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Measurement Procedures for the Radar Spectrum Engineering Criteria (RSEC)

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Certain commercial companies, equipment, instruments, and materials are identified in this report to specify adequately the technical aspects of the reported results. In no case does such identification imply recommendation or endorsement by NTIA, nor does it imply that the material or equipment identified is necessarily the best available for the applications described.

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EXECUTIVE SUMMARY

The National Telecommunications and Information Administration (NTIA) within the Department of Commerce serves as the President's principal advisor on telecommunication policy and is responsible for management of the Federal Government's use of the radio frequency spectrum. Through the Technical Subcommittee (TSC) of the Interdepartment Radio Advisory Committee (IRAC), Federal agencies develop spectrum standards to ensure effective and efficient use of the spectrum.

Federal radio stations and systems must comply with spectrum standards contained in the NTIA Manual of Federal Regulations and Procedures for Federal Radio Frequency Management (referred to herein as the NTIA Manual). A radio frequency spectrum standard is a principle, rule, or criterion that bounds the spectrum-related parameters and characteristics of a radio station or system for the purpose of managing the radio frequency spectrum. Primary radar systems operating as radiodetermination stations, radiodetermination-satellite stations, and space-based radar systems are subject to compliance with the Radar Spectrum Engineering Criteria (RSEC) contained in Chapter 5, Spectrum Standards, of the NTIA Manual.

The RSEC is intended to ensure an acceptable degree of electromagnetic compatibility among radar systems, and between such systems and those of other radio services sharing the frequency spectrum. To promote effective and efficient use of the spectrum, the RSEC includes limits on transmitter spurious and out-of-band emissions, antenna patterns, receiver selectivity characteristics, and radar tunability.

This report describes suggested methods for measuring characteristics of primary radar systems operating in the radiodetermination service for determining compliance with the standards contained in the RSEC. Other methods of measuring primary radar characteristics may be used if they give technically correct results. This report addresses measurement methods for measuring new and advanced radar systems using frequency-modulated and phase-modulated pulses; multi-mode radar systems with interleaving pulse modulations and variable pulse repetition frequencies; and distributed phased-array antennas with complex beam scanning techniques. Examples of RSEC measurements for such radars are presented.

MEASUREMENT PROCEDURES FOR THE RADAR SPECTRUM ENGINEERING CRITERIA (RSEC)

Frank H. Sanders[1], Robert L. Hinkle[2], and Bradley J. Ramsey[3]

The wide application of radar for various functions makes large demands on the electromagnetic spectrum, and requires the application of effective frequency management for the equipment and systems involved. Requirements for certain equipment characteristics are specified in the NTIA Manual of Regulations and Procedures for Federal Radio Frequency Management to ensure an acceptable degree of electromagnetic compatibility among radar systems, and between such systems and those of other radio services in the frequency spectrum. These standards are called the Radar Spectrum Engineering Criteria (RSEC). This report describes techniques for measuring radar spectrum-related parameters and characteristics for compliance with the RSEC. Measurements for both conventional and advanced radar types are addressed. This report supersedes NTIA Report 84-157 of August 1984.

Key words: electromagnetic compatibility; high-power radar; magnetron; radar emission mask; radar emission measurements; radar interference; radar spurious emissions; radar out-of-band emissions; radar unwanted emissions; Radar Spectrum Engineering Criteria (RSEC); Radio Spectrum Measurement System (RSMS); solid-state transmitter; spectrum occupancy.

1. INTRODUCTION

This report is intended to assist spectrum managers and engineers in measuring radar emissions and using those measurements to verify compliance with the National Telecommunications and Information Administration Radar Spectrum Engineering Criteria (RSEC) [1, primarily Chapter 5]. The RSEC contains spectrum engineering standards applicable to primary radar systems. The application of the NTIA RSEC emission mask to emissions of both simple and advanced-technology (multi-mode, multiple waveforms, frequency hopping and phased-array) radars is described.

This report updates and expands upon material presented in an earlier NTIA Report [2]. It is concerned with measurement techniques for verification of compliance with the RSEC. In particular, new measurement techniques are described that are tailored for emissions from recently designed types of radar transmitters. Newer types and models of measurement hardware are accounted for in this report.

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The measurement procedures described in this report are recommendations; alternative measurement procedures that can be documented by measurement personnel to adequately quantify the radar characteristics contained in the RSEC are also acceptable.

In addition, the measurement procedures contained in this report can be used to quantify radar characteristics that are required for NTIA certification of spectrum support [1, Chapter 10]. These include parameters required for submission in NTIA Forms 33–35 and the similar Department of Defense Form 1494.

1.1 Background

NTIA is responsible for managing the Federal Government's use of the radio spectrum. Part of this responsibility is to establish policies concerning spectrum assignment, allocation, and use; and to provide the various departments and agencies with guidance to ensure that their conduct of telecommunications activities is consistent with these policies [1, Section 8.3]. In discharging this responsibility, NTIA: 1) assesses spectrum utilization; 2) identifies existing and/or potential compatibility problems among the telecommunication systems that belong to various departments and agencies; 3) provides recommendations for resolving any compatibility conflicts that may exist in the use of the frequency spectrum; and 4) recommends policy and engineering changes to promote spectrum efficiency and improve spectrum management procedures.

The Federal Government operates a large number of radar stations. Many of these stations produce peak effective isotropic radiated power (EIRP) levels that are among the highest of all radio transmitter systems. (Average radar EIRP levels are typically 30 dB less than the peak levels.) Even theoretically perfect radar transmitters cannot confine their electromagnetic emissions entirely to their assigned operating frequencies, or for that matter even to allocated radar spectrum bands, due to the inherent pulse modulation characteristics of these systems. Furthermore, practical limitations in radar technology and necessary technical compromises in the design of operational radar systems result in higher spurious emission levels than would be theoretically predicted for various pulsed waveforms. Even if spurious emissions are suppressed by 60 dB or more relative to the peak power at the radar fundamental frequencies, the high peak EIRP levels of radar transmitters can cause the out-of-band and spurious emissions of these systems to have a significant impact on other spectrum uses.

1.2 Purpose and Structure of this Report

This report is intended for use by spectrum engineers and managers who must assess the emission characteristics of primary radar[4] systems. The most practical, efficient, and up-to-date techniques for measurement of radar emissions are presented, as developed by NTIA engineers. Application of these measurement techniques is described for advanced radars employing sophisticated pulse modulation and beam-scanning techniques. Measurement approaches are described in the main body of the report. Important definitions are provided in Appendix A. Assessment of required amounts of attenuation in measurement system front ends is described in Appendix B. Measurement system architecture and algorithms are described in detail in Appendix C. Measurement system calibration techniques are described in Appendix D. Methods for positioning measurement systems for radiated measurements are presented in Appendix E. A limited description of radar spurious emissions and their variation with measurement bandwidth are provided in Appendices F and G for the purpose of better understanding the measurement procedures. Appendix H is a description and user's guide for an automated software tool for determining the RSEC emission limit mask, including the capability to import measured emission characteristic data for comparison with the RSEC emission limit mask.

1.3 RSEC Compliance and Interference Resolution Policies

The NTIA manual [1] contains NTIA policies and regulations regarding compliance with spectrum standards and interference resolution. The RSEC is intended to ensure an acceptable degree of electromagnetic compatibility among primary radar systems, and between such systems and those of other radio services sharing the frequency spectrum. RSEC standards are concerned with promoting efficient use of the spectrum. However, compliance with these standards may not preclude the occurrence of interference. Therefore, compliance with the standards does not obviate the need for cooperation in resolving harmful interference problems [1, Chapter 5].

Taken together, out-of-band emissions and spurious emissions [1, Chapter 5] are called unwanted emissions. In principle, unwanted emissions from stations of one radio service shall not cause harmful interference to stations of the same or another radio service within the recognized service areas of the latter stations whether operated in the same or different frequency bands. Providing that appropriate spectrum standards [1, Chapter 5] are met, an existing station is recognized as having priority over a new or modified station. Nevertheless, engineering solutions to mitigate interference may require the cooperation of all parties involved in the application of reasonable and practicable measures to avoid causing or being susceptible to harmful interference [1, § 2.3.7].

The United States allocates many radio bands to radar services (radiolocation, radionavigation, meteorological aids, and other radiodetermination services) on both primary and secondary bases. Radar services can have impacts on spectrum engineering outside the allocated radar

[4] "A radiodetermination system based on the comparison of reference signals with radio signals reflected from the position to be determined," [1, Chapter 6] and ITU Radio Regulations.

bands. Some adjacent-band impacts (e.g., RF front end overload) are due to inadequate design of receivers in adjacent bands; such impacts cannot be mitigated by improving radar transmitters. Other adjacent-band impacts can be due to radar unwanted emission levels, and these can be somewhat mitigated by controlling the levels of radar unwanted emissions.

1.4 Radar Spectrum Engineering Criteria (RSEC)

This section describes the limits that are placed on U.S. radar unwanted emission levels by the NTIA radar spectrum engineering criteria (RSEC) [1].

The RSEC applies to all Federal Government primary radar systems. RSEC specifications are provided in existing NTIA documentation [1, Section 5.5]. The following list identifies the technical radar characteristics for which the RSEC specifies limits:

1) unwanted emission levels relative to the level of the radar fundamental;
2) emission bandwidth;
3) antenna pattern characteristics;
4) frequency tolerance;
5) frequency tenability;
6) receiver IF selectivity;
7) image and spurious rejection.

Since the initial adoption of the RSEC emission level specification (including spurious emission limits) by NTIA in 1973, the RSEC limits have been revised on an ongoing basis. The RSEC is updated periodically [1, Chapter 5].

2. TRANSMITTER OUTPUT POWER DETERMINATION

The RSEC categorizes radars on the basis of groups (A, B, C, D, and E). Membership in a group is determined primarily by radar transmitter peak power, P_p, which is used in RSEC mask computations for some radars to determine the ultimate spurious suppression level (X in dB) that must be achieved. The radar transmitter peak power (P_p) is defined as the peak power at the radar antenna input. In some cases, direct measurement of the radar's power output may be impossible and the specified radar peak transmitter power may have to be taken from radar documentation. Direct measurements are desirable whenever possible. The material in this section describes methodology for this measurement.

2.1 Introduction

For purposes of RSEC mask computations, peak power is measured at the nominal maximum steady-state amplitude of a radar pulse; short-duration peaks within pulses, as may possibly occur at some pulse leading edges, should not be used. Because the goal is to measure all available transmitter power, it is important to measure the pulse peak power in bandwidths that equal or exceed the nominal values presented in Table 1; for multimode radars, using a combination of modulation types, the measurement bandwidth should be determined by selecting the radar mode with the widest bandwidth.

Radiated peak power may be measured directly for radars that can direct their antenna main lobe energy directly into a measurement system antenna, such as might be possible on some test ranges and for some surface-search radars. A procedure for this approach is given in Section 2.3.2, below.

For many operationally deployed radars it may be difficult or impossible to achieve direct coupling between a radar antenna main beam and a measurement antenna main beam.[5] For those systems, peak power should be measured via a hardline connection from within the radar transmitter, if possible. If such a connection is unavailable, then transmitter power must be assessed via radiated measurements in accordance with Section 2.3.2, below.

2.2 Measurements for Radars with Directional Couplers

In this context, a conventional radar transmitter is defined as one that sends all of its transmitter energy through a directional coupler (accessible to measurement personnel) between the transmitter and the antenna, and that does not modulate the pulse frequency during transmission

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[5] The lower edge of the main beam of an air search radar, for example, is often directed more than 1 degree above the horizon. This puts the lower edge of the main beam at a height of 17 m (plus the radar tower height) above the ground at a typical measurement system distance of 1 km. This height considerably exceeds the likely maximum height of a measurement antenna. Furthermore, while main beam gain may be specified in radar documentation, radar antenna sidelobe gain levels illuminating the measurement system will not generally be known with much accuracy.

(ie., that does not chirp). In this case, all the radar transmitted energy is available at that single point and the peak power may be measured at that point.

The key component for this measurement is a wideband detector. The detector needs to be wideband, with a fast-response time. It should be operated at a power input level within its linear-response region. (For typical detectors, this level will often be between +10 dBm to +20 dBm. The maximum permissible detector input level is often about +20 dBm. Detector manufacturers' data sheets should be consulted for guidance regarding this parameter.)

Table 1. Determination of RSEC Measurement Bandwidth (B_m) for Peak Power Measurements.

Radar Modulation Type	**RSEC Measurement Bandwidth (B_m):**
Non-FM pulsed and phase-coded pulsed	$B_m \geq (1/t)$, where t = emitted pulse duration (50% voltage) or phase-chip (sub-pulse) duration (50% voltage). **Example for non-FM pulsed:** If emitted pulse duration is 1 µs, then $B_m \geq 1$ MHz. **Example for phase-coded pulsed:** If radar transmits 26-µs duration pulses, each pulse consisting of 13 phase-coded chips that are each 2-µs in duration, then $B_m \geq 500$ kHz.
FM-pulsed (chirped)	$B_m \geq (B_c/t)^{1/2}$, where B_c = frequency sweep range during each pulse and t = emitted pulse duration (50% voltage). **Example**: If radar sweeps (chirps) across frequency range of 1.3 MHz during each pulse, and if the pulse duration is 55 µs, then $B_m \geq 154$ kHz.
CW	$B_m = 1$ kHz; See sub-paragraph 4.2 of [1, Chapter 5] for RSEC Criteria B, C, and D. **Example:** $B_m = 1$ kHz.
FM/CW	$B_m = 1$ kHz; see sub–paragraph 4.2 of [1, Chapter 5] for RSEC Criteria B, C, and D. **Example:** $B_m = 1$ kHz
Phase-coded CW	$B_m \geq (1/t)$, where t = emitted phase-chip duration (50% voltage). **Example for phase-coded pulsed:** If chip duration is 2µs, then $B_m \geq 500$ kHz.
Multi-mode radars	Calculations should be made for each waveform type as described above, and the maximum resulting value of B_m should be used. **Example:** A multi-mode radar produces a mixture of pulse modulations as used in the above examples for non-FM pulsed and FM-pulsed. These values are 1 MHz and 154 kHz, respectively. Then $B_m \geq 1$ MHz

The measurement setup is shown in Figure 1. Although NTIA RSEC documentation [1, Section 5.5] specifies that power should be measured "at the input to the radar antenna," the reality is that peak power must be measured at a directional coupler in any hardline-coupled scenario. Therefore corrections should be applied to the measured parameters to account for the transmission losses between the measurement point and the antenna input reference point. A coaxial cable of appropriate impedance is connected to the input of a wideband detector.

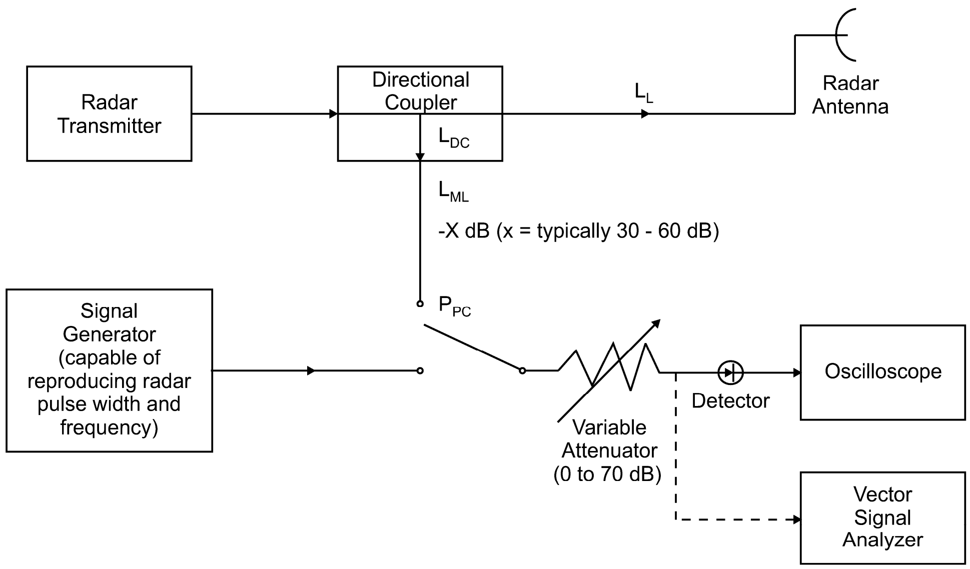

Figure 1. Radar power measurement configuration for a hardline coupled measurement.

A variable attenuator (0–70 dB, for example) is inserted at the detector input and is adjusted to ensure a linear-response input level to the detector.[6] Prior to connecting the detector to the radar, the attenuator is initially set to a sufficiently high level to protect the wideband detector from possible damage.

Referring to Figure 1, the oscilloscope input impedance needs to be matched to the detector output impedance; older detectors often have high-impedance outputs but some newer-model detectors have relatively low (50 ohm) output impedance. Coupling on the oscilloscope input should be set to 'DC'. The oscilloscope is adjusted to display radar pulse envelopes. The flat-top pulse amplitudes (see definition in Appendix A) are recorded.[7] The setting of the variable attenuator is likewise noted by measurement personnel and is used to correct the amplitude displayed on the oscilloscope.

[6] For hardline connections to directional couplers, the initial attenuator setting may be derived from the radar's nominal peak power level and the specified insertion loss of the directional coupler.

[7] Most oscilloscopes can record data to either an internal disk, an external computer via an IEEE-488 (GPIB) bus, or a universal serial bus (USB) external memory unit. Useful results may also be achieved by photographing the oscilloscope screen with a film or digital still-frame camera.

This measurement only determines the peak pulse power at the directional coupler. Coupler loss, external attenuation values, and losses between the coupler and the antenna input must be taken into account to determine the radiated value of P_p. The radar system losses between the directional coupler and the antenna usually must be taken from values noted on radar microwave components (such as waveguide couplers, filters, etc.).

The peak power is calculated from a correction for: 1) the attenuation of the directional coupler; 2) the value of the attenuation between the coupler output and the detector input; 3) the conversion of displayed voltage on the oscilloscope display to the power that would have been present at the detector input to generate that voltage; and 4) the attenuation of the waveguide between the directional coupler and the transmit antenna. The first two factors may be taken directly from the attenuator settings, assuming that the attenuation values were previously calibrated accurately.

$$P_P = P_{PC} + L_{DC} + L_{ML} - L_L + BCF \tag{1}$$

where:

P_P = transmitted peak power at antenna input, dBm;
P_{PC} = measured power at the output of the directional coupler, dBm;
L_{DC} = loss of the directional coupler, dB;
L_{ML} = loss of the measurement line, dB;
L_L = loss between radar antenna and directional coupler, dB;
BCF = bandwidth correction factor, dB (if $B_{det} < B_m$; see below).

The limiting measurement system bandwidth, B_m, should be chosen to exceed the value specified in Table 1 for the radar being measured. Many detectors and oscilloscopes may have detector bandwidth values, B_{det}, that exceed the B_m values of Table 1. But in the event that B_{det} is less than B_m, it is still possible to estimate the total peak power through a directional coupler measurement. To do so, the power is measured in the bandwidth B_{det}. Then it is corrected by a decibel factor of 20 $\log(B_m/B_{det})$:

The conditions for measurement bandwidth correction factor (BCF) for non-FM and phase-coded pulses are:

$$BCF = 20\log\left(\frac{1}{B_m t}\right) \text{for } B_m < \frac{1}{t} \tag{2}$$

where:

B_m = limiting bandwidth of measurement system, MHz;
t = emitted pulse duration (50% voltage), or phase-chip width for (sub pulse duration (50% voltage), microseconds.

The conditions for measurement bandwidth correction factor (BCF) for FM-pulsed (chirped) pulses are:

$$BCF = 10\log\left(\frac{B_c}{B_m{}^2 t}\right) \text{for } B_m < \sqrt{\frac{B_c}{t}} \qquad (3)$$

where:

B_c = frequency sweep range during each pulse of sub-pulse, MHz;
B_m = limiting bandwidth of measurement system, MHz;
t = pulse duration during each pulse of sub-pulse, microseconds.

For improved accuracy and confidence, this conversion may be checked as follows. Once the pulse amplitude has been measured, the detector input is disconnected from the directional coupler and is connected to the output of a signal generator (Figure 1). The signal generator output is adjusted to the same frequency as the radar and a continuous wave (CW) signal is injected into the detector. The level of the input signal is adjusted with signal generator controls and/or an external variable attenuator until the detector produces the same detector output level as was observed for the pulses. This value may be compared to the value that was inferred from the detector manufacturer's data sheets. They should be close to one another (that is, within about a decibel).

