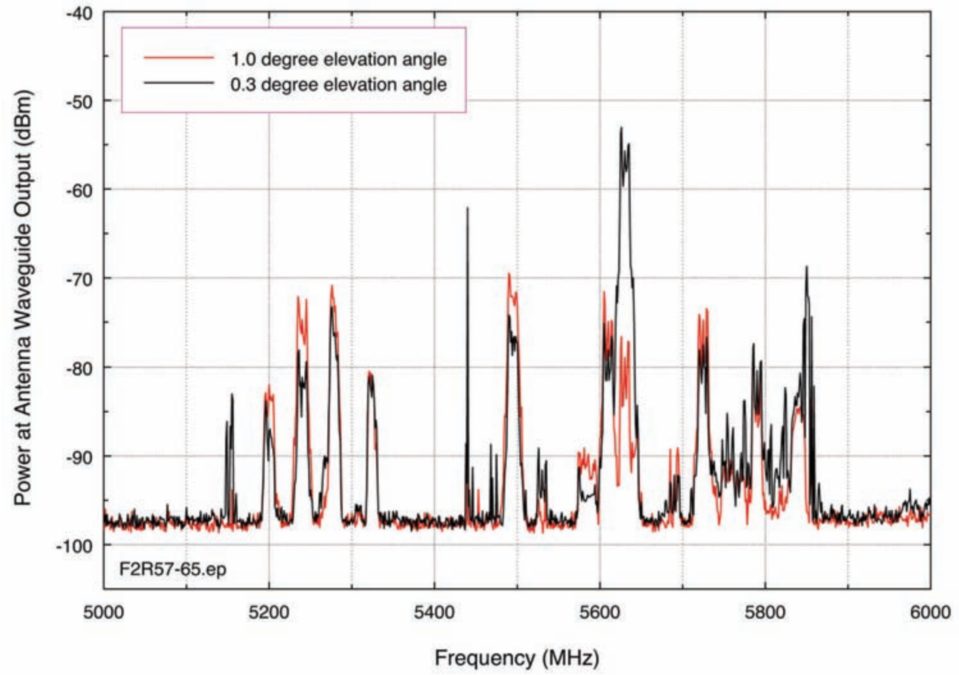

Figure 8. U-NII signals at the TDWR antenna waveguide output at the 154 degree azimuth over a 1 GHz span.

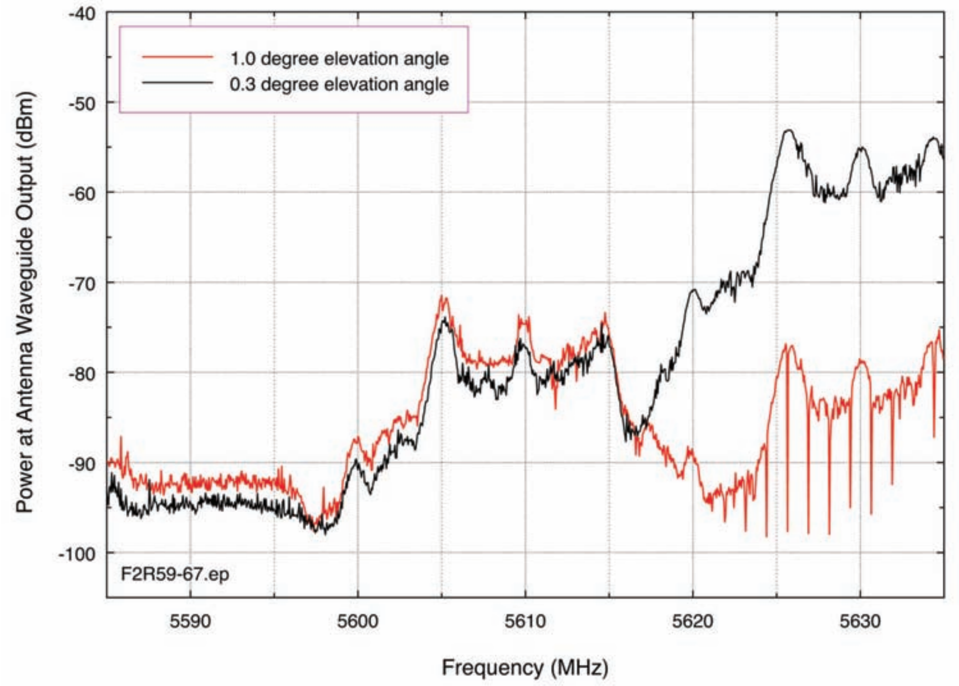

Figure 9. U-NII signals at the TDWR antenna waveguide output at the 154 degree azimuth over a 50 MHz span.

Figures 10 and 11 show the time-domain measurements of the interference source at the 154 degree azimuth at the TDWR antenna waveguide output(5610 MHz) and the TDWR receiver IF output (30 MHz), respectively.

Figure 11 shows the magnitude of interference in the radar's IF stage from an interfering signal produced by an outdoor U-NII device (Model 1) from Manufacturer A, at 5600 MHz (10 MHz below the radar center frequency). The +25 dB interference-to-noise (I/N) level of the interference on the TDWR center frequency caused visible strobes on the radar PPI. Taken together, Figures 8 through 11 indicate that the interference on the TDWR center frequency is due to a U-NII system. Other interference azimuths listed in Table 1 showed the same results (except the one azimuth with broadband noise emanating from a cruise ship).

