NTIA Technical Report TR-11-479

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

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report series

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

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ABBREVIATIONS/ACRONYMS

AWG	Arbitrary Waveform Generator
AGL	Above Ground Level
CBS	Cavity Backed Spiral
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
IEEE	Institute of Electrical and Electronics Engineers
IF	Intermediate Frequency
I/N	Interference-to-Noise Ratio
ITS	Institute for Telecommunication Sciences
LNA	Low Noise Amplifier
MHz	megahertz
NTIA	National Telecommunications and Information Administration
OSM	Office of Spectrum Management
P_d	Probability of Detection
PPI	Plan Position Indicator
PRI	Pulse Repetition Interval
PSF	Program Support Facility
RF	Radio Frequency
TDWR	Terminal Doppler Weather Radar
U-NII	Unlicensed National Information Infrastructure
µs	microsecond
VSA	Vector Signal Analyzer
VSG	Vector Signal Generator

EXECUTIVE SUMMARY

In early 2009, the Federal Aviation Administration (FAA) reported 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 and determined the interference to be from 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 U-NII devices employ technology that is supposed to detect the presence of nearby radar systems and change operating frequencies to prevent interference with incumbent radar systems. Part I of this report series details the results of this measurement effort.

After determining the interference source in San Juan, Puerto Rico, ITS engineers tested these U-NII devices in controlled environments at the ITS laboratory in Boulder, Colorado and at an engineering TWDR system at the FAA's TDWR Program Support Facility (PSF) in Oklahoma City, Oklahoma. ITS tested several U-NII devices, some of which were provided by manufacturers, against emulated TDWR waveforms and FCC certification waveforms at the ITS laboratory, and waveforms generated by an actual TDWR at the PSF. Representatives from the respective U-NII manufacturers were present to witness testing and to provide engineering support. The primary goals of these tests were to: examine DFS detection performance of U-NII devices in the presence of TDWR signals; explore the interference levels at which TDWR performance visibly degrades; examine the U-NII device frequency off-tuning required to eliminate interference artifacts on the TDWR display from incorrectly configured U-NII devices; and explore how U-NII device energy coupling into TDWR antenna sidelobes impacts azimuthal direction finding. These performance tests and field measurements are described in this report.

In laboratory tests with emulated TDWR waveforms, four U-NII devices performed as intended off-the-shelf. One U-NII device did not detect the TDWR waveforms off-the-shelf (although, it did detect waveforms used in FCC certification). Eventually, this U-NII device detected emulated TDWR signals with prototype firmware, provided by the manufacturer that altered the DFS detection algorithms. A different U-NII device was tested against FCC DFS certification waveforms and it did not detect any. It also failed to detect any emulated TDWR waveforms. The device, however, was FCC certified, meaning it had passed these same tests when the FCC laboratory tested its DFS performance. A firmware update from the manufacturer eventually rectified this problem, illustrating how firmware upgrades can lead to DFS non-compliance.

In radiated tests with waveforms generated by an actual TDWR, U-NII device radar detection performance was found to be in agreement with laboratory testing. U-NII devices that failed to detect and avoid the TDWR generated interference artifacts on the TDWR display. Properly operating U-NII devices did not generate interference artifacts on a TDWR display when they operated on the nearest available frequencies (relative to the TDWR fundamental frequency) where their DFS functionality did *not* detect the TDWR. With the antenna geometry and distances tested in this report, a nominal minimum 20-MHz center-to-center frequency separation between the TDWR and the U-NII device was found to eliminate TDWR display interference artifacts.

Part III of this report series describes engineering solutions including frequency separation. These solutions 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 II

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

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. Institute for Telecommunication Sciences (ITS) engineers, with assistance from FAA engineers, determined the interference to be from unlicensed national information infrastructure (U-NII) dynamic frequency selection (DFS) devices, from several manufacturers, operating in the same frequency band as TDWR systems. 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 report describes measurements and results from controlled laboratory and field testing of these U-NII devices. This is the second of a three-part series of reports that describe research efforts by the ITS engineers, with assistance from FAA engineers, to determine the cause of the interference, examine the effects of the interference on TDWR systems, 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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[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 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 Part 15 rules for unlicensed devices and as such they are not permitted to cause interference to allocated and protected systems.[3] References to DFS operational behavior and a brief overview of DFS appear in [2] and [3].

Interference sources cause interference strobes to appear on the 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 from the TDWR in San Juan, Puerto Rico, marked with white lines for graphical clarity.

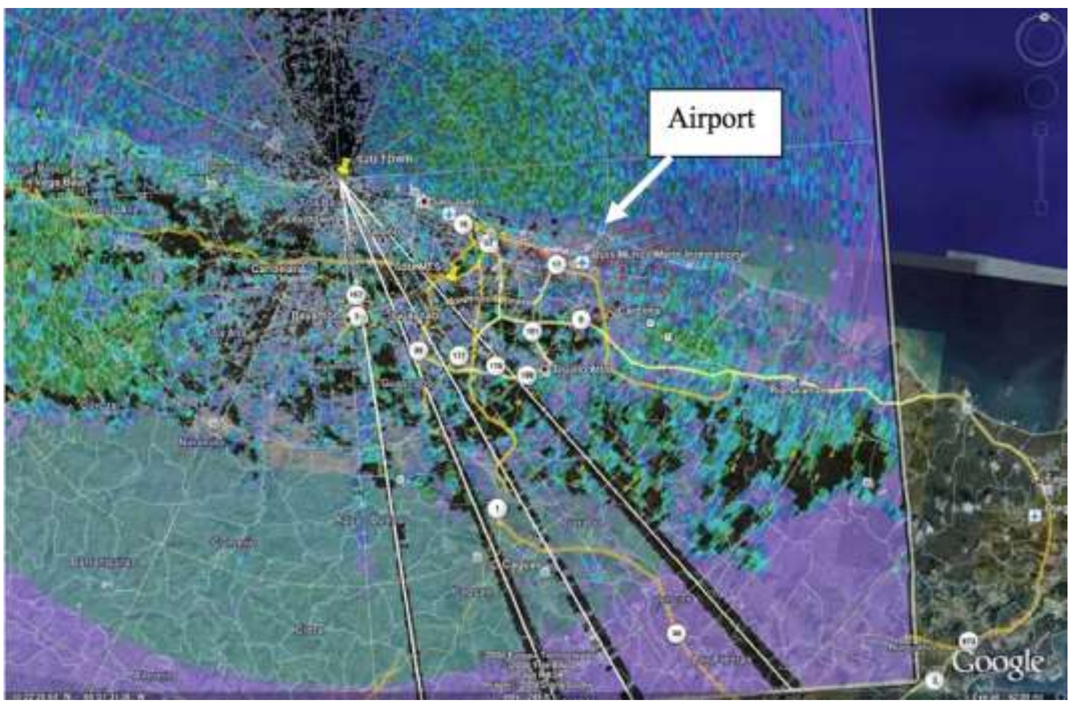

Figure 1. An example of interference artifacts on the San Juan TDWR PPI display. [4]

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 that confirmed 5 GHz U-NII devices, from various manufacturers, as the interference source.

Additional testing was performed in 2009 at the ITS laboratory in Boulder, Colorado and the FAA Mike Monroney Aeronautical Center TDWR program support facility (PSF) in Oklahoma City, Oklahoma, with various 5-GHz U-NII devices in controlled laboratory and field environments. Laboratory testing consisted of synthesizing 24 unique TDWR waveforms whose parameters were provided by the FAA. The 24 waveforms were generated using an Agilent E4438C vector signal generator (VSG). Supplemental laboratory testing of the U-NII devices against the “Bin 1 Waveform” [2] used in the FCC certification process was also performed. Field testing took place at the TDWR PSF. The TDWR PSF possesses an engineering TDWR that is not a part of the national TDWR network and it was made available for these tests.

These laboratory tests examined DFS detection performance of U-NII devices, from various manufacturers, in the presence of emulated TDWR signals. The field tests examined DFS detection performance of the same U-NII devices in the presence of an actual TDWR system, explored the interference levels at which TDWR performance visibly degrades, examined U-NII device frequency off-tuning required to eliminate interference strobes from incorrectly configured U-NII devices, and explored how U-NII device energy coupling into TDWR antenna sidelobes impacts azimuthal direction finding.

2 U-NII DEVICES TESTED

The U-NII devices shown in Table 1 were tested at the ITS laboratory in Boulder, Colorado and at the TDWR PSF, in Oklahoma City, Oklahoma, with an engineering TDWR system. As indicated in the table, some devices were procured by NTIA, while others were provided by manufacturers. IEEE 802.11, IEEE 802.16 and proprietary frame-based signal architectures were tested.