2.3 Measurements for Advanced Radars

2.3.1 Advanced Radars with Directional Couplers

In this context, it is assumed that an advanced radar is one that intentionally modulates the frequency or the phase of transmitted pulses, but that the radar transmitter still utilizes a directional coupler through which all of the transmitted energy passes. In this case, the same measurement procedure may be used as described in Section 2.2. As before the limiting detector and oscilloscope bandwidth, B_{det}, must be verified to meet or exceed the value of B_m in Table 1 for the radar being measured.

2.3.2 Advanced Radars Lacking Directional Couplers

Many advanced radars do not have directional couplers. These include radars with distributed arrays of solid state transmitter modules. For these radars, hardline-coupled measurements are impossible, and transmitter peak power must be determined either from radar data sheets or from radiated measurements.

As noted in the introduction to this section, radiated measurements are often complicated by lack of definitive data on radar antenna gain directed at the location of the measurement system, unless the measurement system can be positioned in the main beam of the radar.

The best option in this case is to position the measurement system so that it is directly scanned by the radar's main beam. To ensure that the beams of the radar transmitter and measurement system receiver antennas are aligned, the following procedure is used. First, visually align the receive antenna approximately with the radar transmitter antenna. Then, if the radar transmitter antenna can be manually directed, it should be moved in all its degrees of freedom until a maximum response occurs in the measurement system. Alternatively, if the transmitter antenna is continuously scanned through space (as is commonly the case), then this initial step is omitted. A more detailed description of procedures for positioning measurement systems and aligning antenna beams is provided in Appendices C and E.

The next step is to slowly move the measurement antenna in azimuth and elevation angle until a maximized response is achieved. At this point, the beams are aligned. If the polarization of both antennas is linear, then the polarization needs to be matched between the two antennas, typically by rotating the measurement antenna about its central axis until a maximal response in the measurement system is achieved. If the radar emission is circularly polarized, then a circularly polarized measurement antenna (with the same polarization sense) should be used. Power is measured via a spectrum analyzer (or a detector-oscilloscope combination as shown in Figure 1). The bandwidth conditions for the measurement system apply as described above. The measured power is corrected to transmitted peak power at the antenna input using the equation:

$$P_p = P_r - G_t - G_r + L_p \tag{4}$$

where

P_p = transmitted peak power at the antenna input, dBm;
P_r = measured power level (corrected for any internal gains and losses), dBm;
G_t = radar transmitter antenna gain, dBi;
G_r = measurement system (receiver) antenna gain, dBi;
L_P = propagation loss (free space) between the radar measurement system antennas, dB.

Note that the rated main beam gain of the transmitter antenna is subtracted from the peak effective isotropic radiated power (EIRP) to arrive at the transmitter peak output power.

For radar transmitters with main beams that cannot be intercepted by the measurement system, and which also lack directional couplers, no direct measurement solution exists. In these cases, the radar's specified transmitter peak power must be used, as extracted from radar documentation.[8]

[8] A radiated measurement of such a radar's emission will at least provide a lower bound on its transmitter peak power.

3. WAVEFORM PARAMETER MEASUREMENTS

3.1 Introduction

This section provides guidance for determination of radar waveform parameters used in computation of the RSEC emission masks. These include:

1) pulse and sub-pulse duration (t);
2) pulse rise and fall times (t_r and t_f) (referred to subsequently in this document as pulse rise/fall time) [9];
3) number of sub-pulses in coded pulses (N);
4) bandwidth of frequency deviation, (B_c) for FM-pulses (chirped), and (B_d) for FM-CW radars;
5) compression ratio of FM-pulses (d).

The pulse parameters need to be measured on only one frequency channel of the radar for each type of waveform. For radars utilizing multiple waveforms (e.g., multiple pulse widths or chirps), the relevant parameters listed above should be measured for each waveform, but still only need to be measured on a single frequency channel for each.

For some radar designs, the pulse parameters (pulse width (t), pulse rise time (t_r), pulse fall time (t_f) and frequency deviation bandwidth (B_c or B_d), if appropriate) may be measured via a hardline connection to a directional coupler. Other radar designs, such as distributed phased array radars, do not provide a directional coupler; for these radars, the pulse parameters listed above must be measured via radiated energy.

3.2 Measurement of Pulse Modulation Parameters

3.2.1 Pulse Width, Rise Time, and Fall Time Definitions

For the RSEC, pulse width, t, is defined at the 6-dB points (50% voltage points) of radar pulses. The rise time, t_r, or fall time, t_f, is measured between the 10%–90% voltage (-20 to -0.9 dB) points on a pulse's leading or trailing edge, respectively, as shown in Figure 2. For coded pulses, t_r and t_f are the rise and fall times of the sub-pulses. If sub-pulses are not discernable, then t_r is defined to be 40% of the time required to switch from one phase or chip to the next.

[9] When the fall time, t_f, of the radar pulse is less than the rise time, t_r, it should be used in place of the rise time in applying the RSEC emission mask.

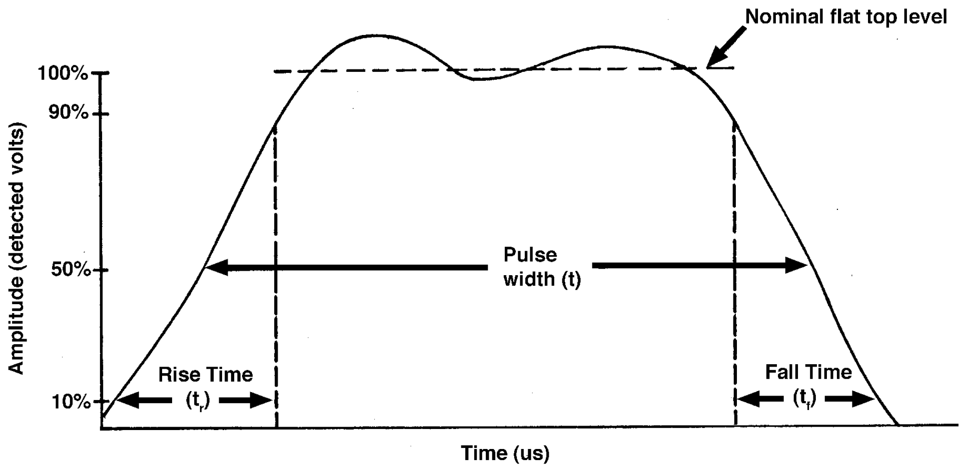

Figure 2. Schematic diagram of RSEC pulse shape parameters. Note that the nominal flat top level may have to be estimated as a best-fit on the detected envelope.

3.2.2 Pulse Modulation Parameter Measurement Procedures

3.2.2.1 Non-FM (CW) Pulses

The key component in this measurement is a wideband detector. The detector needs to be wideband, with a fast response time characteristic. It should be operated at a power input level within its linear-response region. The detector manufacturer’s data sheets should be consulted for guidance regarding this parameter.

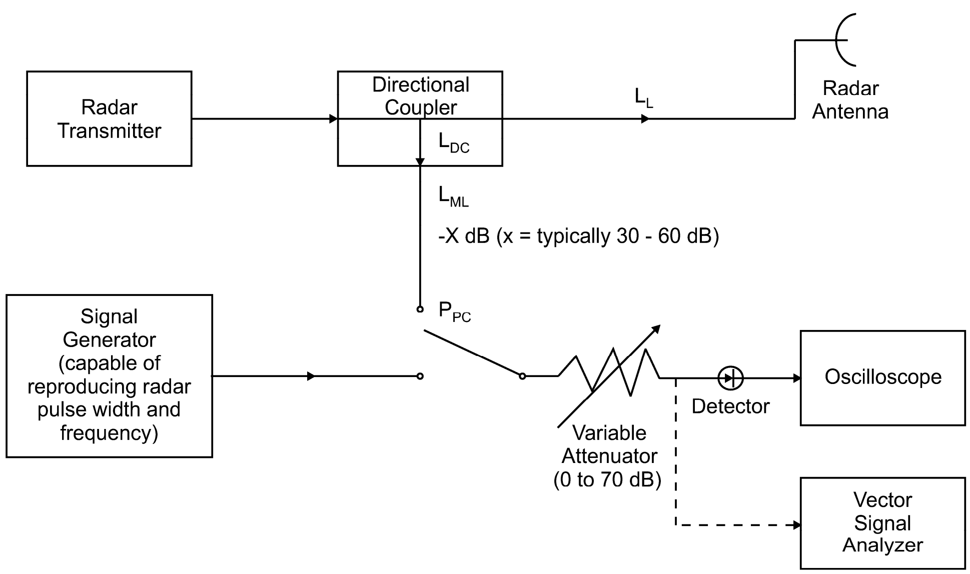

Figure 3. Block diagram schematic for measuring waveform parameters using a directional coupler.

The setup to measure radar pulse width, rise time and fall time parameters is shown in Figure 3. A vector signal analyzer can be substituted in place of the discrete detector and oscilloscope for measurements of pulse phase coding and frequency modulation (chirp) characteristics. A coaxial cable of appropriate impedance is connected to the input of a wideband (bandwidth exceeding ($1/t_r$)) detector. (In the following discussion, t_r is used with the assumption that it is smaller than t_f. But if t_f is the smaller of the two quantities, then it should be used in place of t_r in the RSEC emission mask computations.) A variable attenuator (0–70 dB, for example) is inserted at the detector input and is adjusted to ensure a linear-response input level to the detector.[10]

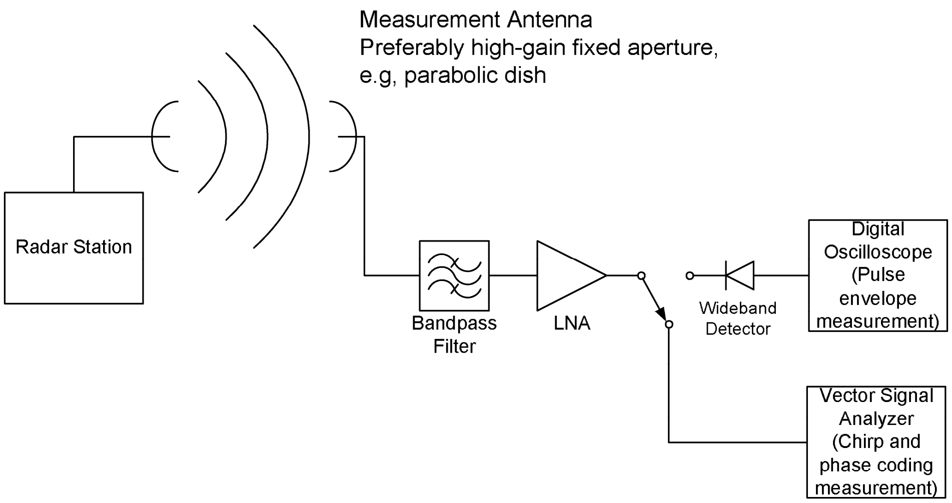

Figure 4. Block diagram schematic for measuring radiated waveform.

Figure 4 shows the setup for making measurements of the radar parameters in the radiated waveform. The discrete detector and oscilloscope are used to measure radar pulse envelope characteristics. A vector signal analyzer can be substituted in place of the discrete detector and oscilloscope for measurements of pulse phase coding and frequency modulation (chirp) characteristics.

The detector output is connected to an oscilloscope. The oscilloscope's bandwidth should be wide enough to ensure that pulse rise/fall time can be measured accurately. Measurement personnel should be aware that some oscilloscopes achieve their widest bandwidth performance in repetitive sampling modes, but that radar pulses need to be measured in single-shot modes. Therefore the oscilloscope bandwidth needs to be known in single-shot mode. For many radar pulses, it is desirable that the single-shot bandwidth be at least a few hundred megahertz. Impedances should be matched appropriately; most modern oscilloscopes have selectable input impedance values. 50 ohms is typically correct. DC coupling should be used on the oscilloscope input. The oscilloscope is adjusted to display and record[11] radar pulse envelopes.

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[10] For hardline connections to directional couplers, the initial attenuator setting may be derived from the radar's peak power level and the specified insertion loss of the directional coupler.
[11] Most modern oscilloscopes can record data to either an internal disk, an external computer via a data link, or a universal serial bus (USB) port connected to an external memory unit.

For the RSEC, radar pulses need to be measured at the 10%, 50%, and 90% voltage points (Figure 2).

A potential impediment to measuring pulse width via radiation is the effect of multipath energy, which typically causes distorted pulse envelope shapes. This effect can be minimized by the use of a narrow-beam receive parabolic reflector antenna on the measurement system. If multipath features (such as a stair-step appearance on the the trailing edge of the pulse) are noted in the pulse envelope even when a parabolic antenna is being used, then slight adjustments in the vertical tilt angle of the antenna should be made, until the multipath features are minimized or eliminated.

Most modern oscilloscopes provide for this type of measurement automatically. For oscilloscopes that do not have this functionality built in, these points may be determined either with manual marker functions; or by performing computations on recorded pulse waveform envelopes; or by inserting attenuation (either with combinations of discrete attenuators or variable attenuator units) ahead of the detector to adjust the output to the specified levels (-0.9 dB, -6 dB, and -20 dB). For the attenuator method, at each of these levels, time markers are placed on the measured pulse envelope at a fixed amplitude level. The resulting time intervals between the markers at these levels provide the pulse width (delta between the 6-dB points), the rise time (delta between the -0.9 dB and -20 dB points on the leading edge), and the fall time (delta between the -0.9 dB and -20 dB points on the trailing edge).[12] In Section 3.3, Figure 5 shows such a pulse envelope measurement for a single-frequency weather radar. Figure 6 shows a similar measurement for a frequency-hopped radar.

3.2.2.2 Coded Pulses

For phase-coded radar pulses (referred to in the RSEC simply as 'coded'), three pulse parameters are required to compute the RSEC emission mask. These are:

1) 'chip duration,' defined as the interval between the 50% voltage points of one chip (intra-pulse single phase sub-pulse). This value is used for the variable (t) in the RSEC equations;

2) chip rise/fall time (t_r),[13] measured between the 10%–90% points on the rising/falling edges of the chips;

3) total number of chips (N) contained within each phase-coded pulse.

There are two fundamentally different approaches to these measurements: envelope-detected and phase-response.

[12] To the extent that detector output is linear, variable attenuation levels might be obviated. Three marker functions at appropriate levels could be used to directly read the 10%, 50% and 90% voltage points.

[13] When the fall time, t_f, of the radar pulse is less than the rise time, t_r, it should be used in place of the rise time in applying the RSEC emission mask.

3.2.2.2.1 Envelope-detected Measurement of Coded Pulses

Measurements of chip duration and rise time/fall time may be performed somewhat similarly to the procedures in Section 3.2.2.1. However, measurement of these parameters is complicated with a wideband detector because although phase is shifted during each pulse (as a series of chips), only the power is observed at the output of a detector. This makes the edges of the chips unobservable, in principle. In application envelope artifacts may occur at the phase transitions between the chips due to the band limitations of the measurement system, and these artifacts may be visible for some types of phase coding. When the transitions are observable, the chip width may be measured as the period between amplitude nulls in the transients. Chip rise/fall time may be taken to be the same as pulse rise/fall time, or else may be taken to be 40% of the time required to switch from one phase or sub-phase to the next. Also, the number of chips may be estimated by counting the artifacts within the envelope (e.g., if 12 artifacts occur, then there are 13 chips in the pulse). Figure 7 shows a wideband detector measurement of a phase coded radar pulse.

For radar systems employing continuous phase modulation (CPM) or other phase-shifting technologies that eliminate artifacts between chips, it is impossible to determine the number of chips, their durations and their rise/fall times by measuring the detected pulse envelope. If phase chips are not discernable, then t_r is defined to be 40% of the time required to switch from one phase or sub-phase to the next. Chip duration and number of chips must be determined from radar system documentation.

3.2.2.2.2 Phase-response Measurement of Coded Pulses

For phase-coded pulses, the chip duration and rise/fall time may be measured directly only if the waveform is sampled without envelope detection. A vector signal analyzer (VSA) can be used for this purpose. Current VSA technology does not always allow direct measurement of RF energy above about 6 GHz. If radar frequencies are too high for direct measurement with a VSA, then a spectrum analyzer may be used to downconvert the RF pulse energy to a lower[14] frequency that can be fed to a VSA, where chip duration and rise/fall time can be measured directly.

3.2.2.3 FM Pulses

Measurements of pulse duration (t) and rise/fall time (t_r) of FM-pulse radars may be performed as described in Section 3.2.2.1. An additional pulse parameter must be measured, the bandwidth of the frequency deviation (chirp), (B_c). This parameter can be measured with a modulation analyzer if the analyzer can operate at the RF frequency of the radar. Alternatively, this parameter can be measured with a vector signal analyzer with an operational setup as shown in Figure 4 (or substituted for the discrete detector and oscilloscope shown in Figure 3) and described in 3.2.2.2.2. An example measurement of B_c made with a VSA is shown in Figure 8.

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[14] The spectrum analyzer output is assumed to be accessible at a point prior to the resolution bandwidth and detection stages.

The compression ratio of FM-pulse radars is calculated as follows:

$$d = B_c \cdot t \, .$$

3.2.2.4 Phase-coded CW

Measurements of symbol duration (t) and symbol rise/fall time (t_r) may be performed as described in Section 3.2.2.2.

3.2.2.5. FM-CW

Measurement of the bandwidth of the frequency deviation (B_d) is required. This may be performed as described for (B_c) in Section 3.2.2.3 and as shown in the example data of Figure 8.

3.3 Example Measurement Data

Figures 5–8 have been taken from three different radars. Note that none of these example radar pulses have completely well-defined maximum amplitudes; the amplitude of the pulses is estimated as described in Appendix A.

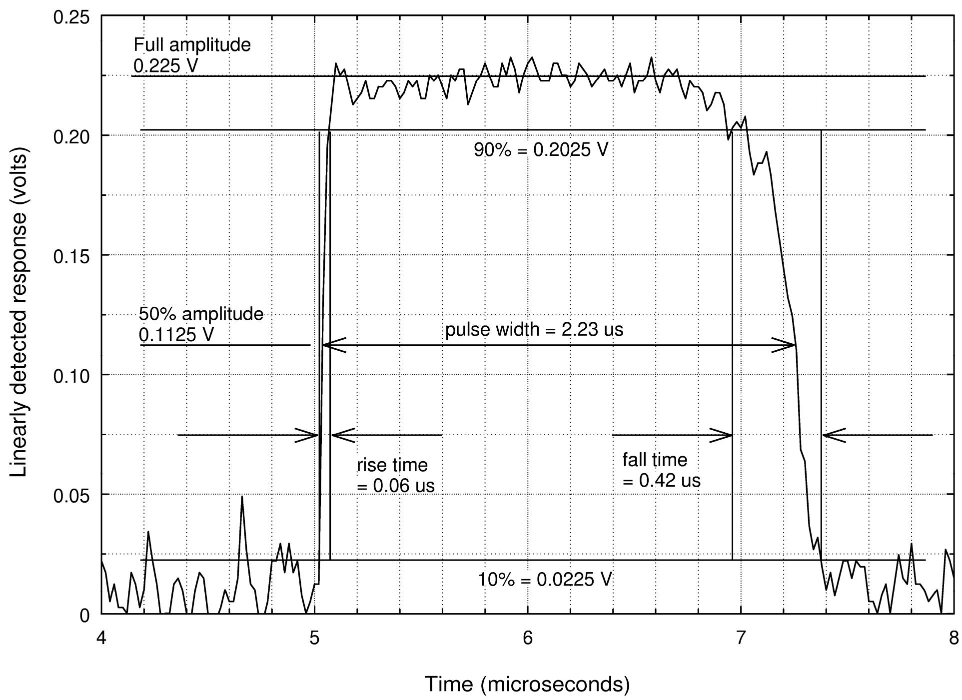

Figure 5. Diagram of RSEC parameters for a weather radar pulse.

The radar measured in Figure 5 operates on a single frequency, has a fixed pulse repetition rate and no modulation of pulse phase or frequency. The measurement was made using the setup shown in Figure 4.