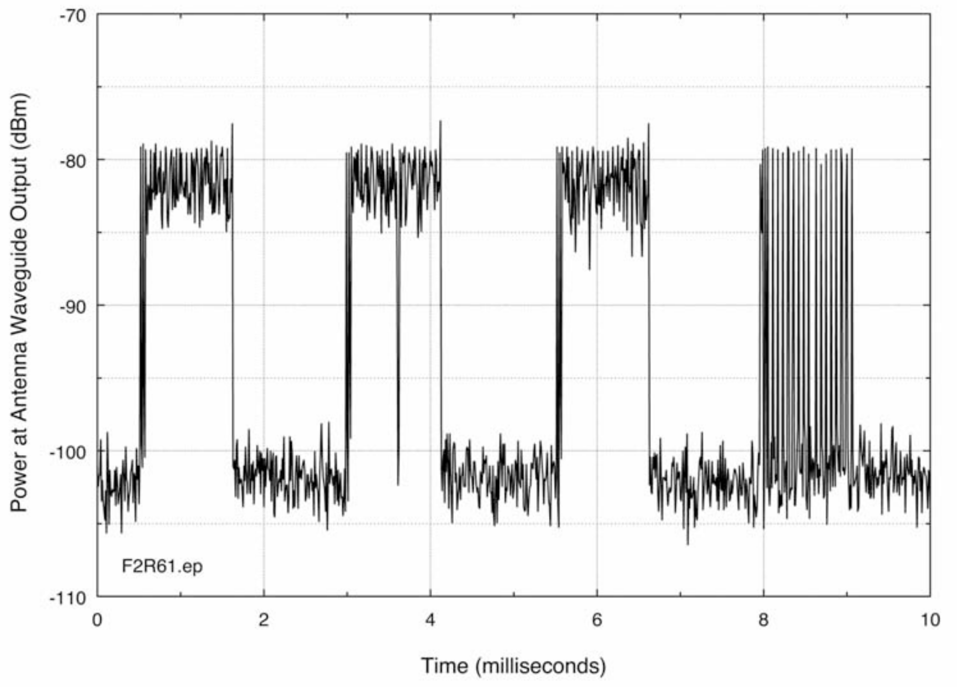

Figure 10. Time-domain view of interference at the TDWR antenna waveguide output at 154 degree azimuth tuned to 5610 MHz.

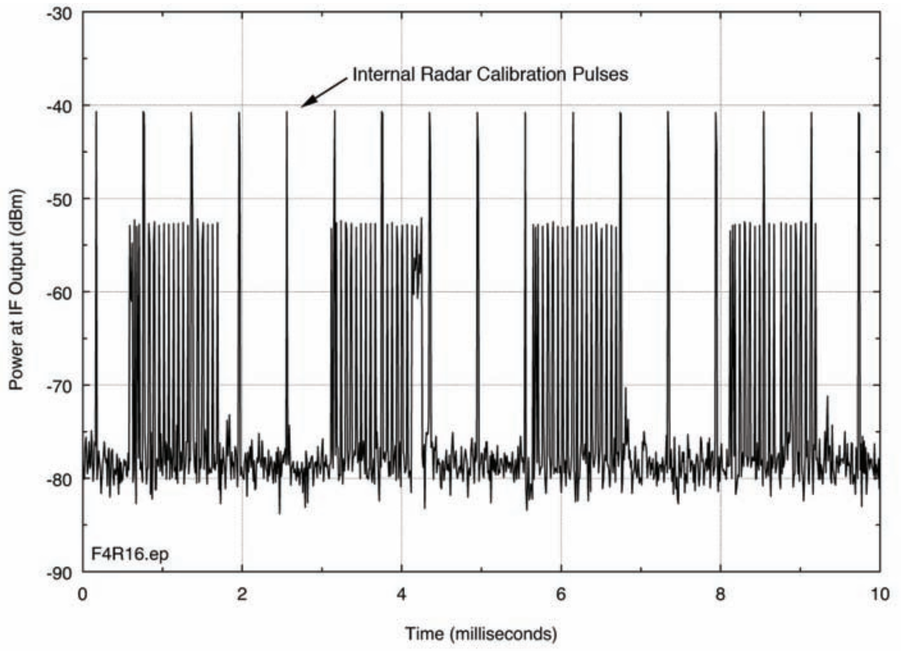

Figure 11. Time-domain view of interference at the TDWR IF output at 154 degree azimuth, tuned to 30 MHz.

The output of the TDWR RF front-end bandpass filter (see Figure 7) is provided in Figure 12 as an example. It is important to note that the bandpass filter can mask the center frequency of the interferer. Therefore, the initial measurements must ***always*** be done at the radar's waveguide antenna output (ahead of the RF bandpass filter) to ascertain the actual frequency of the interfering U-NII signal and to accurately observe its spectrum. Pseudo-peaks seen through the filter are *not* the true center frequencies of the signals.