Table 1. FCC-certified U-NII devices used for DFS performance testing

Device Manufacturer[5]	Model	Ownership	Signal Architecture	Modulation Bandwidth
Manufacturer A	Model 2	NTIA	Frame-Based	20 MHz
Manufacturer A	Model 3	NTIA	Frame-Based	20 MHz
Manufacturer A	Model 4[6]	Manufacturer	Frame-Based	21 MHz
Manufacturer C	Model 1	NTIA	IEEE 802.16[7]	20 MHz
Manufacturer D	Model 1	NTIA	Frame-Based	20 MHz
Manufacturer E	Model 1	NTIA	Frame-Based	20 MHz
Manufacturer F	Model 1	manufacturer	IEEE 802.11	20 MHz
Manufacturer G	Model 1	manufacturer	IEEE 802.11	40 MHz[8]

In the 802.11 architecture, data is transmitted at the first available opportunity, so the channel is accessed on a per-packet basis. In 802.11 networks, channel time is randomly competed for. In 802.16 and other proprietary frame-based architectures, channel access is on a per-frame basis and may contain more than one data packet. In these network types, channel time is partitioned into dedicated transmit and receive segments. In this report, the term “frame-based” only refers to proprietary frame-based architectures. The 802.16 protocol (commonly referred to as WiMAX) is frame-based, however, it is not proprietary.

All tested U-NII devices used publicly available firmware unless otherwise noted.

Manufacturer A supplied a modified device for testing, which was loaded with firmware developed specifically for these tests; the modified firmware is not currently deployed in production Model 4 units from that manufacturer.

A Model 1 U-NII device from Manufacturer F was also modified for the testing. The modification allowed it to operate in the 5600–5650 MHz frequency range for the purpose of this testing; this manufacturer does not market U-NII devices that operate in this frequency range in North America.

[5] Manufacturer B did not provide, nor would they supply to NTIA, a device for this testing.
[6] The modified unit from Manufacturer A had no FCC ID because it was a prototype that had not yet been tested by the FCC.
[7] At the time of testing, this device was not WiMax-Forum certified, but nominally 802.16-compliant devices are commonly referred to as “WiMax” and that usage is adopted here. 802.16 is a frame-based signal architecture.
[8] The unit from Manufacturer G had more than one bandwidth mode available; 40 MHz was selected for this testing.

3 TEST WAVEFORMS

Three waveform categories, listed in Table 2, were used to test the DFS detection performance of the U-NII devices in Table 1. The first two categories are generated using a VSG. The first category is the "Short Pulse Radar Type 1 Waveform [3]," hereafter referred to in this document as the "Bin 1 Waveform." This waveform is currently used by the FCC in their certification process for 5-GHz U-NII devices. It was developed specifically to protect the TDWR.

For the second waveform category, ITS engineers created 24 unique VSG waveforms based on TDWR waveform parameters provided by the FAA. These waveforms replicate the 24 available waveforms in use by the TDWR. For the sake of clarity, these waveforms are referred to as "emulated TDWR waveforms," in that they have pulse parameters that are identical to those of an actual TDWR system, but are generated using a VSG. Only two parameters in the 24 emulated TDWR waveforms vary: pulse repetition interval (PRI) and pulses per burst (pulses per burst is a function of PRI).

Waveforms transmitted by an actual TDWR system constitute the third category. These waveforms are referred to as "actual TDWR waveforms" in this document.

Table 2. Waveform test categories

Waveform Category	Pulse Width	PRI	Pulse Type	Pulses per burst
Bin 1 Waveform	1 µs	1438 µs	Unmodulated	18
emulated TDWR	1 µs	518–3066 µs (24 discrete values)	Unmodulated	18–102
actual TDWR	1 µs	518–3066 µs (24 discrete values)	Unmodulated	N/A[9]

There are two key differences between the actual TDWR waveform category and the emulated TDWR waveform category. First, the emulated TDWR waveforms are a product of low-power, solid-state electronics. The actual TDWR waveforms are a product of high-power klystron vacuum tube amplifiers.

Secondly, unlike the emulated TDWR waveforms, the actual TDWR system will not transmit discrete bursts of pulses in boresight[10] mode or monitor-mode[11]. In monitor-mode, the TDWR system will vary PRI values as a function of antenna elevation angle. A given external location will observe a constant stream of pulses for a given PRI with varying amplitude (due to antenna sidelobe coupling) while the radar completes one azimuthal scan. This pulse sequence will continue with varying PRIs and amplitudes while the TDWR completes an entire scan, then the cycle will repeat.

[9] Due to TDWR antenna sidelobe coupling and changes in antenna elevation angle, an external location will experience a continuous sequence of pulses with varying PRIs and amplitudes.
[10] Boresight refers to the configuration where the TDWR antenna is fixed in both azimuth and elevation.
[11] A second scan mode, known as "hazardous mode" is used by the TDWR but was not tested in this study.

4 ITS LABORATORY MEASUREMENT RESULTS

The objectives of these laboratory tests were to:

- Test off-the-shelf 5-GHz U-NII devices for their DFS performance against the Bin 1 Waveform [2] and against emulated TDWR waveforms.
- Examine the effects on probability of detection (P_d) under different transmit and receive duty cycles. Some U-NII devices allow the user to modify the talk/listen ratio [2] of the device and, consequently, the duty cycle.
- Measure the emission spectra of the U-NII devices.

The test setup is shown in Figure 2.

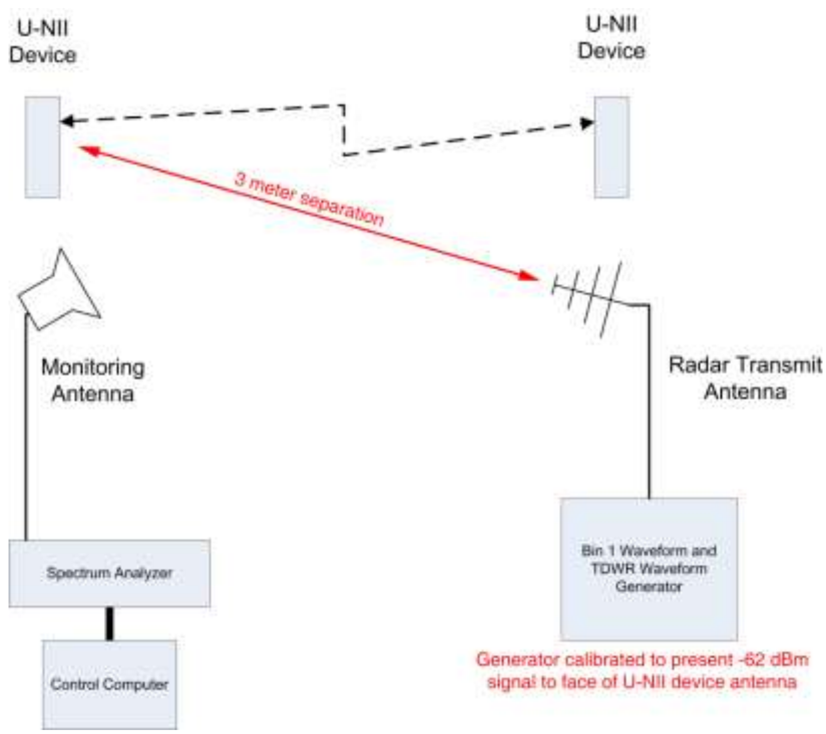

Figure 2. ITS Laboratory Test Setup.

Due to time constraints, it was not feasible to test each U-NII device against all 24 emulated TDWR waveforms. Rather, the U-NII devices were tested against the lowest, midmost, and highest available PRI of the 24 waveforms. These PRIs correspond to 518 µs, 838 µs (some tests inadvertently used 898 µs), and 3066 µs, respectively. At the request of the FAA, U-NII device response to additional PRIs was also examined during laboratory testing.

4.1 Test Results of DFS Detection Capability with Emulated TDWR Waveforms and with the Bin 1 Waveform

U-NII device response to the Bin 1 Waveform was first tested for each U-NII device. Emulated TDWR waveforms were subsequently tested. All waveforms were configured to transmit on the U-NII device operating frequency.