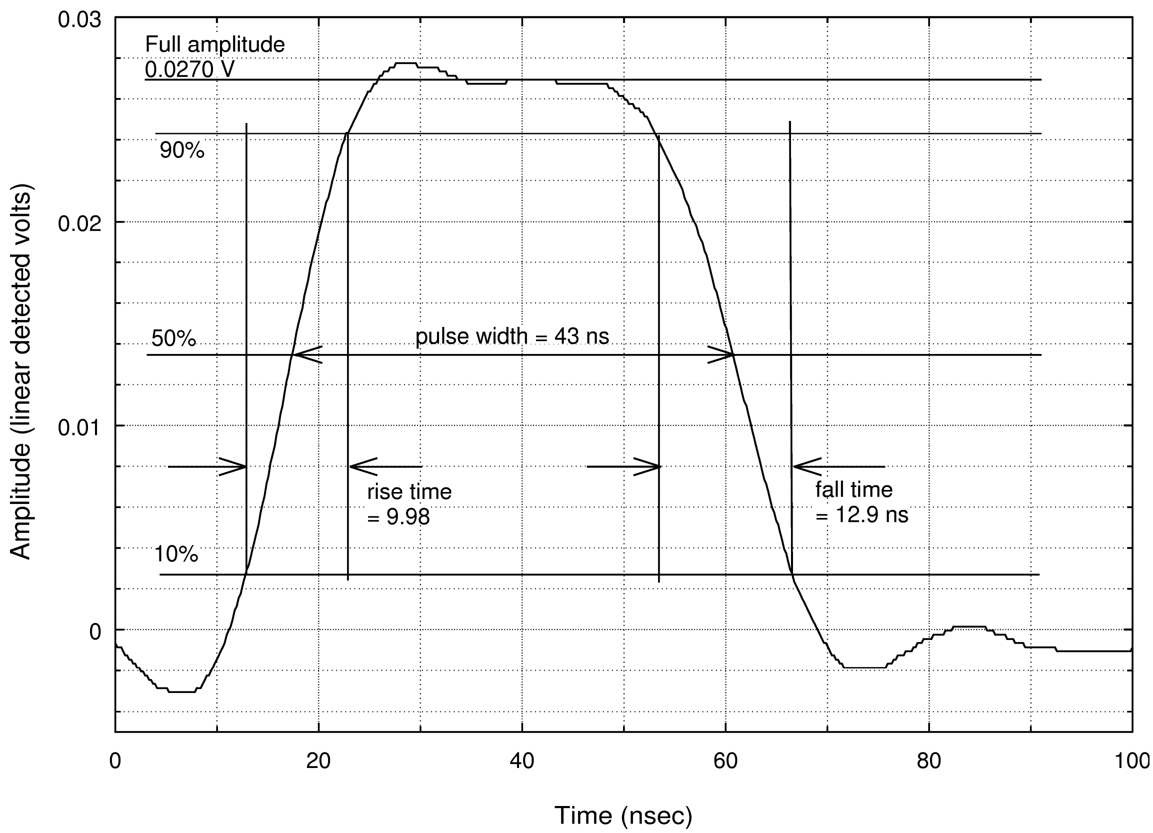

Figure 6. Diagram of RSEC parameters for a short-range search radar pulse.

The radar measured in Figure 6 hops to sixteen frequencies across 500 MHz of spectrum, but with no modulation of pulse phase or frequency. The measurement was made using the setup shown in Figure 4.

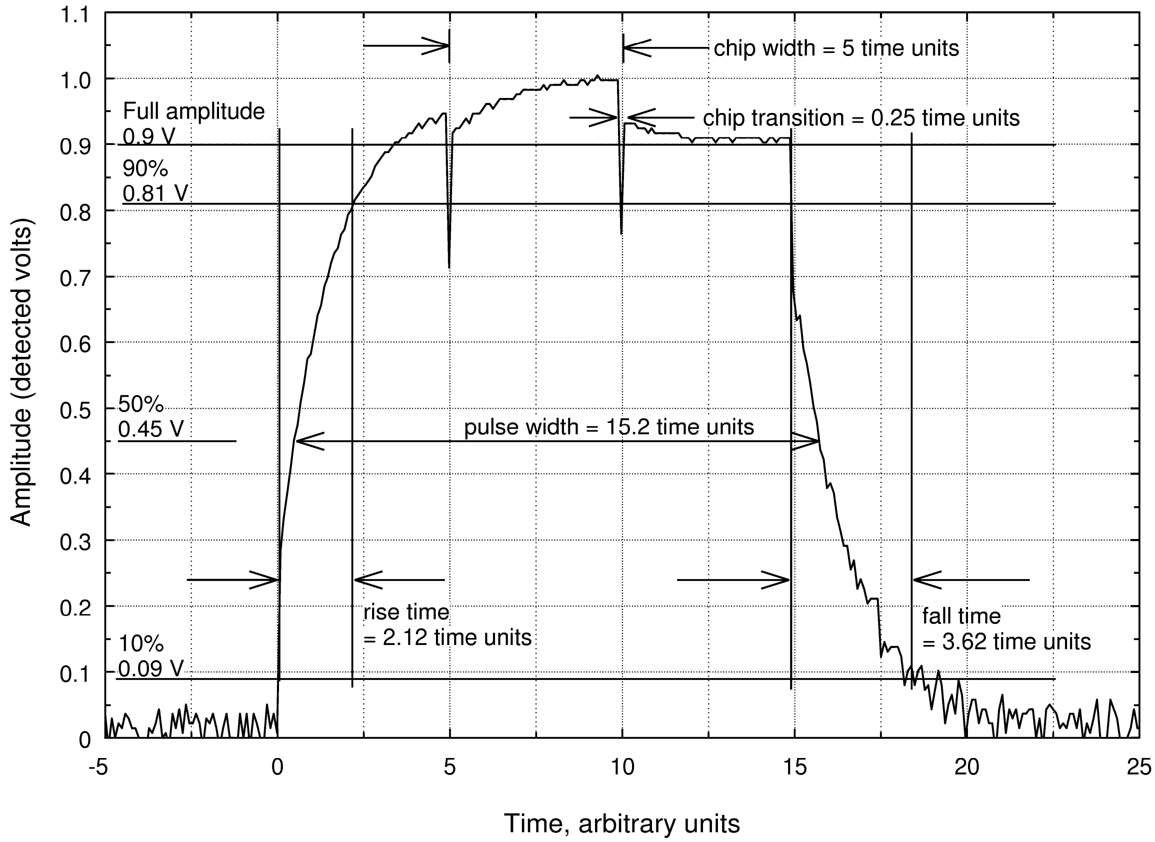

Figure 7. Diagram of RSEC parameters for a phase-coded pulse with three chips.

The measurement in Figure 7 is from a radar that performs frequency hopping and electronic beam scanning. The pulse was measured with a discrete-component detector connected to the IF output of a spectrum analyzer that was in turn tuned to one of the radar frequencies. The oscilloscope trigger was set to capture a single-shot trace whenever a sufficiently high pulse amplitude occurred. The pulse rise time, fall time, and width are directly measurable, as are the chip widths. The chip transition intervals (which are the sum of the chip and rise and fall times) are also directly measurable. But the individual chip rise and fall times are not directly measurable because they are obscured by the overall pulse envelope. The chip rise and fall times could each be estimated as 1/2 of the chip transition interval. Note that the observability of phase transitions will vary depending upon details of the phase modulation; phase transitions will not be observable in the envelopes of continuous phase modulated (CPM) pulses. For such radar pulses, a VSA would be required to measure the phase modulation in time.

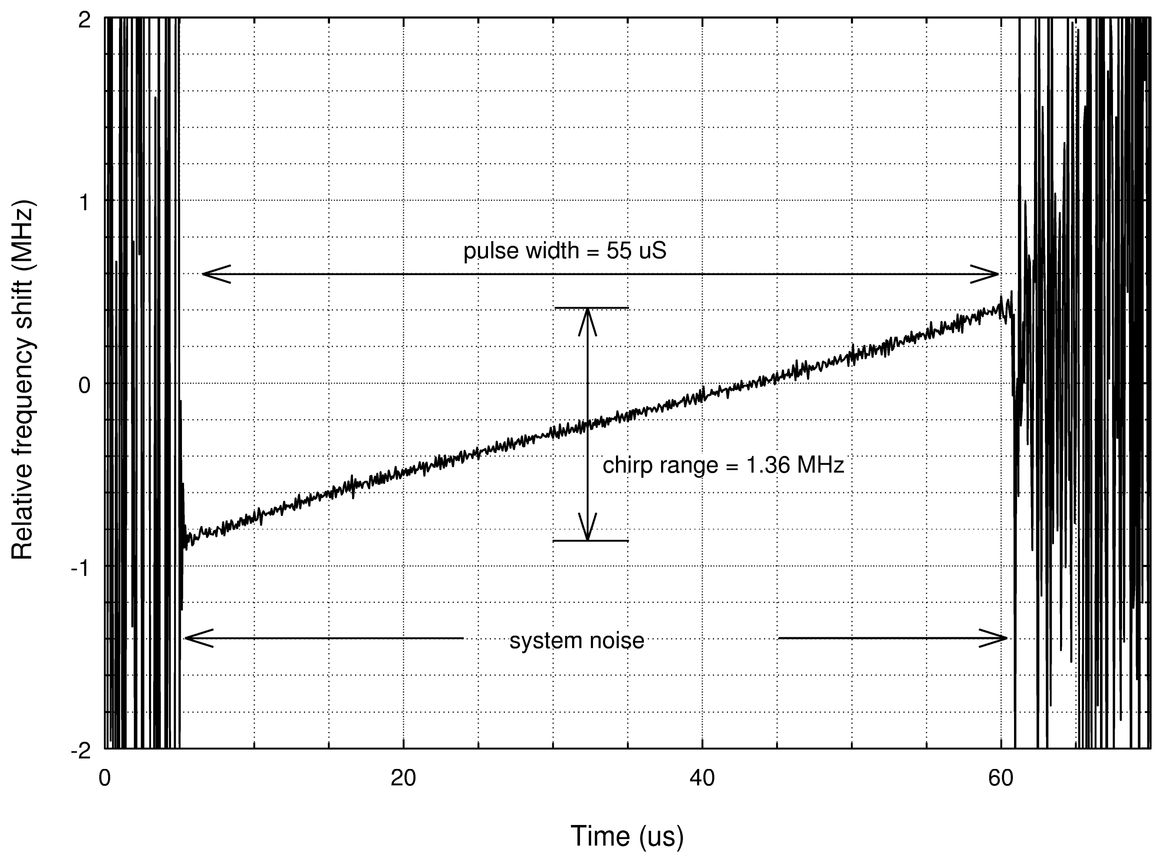

Figure 8. Measurement of the frequency deviation in time of a frequency-modulated pulse.

Figure 8 shows a measurement performed with a vector signal analyzer (VSA) connected to a directional coupler of the radar (as shown in Figure 3) in place of the more conventional discrete wideband detector and oscilloscope. This measurement could be performed as well on radiated pulses. The conventional setup with detector and oscilloscope would be used to measure pulse amplitude and 10%, 50%, and 90% levels and corresponding pulse width, rise time, and fall time would be measured as shown in either Figure 3 or Figure 4.

4. PULSE REPETITION RATE

[*At the time of this writing, the TSC is considering eliminating the PRR parameter for determining the X dB limit for the RSEC mask.*]

Pulse repetition rate (PRR) is used in computation of the RSEC ultimate suppression level for some radars. In some cases, the specified radar pulse parameters may be taken from radar documentation, and direct measurement of the radar's pulse repetition rate may not always be necessary. But in the event that a direct measurement is required, the material in this section describes the methodology for this measurement.

4.1 Introduction

For purposes of RSEC computations, PRR is taken as the average number of pulses per second emitted by a transmitter. If a hardline connection to a radar directional coupler is available, then the PRR measurement is nearly trivial. But if such a connection is not available, then the measurement of radiated energy is somewhat more difficult. This section describes both approaches to the measurement of PRR.

4.2 Measurements for Conventional Radars

In this context, a conventional radar is taken to be a unit that has a directional coupler available. The measurement setup is the same as that shown in any of Figures 1, 3, and 4. On an oscilloscope the pulse sequence is measured over a period long enough to see repetition in the sequence (e.g., for staggered pulse sequences, two or more complete stagger sequences should be displayed on the oscilloscope display). If a radar transmits a non-repeating pulse sequence, then a sequence of pulses should be recorded on the oscilloscope display. For most radars, this would be at least 20 pulses. With the pulses recorded on the oscilloscope display, the PRR is determined by dividing the number of pulses on the display by the total amount of time on the display.

4.3 Measurements for Advanced Radars

PRR may be most easily measured in the radar transmitter IF section. However, in many cases, radar design features (such as inaccessibility of an IF section, lack of an IF section, and multiple transmitter modules) or measurement logistics may make measurement of the radiated PRR necessary. The technique for basic measurement of the PRR through radiated emissions is as follows:

1) Establish the measurement system at a location with clear line-of-sight to the radar antenna, and as close as possible without suffering degradation to the measurement system performance (e.g., feed-through) or loss of power from the radar by locating

too far beneath the radar main beam. This is described in more detail in Appendices C and E.

2) Use a high-gain antenna (e.g., a 1-meter diameter or larger parabolic) on the measurement system to receive pulses from the radar.
3) Detect the radar pulses in the measurement system using the widest bandwidth available.
4) Set the measurement system oscilloscope to a single-sweep mode, with a relatively low trigger threshold. Wait until a series of pulses are recorded. Elevate the trigger threshold and wait for another set of pulses to activate the trigger. Continue this process until the threshold is so high that no more pulses are recorded. Reduce the trigger threshold slightly, and wait for a sequence to be recorded. This is the pulse sequence which should be finally recorded, and from which the PRR should be calculated.

If a radar produces a fixed-rate PRR at a single frequency, this procedure is trivial. Complications arise in radars with three types of complex PRRs:

- The PRR is non-uniform. Examples are staggered pulse trains used by air traffic control radars and some tactical radars.

- The radar frequency-hops (and performs mechanical and/or electronic beam-steering) between pulses, but at a uniform PRR, resulting in only portions of the pulse train being produced at a single measurement frequency. The pulse train is effectively fragmented, with pulses apparently missing in the measured train.

- The radar frequency-hops (and performs mechanical and/or electronic beam-steering) between pulses, with a non-uniform (random or staggered) PRR.

In these cases, there are two problems for RSEC implementation:

1) How should the RSEC PRR parameter be interpreted for radars with complex (i.e., non-periodic) pulse trains?
2) How can the total pulse train structure be reconstructed, so as to know the total number of pulses emitted by the radar per unit time and thus fulfill the requirements for RSEC PRR measurement?

In answer to the first question, the RSEC utilizes PRR for the purpose of determining the average power radiated by the radar. Thus, the aggregate number of pulses emitted, *on average*, *per unit time*, *into all space around the radar, and on all radar frequencies*, is required for accurate RSEC computation. Determination of this value is the purpose of the RSEC PRR measurement. (This is why, if the IF section of a radar transmitter is available for hardline connection to a measurement system, a measurement at this point would be desirable: all pulses produced by the radar would be observable at this point, regardless of the complicating behaviors described above.) The second question, how to reconstruct the average PRR from fragmentary received pulse sequences, is answered in the next three sub-sections.

4.3.1 Non-uniform PRR Radiated at a Single Radar Frequency

Variation of intervals between pulses is called staggering. Eventually a staggered sequence will repeat. Staggering is handled by measuring the radar pulse train for a sufficiently long period of time to capture at least one full stagger sequence. The average PRR can be calculated by dividing the number of pulses in the stagger sequence by the length of time required to complete the stagger sequence. For example, if the stagger sequence consists of eleven pulses emitted in a period of 15 ms, then the average PRR is $\frac{11}{0.015} = 733$ pulses per second. To determine the stagger period, it is necessary to record approximately 20 or more pulses and then measure the intervals between the pulses to determine the point where the sequence of intervals repeats—this is the stagger period.

If the pulses are emitted in a random sequence that never repeats, then the PRR must be determined by recording a statistically significant number of pulses and then calculating the average interval between them. For most radars, a statistically significant number of pulses would be 20 or more (because that is how many pulses are usually needed to obtain a good response to a target). Most stagger sequences will repeat in 10 pulses or less.

4.3.2 Uniform PRR Radiated by a Frequency-hopping (and Mechanically and/or Electronically Beam-steering) Radar

In this case, the measurement system will observe several pulses in a row on a single frequency, at uniform intervals, possibly followed by (relatively large) gaps in time during which no pulses are observed, or during which pulses are observed at relatively low amplitudes. The gaps are due to radar transmissions at frequencies other than the one being monitored and to radar beam-steering to azimuths or elevation angles that are directed away from the measurement system. An example of such a measurement is shown in Figure 10.

With reference to Figure 10, when using a narrow bandwidth measurement system (such as a spectrum analyzer), the PRR *on a single frequency* can be determined by recording the pulse train long enough to establish the PRR that occurs when the radar is tuned to the frequency being monitored, and when the beam is being directed toward the measurement system. The pulse sequence on a single frequency may be recorded and the PRR may be accurately calculated for that frequency.

For determination of the total PRR of the radar, however, *a wideband detector must be used*, as depicted in Figure 4. The detector output is directed to an oscilloscope, as shown in that figure, and the pulse sequence is captured as described in Section 4.2. An example of this type of measurement output is shown in Figure 11.

4.3.3 Non-uniform PRR Radiated by a Frequency-hopping (and Mechanically and/or Electronically Beam–steering) Radar

In this case, the conditions are complicated by the fact that there is no fixed pulse-to-pulse interval that can be observed, even when the radar is tuned to the measurement system frequency and the radar beam is directed toward the measurement system. For determination of the total PRR of the radar, a wideband detector must be used, as depicted in Figure 4. The detector output is directed to an oscilloscope, as shown in that figure, and the pulse sequence is captured as described in Section 4.2. An example of this type of measurement output is shown in Figure 11. Although the PRR of the radar in that figure is fixed, a non-uniform PRR would merely show a non-uniform spacing between the pulses. The average PRR would be computed from the observed data by dividing the total number of pulses in one or more stagger sequences by the total time interval within which those pulses were radiated.

4.4 Example Measurement Data

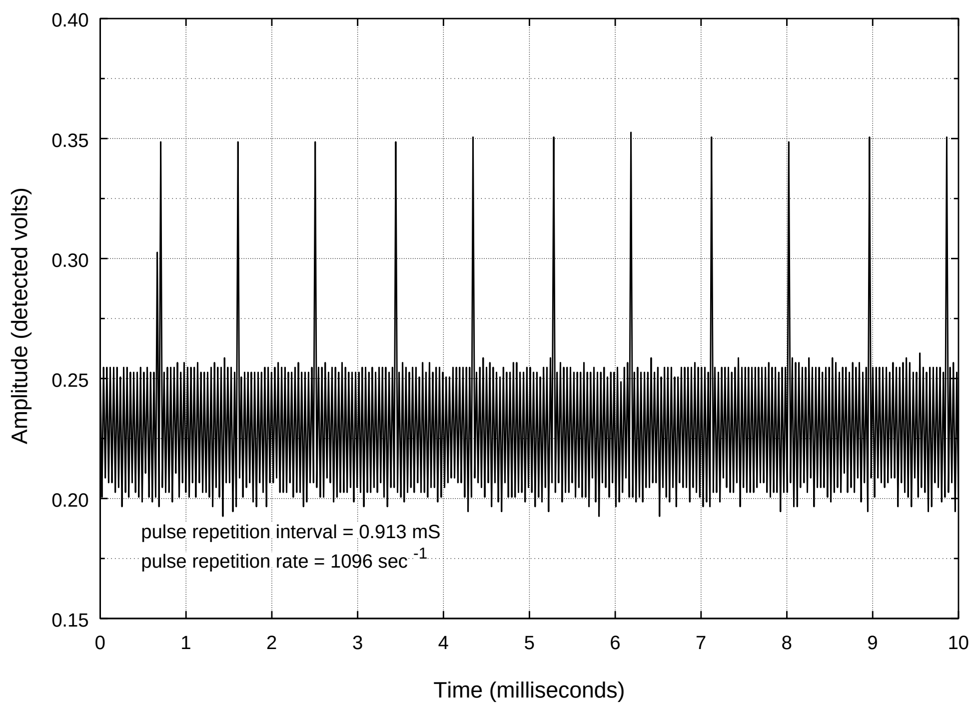

Figure 9. Example of a fixed-PRR radar pulse sequence.