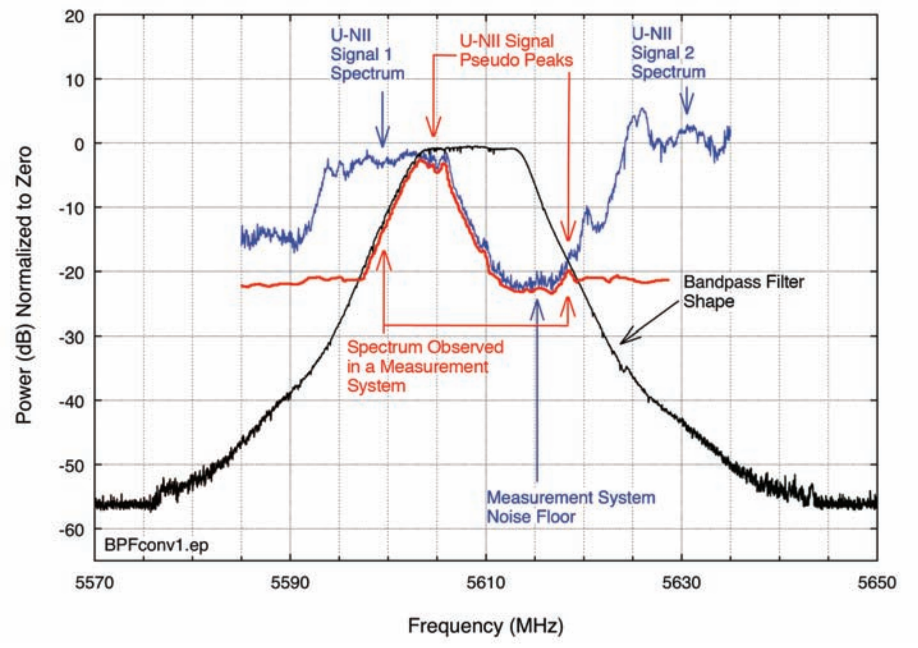

Figure 12. TDWR bandpass filter effect on off-tuned signals in the radar receiver.

### 3.4 Summary of Interference Signals Coupling into the TDWR in San Juan

Table 2 summarizes the results of the NTIA measurements of interference into the TDWR at San Juan. Out of ten interference azimuths, one was due to unknown broadband noise source from a cruise ship and nine were due to both co-channel and adjacent channel emissions from U-NII devices. Red lettering at 5610 MHz and 5615 MHz denotes U-NII systems whose intentional emissions were co-channel with the TDWR.

Table 2. Summary of Interference Measured Within the TDWR Receiver at San Juan

| Az (mag) | Az (true) | Frequency or Frequencies (MHz) | Signal Type | Max *I/N* Level in Radar IF Stage | Comments on interference sources |
|---|---|---|---|---|---|
| 112° | 99° | 5610 | Broadband noise | About 6 dB | Cruise ship; not U-NII |
| 124° | 111° | 5600 | Frame-based U-NII | +6 dB | U-NII device: Manufacturer A, Model 1 |
| 131° | 118° | 5600 | Frame-based U-NII | +10 dB | U-NII device: Unknown Manufacturer |
| 143° | 130° | 5620 | Frame-based U-NII | +8 dB | U-NII device: Unknown Manufacturer |
| 147° | 134° | 5600 and 5630 | 802.11 and 802.16 | +12 dB | U-NII device: Unknown Manufacturer |
| 154° | 141° | 5610 | Frame-based U-NII | +25 dB | U-NII device: Unknown Manufacturer |
| 161° | 148° | 5615 | Frame-based U-NII | +20 dB | U-NII device: Unknown Manufacturer |
| 165° | 152° | 5610 | Frame-based U-NII | +20 dB | U-NII device: Unknown Manufacturer |
| 175° | 163° | 5615 | Frame-based U-NII | +25 dB | U-NII device: Unknown Manufacturer |
| 191° | 178° | 5600 | Frame-based U-NII | +18 dB | U-NII device: Unknown Manufacturer |

# 4 SIGNAL ENVIRONMENT MEASUREMENTS

The next step in the process was to discover why the U-NII devices were failing to detect the TDWR. This required measurements of the incident TDWR peak pulse power at known U-NII transmitter sites in the San Juan area. Then, the DFS functionality of selected U-NII devices[7] was checked against both the actual TDWR signal as well as the Bin 1 Waveform used in FCC compliance testing. The Bin 1 Waveform provided a baseline signal that should have triggered the DFS algorithm to confirm proper DFS operation. All measurements performed in this series of tests used a 1-MHz resolution bandwidth.

## 4.1 Measurements of TDWR Signal at Rooftops

ITS and OSM engineers performed measurements of the maximum incident TDWR pulse power at the U-NII sites shown in Table 3. The measured levels exceeded the minimum DFS detection threshold of -64 dBm in a 1-MHz bandwidth by 47 dB to as much as 60 dB.

Table 3. TDWR Maximum-Power Measurement Sites and Values in the San Juan Area

| Azimuth (magnetic) | Distance from TDWR | Altitude (MSL) | Peak Radar Power Corrected to 0 dBi Receiving Antenna |
|---|---|---|---|
| 124º | 8.6 miles | 270 feet | 0 dBm |
| 147º | 5.3 miles | 300 feet | -15 dBm |
| 161º | 7.9 miles | 500 feet | -11 dBm |

The radar pulses were also well formed (sharp rise and fall times) in the time domain. Figures 13 through 15 show examples of these frequency and time-domain measurements at the location of the interference source at the 124 degree azimuth; other azimuths exhibited the same results. Based on these measurements, the U-NII devices at these azimuths should have detected the radar signal and should have vacated their operating frequency as shown by these measurements.

Measurements taken at U-NII locations in San Juan show that the actual radar pulse environment differs somewhat from the environment originally assumed by DFS designers. It was assumed that radar pulses would occur in isolated, discrete bursts from the radar antenna main lobe only. However, measurements around the San Juan TDWR showed that pulse bursts are also received from radar antenna sidelobes, contradicting the model. The proof is provided by the data of Figure 13, taken 8.6 miles from the San Juan TDWR on a rooftop on the 124 degree azimuth.