To reduce measurement uncertainty, trials for each waveform category were repeated 30 times. During each trial, the device's response (detection or no detection) to a given waveform was recorded. A successful detection was determined in one of two ways. The first was to monitor the U-NII device operating frequency with a spectrum analyzer and observe. If the U-NII device transmission ceased after a radar waveform was transmitted, the trial was considered to be a successful detection. The second method of determining a successful detection was to monitor the U-NII device's diagnostic information. Some manufacturers include notification of radar waveform detection in their device firmware.

The overall P_d for each tested waveform is shown in Table 3. The P_d was calculated by dividing the number of successful detections by the number of trials. A minimum successful P_d of 60% against the Bin 1 Waveform is required to attain FCC certification [3]. Each U-NII device was tested in the In-Service Monitoring mode, with data being sent across the U-NII network.

Some U-NII master devices [3] allow their talk/listen ratio to be configured. On master devices that allow their talk/listen ratio to be configured, the ratio was set to 45%/55% [3] for the results shown in Table 3. At this ratio, the U-NII device will, in any one frame duration, transmit during 45% of the frame time and listen for the remaining 55%. Other frame-based systems tested had a fixed ratio of 50%/50%, which is not user-accessible.

Table 3. U-NII device laboratory test results

Manufacturer	Model	Bin 1 Waveform	Emulated TDWR Waveform PRI Trials			Comments
			518 µs	**838 µs**	**3066 µs**	
Manufacturer A	Model 2[12]	100% P_d	0% P_d	0% P_d	0% P_d	
Manufacturer A	Model 3	100% P_d	73% P_d	0% P_d	0% P_d	
Manufacturer A	Model 4	100% P_d	0% P_d	66% P_d	43% P_d	
Manufacturer A	Model 4[13]	100% P_d	100% P_d	73% P_d	93% P_d	modified firmware
Manufacturer C	Model 1	0% P_d	0% P_d	0% P_d	0% P_d	original firmware
Manufacturer C	Model 1	100% P_d[14]	100%[15]	100%[15]	100%[15]	new firmware
Manufacturer D	Model 1	>60%	>60%	>60%	>60%	informal tests[16]
Manufacturer E	Model 1	>60%	>60%	>60%	>60%	informal tests[16]
Manufacturer F	Model 1[13]	90% P_d	100% P_d	100% P_d[17]	76% P_d	
Manufacturer G	Model 1[18]	100% P_d	100% P_d	100% P_d[17]	100% P_d	

The Manufacturer C, Model 1 device results in Table 2 illustrate how changes in firmware can lead to non-compliant U-NII devices. This U-NII device was tested against many FCC DFS certification waveforms, including the Bin 1 Waveform, and it did not detect any. It also failed to detect any of the 24 emulated TDWR waveforms. However, the device was FCC-certified, meaning it had passed these same tests when the FCC laboratory tested the DFS performance. The Manufacturer C, Model 1 device tested in this report had the same model number and FCC ID number as appeared in the FCC DFS certification database. The difference is in the device firmware; the non-compliant firmware tested by ITS was a later firmware revision than the firmware version tested by the FCC. It is believed that the DFS radar-detection failure of this device was somehow introduced during the firmware evolution. The FCC notified Manufacturer C of the problem and they provided a firmware update. The device was tested again after applying the firmware update and it detected all 24 emulated TDWR waveforms, as well as the Bin 1 Waveform.

4.2 Effects of Varying Master Device Talk/Listen Ratio for Manufacturer A's Device

Manufacturer A employs a frame-based architecture and allows operators to configure the talk/listen ratio of their master devices to various ratios. The FCC Memorandum Opinion and Order [3] currently specifies using a talk/listen ratio of 45%/55% for certification testing.

[12] Additional PRI values were tested for this model: 538 µs (0% P_d), 638 µs (0% P_d), 758 µs (0% P_d), 898 µs (0% P_d), and 938 µs (0% P_d).

[13] Modified firmware provided by the Manufacturer was utilized for this test; this firmware was not publicly available at the time of testing.

[14] This test was performed using only 10 trials, instead of 30.

[15] This device was later tested against all 24 emulated TDWR waveforms, each a single time. It detected all 24 of them. The reported percentages are based on a single trial at the stated PRI.

[16] These tests were conducted separately from the other tests and only success (P_d > 60%) was recorded.

[17] Manufacturer F and G testing inadvertently used a PRI of 898 µs instead of 838 µs. The reported P_d is for 898 µs.

[18] Additional PRI values were tested for this model: 638 µs (100% P_d), 698 µs (100% P_d), 758 µs (100% P_d), and 938 µs (100% P_d).

Manufacturer A user's manual suggests setting the talk/listen ratio to 75%/25% as a typical configuration. ITS engineers examined the overall P_d as a function of varying the talk/listen ratio to progressive reduce the duration of "listen time."

The test results show that the Manufacturer A device's P_d was severely degraded when the talk/listen ratio was set to the 75%/25% talk/listen ratio suggested in the user manual. The results for the Manufacturer A, Model 2 device, tested against the Bin 1 Waveform, are presented in Table 4.

Table 4. Results of Manufacturer A, Model 2, talk/listen ratio tests

Talk/Listen Ratio	**Bin 1 Waveform P_d**
45%/55%	100%
60%/40%	80%
75%/25% (user manual)	40%
95%/5% (highest allowed)	0%

As mentioned earlier, the minimum successful P_d required to obtain FCC certification is 60% for the Bin 1 Waveform. Therefore, if tested with a 75%/25% talk/listen ratio or a 95%/5% talk/listen ratio, the Model 2 device from Manufacturer A would fail to obtain FCC certification.

4.3 U-NII Device Emission Spectra

Radiated emission spectra were measured for several 5-GHz U-NII devices at the ITS laboratory and are presented in Figure 3. The U-NII device spectra generally drop 60–70 decibels (dB) from the peak power at the fundamental frequency within ±25 MHz of the fundamental frequency. Beyond that they tend to flatten out, sometimes for several hundred additional megahertz of spectrum on either side of the fundamental frequency. Note that in the figure, all of the U-NII fundamental-frequency power levels have been normalized to zero dB; actual equivalent isotropically radiated power (EIRP) emission levels of U-NII transmitters vary by tens of dB.

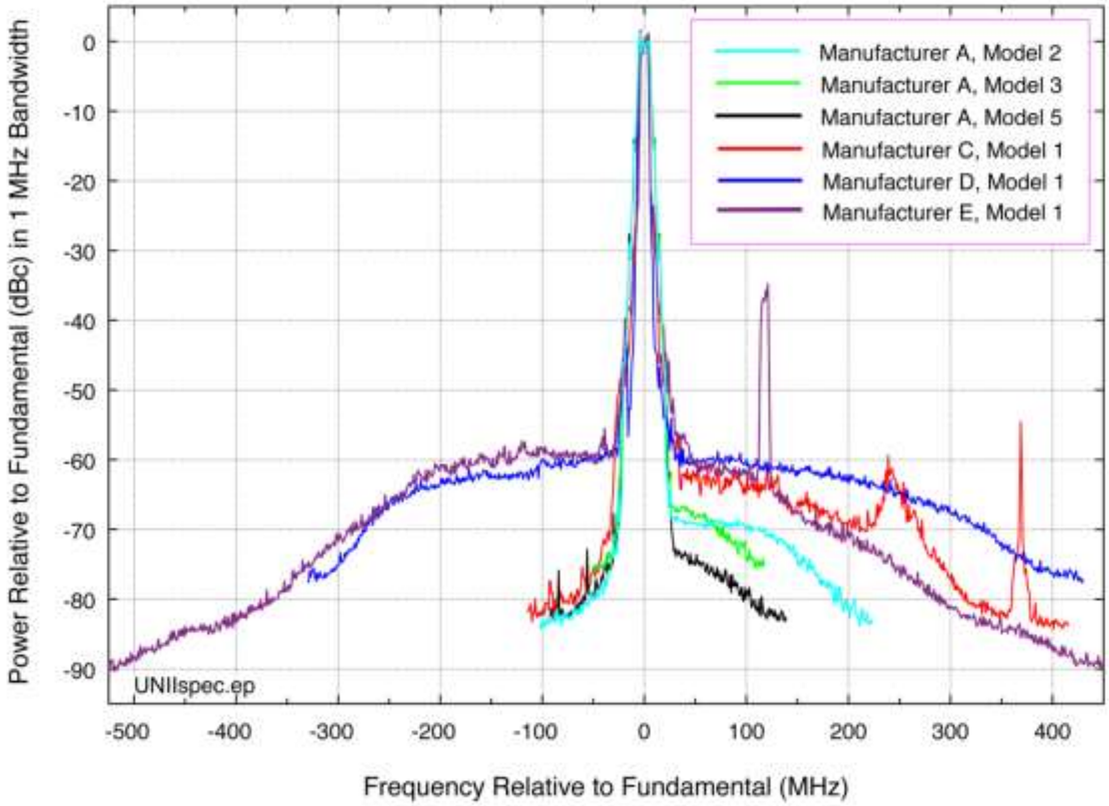

Figure 3. Radiated emission spectra, normalized to zero dB at the fundamental frequency (itself normalized to zero hertz) of several 5-GHz U-NII devices.