The PRR depicted in Figure 9 is from a radar operating on a single frequency. The pulses have been detected with a discrete-component detector connected to the video output of a spectrum analyzer that was in turn connected to an antenna to measure radiated pulses. The same measurement can be performed with the discrete wideband detector and oscilloscope setup of Figure 3, or with a discrete wideband detector and oscilloscope connected to an antenna as shown in Figure 4. If a radiated measurement is performed, a slight modulation of the pulse amplitudes will be observed within the 3 dB points of the radar beam. (For most radars, 10 to 20 pulses will be observed within that portion of the radar main beam, more than adequate for an assessment of the average PRR.)

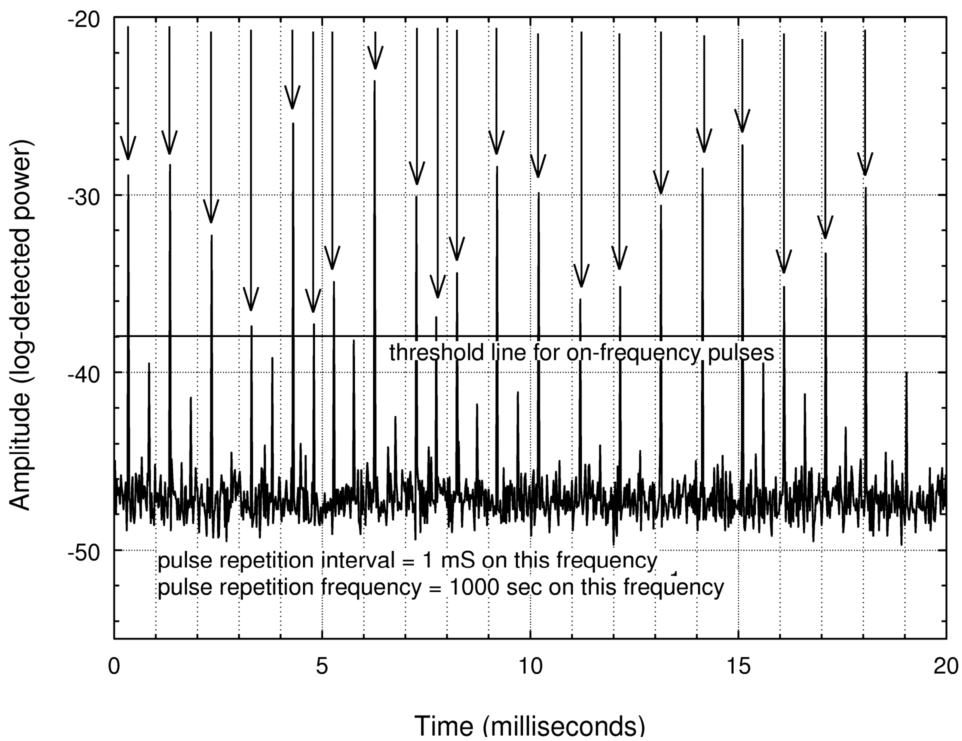

Figure 10. Pulse repetition measurement on a single channel of a frequency-hopping radar made with a spectrum analyzer in a zero-Hertz span mode and positive peak detection. The line is an estimated threshold for on-frequency pulses.

The radar measured in Figure 10 hops through sixteen frequencies that are spread across 500 MHz of spectrum, for a spacing of (500/(16-1))=33.3 MHz between frequencies. This measurement has been performed in a bandwidth of 3 MHz, which is an order of magnitude less than the channel spacing. Despite the relative narrowness of the measurement bandwidth compared to the channel spacing, the out-of-band emission levels of off-tuned pulses on an adjacent channel are high enough to make them visible on the spectrum analyzer display, interleaved between the on-tuned pulses (which are indicated with arrows). As a result, the apparent spacing between pulses as measured by the spectrum analyzer is half of its true value (the apparent spacing being 0.5 ms, whereas the true pulse-to-pulse spacing on a single channel of this radar is nominally 1 ms). This artifact can be eliminated by carefully observing that there are two classes of pulse amplitude in this measurement. Half the pulses occur at amplitudes above a fixed threshold line and half occur below that threshold, and they regularly alternate. This pattern can be interpreted by trained personnel as being a set of on-tuned pulses with a higher amplitude alternating with off-tuned pulses of lower amplitude. (The same effect can occur for radars with multiple beam elevation modes, one high and the other low.) When the spacing is measured between the high-amplitude pulses that exceed the critical threshold level, the true nominal spacing of 1 ms (actually a measured value of 0.97 ms) on the measurement channel is observed. This demonstrates that this technique can provide a valid assessment of the pulse-to-pulse spacing on a single channel of the radar, but substantial knowledge on the part of measurement personnel is required to correctly interpret this information.

The same radar is measured with a wideband detector in Figure 11. The detector's frequency response range far exceeds the 500 MHz frequency hop range of the radar. Therefore all pulses from all 16 radar channels are observed. The envelope of the pulse amplitudes is the *beam shape* of the main lobe of the radar antenna, observed as the beam sweeps past the measurement location. (Note that there are about 18 pulses within the half-points of the beam, consistent with standard radar theory for reliable detections of targets.) The measured PRR is 16,470 pulses per second. Compare these data with those of Figure 10, in which pulses from a single channel are observed at 1/16 of the nominal rate, along with lower-amplitude responses from adjacent channels.

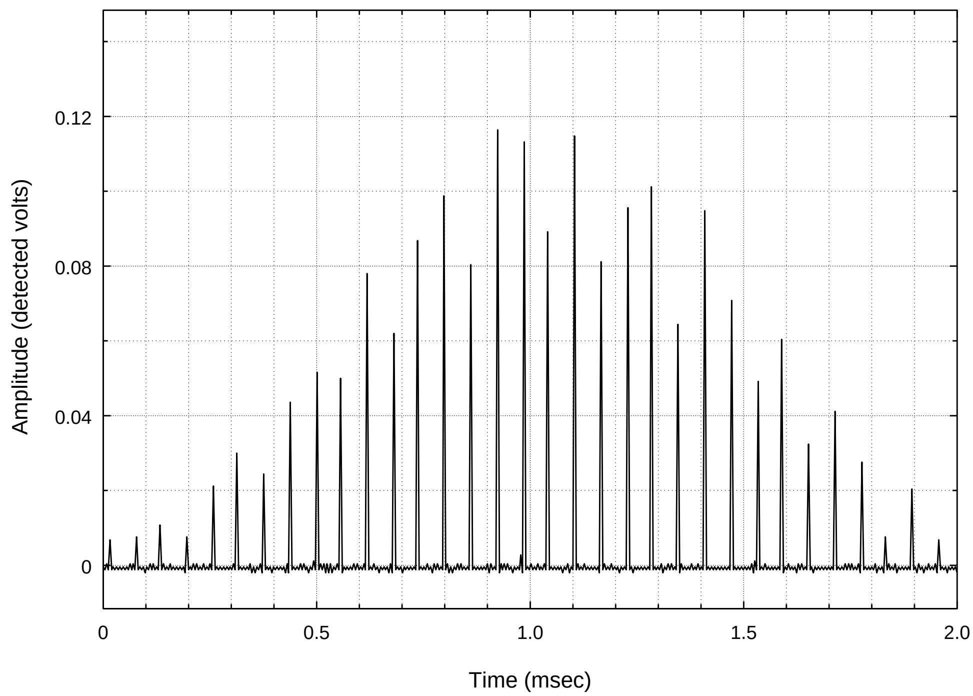

Figure 11. The pulse repetition rate of the same frequency-hopping radar as that shown in Figure 10, but measured with a broadband detector configured as in Figure 4. In this measurement mode the radar PRR may be accurately measured directly off the graph.

5. EMISSION SPECTRA

5.1 Introduction

Limits on unwanted (out-of-band and spurious) radar emissions are critical to spectrum efficiency. Radar design factors affecting emission spectrum characteristics include pulse shaping, the selection of radar output device, RF output filtering, and antenna frequency selectivity (e.g., slotted arrays). These design factors are discussed further in Recommendation ITU-R M.1314. Controlling the levels of unwanted emissions is key to ensuring compatibility with other systems. This section describes the methodology for measuring compliance with RSEC emission spectrum limits.

Formulas for the computation of RSEC emission mask limits are provided in existing NTIA documents [1, Chapter 5]. These can be performed with handheld calculators, if necessary. But in order to assist the technical community that must compute RSEC masks for radars, NTIA has developed an analytical software tool that calculates the RSEC emission limit mask, and alternate emission limit masks. It includes the capability to import measured radar emission characteristic data. The analytical tool is available at http://www.ntia.doc.gov/osmhome/. Appendix H provides an overview of this analytical tool, including a user's guide.

Radar emission spectra present the most difficult challenge in acquiring the data that are needed to verify RSEC compliance. Difficulties that must be overcome in acquiring radar emission spectra include:

1) the need to measure emission spectra over a wide dynamic range (90 dB or more);
2) the need to measure spectra over a wide measurement frequency range (sometimes several gigahertz, plus harmonics);
3) the need for high sensitivity (usually 10 dB noise figure or less) in the measurement system;
4) the sometimes challenging task of assessing the proper bandwidth in which to perform the emission spectrum measurement;
5) proper postioning and operation of a measurement system near a radar, often under difficult circumstances.

A detailed discussion of the measurement system used by NTIA for measuring radar emission spectrum characteristics is given in Appendix C. Calibration procedures are described in Appendix D. Positioning relative to radar stations for radiated measurements is described in Appendix E. The following is a discussion of the procedures used to measure radar emission spectra using the NTIA measurement system with some comments on alternative measurement procedures. Alternative measurement techniques that give equivalent results may be used.

5.2 Measurement Point (Hardline vs. Radiated)

Currently, the RSEC specifies that emission spectra should be measured "at the antenna input" [1, Chapter 5]. (At the time of this report's release, consideration is being given by the Technical Subcommittee (TSC) of the Interdepartment Radio Advisory Committee (IRAC) to use radiated emissions.) Hardline connection points are available in some radars. These are normally directional couplers, but they are not generally located at the antenna input. However, some modern radars, such as those with distributed phased array antennas, do not have directional couplers and cannot be measured at the antenna input.

Hardline-coupled emission spectrum measurements have some inherent technical drawbacks. First, they do not include the effects of frequency selectivity by components after the directional coupler including RF filters and the radar antenna. Secondly, directional coupler frequency responses usually decrease significantly outside operational bands, whereas RSEC compliance measurements (including harmonics) typically need to go well beyond those band edges. Thirdly, waveguide modes between the directional coupler and the measurement system input have been observed during measurements to result in *higher* measured levels of unwanted emissions than those observed in radiated spectra.

Radiated emissions determine technical compatibility with other systems. It is therefore desirable that RSEC compliance measurements reflect as nearly as possible the emissions that exist in space. Due to the drawbacks of using hardline coupling described above, and considering the desirability of measuring as nearly as possible the radiation in space, it is recommended that RSEC compliance spectrum measurements be performed on radiated emissions, if possible.

Radiated emission spectrum measurements do present complications due to the following factors: rotating radar antennas; radar beam scanning; and radar frequency hopping. Therefore, a stepped-frequency measurement procedure, as described in Appendix C, is desirable. Other measurement procedures may be used as alternatives to the procedures described in Appendix C. But alternative procedures must demonstrably always obtain the maximum peak power emitted by the radar at each measured frequency; this is a difficult requirement to satisfy.

5.3 Measurement Bandwidth for RSEC Measurements

The appropriate measurement bandwidth is a function of the time waveform characteristics of the radar. There are three main types of radar pulsed emissions: non-FM pulsed; phase-coded pulsed; and FM-pulsed. Three other radar modulations include: CW; FM/CW; and phase-coded CW. The appropriate measurement bandwidths for each waveform type are given in Table 2. The criteria of Table 2 should be used for selection of RSEC-compliance spectrum measurement bandwidth.

In addition to performing the above calculations, it is advantageous to confirm the appropriate value of measurement bandwidth, B_m, for any given radar system with an empirical observation. This observation, called a bandwidth progression measurement, is performed as follows: The measurement system receiver is tuned to the fundamental frequency (or the frequency of a single channel if the radar frequency-hops), or within the frequency chirp range if the radar chirps. The frequency-span range of the measurement system is set to zero hertz. The sweep time is set to a value somewhat greater than the radar beam-scanning and frequency-hopping interval, so that a maximum-amplitude peak power value is measured for each measurement system sweep. The measurement system IF bandwidth is set to the widest available value, and the received peak power level from the radar in this bandwidth is noted. The measurement bandwidth is then progressively narrowed, and the peak received power level is recorded as a function of the increasingly narrow bandwidths. The end result is a graph or table showing measured power as a function of measurement system IF bandwidth. The value of B_m will be the *widest* available bandwidth that gives a peak power reading that is *less than or equal to* the full-peak power reading.

For example, if the maximum peak power reading occurs at 300 kHz and wider measurement bandwidths, and a measurement bandwidth of 100 kHz is the next-smaller available bandwidth that gives a peak power reading that is less than the maximum peak power reading, then B_m should be 100 kHz or less. An example is shown in Figure 12.

Table 2. Determination of RSEC Measurement Bandwidth (B_m)

Radar Modulation Type	**RSEC Measurement Bandwidth (B_m):**
Non-FM pulsed and phase-coded pulsed	$B_m \leq (1/t)$, where t = emitted pulse duration (50% voltage) or phase-chip (sub-pulse) duration (50% voltage). **Example for non-FM pulsed:** If emitted pulse duration is 1 µs, then $B_m \leq 1$ MHz. **Example for phase-coded pulsed:** If radar transmits 26-µs duration pulses, each pulse consisting of 13 phase-coded chips that are each 2µs in duration, then $B_m \leq 500$ kHz.
FM-pulsed (chirped)	$B_m \leq (B_c/t)^{1/2}$, where B_c = frequency sweep range during each pulse and t = emitted pulse duration (50% voltage). **Example**: If radar sweeps (chirps) across frequency range of 1.3 MHz during each pulse, and if the pulse duration is 55 µs, then $B_m \leq 154$ kHz.
CW	$B_m = 1$ kHz; See sub-paragraph 4.2 of [1, Chapter 5] for RSEC Criteria B, C and D. **Example:** $B_m = 1$ kHz.
FM/CW	$B_m = 1$ kHz; See sub-paragraph 4.2 of [1, Chapter 5] for RSEC Criteria B, C and D. **Example:** $B_m = 1$ kHz
Phase-coded CW	$B_m \leq (1/t)$, where t = emitted phase-chip duration (50% voltage). **Example for phase-coded pulsed:** If chip duration is 2µs, then $B_m \leq 500$ kHz.
Multi-mode radars	Calculations should be made for each waveform type as described above, and the minimum resulting value of B_m should be used for the emission spectrum measurement. **Example:** A multi-mode radar produces a mixture of pulse modulations as used in the above examples for non-FM pulsed and FM-pulsed. These values are 1 MHz and 154 kHz, respectively. Then $B_m \leq 154$ kHz.

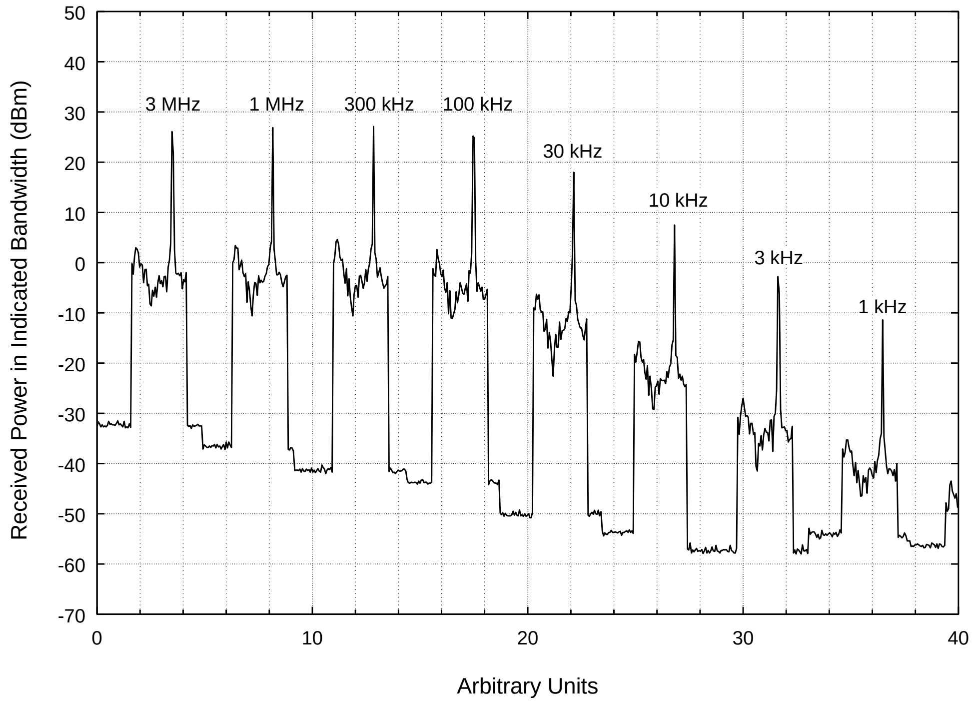

Figure 12. Example of a bandwidth progression measurement for assessment of the proper bandwidth in which to measure a radar spectrum for RSEC compliance. Because 100 kHz is the *widest* bandwidth that gives *less* than a full-power response, it is the ideal bandwidth to use for this radar.

Figure 12 data, collected on the radiated emissions of an operational air search radar, provide an example of how to perform a bandwidth progression measurement on a radar emission. The measurement system was fix-tuned in a zero hertz span to the radar fundamental frequency with positive peak detection selected. The spectrum analyzer sweep time was set to slightly more than eight rotation periods of the radar transmitter antenna, and the spectrum analyzer's sweep mode was set to 'single.' The initial spectrum analyzer IF bandwidth was set to the widest available value (3 MHz for this particular analyzer model). After the sweep was commenced, the operator waited until the full radar power (in the main antenna beam) had been observed, and then the operator switched the bandwidth to the next smaller value in a logarithmic progression (1 MHz) and waited until the radar main beam power was measured in that bandwidth. Then the IF bandwidth was reduced in the next step of a log progression (to 300 kHz), and the process was continued until the radar measured power was observed to clearly roll off at sufficiently narrow bandwidths. (The pedestal-like featuress in the trace are sector blanking by the radar transmitter.)

Figure 12 shows that full radar power was received in 300 kHz but that a slight reduction began at 100 kHz. Therefore, based upon the criteria described above, the proper bandwidth for measurement of this radar emission spectrum would be 100 kHz or less. A bandwidth of 300 kHz might even be marginally acceptable, but if the radar spectrum were to be measured in 1 MHz or wider bandwidths, there would be a risk that the spectrum might *appear* to not meet RSEC mask criteria. Unwanted (out-of-band and spurious) emission levels would appear in their proper relationship to measured power at the radar fundamental in spectrum measurement bandwidths of 100 kHz or less. But measurement of the extended spectrum in bandwidths less than 100 kHz would probably be impractical due to the length of time that would be required to make the measurement in such narrow bandwidths.

If multi-mode radars emit specific time waveforms on specific frequencies (e.g., if non-FM pulses are emitted at frequency f_1 and chirped-pulsed emissions occur at frequency f_2), and if the calculated measurement bandwidths are different for these two waveforms, then the spectrum should be measured in *both* bandwidths. An example is shown in Figure 13. One fundamental frequency (or channel) (left) is unchirped and another channel (right) is chirped. The appropriate measurement bandwidths are 100 kHz for the lower-frequency channel (left) and 300 kHz for the higher-frequency channel (right). The radar spectrum therefore needs to be measured in both bandwidths, as shown in Figure 13.