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[7] These devices were made available to NTIA on a temporary basis by local wireless internet service providers (WISPs) who were using them on rooftops. Alterations were not made to the hardware or firmware of any of the devices that were examined in San Juan.

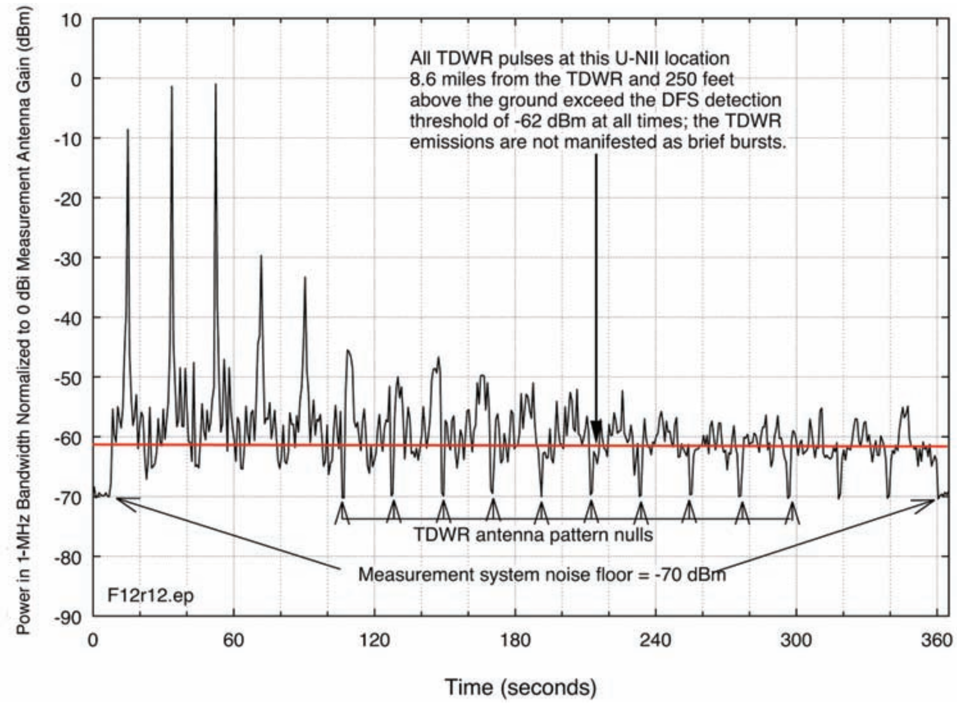

Figure 13. The time-domain behavior of the San Juan TDWR measured through one complete volume scan at a distance of 8.6 miles.

The measurement shown in Figure 13 was made through one complete volume-scan cycle of the radar. Every 20 seconds, the radar beam scanned past the azimuth where the measurement system was situated. But as the elevation of the beam varied from one scan to the next, variations occurred in the maximum power received at the rooftop from one radar rotation to the next. The TDWR beam in the first rotation of the volume scan actually hit the measurement location *above* the building rooftop. The next two rotations of the TDWR volume scan reduced the elevation angle by a factor of two and caused the TDWR beam to hit the measurement location at approximately rooftop height. The calculations of the location of the TDWR beam on a given elevation angle were based on the San Juan TDWR scan strategy provided by the FAA. (It should be noted that scan strategies will vary from one TDWR location to the next.) After that, the radar beam elevation gradually increased higher and higher above the rooftop, and the measured power in the beam decreased steadily from one rotation to the next. The DFS detection threshold, indicated by the red line in Figure 13, is nearly always exceeded throughout the volume scan.

By the twelfth rotation of the radar, the well-formed antenna pattern characteristic of the main beam was lost. Instead, the first sidelobe below that beam was seen during each TDWR rotation. After 18 radar rotations had elapsed (taking a total time of six minutes), the volume scan was been completed and the next volume scan begun.

*For the purpose of this discussion, the most remarkable feature of the data in Figure 13 is the fact that never, during the entire volume-scan cycle of the TDWR, even when its beam was tilted 60 degrees above the horizon and directed over the ocean away from the measurement location, did the stream of pulses from the radar cease to reach the measurement location where U-NII devices were positioned.*

The peak backlobe and sidelobe emissions from the TDWR were nearly always above the DFS detection threshold at the measurement location. The measurements in Figure 13 were taken with a 10-dBi gain measurement antenna, but the data in the figure have been adjusted (by subtracting 10 dB from each of the raw measurement point amplitudes) to the power that would have been measured by a 0-dBi gain measurement antenna. In general, the radar pulses never dropped below -60 dBm with a 0-dBi gain measurement antenna at this location. Since the DFS detection threshold is either -62 or -64 dBm peak power, this means that a DFS device at this location should *constantly* detect radar pulses as the radar pulses do not occur in isolated burst.

Figure 14 shows a set of individual pulses measured in the TDWR backlobes while the radar was rotating away from the measurement location at a high elevation angle. The structure of the backlobe pulses is the same as the pulses that occur when the radar beam is aimed at the measurement location, albeit at a lower amplitude.