5 TDWR PSF TEST AND MEASUREMENT RESULTS

The objectives of the work at the FAA's TDWR PSF were to:

- Determine whether selected U-NII devices can reliably detect the TDWR signal in boresight mode and monitor-mode.

- Use emulated U-NII signals produced by a vector signal generator (VSG) coupled into the TDWR receiver via a hardline coupler to determine, qualitatively, the visible effects on the TDWR PPI at calibrated levels of interference power, *I*, to radar-receiver noise power, *N*, or (*I/N*), in the TDWR receiver.[19] These data were gathered for both the existing (legacy) TDWR receiver and for a new model of TDWR receiver that is currently in development but has not yet been deployed at operational sites, known as the "Sigmet RVP8."

- Determine the effect of TDWR antenna sidelobes on the reported interference azimuths on the PPI display.

- Measure the emissions of an actual TDWR system in the time and frequency domains.

- Determine the amount of required frequency off-tuning of a incorrectly functioning U-NII device to eliminate strobes on the PPI display.

To meet the first two test objectives, a suitable location for U-NII operation was identified where the signal power of the TDWR exceeded the -62 to -64 dBm FCC DFS detection threshold. An FAA warehouse located 2.97 miles (4.78 km) northeast of the TDWR was used for this purpose (Figure 4). The U-NII devices were positioned on the rooftop of the warehouse, 35 feet (10.6 m) above the ground, with a clear line-of-sight to the 80-foot-high (24.3-meter-high) TDWR antenna. The NTIA/ITS RSMS-4 vehicle, positioned next to the warehouse, provided electrical power and housing for computer control of the U-NII devices via cabling that was draped over the side of the building.

[19] See the Appendix of this report. Also, refer to [4] for the definition and meaning of this parameter.

Figure 4. Geometry of the PSF TDWR and the FAA warehouse facility where the U-NII master devices were located. [20]

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

To meet the third test objective, the interference injection and intermediate frequency (IF) monitoring equipment, shown in red in Figure 5, were located in the TDWR equipment shelter located at ground level directly adjacent to the elevated TDWR antenna.

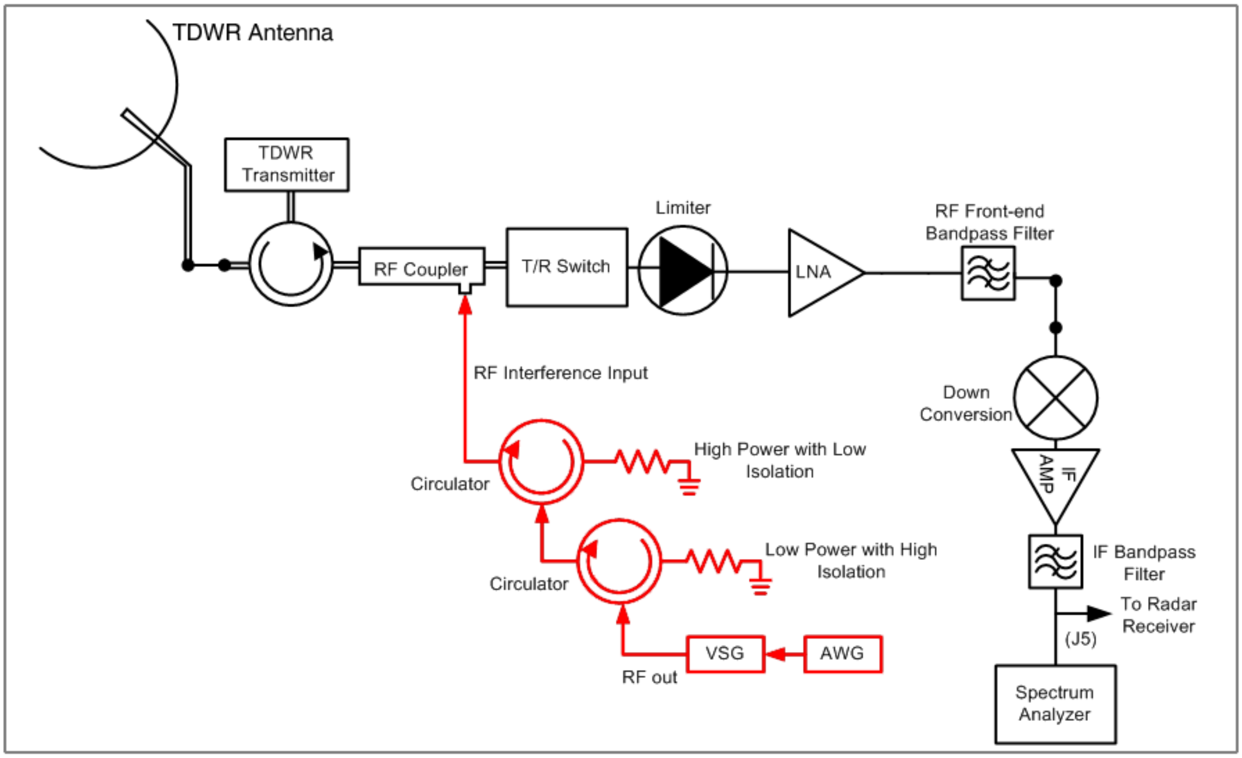

Figure 5. Block diagram for injection of U-NII interference waveforms into the TDWR receiver. Items shown in red were provided by NTIA.

5.1 Measurements of Actual TDWR Emissions in the Time Domain

A spectrum analyzer and measurement antenna (placed on the roof of the warehouse in the same position as the U-NII devices) were used to measure the TDWR signal power in the time domain. The spectrum analyzer was located inside the RSMS-4 vehicle, as was the control computer. Measurements were made with the TDWR boresighted on the warehouse and in its monitor-mode scan. The analyzer resolution bandwidth was set to 1 MHz and the detection mode was set to positive-peak. The 1-MHz resolution bandwidth matched the TDWR receiver's IF processing bandwidth. The measurement antenna was a cavity-backed spiral (CBS) antenna that has a gain of 6.5 dBi and is circularly polarized.

Figure 6 shows that the incident TDWR power at the warehouse rooftop was well above the -64 dBm threshold, even when the TDWR main beam was not aimed directly at the rooftop. For low-elevation angle scans, the incident peak power in a 1-MHz bandwidth was as much as -20 dBm. The power out of the antenna sidelobes was also usually above the DFS detection threshold. The power from the TDWR has been corrected to the level that would have been measured with a 0-dBi gain antenna with linear polarization.

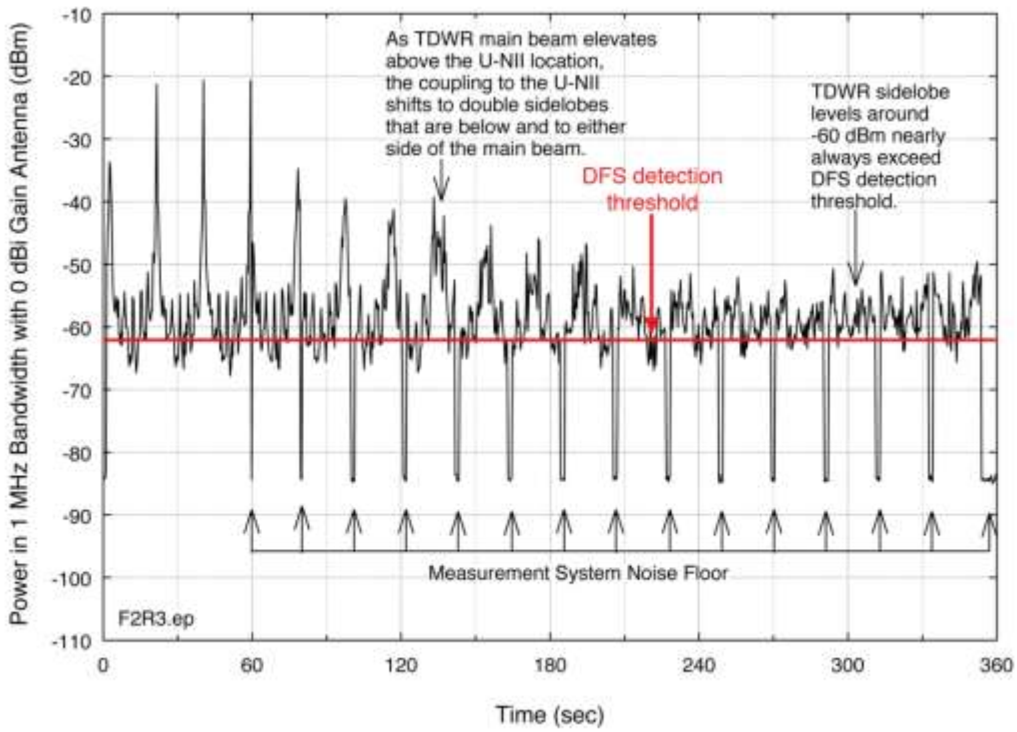

Figure 6. Power received from the TDWR at the FAA warehouse facility U-NII location throughout one complete monitor-mode scan.