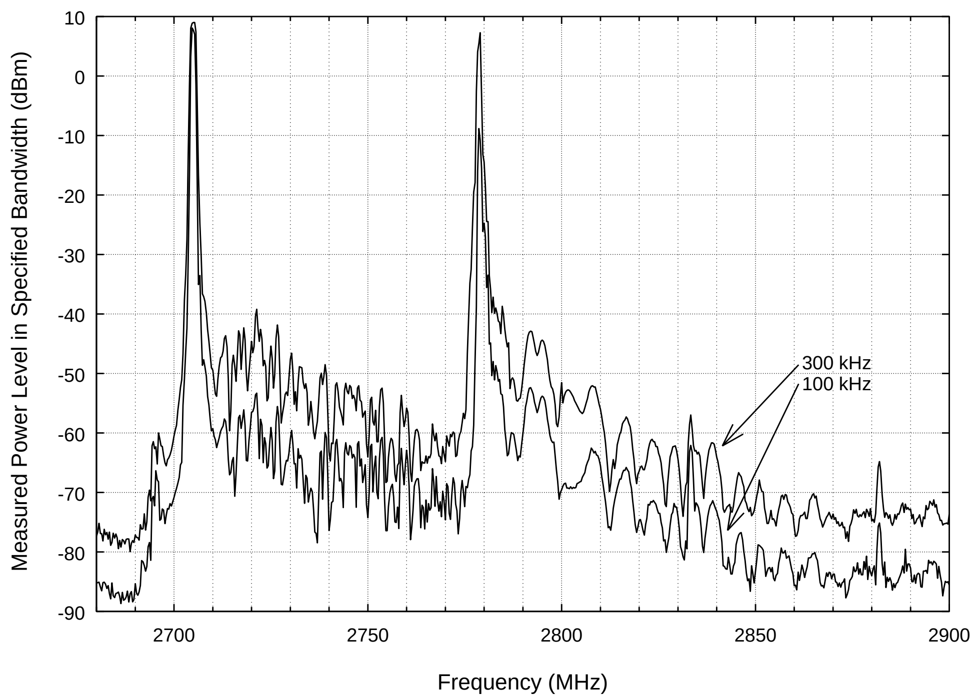

Figure 13. Emission spectrum measurement performed on a multi-mode chirped radar.

5.4 Variation in Measured Spectra as a Function of Measurement Bandwidth

Radar emission levels are bandwidth-limited at their fundamental frequencies. That is, when measurement bandwidths equal or exceed the B_m values given in Table 2, the measured peak power will be constant no matter how much the measurement bandwidth is increased.

Conversely, in the radar unwanted (out-of-band and spurious) emission spectrum domain, measured levels of unwanted emissions will increase for measurement bandwidths that are wider than the B_m values given in Table 2. Consider for example the non-FM pulsed radar emission of Table 2, with a critical measurement bandwidth, B_m, of 1 MHz. The peak power measured at its fundamental frequency will be constant (or nearly so) for measurement bandwidths greater than B_m (1 MHz). However, the measured levels of unwanted emissions will vary as described in

Appendix G. Thus measurements performed in bandwidths inappropriate to Table 2 may result in apparent non-compliance with the RSEC, when the radar under test would have in fact been in compliance had it been measured in accordance with the Table 2 values of B_m. Emission levels can be made to appear arbitrarily high relative to the power at the radar fundamental if measurement bandwidths exceed the Table 2 values. This problem is discussed further in Appendix G, and is diagrammed graphically in Figure G-7.

5.5 Determination of Frequency-Stepping Time Interval (Dwell Time)

As noted in Appendix C, the most practical approach to measurement of radar emission spectra is to implement frequency-stepping rather than frequency-sweeping across the spectrum. This section describes the procedures for determining the time interval needed to determine peak power at each measured frequency (called dwell time) for radar emission spectra that are measured with the stepped-frequency approach.

As described in Appendix C, implementation of the dwell-time stepped-frequency measurement approach requires computer control of a spectrum analyzer. Alternative approaches that do not require computer control (such as sweeping across the spectrum in a maximum-hold trace mode) may be used, but with the caveat that they suffer from significant limitations for the purpose of determining compliance of the spectrum with RSEC mask limits. Approaches that do not utilize computer controlled frequency stepping of the measurement system tend to be more difficult to implement because they are probabilistic instead of deterministic in nature.

The necessary dwell time is a function of the radar antenna beam-scanning and frequency-tuning (fixed-tuned vs. hopping) characteristics. Section 5.5.1 describes the procedure for determining dwell time for fixed-tuned radars utilizing conventional beam-scanning techniques. Section 5.5.2 describes the determination of the dwell time for complex beam-scanning (combined vertical and azimuthal beam scanning) and frequency-hopping radars.

If the radar beam scanning can be stopped for the duration of the emission measurement, then the measurement step dwell time can be reduced to about 1 or 2 seconds, and the overall amount of time required to complete the measurement will be significantly reduced.

5.5.1 Conventional Beam-scanning, Fixed-tuned Radars

In this context, a conventional radar is one that scans a beam only in one dimension (usually azimuth); that repeats the scanning in a predictable, periodic manner; and that does not frequency-hop. Examples include air search radars with broad vertical beam patterns and mechanical azimuth scanning; sector-scanned radars (typically on aircraft); and phased-array radars that scan a beam only in azimuth.

The procedure for determining dwell time is as follows: First, a measurement location is identified (see Appendices C and E). Then the measurement system is tuned to the radar fundamental frequency and maximum attenuation is invoked in the RF front-end. The measured level is verified to be less than the saturation level of the measurement system. Attenuation (10 dB is suggested) may be inserted and removed from the measurement path to check for measurement system linearity.

The dwell time for each measured frequency needs to be slightly longer than the radar beam scanning interval. If the radar rotation interval is already known with certainty (e.g., 6 rpm = 10 seconds per rotation), then the dwell time may be set immediately, to a slightly longer interval (e.g., 11 seconds dwell time for a 10-second antenna rotation time.)

Alternatively, if the radar antenna rotation rate is not precisely known *a priori*, the following procedure may be used to measure it. The measurement system is tuned to the radar fundamental frequency. The frequency span of the measurement system (usually a spectrum analyzer) is set to zero hertz, so that the radar beam scanning characteristic is now observed in the time domain on the system display. The sweep time of the measurement system is initially set to a few seconds, so that the radar beam is seen at least once on the measurement system display. Then the sweep time is gradually lengthened and additional sweeps are taken, until the radar main beam appears at least twice on the display. When such a display is achieved, a marker function is used to determine the time interval between the main beam features; this is the rotation (or sector-scan, if appropriate) interval for the radar. The dwell time of the spectrum measurement needs to be set at a value slightly longer than this, as mentioned in the paragraph above.

5.5.2 Complex Beam-scanning and Frequency-hopping Radars

Some classes of radar scan space in elevation as well as azimuth, and may scan both these degrees of freedom with some amount of randomness; this is complex beam-scanning. Some radars change their tuned frequency on a pulse-to-pulse basis or at fixed or random intervals (i.e., they frequency-hop). And some radars combine complex beam scanning with frequency-hopping. The procedures for measuring the spectra of complex beam-scanning and frequency-hopping radars are nearly identical to those described above. The major difference is that the dwell time will need to be lengthened to ensure that a maximum peak level measurement will occur at each measurement step in the spectrum.

Complex beam scanning and frequency-hopping by a radar transmitter have the effect that maximum-amplitude pulses may not necessarily be directed toward the measurement system on its tuned frequency at predictable intervals, as is the case for conventional radars. Nevertheless, the antenna beam and the transmitted frequency will revisit the measurement system location and tuned frequency with a high probability within *some* interval; the problem is to determine that interval.

To do this, the measurement system is tuned to a radar fundamental frequency with the spectrum analyzer set to a zero hertz span. The RF front-end attenuation is set to a maximum value. The spectrum analyzer sweep time is set to a long interval, on the order of one minute. A single sweep is taken. The highest peak is identified, and then a delta marker is used to find the next-highest peak. The delta marker is used again, to find the next-highest peak after that. The process is continued until all peaks with amplitudes within 2 dB of the highest peak have been catalogued. A pattern normally emerges. This pattern in time intervals between the highest peaks indicates the most probable interval that will elapse between radar main beam scans across the measurement location on the tuned measurement frequency. Unlike the situation for conventional radars described in the previous section, the dwell time for complex radars may require *two* or more antenna rotation periods (e.g., the radar may have a nominal 10-second antenna rotation period, but the dwell time required to measure a consistent peak value may be 20 or 30 seconds). In other words, the necessary time interval may be a random variable with a wide variance; in such cases, the dwell time needs to be long enough to assure that a valid peak is always measured, and this could turn out to be two or more antenna rotation periods.

The selected dwell time may be verified as correct by obtaining data in that interval a total of ten or twenty times, and noting the peak values returned from each of those individual times. If all these peak values are within 2 dB of each other, then the selected dwell time is adequate for the RSEC measurement.

As a matter of efficiency, it has been observed that this dwell time, while necessary for measurement of the radar spectrum at fundamental frequencies and within immediately adjacent out-of-band spectrum, is longer than what is required for measurement of the spurious spectrum. The dwell time required in the spurious domain for complex-beam-scanning and frequency-hopping radars is *less* than that required at the fundamental frequencies. This is partly because the antenna does not generate a well-formed beam in the out-of-band and spurious domains and also because hopping of the fundamental frequency does not affect out-of-band and spurious emissions to much extent.

To determine how much shorter the dwell time can be in the out-of-band and spurious domains, measurement personnel should observe the radar's beam pattern carefully, on a step-by-step basis, as the measurement progresses across these domains. Eventually, they will observe that the radar peak amplitude is always repeated *twice* during each step. When this happens, the dwell time may be reduced by a factor of two. As the measurement progresses further through the spectrum, the phenomenon may occur again. If it does, the dwell time may again be reduced by half. This process may be continued as necessary while the measurement progresses, and will greatly reduce the overall measurement time without causing any degradation in the results.

5.6 Emission Spectrum Measurements and Data Recording

5.6.1 Overview of Spectrum Measurement Procedure

The radar emission spectrum measurement is performed using the calibration procedure of Appendix D and frequency-stepping algorithm described in Appendix C with measurement bandwidth selected in accord and with Table 2 and dwell time selected as described above. The frequency interval from step to step is typically about equal to the measurement bandwidth (e.g., if the measurement bandwidth, B_m, is 1 MHz, then the frequency interval between successive steps is nominally 1 MHz. (See Appendix C for further discussion of frequency-step interval.)

It is recommended that the measurement be performed in spectrum segments of about 200 frequency steps (each step corresponding to a single data point in the spectrum) per recorded data file. This has been found to strike a reasonable balance between acquisition of a significant amount of data per file versus not risking the loss of a large amount of unrecorded data as a result of possible measurement system failures.

The first segment of spectrum can conveniently bracket the radar fundamental frequency. The next segment begins at the last frequency of the first segment. This sequence of segments continues until the radar spectrum is lost in measurement system noise at the high-frequency end. Depending upon the radar, such a measurement may extend to as much as a few gigahertz above the radar fundamental frequency. Then, the spectrum measurements resume on the low side of the fundamental frequency. They continue until the radar emissions are again lost in the measurement system noise, this time at the low-frequency end. At this point, the RSEC spectrum measurement can proceed to harmonics and possibly sub-harmonics.

It may also be desirable to measure the emission spectrum in additional bandwidths. Such a set of spectra may be found to be useful at a later date, for they will show the progression of measured levels as a function of B_m across the spectrum (see Appendix G).

5.7 Potential Measurement Problems and Solutions

There are at least four major potential problems that may occur in the course of a spectrum measurement. These are:

1) failure to change attenuation appropriately during measurements;
2) unanticipated changes in radar operating mode during measurements;
3) RF energy feed-through (also known as case penetration) into measurement circuitry;
4) overload of the RF front-end amplifier.

5.7.1 Possible Attenuation Mistakes During Measurement

It is often difficult to change attenuation appropriately for every data point. Attenuation errors will often appear as vertical cliffs in the spectrum, as shown in Figure 14. In this case, too much RF attenuation was removed prematurely, at the point indicated by the arrow, as the measurement progressed. Without sufficient attenuation the measurement system front end was saturated at a level that was lower than the actual signal level, with the result that the spectrum level indicated in the (inaccurately corrected) measurement data is too low at the indicated frequency. The measured power levels became accurate again when the radar spectrum power dropped below the measurement system saturation level, one division to the right of the arrow on the spectrum. This situation illustrates the desirability of having a re-measurement feature in the measurement software. Such a feature can be applied to any portions of a radar spectrum that are suspected of having been measured with incorrect attenuation.

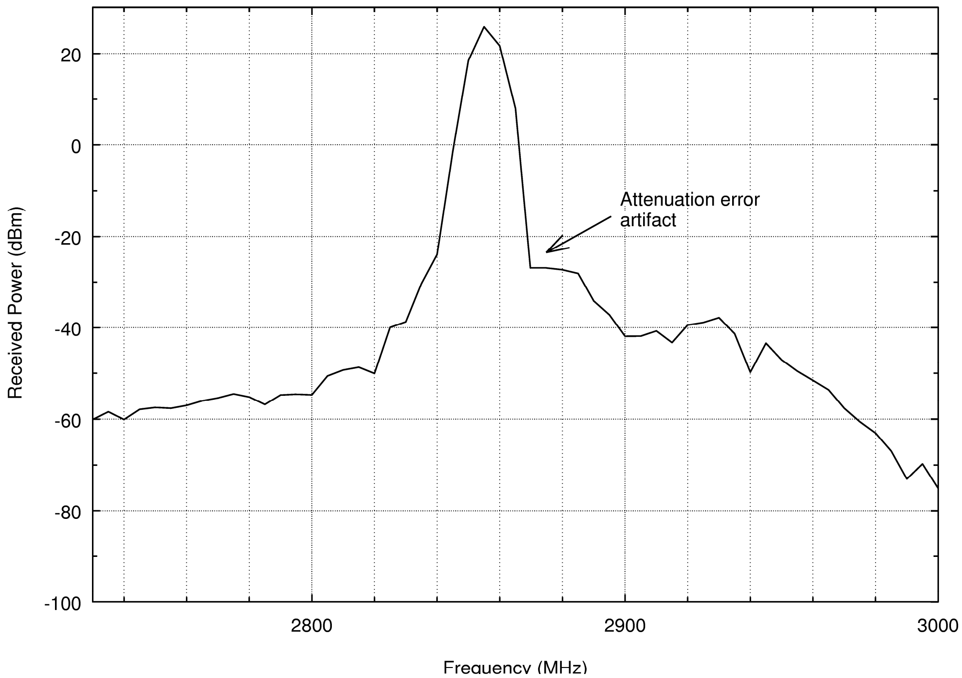

Figure 14. An example of a spectrum measurement error caused by an incorrect RF attenuation setting.

5.7.2 Changes in Radar Operating Mode During a Measurement

Radar transmitters sometimes change modes or cease to function while measurements are proceeding. Such changes may not be apparent to measurement personnel. Therefore, an auxiliary measurement system may be useful during measurements to verify that the radar mode is constant. The auxiliary system consists of an omni-directional antenna connected to a second spectrum analyzer. The analyzer is fixed-tuned to the radar fundamental frequency. The radar beam scanning, frequency-hopping (if any), and peak measured power at that frequency are monitored throughout the measurement. Radar mode changes will be indicated by changes in any of the observed parameters on the monitor.

5.7.3 Feed-through and RF Front-end Overload

These are system-linearity problems, and will result in incorrect power measurements. Because they are somewhat difficult to detect, **it is critical that measurement personnel verify repeatedly during the spectrum measurement that the measurement system is behaving linearly.** Brief descriptions of these problems, diagnostics for their identification, and solutions for them are described in this section.

Feed-through (case penetration) of radar energy directly into measurement system circuitry can occur due to the high-energy radar signal coupling directly into measurement system circuitry. Resulting measured levels are obviously incorrect in that circumstance.

Front-end overload occurs when the measurement system RF front-end amplifier is saturated by the radar fundamental frequency energy. This results in gain-compression of the amplifier. In this circumstance the amplifier output is no longer calibrated. Front-end overload typically occurs when spectrum levels decrease (roll off) rapidly around the fundamental. To measure those lower levels, RF front-end attenuation must be reduced from the value used to measure at the fundamental frequency. But in some cases the attenuation must be reduced so much that the radar fundamental frequency energy overloads the first amplifier. Although the RF front-end tunable bandpass filtering described in Appendix C is specifically intended to mitigate this problem, radars with extremely fast spectrum roll-off may nevertheless tend to produce this problem.

Measurement personnel need to perform diagnostics to verify that neither feed-through nor front-end overload are occurring, and to mitigate them if they do occur. Both problems are diagnosed by changing the measurement system RF front-end attenuation by 10 dB to verify system linearity. If the measurement system is linear, a 10 dB change in attenuation should result in exactly 10 dB of change in the measured power level.[15]

5.7.3.1 Mitigation of Feed-through and RF Front-end Overload

If feed-through occurs, additional shielding of the measurement system may be necessary. Such shielding may be accomplished by positioning the measurement vehicle behind a building or dense foliage, while the measurement antenna is mounted high enough (as on a mast) to see over the obstacle(s) toward the radar antenna.

If front-end overload occurs even though a high-quality, tunable bandpass filter is being used ahead of the RF front-end amplifier (as described in Appendix C), then the problem may be mitigated by adding a notch filter ahead of the amplifier, with the notch being tuned to the radar fundamental frequency. (The measurement system will need to be re-calibrated with the notch in place.) The notch is intended to provide the necessary additional frequency-dependent attenuation to prevent overload of the amplifier when RF front-end attenuation has to be reduced to measure low-level emissions near the fundamental frequency.

Alternatively, it may be possible to solve the problem by slightly off-tuning the RF front-end bandpass filter, so that it is not centered at the measurement frequency. Effectively, this attenuates the fundamental by a larger amount than would otherwise be obtained at the frequency separation between the radar fundamental and the measured frequency.

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[15] Or, if automated calibration and attenuation corrections are being made, then the power levels obtained with 10 dB attenuation should have the *same* values as when measured with the original attenuation setting.

5.8 Example Emission Spectrum Data

Example emission spectra are shown in Figures 15, 16, and 17. The data in Figure 15 demonstrate the need for wide dynamic range in the measurement system as a whole and high-performance RF bandpass filtering in the front end. The measurement system noise floor is at –90 dBm and the peak measured power level is at almost +30 dBm, for a total dynamic range of nearly 120 dB. But while the measurement spans a frequency range of 1500 MHz, most of the dynamic range is required in a frequency span of just 150 MHz near the fundamental frequency. Without adequate front end preselection, the high power at the fundamental will overload the measurement system at all other frequencies. Great care must be taken to avoid attenuation errors such as those shown in Figure 14. A measurement system such as that described in Appendix C is required to accomplish this sort of measurement.

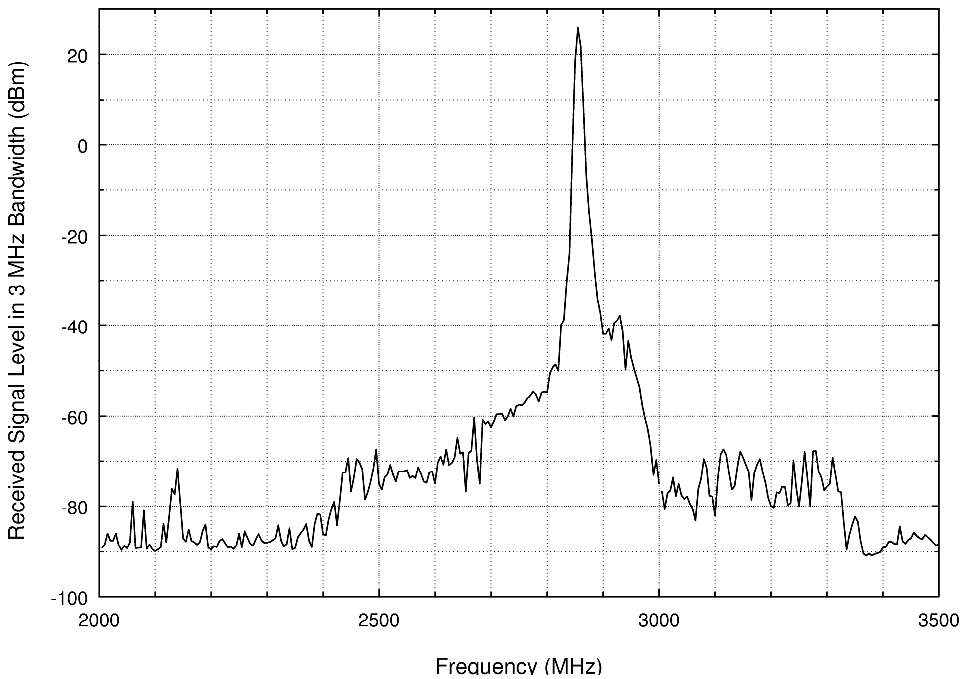

Figure 15. Example spectrum of an air search radar.