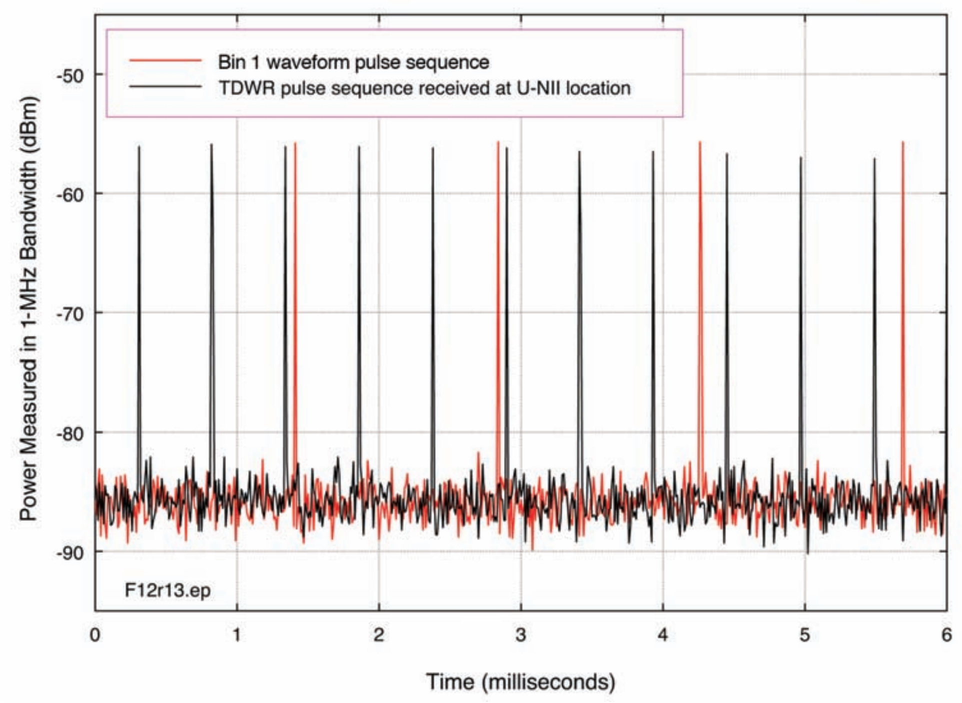

Figure 14. A sequence of pulses in the TDWR backlobe (black) compared to the Bin 1 Waveform sequence (red).

The TDWR pulse sequence and the individual TDWR pulse envelope are overlaid in Figures 14 and 15 with a pulse sequence and the Bin 1 Waveform generated by a VSG, respectively. The actual TDWR and Bin 1 Waveform pulse envelopes are similar. The only significant difference between the actual TDWR emission and the Bin 1 Waveform is the PRI for the given elevation scan (the TDWR PRI varies depending on elevation); the PRI of the Bin 1 Waveform sequence is almost three times longer than the TDWR PRI (for the elevation where the emission was captured).

The individual TDWR pulse envelopes are well-defined (sharp pulse rise and fall times), as exemplified by the individual radiated TDWR pulse shown in Figure 15. This pulse, like the sequence shown in Figure 14, was captured while the radar beam was pointing directly away from the measurement location and was tilted at a high elevation angle. The pulses in Figure 15 are offset slightly in time for graphical clarity. The pulse widths and shapes in this figure are virtually identical.

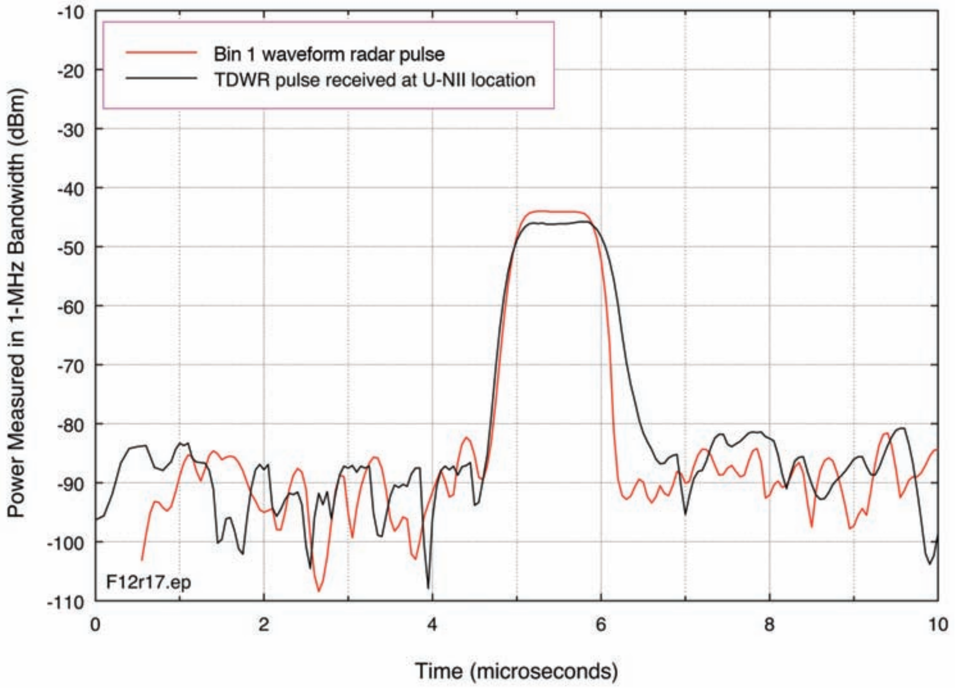

Figure 15. A radiated single-pulse envelope from the TDWR in the backlobe of the antenna pattern (black) compared to Bin 1 Waveform pulse (red).