Measurements were also made of individual pulses in the time domain to show that the radar pulse-shape envelopes were without distortion at the U-NII location. A typical pulse envelope measured at that location is shown in Figure 7. As shown in this figure, the pulse is very similar to the transmitted rectangular pulse shape.

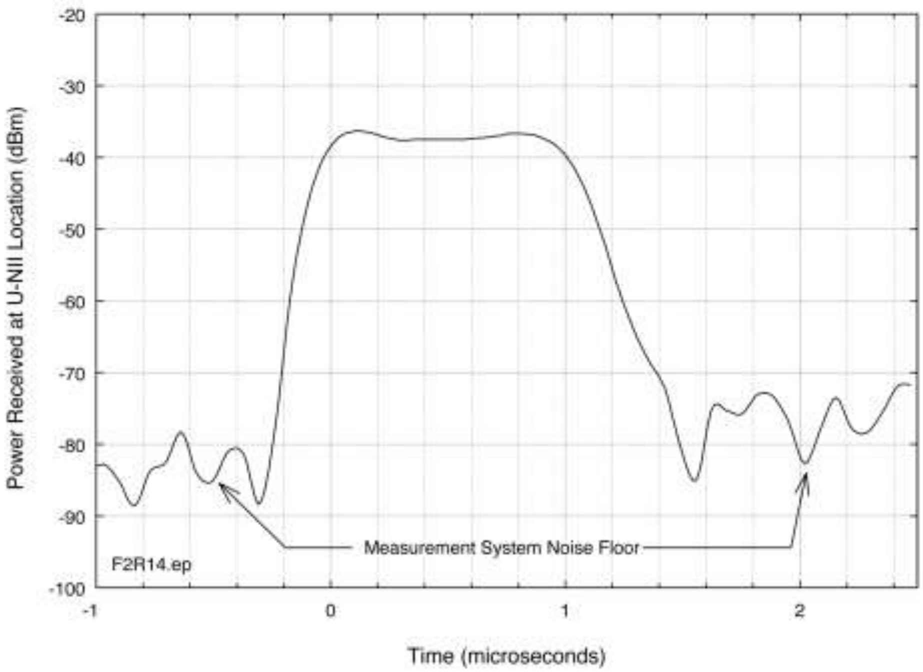

Figure 7. A single TDWR pulse in the time domain at the U-NII location.

5.2 U-NII DFS Performance Against Actual TDWR Waveforms

Each of the U-NII devices in Table 1 was tested in the presence of actual TDWR emissions, with the U-NII master device placed on the warehouse rooftop. For all but one case, the U-NII client device [3] was nearly co-located on the rooftop.[21] An MPEG test file was streamed between the master and client device to simulate a loaded U-NII channel. U-NII device detection capability was tested while the TDWR operated in monitor-mode scan where the PRI varies with the antenna elevation angle. Fixed PRI testing was performed with the antenna beam boresighted on the warehouse rooftop with PRI values of: 518, 598, 798, 838, and 3066 µs. Table 5 summarizes the results for U-NII detection of selected TDWR PRI values, spanning the range of PRI values available in the radar design. Each PRI was tested between five to ten times per device.

[21] In one exception, a Manufacturer D U-NII device was located about 2.3 miles (3.7 km) from the warehouse and 0.72 miles (1.15 km) from the TDWR, on the tower of an L-Band radar system. This separation between the U-NII device pair was necessary to ensure the proper functioning of the U-NII devices.

Table 5. Summary of DFS detection of selected, actual TDWR waveforms

U-NII Device	TDWR Waveform PRI Trials					Monitor Mode
	518 µs	598 µs	798 µs	838 µs	3066 µs	
Mfr. A Model 2	100%	0%	0%	0%	0%	no
Mfr. A Model 4[22]	100%	100%	100%	100%	100%	yes
Mfr. C Model 1	0%	0%	0%	0%	0%	yes[23]
Mfr. D Model 1	100%	100%	100%	100%	100%[24]	yes
Mfr. E Model 1	100%	100%	100%	100%	100%	N/A
Mfr. F Model 1	100%	100%	100%	100%	100%	N/A
Mfr. G Model 1	100%	100%	100%	100%	100%	N/A

The Model 2 device from Manufacturer A with the off-the-shelf firmware available at the time and the Manufacturer C device did not reliably detect the TDWR waveforms. Five U-NII devices, including the Model 4 device from Manufacturer A (using modified firmware not publicly available) reliably detected all of the actual TDWR waveforms.

5.3 Qualitative Determination of U-NII *I/N* Levels that Cause TDWR PPI Strobes

Emissions of selected U-NII devices were digitized using an Agilent 89601 vector signal analyzer (VSA) at the ITS laboratory in Boulder, Colorado. The recordings were injected (Figure 5) into the TDWR receiver, generated with an Agilent E4438C VSG, at the RF stage to determine the Interference-to-Noise (*I/N)* levels at which strobes appear on the meteorological PPI display. The simulated U-NII emissions were co-channel with the TDWR. The PPI screens were recorded in JPEG format for each *I/N* level[25] for each U-NII waveform. The test equipment was set up so that the Arbitrary Waveform Generator (AWG) would trigger the VSG to output U-NII device emissions such that 10 azimuths of interference would be visible on the PPI when the strobe threshold was exceeded. This process was repeated for both the existing (legacy) TDWR receiver as well as the newly developed TDWR receiver (Sigmet RVP8) which has not yet been deployed operationally. Tests in Oklahoma City with the RVP8, showed corresponding levels of effects at *I/N* levels that were 3 dB lower than observed with the legacy receiver.

[22] Modified firmware was used for this device; this firmware was not publicly available at the time of testing.
[23] The device took approximately 12 minutes to detect the TDWR. In general, the device did not detect the TDWR waveforms.
[24] The device took anywhere from 45 seconds to 135 seconds to detect the 3066 µs PRI.
[25] See the Appendix to this report. Additionally, the I/N measurement method described here is detailed in [3].

Regardless of the U-NII signal type (frame-based, 802.11, or 802.16), strobes begin to appear very faintly (at a level that is almost invisible to human observers) on the TDWR PPI with the legacy receiver at *I/N* = -6 dB and on the same display with the Sigmet RVP8 receiver at *I/N* = -9 dB. Such displays are shown in Figures 8 and 9. The strobes were observed when emissions replicating the modulation of Manufacturer E's U-NII device were injected into the radar receiver.