Figure 16 illustrates the effect of variations in the measurement bandwidth. The correct bandwidths for measurement of this radar are 1 MHz or less, because 1 MHz is the *widest* bandwidth that gives *less* than the full-power response of 3 MHz. Bandwidths wider than 1 MHz should not be used because they will result in measured levels of unwanted emissions that are too high compared to the power at the fundamental frequency. This is demonstrated by the data taken in 3 MHz in Figure 17. In that figure, the curves measured in 3 MHz and 1 MHz both attain the same measured maximum power, but the levels of unwanted emissions measured in 3 MHz are relatively much higher than for the 1 MHz measurement. This is an indication that a bandwidth of 3 MHz is too wide for this radar for purposes of assessing RSEC compliance, a fact borne out by the result shown in Figure 17. The measurement bandwidths of 1 MHz and 300 kHz, conversely, show approximately the same relative levels for unwanted emissions, when their measured peak power levels at the radar fundamental frequency are normalized. So from the standpoint of assessing RSEC compliance, the 300 kHz data are as good as the 1 MHz data. The only drawback to using 300 kHz or narrower bandwidths is that more data points are required to fill in such curves.

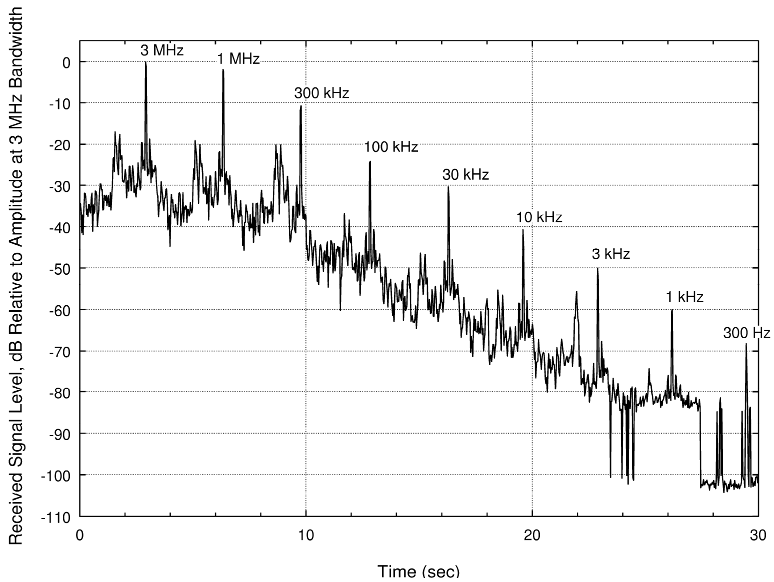

Figure 16. Example bandwidth progression measurement of the fundamental for the radar having the measured emission spectra of Figure 17. The ideal measurement bandwidth is 1 MHz.

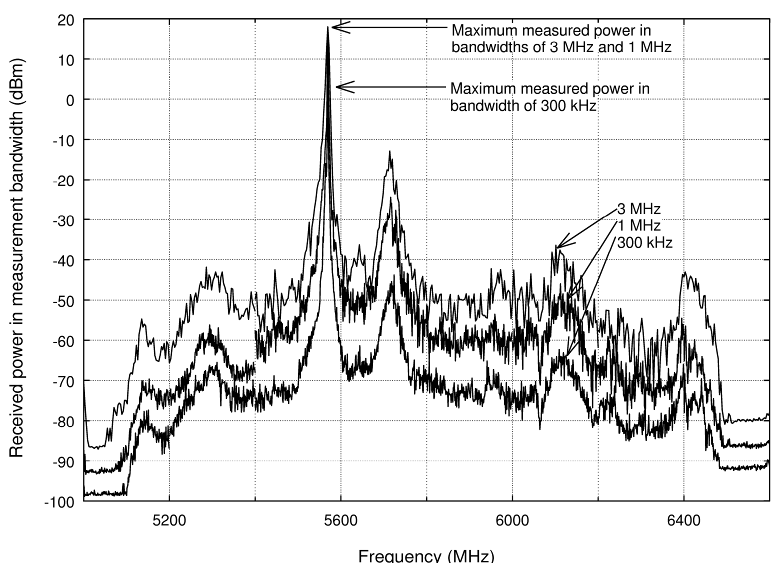

Figure 17. Three spectra for a single radar for which the bandwidth progression is shown in Figure 16. A bandwidth of 3 MHz obtains the same maximum fundamental frequency power as in 1 MHz, but the unwanted emission levels are higher than in 1 MHz. This shows that 3 MHz is an incorrect bandwidth for RSEC compliance measurements, but bandwidths of 1 MHz or less will give correct results.

6. ANTENNA PATTERNS

The RSEC requires suppression of radar antenna gain outside the main lobe for radars falling into the RSEC Criteria Groups C and D.

6.1 Introduction

Antenna gain suppression specifications apply to the portion of the antenna pattern that does not include the main lobe. They are divided into two categories. For antennas that scan through 360 degrees of azimuth, the suppression is specified in terms of the median antenna gain as decibels relative to the peak of the antenna pattern. The median value of the pattern is the smallest value that is greater than or equal to 50% of the measured points. For such radars, the median antenna gain in the principal horizontal plane should be –10 dB or less. For other antennas, suppression is defined relative to the peak gain of the radar main beam.

Antenna patterns of operational radar transmitters can not generally be measured in the radar main beam, because the main beam energy is usually directed into space in directions inaccessible to terrestrial measurement systems. (An example is the beam of a typical air search radar, the lower edge of which is ordinarily tilted about a degree above the horizon.) But the RSEC is concerned mainly with emissions directed toward terrestrial-based receivers. Hence terrestrial-based measurements are adequate for purposes of determining RSEC compliance. This section describes procedures for this measurement.

Radar antenna patterns should be measured from a location that maximizes the signal to noise ratio at the measurement system. Guidelines for determining such a location are described in Appendices C and E.

6.2 Measurements of Conventional Antenna Patterns

The measurement system is fixed-tuned to a radar fundamental frequency in a zero-hertz span. The sweep time is set slightly longer than the radar's beam scanning interval. A single complete rotation (or scan) of the radar is recorded. (A stopwatch is useful as an aid to anticipate when to trigger the sweep.) The same bandwidth should be used as for the RSEC spectrum measurement (Table 2), as this provides maximum dynamic range (signal-to-noise ratio) for the antenna pattern measurement. Positive peak detection should be used. Figure 18 shows an example pattern.

If the measurement system has 60 dB or more of instantaneous dynamic range, then the resulting antenna pattern should be adequate for purposes of RSEC compliance verification. But if the dynamic range is inadequate, then the antenna pattern may have to be measured twice. The first time, full attenuation is used. The second time, 20 dB less attenuation is used. The radar will saturate on one or more beam peaks. But the lower-amplitude portions of the pattern will emerge from the measurement system noise floor. These two measurements may be merged graphically or digitally to reveal the complete antenna pattern with the requisite dynamic range.

6.3 Antenna Pattern Measurements for Advanced Radars

The problem for advanced radars is that the electronic scanning and frequency-hopping of the beams causes antenna patterns to be measured as discontinuous points rather than smooth envelopes. To produce a smooth or nearly smooth envelope, the measurement system should be set to measure the radar as described in Appendix E, but the measurement should be repeated ten or twenty times. Subsequently, the resulting raw data should be normalized in time and added together digitally, to make the final resulting pattern a reasonably smooth envelope.

6.4 An Advanced Antenna Pattern Measurement for All Radars

A problem with all antenna pattern measurements on radars is that multipath-generating obstacles in the vicinity of the radar will cause nulls and peaks in any given pattern measurement. Variations such as multipath due to vehicles, buildings and other radio-reflective objects will also occur. To mostly eliminate these features, perform the following procedures:

1. Measure the radar antenna pattern several times at one location, and cross-correlate the results to eliminate temporal multipath effects at that location;
2. Then, move the measurement system to another location and repeat the procedure to eliminate temporal variation at the second location;
3. Find the median of the patterns from these first two separate locations;
4. If desired or necessary, repeat this procedure at a third measurement system location, and find the median of the three patterns.

An example result is shown in Figure 19. This pattern should approach the result that would be obtained if the radar antenna pattern had been measured in an anechoic chamber.

6.5 Antenna Pattern Statistics

Antenna pattern statistical analysis may be performed on the final pattern(s) that result from the procedures described above. The analysis will be statistical in nature and will virtually necessitate the use of computer-implemented algorithms. Median statistics, such as those required by the RSEC, may be easily computed in this manner.

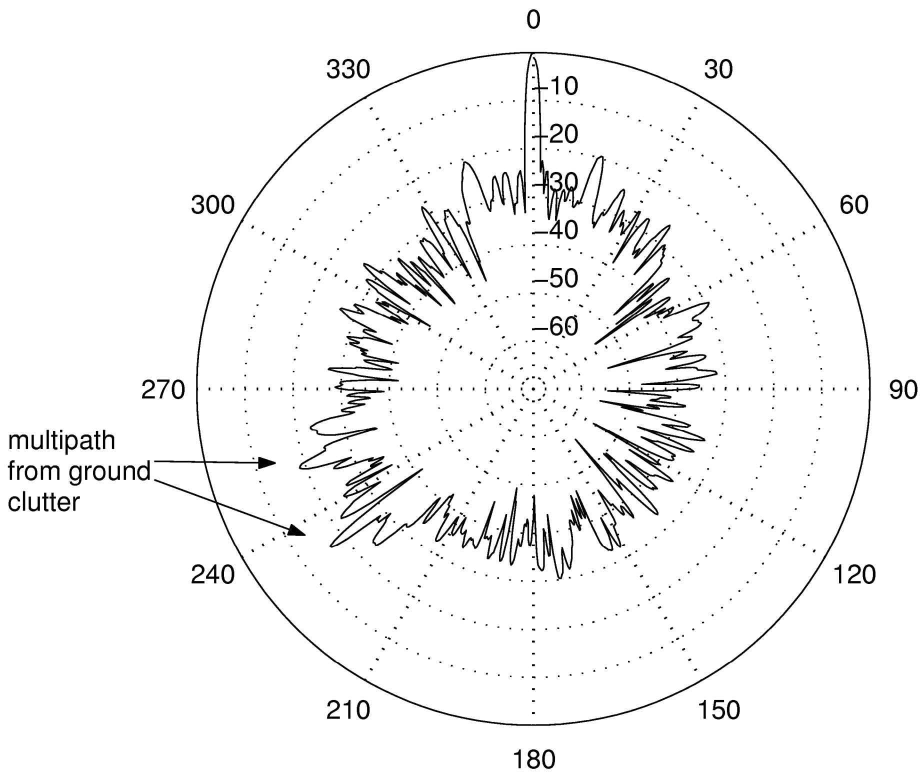

Figure 18. Example radar antenna pattern for a surface search radar.

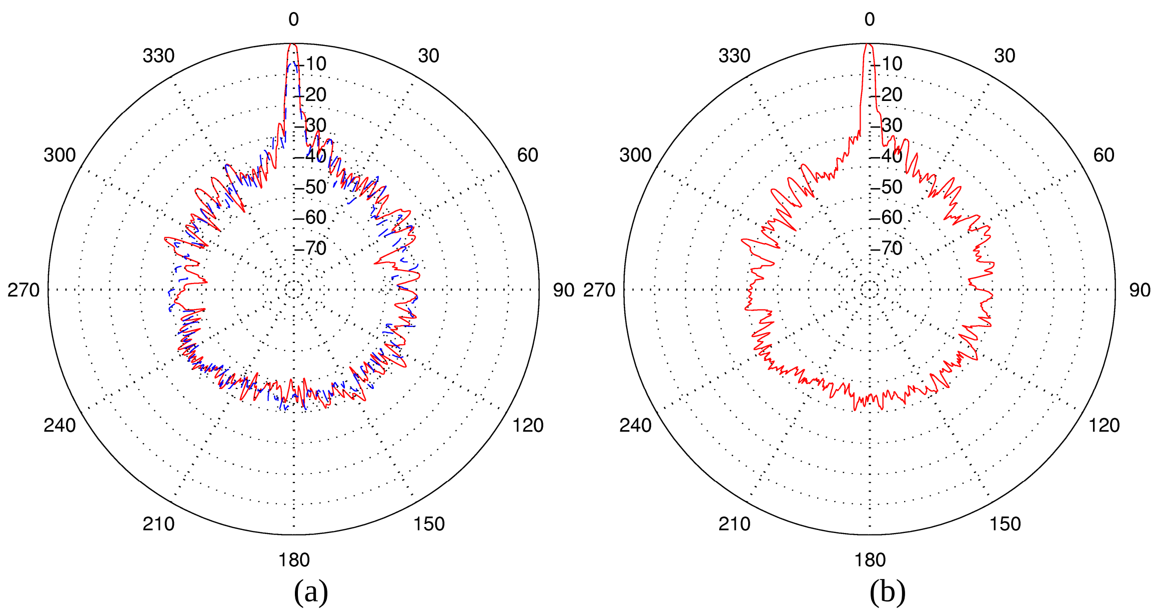

Figure 19. Three antenna patterns. Multipath clutter (a), and median of patterns (b).

7. FREQUENCY TOLERANCE AND TUNABILITY

7.1 Introduction

The RSEC [1, Chapter 5] specifies a maximum allowable amount of unintentional change in the operating frequencies of radar transmitters in Groups B, C, and D. This is called "frequency tolerance." The actual amount of unintentional change in radar transmitter frequency is defined as "frequency drift." RSEC compliance requires that the measured frequency drift is not to exceed the frequency tolerance for the radar [1, Chapter 5].

Frequency drift, as defined here, is an unintentional change in the average radar transmitter frequency, relative to the desired frequency, over a period of time that is long compared to the pulse repetition interval. It does not include the effects of transmitter tube frequency pulling, intentional frequency modulation, or frequency hopping. For purposes of determining RSEC compliance, it is measured in parts per million (ppm) of the desired operating frequency. For example, a tolerance of 800 ppm for a radar operating at 2800 MHz would be:

$$800 \cdot 10^{-6} \cdot 2800 \cdot 10^{6} = 2.24\,\text{MHz}.$$

7.2 Setup for Measurement of Drift in Operating Frequency

This measurement is performed with a spectrum analyzer that is coupled to the radar either through a hardline connection (i.e., through the radar's directional coupler, if one is available) or else via a radiated signal. Whichever configuration is used for this measurement, Appendix B describes the procedure for setting external RF attenuation prior to the start of the measurement. If measurements are to be performed in a radiated mode, then Appendix E should be consulted for guidance on the positioning of the measurement system relative to the radar.

With attenuation both outside and inside the spectrum analyzer adjusted as specified in Appendix B, the remaining spectrum analyzer settings are configured as follows:

Table 3. Spectrum Analyzer Parameter Settings for Measurement of Frequency Drift.

Spectrum analyzer parameter	**Value for parameter setting**.
Center frequency	Set to any one of the radar's nominal operating frequencies.
Frequency span	For non-chirped radars, set three to five times wider than the value of B_m specified for the radar in Table 2. For chirped radars, the frequency span is set three to five times wider than the chirp width of the radar.
Detection mode	Positive peak.
IF (resolution) bandwidth	For non-chirped radars, set between 1/10 to 1/3 of the value of B_m specified for the radar in Table 2.
Video bandwidth	Equal to or greater than the value of the analyzer's IF (resolution) bandwidth.
Data trace mode	Refresh (clear-write) continuously.

For example, suppose a simple pulsed radar has a fundamental frequency of 9500 MHz and a pulse width of 50 ns. The nominal necessary bandwidth of the radar is (1/50 ns) = 20 MHz. Then the spectrum analyzer center frequency would therefore be tuned to 9500 MHz, with a frequency span of 60–100 MHz. The IF (resolution) bandwidth would be set anywhere from 2–7 MHz.

7.3 Measurement of Frequency Drift

With the spectrum analyzer configured as described in Table 3, and with the analyzer sweeping repetitively across the spectrum range of interest, the radar activity should be observed on the analyzer display on the channel that has been selected for the measurement. The spectrum analyzer center frequency, reference level, or attenuation level may need to be adjusted slightly to center the display on the radar activity on the selected frequency.

With these adjustments accomplished, the spectrum analyzer data trace mode is put into a maximum-hold configuration. Within a few seconds, the peak emission envelope of the radar emission on the frequency of interest will fill in a smooth curve. This curve is recorded, either electronically or via a photographic image of the instrument display.

With that operation completed, the trace should be frozen so that no further updates can occur. Without changing any spectrum analyzer settings, a second trace is started in an update (clear-write) mode, and is then placed into a maximum-hold mode. This second trace will at first exactly overlie the first trace. But over an interval of minutes or hours, the envelope may be observed to drift relative to the first trace. The frequency change observed over the measurement time period is the drift.

The second trace is recorded to document the drift. Screen cursor functions may be used to most easily assess the absolute amount of drift. To determine relative drift in parts per million (ppm), divide the absolute drift by the nominal operating frequency (keeping the frequency units the same for both the numerator and the denominator in the fraction) and multiply by 10^6. The resulting value is compared to the allowed tolerance listed in the RSEC [1, Chapter 5].

7.4 Radar Tunability

As noted in the RSEC [1, Chapter 5], radar tunability verification is left to the agency that controls any given radar. But the technique provided here for observing radar frequency drift can also be used to check tunability at any given desired frequency.

7.5 Sample Data and Calculations

Suppose that a radar operates at 9500 MHz on the first spectrum analyzer trace (taken at the beginning of the measurement). After half an hour, the envelope of the second spectrum analyzer trace has shifted down in frequency by 11.5 MHz relative to the envelope of the first trace. Relative drift is computed as $(-11.5/9500)\bullet 10^6 = -1210$ ppm.

8. RSEC RADAR RECEIVER PARAMETERS

8.1 Introduction

RSEC receiver parameter measurements include selectivity, receiver image and spurious response, and receiver local oscillator radiation. These parameters are addressed in this section. Radar receiver characteristics affect the efficiency with which any given radar system can share spectrum with other radars and with non-radar systems. Characterization of receiver parameters is thus part of the RSEC.

8.2 Selectivity

The RSEC specifies characteristics for “overall receiver selectivity” [1, §5.5]. This is meant to include all components that might affect the shape of the bandpass of the radar receiver, from the antenna to the final display of data output. In many cases, the receiver selectivity of a radar is essentially synonymous with the selectivity of the IF section. This is because the RF bandpass width is usually at least ten times wider than the IF bandpass and thus has a negligible effect on the overall selectivity of the receiver.

This does not mean that the RF bandpass selectivity is of no concern to spectrum managers. The less selective (wider) an RF front end section is, the more vulnerable it is to both unintentional and intentional jamming by strong signals that are off-tuned from the radar receiver’s nominal operating frequency or frequencies.

NTIA recognizes that, in the interest of higher spectrum efficiency, it is desirable that every radar RF front end should at least be bandpass filtered for the operational band of each radar. Even better, from a spectrum efficiency point of view, is for each radar RF front end to be relatively narrowly bandpass filtered. If made necessary by frequency hopping modes, such bandpass filtering might need to be tunable. This capability can be effected through such technology as electronically tunable yttrium-iron-garnet (YIG) filters.

Lack of RF selectivity is sometimes considered to be an inherent characteristic of distributed-array radar transmitter-receiver (T/R) systems, such as arrays of solid state T/R modules. But from the standpoint of improved spectrum management practices, inclusion of YIG (or other technically feasible) filtering is desirable in the T/R modules of distributed-array systems, at least in the operational band of each radar.

8.2.1 Receiver IF Selectivity Measurement Overview

The receiver selectivity is required to be "commensurate with" (taken to mean "approximately equal to") the transmitter bandwidth. In the case of radars belonging to Group B, the term "commensurate with or narrower" is used. In the case of radars belonging to Groups C and D, it is also required that a change in pulse width be associated with a corresponding change in receiver bandwidth.

Since the receiver response is usually approximately that of the IF section, the procedures described here are designed to check the receiver's IF bandwidth at the 3 dB, 20 dB, 40 dB, and 60 dB points.

Receiver selectivity is measured on a test frequency (or frequencies) near the midpoint of the radar operating frequency band. If more than one receiver bandwidth is available (either for multiple pulse widths or for multiple radar signal processing modes), then all available radar receiver bandwidths will be measured. The exact receiver input and output test points are not specified and will vary between equipment types. But at a minimum the IF bandpass (or its equivalent in digital processors) must be included between the input and output test points.

In many cases it will be necessary to disable or bypass electronic gain controls that normally attenuate returns from objects with large cross sections. In the case of advanced radars, it may be necessary to treat the entire radar as a black box for the purpose of bandwidth determination, as described below.