# 5 MEASUREMENTS OF U-NII DEVICES AGAINST ACTUAL TDWR EMISSIONS AND BIN 1 WAVEFORM PULSES

The DFS functionality of selected U-NII devices[8] was checked against both the actual TDWR signal as well as the Bin 1 Waveform. The devices that were tested are shown in Table 4. Firmware revisions for these devices were found to be critical to proper DFS radar-detection functionality.[9]

Table 4. U-NII Devices Tested Against Actual TDWR and Bin 1 Waveform in San Juan

| Device | Model | Modulation |
|---|---|---|
| Manufacturer A | Model 2 | Frame-Based |
| Manufacturer B | Model 1 | WiMAX (802.16) |
| Manufacturer C | Model 1 | WiMAX (802.16) |

## 5.1 DFS Tests on a Model 2 U-NII Device from Manufacturer A

Manufacturer A's Model 2 device was individually correlated with the interference strobe on 124 degree azimuth at the TDWR location (Table 2) by FAA engineers, the local FCC Resident Agent and a local WISP operator. FAA and FCC personnel located a U-NII device in use at 5600 MHz (Table 2), which was 10 MHz below the TDWR frequency and contacted the WISP operator using the U-NII device. The local WISP operator voluntarily off-tuned Manufacturer A's Model 2 device to 5590 MHz and, after the device was off-tuned, FAA engineers confirmed via the TDWR PPI that the strobes on the 124-degree azimuth disappeared; they were present minutes earlier.

ITS and OSM measurements in the TDWR receiver showed this U-NII device, while off-tuned 10 MHz from the TDWR frequency, produced enough unintentional energy on the TDWR frequency to produce an *I/N* level of +6 dB in the radar receiver (Table 2). In other words, this device was failing to sense the TDWR emissions when it was off-tuned by 10 MHz, yet its detection bandwidth, based on DFS compliance test results performed by the FCC, was listed as ±11 MHz. Based on the FCC's results, it should have detected the TDWR even though it was off-tuned by 10 MHz.

A second Model 2 U-NII device from Manufacturer A was tested in situ on a rooftop with the help of a local WISP operator. This device had the same model number, and used the same firmware version as the Model 2 device tested by the FAA and FCC. On the rooftop, in the in situ signal environment that is shown in Figures 13 through 15, the U-NII device was mounted on a metal pipe approximately 1.8 m above the rooftop and was rotated to face toward the TDWR. It was tuned to the TDWR frequency (5610 MHz) and was verified to be operating with the proper regional/country code (some U-NII devices are sold to operate in different regions, with varying rules on DFS implementation). This U-NII device was operated without a client, and was not transmitting or receiving network traffic; it was only transmitting Network Initiation

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[8] Firmware builds and FCC IDs were collected for these devices.

[9] Firmware changes have the potential to alter or even disable DFS detection ability.

data. This should have given it a maximum probability of detecting radar pulses as it was not receiving data from a client and so could utilize the entire time it was not transmitting for radar detection. It correctly performed the 60-second Channel Availability Check before it transmitted, but then it began to transmit on the TDWR frequency. Because the TDWR pulses were, as shown in Figure 13, always above the DFS detection threshold at this location, the U-NII device should have detected the radar and moved to another frequency.

After three minutes of operation on the TDWR frequency, while in In-Service Monitoring mode, it did detect the actual TDWR, declared this in its software interface, and ceased to transmit on the TDWR frequency. The test was repeated, and again the device began to transmit on the TDWR frequency after performing the 60-second Channel Availability Check. During this second trial, it transmitted for five minutes on the radar frequency, before it finally shut itself off after detecting the TDWR signal (as again indicated by a user-interface message).

Next, the same test procedure as described above was repeated with the U-NII device's antenna rotated so that it faced 180 degrees away from the TDWR, and finally with the device's antenna rotated 90 degrees away from the TDWR. These two cases should have resulted in reduced antenna directional gain and possibly reduced probability of detection of the TDWR signal. When facing 180 degrees from the TDWR, the device operated for 15 minutes but never detected the actual TDWR signal (FAA engineers did confirm that an interference strobe occurred during this test.) The device was manually powered off after 15 minutes. When facing 90 degrees from the TDWR, it did eventually detect the TDWR signal, but only after 12 minutes (two complete volume scans of the radar) had elapsed. FAA engineers confirmed interference strobes occurred with the device facing 90 degrees away from the TDWR.

The Detection Bandwidth of the U-NII device was checked by rotating its antenna to face the radar and then operating it on frequencies spaced 10 MHz and 15 MHz away from the TDWR frequency. It never detected the TDWR signal when it was off-tuned by 15 MHz. It continued to require many minutes to detect the TDWR when it was off-tuned by 10 MHz below the TDWR frequency (to 5600 MHz), but it eventually detected the radar after 5 minutes had elapsed. When it was tuned 10 MHz above the TDWR frequency (to 5620 MHz), however, it never detected the TDWR signal after 10 minutes of elapsed operation; it was finally turned off by the operator.