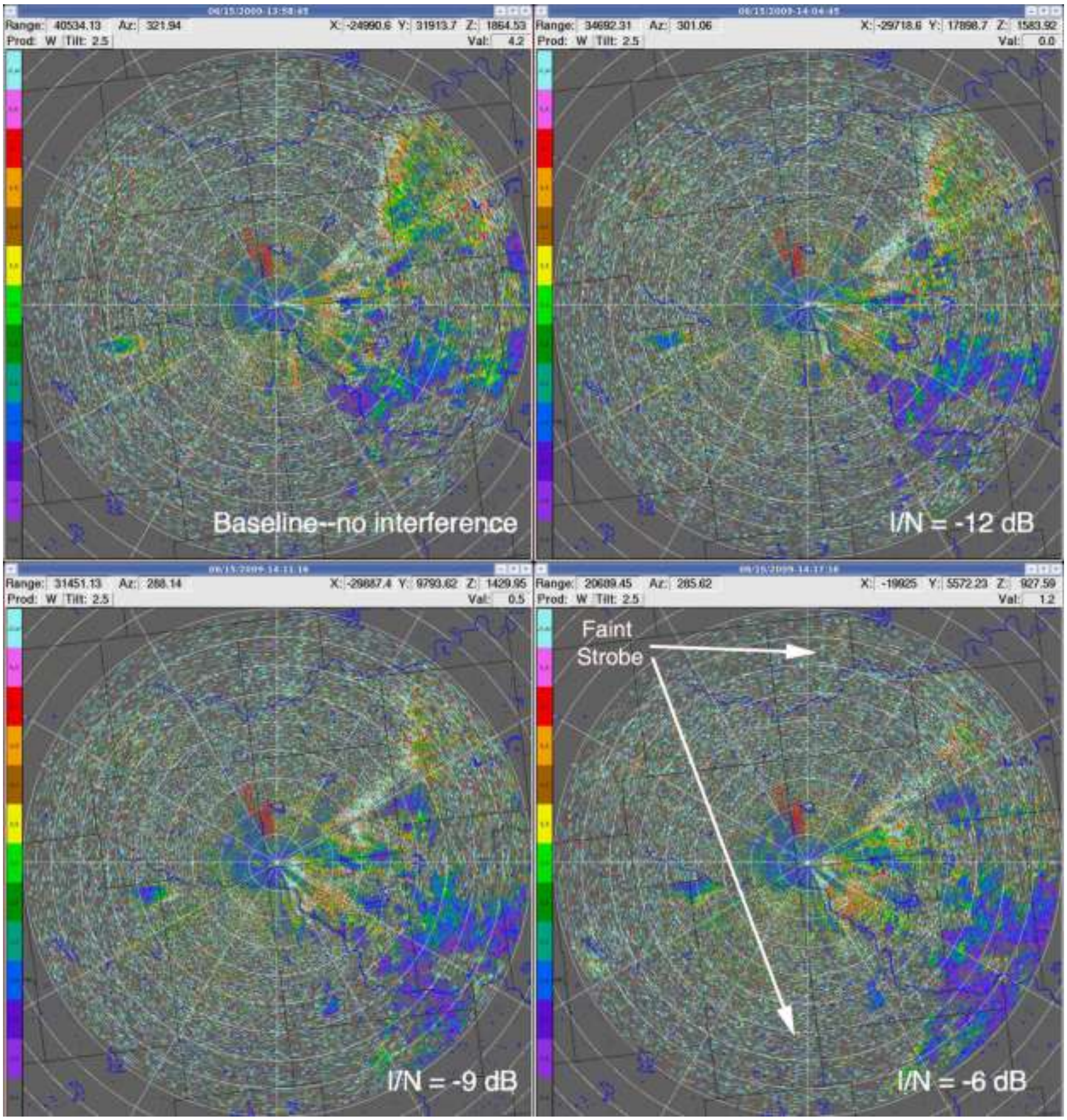

Figure 8. TDWR meteorological display PPI showing effects of frame-based interference (Manufacturer E) injected on a hardline from a VSG at baseline (no interference), and *I/N* = -12 dB, -9 dB, and -6 dB, respectively.

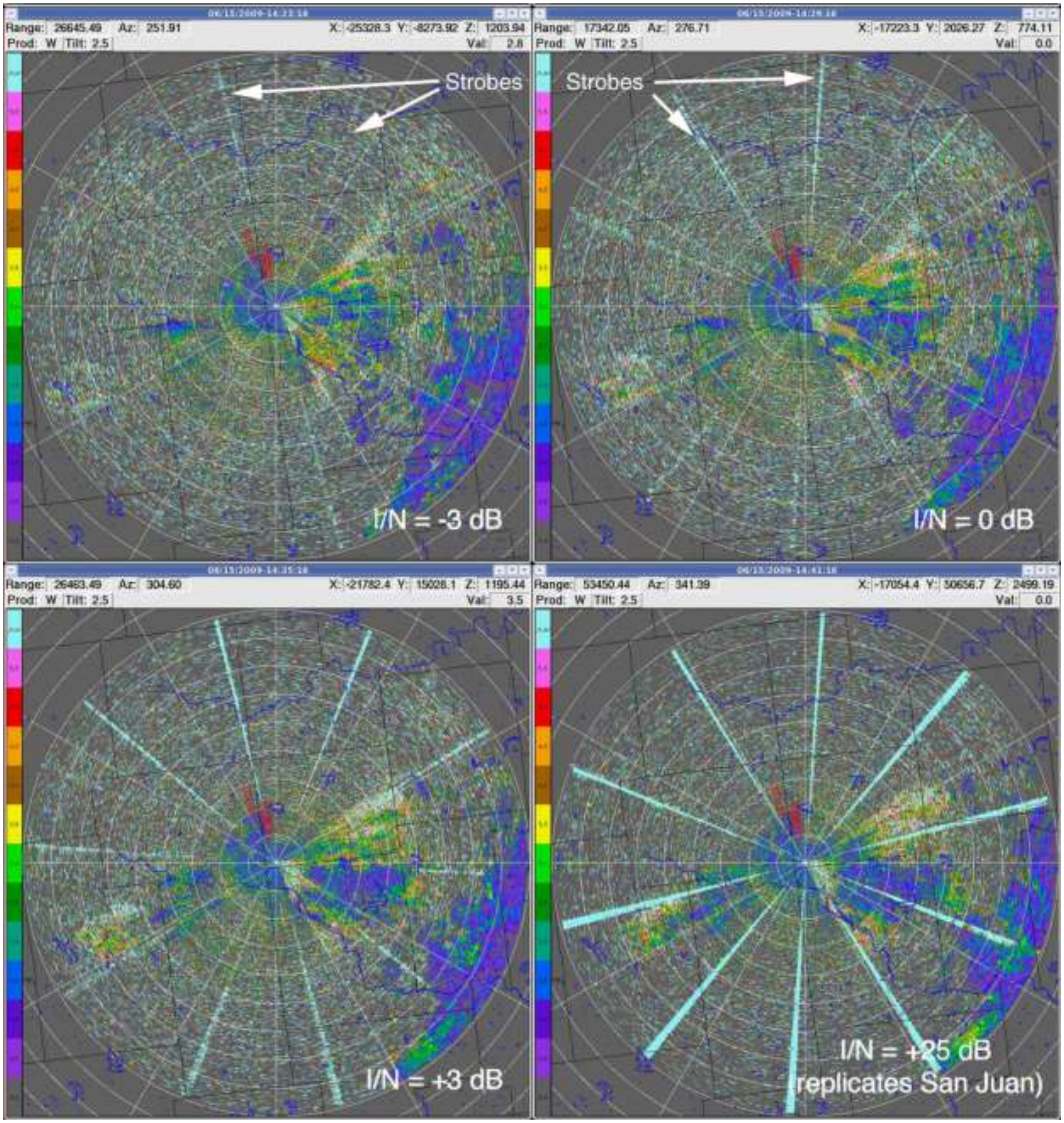

Figure 9. TDWR meteorological display PPI showing effects of frame-based interference (Manufacturer E) injected on a hardline from a VSG at *I/N* = -3 dB, 0 dB, +3 dB, and +25 dB, respectively.

It is important to note that the possibility of TDWR data corruption exists at I/N levels below the point at which visible strobes occur on the PPI [4]. The effects of this are insidious; data gathered from certain azimuths may be corrupt, but no indication to the user exists. During these tests, NTIA and FAA engineers had no readily available mechanism to confirm if this was occurring.

5.4 Effects of TDWR Antenna Sidelobes on PPI Displays

For this portion of testing, some of the U-NII devices were forced to *not* vacate the TDWR channel when the radar was detected.[26] The purpose was to observe interference strobes on the PPI display in such a way as to replicate the behavior of U-NII devices that might not, due to a failure of DFS sensing, vacate a TDWR's frequency.

The results showed that co-channel U-NII emissions at a distance of 2.97 miles (4.78 km) from the TDWR receiver can produce strong (meaning well-defined and opaque) interference strobes on the radar's PPI display.

It was also observed that single U-NII sources produce strobes on multiple azimuths, as shown in Figure 10. The PPI in Figure 10 shows areas of non-U-NII clutter; these areas of clutter were visible on the PPI with the U-NII devices powered off. The U-NII device strobes are due to coupling from the U-NII to the sidelobes of the TDWR antenna. As the TDWR antenna main beam elevation angle increases from 0.3 degrees to 30.6 degrees, the coupling of the U-NII signal into the TDWR antenna side lobes causes the intensity and azimuths of the strobes to vary considerably. Strobe width increases as interference power in the TDWR antenna pattern increases, resulting in variation in the interference azimuthal widths. In this geometry, a single strobe occurring on the U-NII azimuth is never witnessed, instead strong strobes occur on azimuths that are anywhere from tens of degrees to as much as 180 degrees away from the U-NII azimuth, and sometimes are not observed on the U-NII azimuth at all. (It is emphasized that this U-NII device had to be forced, via the use of an engineering mode not accessible to users, to operate co-channel with the TDWR for this strobe test. Operated under normal DFS software control, it would not tune closer than 41 MHz to the TDWR frequency, and did not produce strobes under that condition.)