8.2.2 Swept CW IF Selectivity Measurement

If an output is available for the receiver IF section, then its bandwidth can be determined by injecting a CW signal and assessing the response at the output as the input signal frequency is changed.

This measurement is nominally performed as shown in Figure 20. The exact configuration used will be determined by the radar block diagram and design. Desirable test conditions are for the radar to operate in a mode that satisfies the following conditions:

a) operation with constant gain (AGC fixed);
b) operation at a constant frequency;
c) identical amplitude for pulsed and CW signals;
d) available test points that are accessible, as shown in Figure 20.

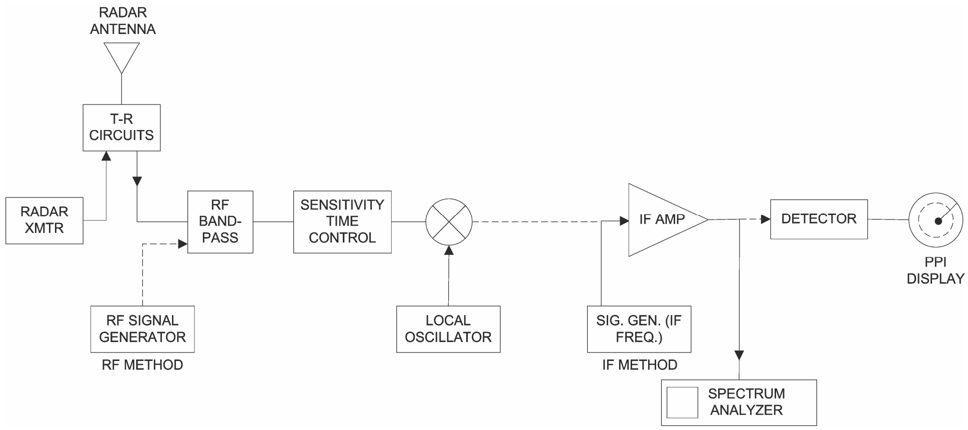

Figure 20. Block diagram for receiver IF selectivity measurement.

The above conditions are usually not met by radars in their normal operational modes. But these conditions can often be met by carefully selecting test points (sometimes requiring resoldering of circuit cards). The requirements can also often be met in newer radars by changing radar control software or using special diagnostic software. Such access to either circuit cards or software will require the assistance of specially trained and knowledgeable technicians or radar engineers.

With regard to the fourth criterion listed above, some radars perform special diagnostics for internal and external noise assessment during a portion of the nominal interpulse interval. For these radars, a CW signal injection can effectively ruin the internal calibration and ultimately halt radar operation; in this case the test signals must be injected as pulses (preferably about ten times longer than the radar nominal pulses) rather than as CW energy.

Regarding sensitivity time control (STC) most radars use this feature or something similar to it to compensate for the strongest target returns. Under normal operating conditions, these radars have a rapidly changing gain. If the STC is produced at a single point within the radar circuitry, then the gain change can be negated by injecting the test signal after that critical point on the block diagram. But if the STC is produced in multiple circuits spread throughout the radar receiver, it may be necessary to turn off the STC. This may require the assistance of software specialists for advanced radar designs.

Similarly, with regard to maintaining operation on a single frequency during operation, it may be necessary to suspend frequency hopping and other diversity modes in the radar’s operation. This may be controllable at an operator’s station, or it may require the assistance of software specialists for some advanced radar designs. Alternatively, the test signal may be injected following the mixer (where the radar operates at a constant frequency).

Although this measurement is usually best performed by injecting a test signal at the RF input to the radar receiver, it may be easier with some radar receivers to inject a test signal at the IF input. This is normally acceptable because, as noted above, the overall receiver selectivity of most radars is essentially identical to the IF selectivity.

Whichever injection point (RF or IF) is selected for the test signal injection, the following procedure is applicable. For injection at the IF, the signal generator is tuned to the frequency of the IF amplifier immediately following the first mixer. For RF signal injection the signal generator of Figure 20 will be set to one of the radar's operational frequencies and a coupler needs to be available at the RF front end.

A spectrum analyzer is connected to the IF output, so that as much of the IF selectivity as possible is included in the test path. The radar transmitter may be turned on or off, but in either case tests should be made to determine that the RF and IF stages are operating normally. (Only the IF stages are important if the test signal is injected at the IF.) If automatic gain control (AGC) causes receiver gain to change with a test signal, it may be necessary to modulate the test signal with a duty cycle similar to the normal PRF and a pulse width about ten times longer than the transmitted pulses. As noted above, this expedient is also necessary for advanced radar designs that assess noise levels and perform self-calibrations during selected interpulse intervals. The spectrum analyzer display will develop to look like Figure 21. With all radar and test instrumentation connected together, the test procedure is performed as follows.

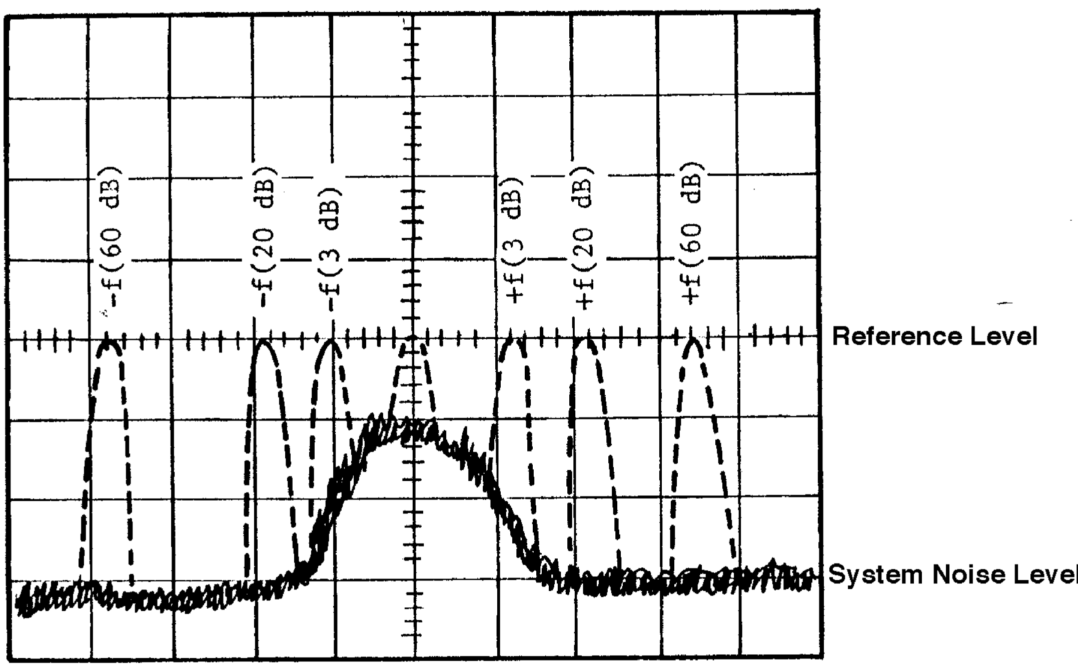

Figure 21. Receiver selectivity measurement as it will develop on a spectrum analyzer screen display.

1) Tune the spectrum analyzer to the IF frequency. Set the analyzer frequency span to about 10-100 times the nominal radar IF bandwidth. Set the analyzer resolution (IF) bandwidth to about 0.1 times the nominal radar IF bandwidth and detection is set to peak. System noise through the IF amplifier will cause a broad noise peak to appear at the IF frequency. The analyzer frequency display should be centered on this peak.

2) Manually adjust the signal generator frequency and amplitude so that the signal appears at the center of the spectrum analyzer display with an amplitude about 10 dB higher than the noise. Adjust the spectrum analyzer reference level so that the maximum level of the signal response touches a horizontal display graticule, which will be called the reference level. Note the signal generator amplitude for the reference level.

3) Increase the signal generator amplitude by 60 dB. Tune the signal generator higher in frequency until the amplitude of the signal displayed on the spectrum analyzer equals the reference level established in Step (2) above. Increase the spectrum analyzer span if necessary to display this frequency. Note the new frequency and use the spectrum analyzer frequency delta function to verify the new frequency. Repeat this process by decreasing the frequency of the signal generator until the same effect is achieved on the low side of the center frequency, and note that frequency as well. The difference between the high and low frequencies is the approximate 60 dB bandwidth of the radar.

4) Repeat Steps (2) and (3) to determine the 40 dB, 20 dB, and 3 dB bandwidths of the radar receiver. The only difference is that, each time Step (3) is performed, the signal generator must be set to the level relative to the reference that corresponds to the bandwidth that is to be assessed (40 dB for the 40 dB bandwidth, etc.). The spectrum analyzer frequency span may need to be periodically readjusted to keep the frequency delta values easily measurable and readable.

8.2.3 Receiver Selectivity Measurement Methods for Advanced Radars

There are a variety of methods for measuring the receiver selectivity that are closely related to the procedure outlined above. A very convenient method is to replace the manually controlled signal generator with a tracking generator that is linked to the spectrum analyzer. This method has the advantage of enabling the entire bandpass characteristic to be recorded as a single trace on the spectrum analyzer. The major disadvantage of this method is that it cannot be used to measure many IF amplifiers that are designed to saturate before the 60 dB signal is injected.

For advanced radars that do not have necessary internal inputs and outputs available, and to achieve a more accurate result in general, the test signal may need to be injected at the radar RF. This approach will require that radar frequency agility, STC, and AGC all be disabled, or else that the test signal be injected as pulses that are synchronized with internal radar trigger pulses.

For the most advanced radars, in which the entire system must be treated as a black box, the following procedure can be used. In this approach, a simulated target (or set of targets) is produced at the radar RF front end, and the target frequencies are progressively off-tuned from the center frequency at progressively higher amplitudes, those amplitude levels being adjusted to make the targets barely visible on the plan position indicator (PPI) for any given amount of frequency off-tuning. The radar receiver selectivity is estimated from the combinations of measured frequency offsets and corresponding increases in amplitudes that are required to keep the targets visible.

1) Radar targets are produced with a signal generator that generates pulses at a nominal radar center operating frequency with pulse widths approximately equal to the radar pulse width. The output is the radar plan position indicator (PPI) display. For convenience, the simulated targets should be generated in synchronicity with the radar trigger pulses so as to produce a ring of targets around the center of the PPI as the radar scans progress.

2) The amplitude of the injected pulses is at first made high enough to clearly identify the pulses as targets on the PPI display. Then the amplitude of the pulses is reduced to a level at which the target indications reach the threshold. The output level of the pulse generator is noted as a reference.

3) The pulse amplitude is increased by 3 dB relative to the reference level and the frequency of the pulse generator is gradually off-tuned, either to higher or lower frequency, until the targets again nearly disappear. Then the process is repeated with the signal off-tuned in the opposite direction. The total frequency shift is noted as the 3 dB bandwidth of the radar receiver.

4) The preceding step is repeated for pulses at amplitudes increased by 20 dB, 40 dB, and 60 dB relative to the reference level. At each amplitude, the frequency is shifted both upward and downward to the limits at which the targets just disappear, the limit at which the corresponding total delta frequency shifts are the corresponding bandwidths of the receiver.

8.3 Receiver Image and Spurious Response

This test determines the response of the radar receiver to signals of frequencies far removed from the nominal radar receiver frequency. These responses are divided into the response of the IF image frequency (called the image response) and the rest of the responses (called spurious responses). These responses are defined relative to the radar receiver response to a signal at the radar receiver tuned frequency. The responses are measured in terms of decibels below the desired response, or simply as decibel suppression. This test only applies to the receiver IF and RF characteristics; signal processing rejection is not included.

For radar receivers in RSEC Group B, image responses have no specified limit and all spurious responses are to be suppressed at least 50 dB. For radar receivers in Groups C and D, the image response shall be suppressed at least 50 dB and all spurious responses are to be suppressed at least 60 dB.

Radar receiver spurious and image responses are measured by injecting a test signal as shown in Figure 22. The receiver shall be tested to the lower frequency limits shown in Table 4. The receiver will be tested to the upper frequency limits shown in Table 5.

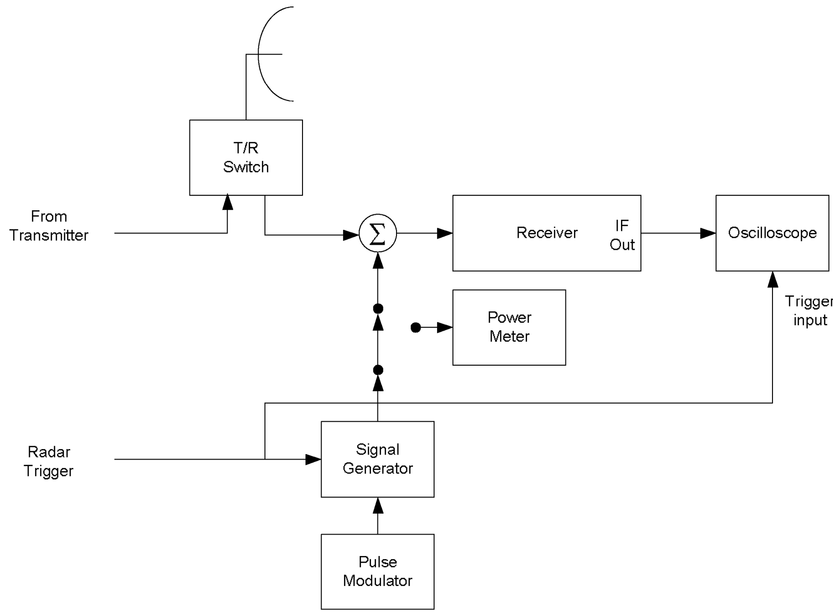

Figure 22. Block diagram for receiver spurious response measurement.

Table 4. Lower Frequency Limits for Radar Receiver Spurious and Image Response Testing

Type of connection between radar transmitter and antenna	**Minimum frequency to be tested**
coaxial	the lesser of 0.5 F_0 or F_{base}, where F_{base} is the lowest frequency used in a frequency multiplying or frequency synthesizing method of generating F_0
waveguide	the greater of 0.5 F_0 or 0.9 F_{cutoff}, where F_{cutoff} is the waveguide cutoff frequency

Table 5. Upper Frequency Limits for Radar Receiver Spurious and Image Response Testing

F_0, GHz	**Maximum frequency to be tested**
0 to 2	10 F_0 or 10 GHz, whichever is less
2 to 5	5 F_0 or 18 GHz, whichever is less
5 to 12	4 F_0 or 26 GHz, whichever is less
12 to 40	3 F_0 or 40 GHz, whichever is less

Measurements made in waveguide systems at frequencies above the the normal operating range of the waveguide (e.g., harmonics of a signal) are likely to be very difficult and may ultimately become impractical for any degree of desired accuracy in the outcome. If such a frequency has been reached in the course of testing that it becomes obvious that the coupling loss factors through the waveguide components are extremely high, then it may be assumed that spurious response is no longer of concern because only a small fraction of incident energy at such frequencies would ever be able to reach the radar receiver from the outside world.

The test is performed as follows: A pulsed RF signal is injected into the radar receiver at frequencies relatively far away from the radar operating frequency. The selection of a point in the signal path to inject the test signal should be made as close to the radar antenna as is convenient.

For advanced radar designs in which no coupler may be available after the antenna, it may be necessary to couple directly into a front-end RF amplifier with a coaxial hardline from the test instrumentation (as in some types of radars with solid state front end arrays) or else to radiate into the radar from a distance. In this case, the reference response to the injected signals must be determined relative to the level coupled in at a nominal value of (one of) the radar's fundamental frequencies, F_0.

If the test signal is internally connected, the test point should be chosen so that any bandpass filters are in the signal path, but it is critical to avoid damage to the test equipment that could be caused by exposure to the radar transmitter output. If an RF filter is used in a signal path shared by the transmitted and received signal, then it may be necessary to turn off the transmitter while this measurement is in progress. For some advanced radar designs in which such deactivation may not be possible, then the option of performing the test via radiated signals, as outlined above, may need to be exercised.

A detector and oscilloscope are connected at the output of the IF section to identify responses caused by the input test signal. If possible, the oscilloscope is adjusted so that the test pulse appears at a steady point on the scope display; the radar trigger pulse, if available, can be used for this purpose.

The test signal is produced by a signal generator (or a combination of signal generators) which covers the required frequency test range. The signal generator is modulated with a pulse of duration that is comparable to the nominal pulse width of the radar. The test pulses must be synchronized to the radar operation with a delay such that they are placed within the time window of maximum receiver sensitivity. For advanced radars that are being assessed via radiated pulses, the pulses will have to be transmitted without synchronization but at a high enough rate to ensure that some of them always fall within this time window.

The same trigger pulse is used to synchronize the oscilloscope display to the pulse generation. For advanced radars being tested radiatively, the pulses cannot be synchronized and they have to be distinguished by using a somewhat different pulse width than the radar generates. Frequency-hopping radars are tested on a single frequency at a time. Chirp radars are tested with a CW signal.

Expected image and spurious response frequencies can be calculated as follows:

$$F_{spurious} = \frac{(p \cdot F_{LO} \pm F_{IF})}{q}$$

where p and q are integers (1, 2, 3, …); F_{LO} is the local oscillator frequency; and F_{IF} is the frequency of the first IF. These frequencies should be calculated for all values of p and q up to 10 or until $F_{spurious}$ is out of the frequency range of Tables 4 and 5. The receiver should be tested at these frequencies with special care when the frequencies are encountered in the next several test steps, since spurious responses are possible at these frequencies. Signals at frequencies associated with low values of p + q equal to three or less are especially likely to produce responses when they fall within the normal operating range of the radar.

To conduct the test, the following steps are performed:

1) The radar is tuned to a frequency near the lower edge of the operating band. The pulse modulator is adjusted to give a duty cycle of 100% (CW). The signal generator is tuned to the radar operating frequency and the signal generator is set to deliver a reference level (nominally 0 dBm, but other values can be used) to the receiver. Whatever the reference level that is used, the signal generator(s) settings must be determined that will generate this level at every frequency that is to be tested; approximately twenty frequencies may need to be checked across this range to determine the signal generator settings required to achieve this result at each frequency.

2) The signal generator is tuned to the radar operating frequency and the signal is injected. The level needs to be high enough to produce an observable effect on the oscilloscope. The pulse modulator is adjusted to produce pulses with approximately the same duration and PRF as those under test. (But for radiated tests, the pulse width and PRF need to be slightly different from the radars', so that they can be distinguished.) If possible, the pulse modulator is synchronized to the pulse trigger of the radar. The signal amplitude is kept below the saturation point of the IF amplifier(s). The displayed amplitude of the pulses on the oscilloscope display is noted as a reference level.

3) The signal generator level is increased by 60 dB (for a Group B radar) or 70 dB (for Group C and D radars). The signal is tuned above the radar receiver frequency by about ten times the bandwidth of the radar receiver. The nominal 60 dB or 70 dB level adjustment will probably need to be corrected slightly, using the values determined in Step (1). The oscilloscope is monitored constantly for any signals that occur above the reference level. If any such signals are observed, the signal generator frequencies that produce such responses are noted as the work progresses.

Steps 1 through 3 are continued until the entire operational frequency range of the radar has been tested.

4) For each frequency on the list generated in Step (3), the suppression is measured. This is accomplished by tuning back to each of these frequencies and then adjusting the signal generator output level until the level displayed on the oscilloscope is equal to the original reference level. The power level required to produce this level is noted at each of these frequencies. The difference between the nominal signal generator output level originally used and this new level required at each spurious response frequency is the suppression at each of those frequencies. Any suppressions smaller than the RSEC requirements should be noted in the test report.

8.4 Receiver Local Oscillator (LO) Radiation Measurement

[*At the time of this report's writing, the TSC is considering eliminating LO radiation from the RSEC.]*

Figure 23 shows the instrumentation required for this measurement. The same receiver input point should be selected as for the spurious response measurement (above). The need for a power meter will be obviated if the signal generator output is accurately calibrated.