A third Model 2 U-NII device from Manufacturer A was then tested indoors at the San Juan FCC office against the Bin 1 Waveform (Figures 14 and 15) in both Channel Availability Check and In-Service Monitoring modes. It should be noted that this was not the unit tested on the rooftop, but another, apparently identical, unit with the same model number provided by the same WISP operator that participated in the roof-top testing with ITS and OSM engineers. It is not known if the firmware version was the same as the one tested on the rooftop as the WISP operator lacked the means to check. In this indoor environment, which was radio-quiet but which probably caused a significant amount of multipath in the Bin 1 Waveform pulses, the U-NII device always immediately detected the radar bursts at peak amplitudes ranging from -62 dBm to approximately -30 dBm. The device was able to consistently detect the Bin 1 Waveform, both when the pulses occurred in bursts (as specified in section 7 of the Appendix of [1]) and when they occurred in a continuous stream (as a replication of the local TDWR pulse environment). It is noted, with reference to Figure 14, that the PRI of the TDWR pulses was about half as long as the PRI of the Bin 1 Waveform pulses.

In summary, Manufacturer A's Model 2 device was not able to consistently detect actual in situ TDWR pulses in either operating mode. However, it was able to consistently detect both bursts and continuous streams of the Bin 1 Waveform. In situ testing indicates that the device did not always achieve ±10 MHz Detection Bandwidth, even though FCC certification testing had indicated that this value should be ±11 MHz.

Manufacturer A's devices were found to be deployed with at least three different antenna configurations in the San Juan area.

## 5.2 DFS Tests on a Model 1 U-NII device from Manufacturer B

The Model 1 U-NII device from Manufacturer B lacked an FCC ID on its case. It was tested against TDWR pulses on a 300-ft-high rooftop on the 147-degree azimuth from the radar as well as the Bin 1 Waveform at a relatively radio-quiet outdoor location at the San Juan Federal Building. It failed all In-Service Monitoring tests performed by NTIA, as described in more detail below.

During the rooftop tests against the actual TDWR signal, the maximum received peak power level of the TDWR pulses, the radar beam-scanning pattern and the pulse formation at the rooftop location were very similar to those of Figures 13 through 15. The device was intentionally and repeatedly tuned to the TDWR frequency while it was on the rooftop and operating in In-Service Monitoring mode. In no case did it detect the TDWR. Furthermore, it provided a user-accessible option for disabling DFS functionality. The device was tested on the rooftop in both DFS-enabled and DFS-disabled modes; in neither case did it detect the actual TDWR pulses.

Subsequently, the Manufacturer B, Model 1 device was tested at an outdoor location at the Federal Building in San Juan against calibrated Bin 1 Waveform pulses (Figures 14 and 15, shown in red), directed at it via a horn antenna. The received power level of the Bin 1 Waveform was directly calibrated through the U-NII receiver antenna. The tests were performed with the calibrated pulse bursts adjusted to peak amplitude levels in the Manufacturer B receiver of -62 dBm, -52 dB, -42 dBm, -32 dBm, -22 dBm, and -12 dBm, while the device was in In-Service Monitoring mode. In no case did the device detect any of the Bin 1 Waveform pulse bursts.

## 5.3 DFS Tests on a Model 1 U-NII Device from Manufacturer C

The Manufacturer C, Model 1 U-NII device was tested in its In-Service Monitoring mode in the same outdoor area as Manufacturer B's device. Bursts of Bin 1 Waveform pulses were transmitted at peak amplitude levels in the Manufacturer C receiver of -62 dBm to -12 dBm. The DFS system of Manufacturer C, Model 1, consistently and immediately detected all of these radar pulse bursts. Due to logistical constraints, this device was not tested against the TDWR.

### 5.4 Overall Results of U-NII Device Performance Against the San Juan TDWR and Bin 1 Waveform Pulse Bursts.

A summary of the results from specific U-NII device tests are given in Table 5. Entries highlighted in red indicate failures to detect.

Table 5. Summary of DFS Performance of U-NII Devices Tested In Situ Against the San Juan TDWR and Bin 1 Waveform Pulse Bursts.

| **Test** | **Source** | **Manufacturer A Model 2** | **Manufacturer B Model 1** | **Manufacturer C Model 1** |
|---|---|---|---|---|
| Channel Availability Check | Using actual TDWR signal | No radar detection | Not tested[1] | Not tested[1] |
| Channel Availability Check | Using Bin 1 Waveform | Consistent radar detection | Not tested[1] | Consistent radar detection |
| In-Service Monitoring | Using actual TDWR signal | Inconsistent radar detection | No radar detection | Not tested[1] |
| In-Service Monitoring | Using Bin 1 Waveform | Consistent radar detection | No radar detection | Consistent radar detection |
| [1] Not tested due to logistical constraints | | | | |

# 6 SUMMARY OF RESULTS

At the request of the FAA, NTIA's OSM and ITS provided technical assistance to examine interference into their San Juan, Puerto Rico TDWR. This was a two-week long, labor-intensive effort that required cooperation with local U-NII system operators and personnel from the ITS, OSM, FCC, and FAA. Measurements performed by these agencies ultimately confirmed that the interference was from U-NII devices operating in the 5 GHz band; specifically, devices operating between 5600-5650 MHz.

A carefully developed test plan for the investigation of interference to TDWR receivers was implemented in San Juan by a combined team of engineers from ITS, OSM, FAA, and the FCC. A brief summary of the results follows, categorized by general results and by results that are specific to the interference into the TDWR and to the U-NII devices themselves.

## 6.1 General Results

1. The U-NII interference was located using the radar's PPI display, combined with GPS mapping. The U-NII devices causing interference were found to be on the rooftops of tall buildings and towers located on hills in the San Juan area.

2. Many of the rooftops and towers have installations of 5 GHz U-NII systems from various manufacturers. Leading examples are point-to-point and point-to-multipoint U-NII devices operated by WISPs. The deployment of U-NII devices has become increasingly dense in the San Juan area.