The implications of this sidelobe-coupling behavior are:

1. A single U-NII device can and will produce strobes on multiple azimuths on a TDWR display.

2. The strobe azimuths will vary as a function of the TDWR antenna main beam elevation angle.

3. At some TDWR antenna main beam elevation angles, *no* strobes will occur on the actual azimuth of the U-NII device, but some strobes will occur on azimuths on either side of the true azimuth of the U-NII device.

4. Locating incorrectly operating U-NII devices based on observed strobe azimuths on the TDWR PPI display will generally be a difficult problem to solve.

[26] This non-vacating behavior was accomplished by accessing U-NII test-and-engineering modes that are not accessible to users.

5. If any U-NII device that is producing strobes at a TDWR field site can be located, multiple strobe azimuths may be eliminated.

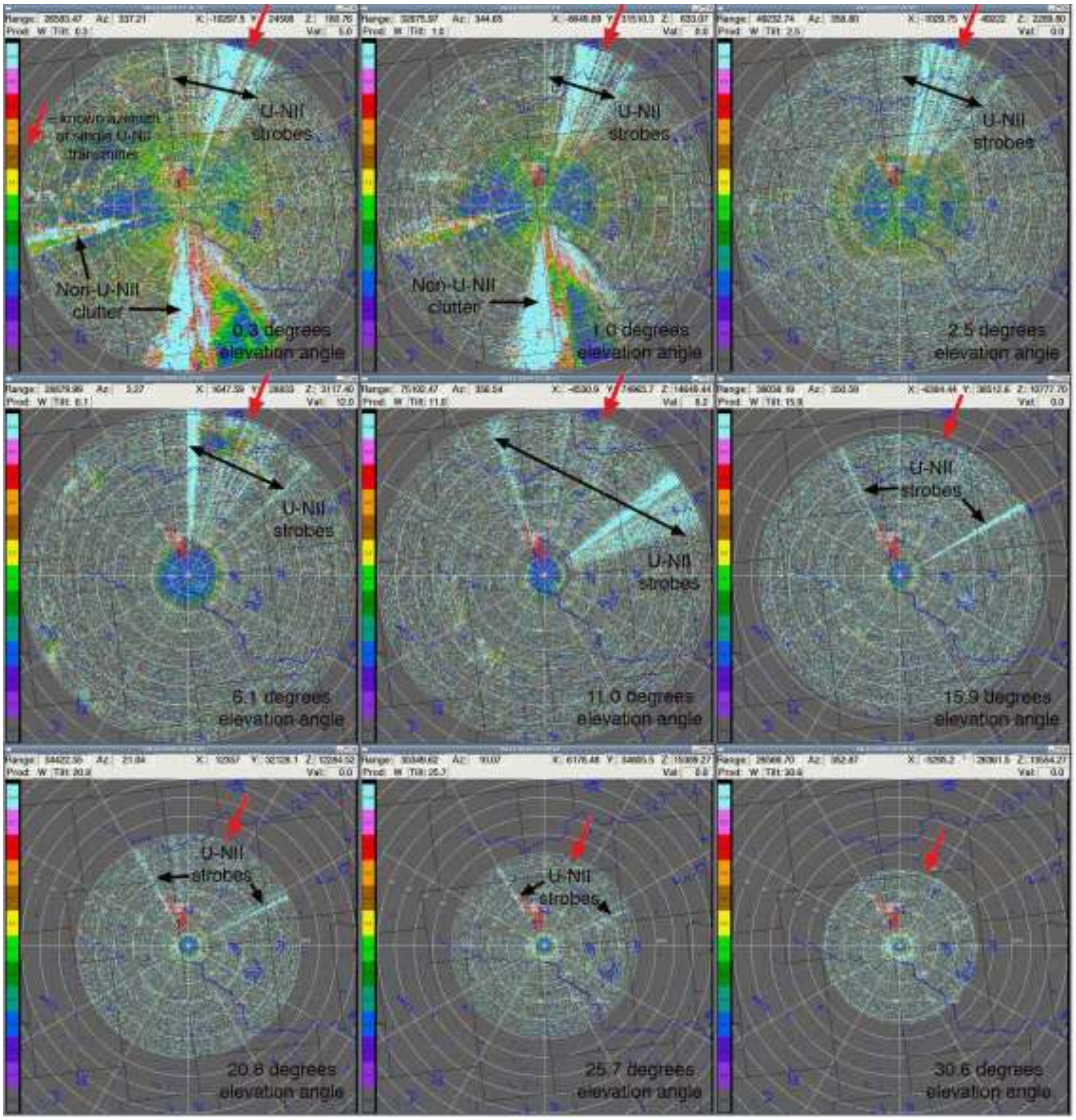

Figure 10. TDWR 360-degree-scan interference strobes generated by a U-NII transmitter (Manufacturer D, Model 1) on a rooftop 2.97 miles (4.78 km) from the TDWR, at an azimuth indicated by the red arrows and at a height of 35 feet (10.6 m) above the ground.

5.5 U-NII Device Off-Tuning For Strobe Elimination

Some of the U-NII devices were again forced to *not* vacate the TDWR channel when the radar was detected. The purpose was to observe interference strobes on the PPI display in such a way as to replicate the behavior of U-NII devices that might not, due to a failure of DFS sensing, vacate a TDWR's frequency. U-NII device frequencies were then manually tuned away from the

TDWR operating frequency until PPI strobes disappeared. During the field tests at the TDWR PSF, the coupling between the U-NII device antennas and the TDWR antenna was mainbeam-to-sidelobe.[27] In this geometry, a frequency separation of 10 MHz (or more) between the TDWR frequency and the 3-dB point of the U-NII device emission spectra or a nominal minimum 20-MHz center-to-center frequency separation between the TDWR and the U-NII device was found to eliminate PPI strobes. This observation is based on measurements of a limited number of U-NII devices (five) operating line-of-sight to the TDWR in this geometry.

As was earlier observed in San Juan, PR (Part I of this series), the coupling between the U-NII transmitter antennas and the TDWR antenna can often actually be mainbeam-to-mainbeam. This interference coupling scenario could not be empirically examined at the TDWR PSF location due to logistics. Report III of this series discusses mainbeam-to-mainbeam coupling in further detail.

[27] The TDWR antenna height above ground level (AGL) was 98 feet (29.8 m) and the U-NII height was 40 feet (12.2 m) AGL, at a separation distance of 2.97 miles (4.78 km).

6 SUMMARY OF TEST RESULTS

1. A Model 2 U-NII device from Manufacturer A detected the Bin 1 Waveform used in FCC certification but did not detect the emulated or actual TDWR waveforms at the ITS Laboratory or at the TDWR PSF.

2. A Model 2 U-NII device from Manufacturer A with modified firmware (provided by the manufacturer) successfully detected the emulated and actual TDWR waveforms at the ITS lab and at the TDWR PSF.

3. The Manufacturer A U-NII devices' ability to detect the radar signal in the ITS laboratory was severely degraded using the Bin 1 Waveform for in-service monitoring when the talk/listen ratio was set to the user manual suggested value of 75%/25%.

4. A Model 1 device from Manufacturer C failed to detect the actual TDWR signal at the TDWR PSF during boresight testing, only detected the actual TDWR signal at the TDWR PSF on two out of four monitor-mode scans, failed to detect the Bin 1 Waveform, and failed to detect all 24 emulated TDWR waveforms during laboratory testing. This device was certified for DFS functionality with a different firmware revision number than the one that failed both the laboratory and field tests, although it was still using the original FCC ID number. After new firmware was loaded onto this device, it successfully detected the Bin 1 Waveform and all 24 emulated TDWR waveforms during subsequent laboratory testing.

5. Four off-the-shelf U-NII devices from Manufacturers D, E, F and G reliably detected the actual TDWR waveforms at the TDWR PSF; a device from Manufacturer A reliably detected the actual TDWR signals after a firmware upgrade provided by the manufacturer (see item 2 above).

6. Properly operating U-NII devices did not generate strobes on the TDWR PPI display when they operated on the nearest available frequencies (relative to the TDWR fundamental frequency) and when their DFS functionality did *not* detect the TDWR emission.

7. A frequency separation of 10 MHz (or more) between the TDWR center frequency and the 3-dB point of the U-NII device emission spectra or a nominal minimum 20-MHz center-to-center frequency separation between the TDWR and the U-NII device was found to eliminate PPI strobes in interference geometries with U-NII device mainbeam to TDWR antenna sidelobe coupling. This observation is based on measurements of a limited number of U-NII devices operating line-of-sight to the TDWR.

8. The results of laboratory versus field measurements and tests of the DFS functionality of the seven U-NII devices that were evaluated are in agreement with each other. Therefore, any additional testing with U-NII devices (for their ability to detect the actual TDWR radar signals) can be done in the ITS or FCC laboratories with emulated TDWR signals. Additional in-situ tests at TDWR facilities are not necessary.

9. Strobes appear very faintly on the TDWR PPI at some elevation angles at an *I/N* of -6 dB, regardless of the type of U-NII signal modulation, for the existing (legacy) TDWR receiver. They appear faintly at an *I/N* of -9 dB for the newly developed, but not-yet-deployed RVP8[28] TDWR receiver. Strobes become progressively stronger in appearance as the *I/N* level increases.

10. The TDWR sidelobe interaction with a single U-NII interference source will generate strobes at multiple azimuths on the PPI display. The response depends on the TDWR antenna main beam elevation angle: this sidelobe coupling occurs even when the TDWR main beam is elevated substantially above the angle where it would directly illuminate a U-NII location. In this geometry, little or no strobe activity occurs solely on the U-NII azimuth; instead, strong strobes occur on azimuths that are anywhere from tens of degrees to as much as 180 degrees away from the U-NII azimuth. This increases the difficulty of identifying interference sources based on strobe-azimuth data, but also means that elimination of a single U-NII interference source may eliminate multiple TDWR strobes.

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[28] Two new TDWR receiver designs, the 14-bit RVP8 and the 16-bit RVP9, are currently in progress. The RVP9 is predicted to show interference effects at *I/N* levels that are around -12 dB, but no RVP9 was yet available for evaluation when the U-NII interference tests were performed.

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APPENDIX: INTERFERENCE-TO-NOISE RATIO IN RADAR RECEIVER PERFORMANCE TESTS

Microwave radar receivers detect objects in space (generically referred to as targets) by processing the power in successive transmitted-pulse echoes in such a way as to reinforce a series of echoes from a single object or weather phenomenon into a power level that exceeds a detection threshold. Non-meteorological radars perform this target-detection function for discrete targets such as aircraft, while meteorological radars detect spatially-extended atmospheric phenomena. All microwave radars are ultimately limited in their target-detection capability by electronic noise that is generated by thermal electrons in the receiver circuitry. In many radar receivers, the performance of a single component, the RF front-end low-noise amplifier (LNA), determines the overall thermal-noise limit for the entire receiver, and thus is critically important to the overall performance of the entire receiver. The thermal noise generated by an LNA is equal to the fundamental noise limit imposed by quantum-atomic physics, multiplied by a coefficient called the noise factor:

$$\boldsymbol{n = (kTB) \cdot nf} \qquad (1)$$

where:

n = noise power generated by the LNA (W);
k = Boltzmann's constant, 1.38×10^{-23} J/K;
T = temperature of the receiver (K);
B = bandwidth of the receiver circuitry (Hz);
nf = noise factor of the LNA (dimensionless).

Rendered into decibel terms, (1) becomes:

$$\boldsymbol{N = 10log_{10}(kTB) + NF = \left(-204\frac{dBW}{Hz}\right) + NF = \left(-174\frac{dBm}{Hz}\right) + NF} \qquad (2)$$

where:

N = noise power generated by the LNA (conventionally dBW or dBm);
$NF = 10\log_{10}(nf)$ = so-called noise figure of the LNA.

For T = 290 K and B is 1 Hz, $10\log_{10}$(kTB) = -204 dBW = -174 dBm. For a TDWR with a 1 MHz-wide receiver bandwidth, the value of $10\log_{10}$(kTB) is (-174 dBm + 60 dB) = -114 dBm. If the noise figure, NF, of the LNA is 1 dB, then the thermal noise limit, N, against which meteorological phenomena must be detected is N = -113 dBm.

Due to engineering limitations on the EIRP that radar transmitters can generate, along with the relatively small reflection cross sections of most radar targets, the pulse-echo energy from most radar targets, including meteorological phenomena, is actually lower than N. Such energy can nevertheless be detected for two reasons: first, since the pulse-echo energy adds linearly to the thermal noise power in the receiver, the sum of the two power levels can sometimes be detected directly; second, radar receivers do not generally detect the echoes of single pulses, but instead use the coherently correlated power in successive pulse echoes to integrate a final power level that does exceed N.

Radars that detect and track aircraft typically need 15-20 successive pulse echoes to form a detectable target in the receiver circuitry, while meteorological radars need about 30-50 successive pulse echoes to form detectable patterns of atmospheric phenomena. This requirement for a minimum number of pulse echoes to detect targets, combined with the minimum requisite interval between pulses to meet maximum-range requirements, ultimately determines the rate at which a radar beam can be scanned through space.

The most important point to understand about this entire process is that all microwave radars operate against their own receiver's thermal noise. But just as echo power from desired targets or meteorological phenomena adds to N, so too does RF interference energy in the receiver add to N. As RF interference power, i, adds to n, desired targets are obscured in the radar receiver detection circuitry. In the presence of interference power the radar power level against which targets must be detected is not n, but instead is (i + n). Consider, for example, a situation in which the level of i is 9 dB lower than n. In that case, the sum of the two power levels, expressed in decibels, is:

$$\mathbf{10}\boldsymbol{log}_{\mathbf{10}}(\boldsymbol{i}+\boldsymbol{n}) = \mathbf{10}\boldsymbol{log}_{\mathbf{10}}\left(\mathbf{10}^{-\frac{\mathbf{9}}{\mathbf{10}}} + \mathbf{10}^{\frac{\mathbf{0}}{\mathbf{10}}}\right) = \mathbf{10}\boldsymbol{log}_{\mathbf{10}}(\mathbf{0.13}+\mathbf{1})$$
$$= \mathbf{0.5}\ \boldsymbol{dB\ higher\ than\ N}$$

where *N* is normalized to 0 dB, and *i* and *n* are the linear power levels corresponding to the decibel values of *I* and *N*.

If the interference power is 6 dB lower than the radar receiver's inherent thermal noise floor, then the sum of the two quantities raises the effective limit against which targets must be detected by $10\log_{10}(0.25+1) = 1$ dB. If the interference power is equal to the radar receiver's inherent noise floor, then the effective limit against which targets must be detected increases by $10\log_{10}(1+1) = 3$ dB, and so on. Table A-1 shows how effective radar receiver noise, $\mathbf{10}\boldsymbol{log}_{\mathbf{10}}\left(\frac{\boldsymbol{i}+\boldsymbol{n}}{\boldsymbol{n}}\right)\ \boldsymbol{or}\ \frac{\boldsymbol{I}+\boldsymbol{N}}{\boldsymbol{N}}$ (in decibels), varies as a function of *I*/*N*.

Table A-1. Effective radar receiver noise-limit increase, (I+N)/N, as a function of I/N

I*/*N	**Effective Increase in Radar Receiver Noise, (*I*+*N*)/*N***
-9 dB	0.5 dB
-6 dB	1 dB
0 dB	3 dB
10 dB	10.4 dB (notice that (*I*+*N*)/*N* approaches *I*/*N* as $I \gg N$)

Because the ratio, I/N, of the interference power level to the radar receiver's inherent noise-power level is the quantity of concern in this analysis, measurements of radar receiver performance in the presence of interference are always quantified by NTIA in terms of radar target-detection performance as a function of that ratio. NTIA studies [1] have shown that when I/N = -6 dB, most radars begin to show measurable losses in target-detection performance.

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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 safety of operations in and around major airports. Institute for Telecommunication Sciences (ITS) engineers, with assistance from FAA engineers, determined the interference to be from unlicensed national information infrastructure (U-NII) dynamic frequency selection (DFS) devices, from several manufacturers, operating in the same frequency band as TDWR systems. 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 report describes measurements and results from controlled laboratory and field testing of these U-NII devices. This is the second of a three-part series of reports that describe research efforts by the ITS engineers, with assistance from FAA engineers, to determine the cause of the interference, examine the effects of the interference on TDWR systems, and 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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