3. The U-NII devices can be manually tuned away from the TDWR if the operators can be found and contacted. This will eliminate or reduce the number of interference strobes. However, this mitigation technique is only temporary and defeats the purpose and function of DFS.

## 6.2 TDWR Results

1. Interference to the TDWR receiver was due to U-NII signals at nine out of ten azimuths.

2. The duty cycle of the U-NII devices (typically 40% or greater) is well above the TDWR receiver's ability to process and mitigate that type of interference. With radar systems in general, mitigation is possible with duty cycles less than approximately 3%.

3. The U-NII interference was either co-channel or adjacent channel to the TDWR operating frequency at those azimuths. Both conditions caused visible interference strobes on the TDWR's PPI display.

## 6.3 Signal Environment Results

1. The signal power of the radar at the U-NII locations on the nine affected radar azimuths was at least 40 dB above the U-NII detection threshold.

2. The TDWR pulses were well-formed (sharp pulse rise and fall times) at the rooftop and tower locations where U-NII interference was originating.

## 6.4 Results for the Identified U-NII Devices

1. The Manufacturer B, Model 1 device case did not have an FCC ID label affixed.

2. The Manufacturer B, Model 1 device did not detect the TDWR signal or the Bin 1 Waveform radar pulse bursts in the In-Service Monitoring mode.

3. The Manufacturer C, Model 1 device consistently detected Bin 1 Waveform pulse bursts in both In-Service Monitoring and Channel Availability Check modes. Due to logistical constraints, it was not tested against the actual TDWR pulses.

4. The Manufacturer A, Model 2 device did not detect the TDWR during a pair of 60-second Channel Availability Check tests on a San Juan rooftop. It sometimes failed to detect the TDWR when it was operating in its In-Service Monitoring mode. When it did detect the TDWR during its In-Service Monitoring operation, such detections only occurred after several minutes, during which time it continued to transmit.

5. The Manufacturer A, Model 2 device consistently detected the Bin 1 Waveform pulse bursts. This waveform used pulses with the same width as those of the TDWR, but the PRI of these pulses differed from the PRI of the actual TDWR pulses.

6. The Manufacturer B, Model 1 provides users with an option to deactivate DFS functionality.[10] Some U-NII devices invoke DFS protocols that depend upon the geographic region in which the device is deployed. The operational region is a user-dependent setting, and some geographic zones have no DFS rules.[11] The extent to which individual users properly configure their DFS devices for geographic zones is not known.

After obtaining the initial results reported here, ITS performed additional testing in controlled environments to better understand how to resolve the interference, beyond the immediate, ad-hoc solution of having operators manually move their U-NII devices' frequencies away from the TDWR frequency—a temporary solution that defeats the purpose of DFS.

Part II will detail additional, follow-up testing at the ITS laboratory in Boulder, CO, and the FAA's Mike Monroney Aeronautical Center in Oklahoma City, to determine why some devices

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[10] This is not permitted under the U-NII rules.

[11] This is not permitted for operation in the United States.

fail to detect TDWR signals, understand the interference mechanism into TDWRs, and explore at what interference levels the TDWR performance degrades. ITS obtained several U-NII devices from various manufacturers to test against an engineering TDWR system, with representatives from the respective manufacturers present to witness testing and provide engineering support.

Part III of this series will contain engineering solutions that may be used as part of a strategic plan to resolve interference to TDWRs.

# 7 REFERENCES

[1] U.S. Department of Transportation, Federal Aviation Administration, Advisory Circular 00-54, *Pilot Windshear Guide*, Nov. 1988. <http://rgl.faa.gov/Regulatory_and_Guidance_Library/rgAdvisoryCircular.nsf/list/AC%2000-54/$FILE/AC00-54.pdf>, accessed on Sept. 25, 2010.

[2] Federal Communications Commission, *Revision of Parts 2 and 15 of the Commission's Rules to Permit Unlicensed National Information Infrastructure (U-NII) devices in the 5 GHz band*, ET Docket No.03-122, *Memorandum Opinion and Order*, 21 FCC Record 7672 (2006). <http://hraunfoss.fcc.gov/edocs_public/attachmatch/FCC-06-96A1.pdf>, accessed on Jul. 8, 2010.

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14. SUPPLEMENTARY NOTES

15. ABSTRACT

In early 2009, the Federal Aviation Administration (FAA) became aware of interference to Terminal Doppler Weather Radars (TDWRs) that operate in the 5600–5650 MHz band and provide quantitative measurements of gust fronts, windshear, microbursts, and other weather hazards for improved the safety of operations in and around major airports. This report describes field measurements and results from an interference examination of a TDWR in San Juan, Puerto Rico from unlicensed national information infrastructure (U-NII) dynamic frequency selection (DFS) devices operating in the same frequency band. Several U-NII devices from different manufacturers were found to be causing interference into the TDWR. These devices operate in the same bands as these Federal radar systems, but employ DFS technology that is supposed to detect the presence of nearby radar systems and change operating frequencies to prevent interference with an incumbent radar system. This is the first of a three-part series of reports that describe research efforts by the Institute for Telecommunication Sciences (ITS) engineers, with assistance from FAA engineers, to determine the cause of the interference, understand why some devices fail to detect TDWR signals, and to engineer solutions.

16. Key Words

dynamic frequency selection; unlicensed national information infrastructure; spectrum sharing technology; radar interference; RF interference; radar performance degradation ; terminal Doppler weather radar

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