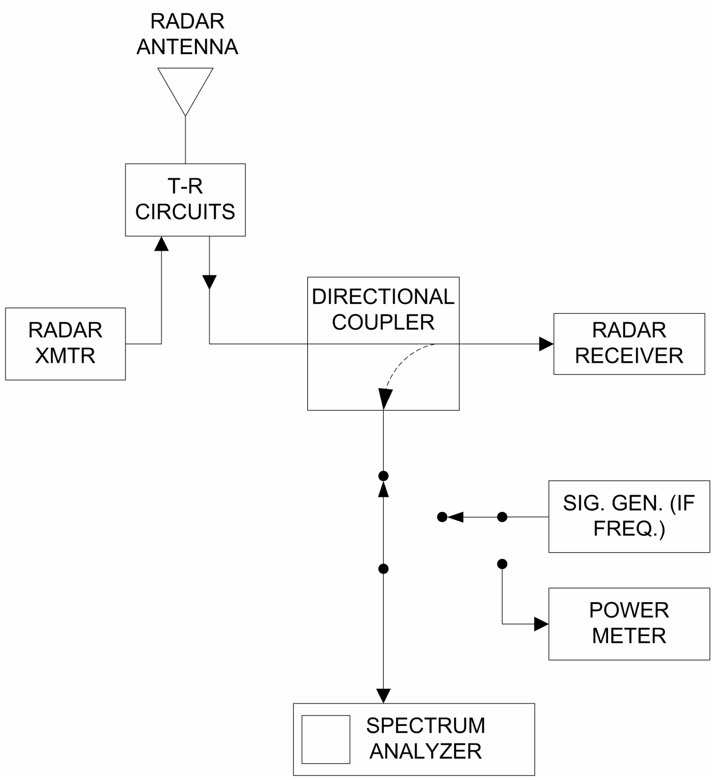

Figure 23. Block diagram for local oscillator radiation measurement.

The measurement procedure is as follows. First connect the equipment as shown in Figure 23. The spectrum analyzer may be set at a nominal frequency span of 100 MHz with center frequency tuned to the radar local oscillator frequency, an IF bandwidth of about 100 kHz selected, and a sweep time of about 100 ms selected.

Next, tune the radar to an operating frequency near the lower edge of the operating frequency band and center the spectrum analyzer display at the nominal LO frequency. (The spectrum analyzer and cable combination may be calibrated by disconnecting the test cable from the receiver input and applying a –40 dBm signal at the LO frequency to the receiver end of the cable.)

With the test cable reconnected to the receiver input port, tune the spectrum analyzer to the LO frequency and use the calibration derived in the step above to calculate the LO emission referred to the receiver input.

Finally, repeat all the steps above with the radar tuned to the mid-band and the upper edge of the operating band.

8.4.1 LO Radiation Considerations for Advanced Radars

Local oscillator radiation is probably becoming an anachronistic concern for most modern radars, inasmuch as local oscillators are disappearing as a design element in most modern radar designs. To the extent that LO's are still incorporated into radar designs, radiation from these elements has not been found to be a significant concern.

9. REFERENCES

[1] *Manual of Regulations and Procedures for Federal Radio Frequency Management*, May 2003, Revisions September 2004, NTIA Office of Spectrum Management, U.S. Government Printing Office, Stock No. 903-008-00000-8.

[2] J.J. Sell, coordinator, “Measurement procedures for the radar spectrum engineering criteria,” NTIA Report 84-157, Aug. 1984.

[3] R.J. Matheson, J.D. Smilley, G.D. Falcon, and V.S. Lawrence, “Output tube emission characteristics of operational radars,” NTIA Report 82-92, Jan. 1982.

[4] William A. Kissick , Ed., “The temporal and spectral characteristics of ultrawideband signals,” NTIA Report 01-383, Jan. 2001.

APPENDIX A: DEFINITIONS

For purposes of spectrum management, boundaries within emission spectra are defined by NTIA. These are necessary bandwidth, out-of-band emissions, spurious emissions and unwanted emissions. They are shown in Table A-1.

A.1 Spectrum Regions

Table A-1. Definitions of Spectrum Regions and Related Terms, from Chapter 6 of [1].

Term	Definition
Necessary bandwidth	For a given class of emission, the width of the frequency band which is just sufficient to ensure the transmission of information at the rate and with the quality required under specified conditions. Necessary bandwidths for radars as a function of emission type are provided in Annex J of [1].
Out-of-band emissions	Emission on a frequency or frequencies immediately outside the necessary bandwidth which results from the modulation process, but excluding spurious emission.
Spurious emissions	Emission on a frequency or frequencies which are outside the necessary bandwidth and the level of which may be reduced without affecting the corresponding transmission of information. Spurious emissions include harmonic emissions, parasitic emissions, intermodulation products and frequency conversion products, but exclude out-of-band emissions.
Unwanted emissions	These consist of spurious emissions and out-of-band emissions.

For radars, the necessary bandwidth is defined in Annex J of [1]. It is determined at a point that is 20 dB below the peak envelope of the spectrum.

A.2 Frequency Tolerance

The maximum permissible departure by the center frequency of the frequency band occupied by an emission from the assigned frequency or, by the characteristic frequency of an emission from the reference frequency. The frequency tolerance is expressed in parts per million (ie., in hertz per megahertz). For example, a tolerance of 800 ppm at a frequency of 1000 MHz would be 800 kHz.

APPENDIX B: ENSURING ADEQUATE MEASUREMENT SYSTEM INPUT ATTENUATION FOR RSEC MEASUREMENTS

Radar transmitters commonly produce peak power levels of +90 dBm or more at the transmitter output. Peak EIRP levels radiated into space may be 30 dB higher, on the order of +120 dBm. It is important to ensure that the maximum allowable input level to spectrum analyzers and other measurement instrumentation is not exceeded by the radar peak output level.

Maximum allowable input power levels are specified by equipment manufacturers for their equipment. The maximum allowable peak level is often higher than the maximum allowable average level. For spectrum analyzers, the maximum allowable *average* level is typically about +30 dBm, but the maximum allowable *peak* level is sometimes not specified by the manufacturer for these devices. In that case, the maximum allowable average level should not be exceeded. It is usually also important to keep input signal levels within the linear, calibrated response range of measurement devices.

B.1 Hardline Coupling to a Radar Transmitter

For hardline-coupled measurements, some attenuation will likely be required between the directional coupler output and the measurement device input (see Figure 1). Referring to this diagram, the minimum decibel amount of attenuation, A, required will be:

$$A_{ext} = P_p - L_c - A_{in} - P_m \qquad \text{(B-1)}$$

where

A_{ext} = external attenuation (dB) as shown in Figure 1
P_p = peak power produced by the radar transmitter (dBm)
L_c = loss through the coupler (dB)
A_{in} = attenuation provided internally at the measurement device front end input (dB)
P_m = maximum input power to measurement instrument after input attenuator (dBm).

For example, if the radar transmitter produces 1 MW (+90 dBm) peak power, if the directional coupler output is 20 dB lower than that value, and if the maximum permissible signal allowed at the spectrum analyzer input is +10 dBm with 50 dB of internal spectrum analyzer attenuation invoked at the front end, then the amount of attenuation that needs to be inserted between the coupler output and the spectrum analyzer input is

$$(90–20–50–10) = 10 \text{ dB}.$$

In this case, even with 50 dB of RF attenuation invoked in the instrument's front end, an additional 10 dB of external RF attenuation is required between the directional coupler and the measurement device input.

B.2 Radiated Coupling to a Radar Transmitter

All the caveats regarding maximum allowable input power levels and optimal linear response and calibration range for measurement instrumentation, as described in section B.1 above, also apply to the case of radiative coupling between the measurement system and the radar transmitter. Here, the external attenuation, A_{ext}, is inserted between the measurement antenna output connector and the measurement device (e.g., spectrum analyzer) input port. The difference is that the term for peak power at the measurement system antenna output connector, P_r, is [4, Appendix C]:

$$P_r = P_p + G_t + G_r + 27.6 - 20\log(f) - 20\log(r) \qquad \text{(B-2)}$$

where

P_r = peak power at the measurement system antenna output connector (dBm);
P_p = peak power produced by the radar transmitter (dBm);
G_t = radar transmitter antenna gain (dBi);
G_r = measurement system antenna gain (dBi);
f = measurement frequency (MHz);
r = distance between radar antenna and measurement antenna (meters).

The variable P_r takes the place of P_p in Eq. B-1, and the value for the external attenuation, A_{ext}, becomes:

$$A_{ext} = P_r - A_{in} - P_m \qquad \text{(B-3)}$$

where all variables are as defined for Eq. B-1.

For example, suppose a radar transmitter operates at 2800 MHz; that the transmitter produces 1 MW peak power (+90 dBm); that the transmitter antenna gain is +35 dBi; that the measurement system antenna gain is +25 dBi; that the measurement system is positioned 0.5 miles (0.8 km, or 800 m) from the radar; that the maximum allowable peak power to be coupled into the measurement system is +30 dBm; and that 50 dB of RF attenuation is to be invoked within the measurement instrument RF front end. Then from Eq. B-2,

$$P_r = 90+35+25+27.6–20\log(2800)–20\log(800) = +50.6 \text{ dBm}$$

And from Eq. B-3,

$$A_{ext} = 50–50–30 = –30 \text{ dB}.$$

The negative sign in the answer means that the signal coupled past the measurement instrument RF front end will actually be 30 dB below the maximum allowable limit of +30 dBm for this situation. No external attenuation is needed in this case.

On the other hand, if the goal is to limit the peak power level that couples into the measurement instrument beyond its own RF front end attenuation to a value of –20 dBm or less, then

$$A_{ext} = 50–50–(–20) = 20 \text{ dB}.$$

So in this case 20 dB of external attenuation would need to be inserted between the measurement antenna output connector and the input port of the measurement device.

APPENDIX C: RSEC MEASUREMENT SYSTEM ARCHITECTURE AND ALGORITHMS

C.1 Hardware Requirements

For spectrum measurements and antenna pattern characterization, a general-purpose RSEC measurement capability requires that the measurement system hardware have the following capabilities:

1) RF tuning across as much as several gigahertz above and below the radar fundamental. The exact amount of tuning capability will depend upon how extensive the radar's spurious emissions are.

2) Instantaneous measurement dynamic range of about 60 dB. This dynamic range can be extended to as much as 120 dB through the use of a measurement algorithm described below. Note that approximately 90 dB total dynamic range is required for many RSEC spectrum emission compliance measurements.

3) Measurement system bandwidth as specified in Table 2.

4) Peak detection.

5) Low noise figure, usually no higher than 10 dB.

6) The ability to substantially reject radar fundamental-frequency energy when the system is tuned to unwanted emission frequencies. In practice, this amounts to using effective bandpass filtering (60-70 dB rejection outside the filter's bandpass) that tracks the measurement system's tuned frequency. Yttrium-iron-garnet (YIG) filters are a practical solution to this problem for frequencies between 0.5 GHz and 26 GHz.

7) The incorporation of a variable RF attenuator. This attenuator is used to extend the dynamic range of the measurement system.

8) A constant-aperture receiving antenna with gain above isotropic on the order of 20–30 dBi. In practice, a parabolic reflector antenna with a 1-m diameter is usually adequate. This antenna gain plays two roles:

5. it allows the measurement system to observe low-level spurious emissions while tending to reject energy from other radars in the vicinity of the measurement system
6. it tends to reject energy from multipath propagation from the radar.

9) A mounting arrangement that raises the receiving antenna to a height above ground of between 3 m and 10 m is highly desirable. This reduces the amount of multipath energy arriving at the antenna, while also providing a clear line-of-sight to the radar transmitter antenna in cluttered environments. A rooftop mount or a telescoping mast on a van are ideal.

For pulse-characterization measurements, a general-purpose RSEC measurement capability requires that measurement system hardware have the following capabilities:

1) Adequate bandwidth to measure 10%–90% rising edges and falling edges on radar pulses, assuming that this parameter needs to be directly characterized by the measurement system. Since these intervals may be as short as a few nanoseconds, a bandwidth of as much as 1 GHz may be required. This bandwidth should be a single-shot capability in an oscilloscope; repetitive sampling techniques that effectively increase a measurement system's bandwidth may not be feasible for some radar pulse sequences. This requirement often means that the rising edge measurement will have to be performed on a hardline connection to a radar, through a wideband detector and a high-speed oscilloscope.[16]

2) To measure pulse widths, the measurement system only requires bandwidths as specified in Table 1. This measurement may be performed with a wideband detector and an oscilloscope connected directly to a hardline coupling on the radar. If such a coupling is not available, or if other factors do not allow for hardline-connected measurements, then this measurement may also be performed by receiving the radiated pulses with a spectrum analyzer and connecting an oscilloscope to the analyzer's video output or (via a detector) an analyzer IF output.

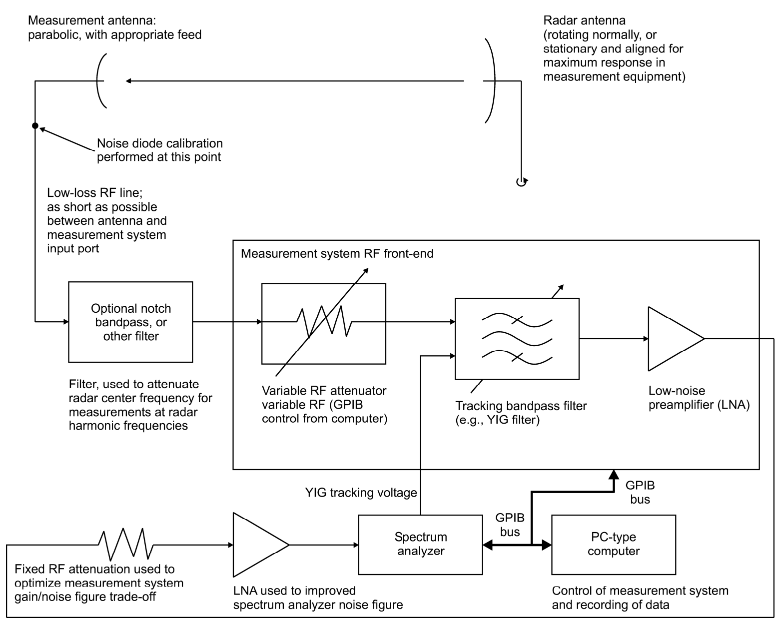

Figure C-1. Block diagram of the RF front end and associated hardware required for RSEC radar emission spectrum compliance measurements.

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[16] Most modern oscilloscopes can record data to either an internal disk, an external computer via a data link, or a universal serial bus (USB) port connected to an external memory unit.

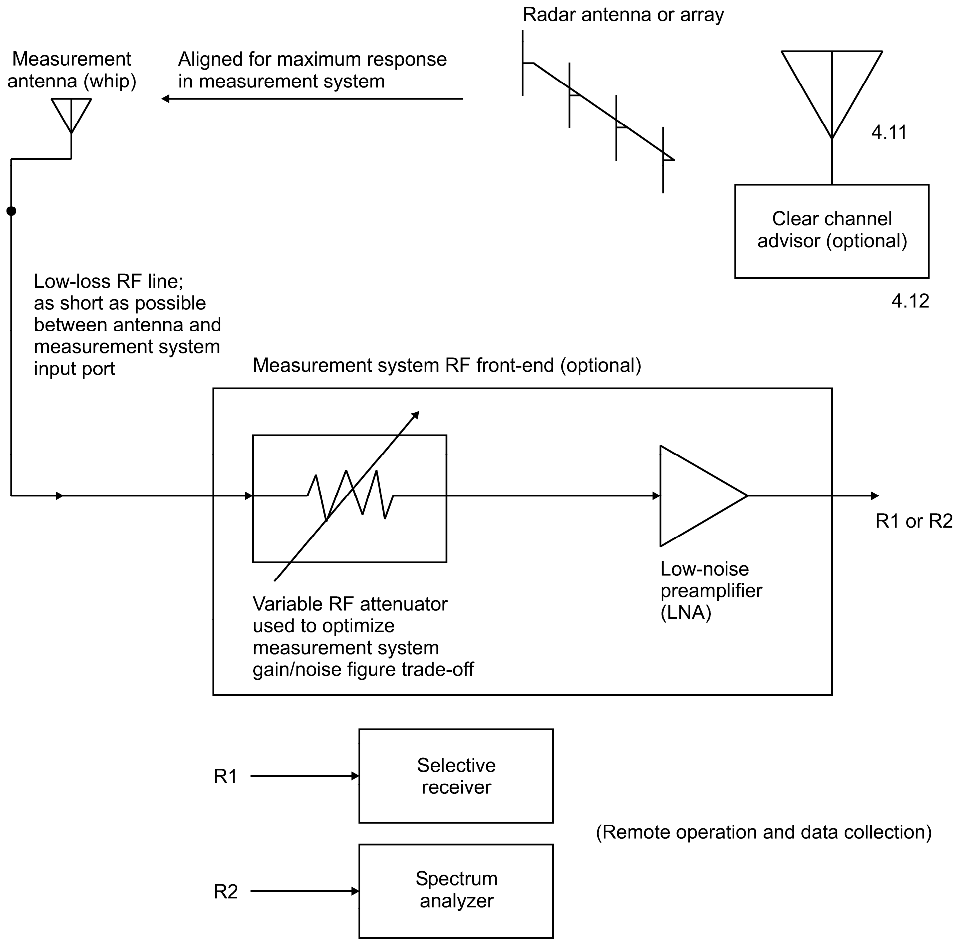

Figure C-2. Block diagram of the RF front end and associated hardware required for RSEC radar emission spectrum compliance measurements on high frequency (HF) radars operating below about 50 MHz.

C.1.1 Radiofrequency (RF) Front-end Design

The necessary RF front end hardware and associated equipment required for an RSEC radar emission spectrum measurement is shown in Figures C-1 and C-2. The RSEC requirement to measure radar spurious emissions as low as 80 dB below the peak measured power at the fundamental has significant consequences for the design of the spectrum measurement system. The 80 dB limit effectively forces the measurement system to achieve at least 90 dB of dynamic range. In many measurement scenarios using a spectrum analyzer the measurement system has 60 dB or less of total instantaneous dynamic range. The two primary factors that contribute to this condition are the available power from the emitter at the receiver and the sensitivity of the measurement system. The available power from the radar is fixed and the distance between the radar and the measurement system must exceed the far-field boundary, so something must be done to extend typical measurement system dynamic range by 30–50 dB or more. This usually necessitates the use of a low noise amplifier (LNA) in front of the spectrum analyzer's input. But with the measurement system tuned to a frequency in the radar's spurious emission spectrum, energy from the radar fundamental frequency (perhaps 80-90 dB higher than that being measured) will overload the LNA, driving down its gain and resulting in an uncalibrated measurement.

The solution is to build an RF front end as shown in the block diagrams in Figures C-1 and C-2. In this design, received radar signals first pass through a variable attenuator. During a spectrum measurement, the attenuator setting is varied as a function of measurement frequency to keep the received signal level within the dynamic range of the rest of the measurement system. The maximum value of the attenuator should be equal to the difference between the dynamic range required for the RSEC measurement (90 dB) and the maximum instantaneous dynamic range of the rest of the measurement system (typically 60 dB). That is, the attenuator should go at least as high as 30–50 dB.[17]

The next stage in the RF front-end is a tunable bandpass filter that tracks the tuned frequency of the measurement system. This filter should have 60-70 dB of off-tuned rejection. As this filter rejects radar fundamental-frequency energy when the measurement system is tuned to the spurious spectrum, it prevents front-end overload of the next measurement stage: the LNA. In practice, NTIA/ITS engineers have found that yttrium-iron-garnet (YIG) filters effectively solve this measurement problem.

The LNA is used to provide sufficient sensitivity to measure spurious emissions 90 dB below the measured peak power of the radar at the fundamental. LNA noise figure should generally be 10 dB or less. LNA gain should be just high enough to overdrive the noise figure of the rest of the measurement system. For example, if the signal passes from the front-end box through an RF line to a spectrum analyzer input, then the following condition should be met by the LNA gain:

$$G_{LNA} = NF_{SA} + L_{line} - NF_{LNA} \tag{C-1}$$

where

G_{LNA} = LNA gain, dB
NF_{SA} = noise figure of spectrum analyzer, dB
L_{line} = line loss between RF front-end and spectrum analyzer, dB
NF_{LNA} = noise figure of the LNA, dB.

For example, if the spectrum analyzer noise figure[18] is 25 dB, the line loss is 3 dB, and the LNA noise figure is 8 dB, then the ideal gain specification for the LNA would be (25 + 3 - 8) = 20 dB.

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17 NTIA/ITS measurement systems actually use attenuators that go as high as 70 dB, in increments of 10 dB. This provides 110–120 dB dynamic measurement range for these measurement systems. A dynamic range of 110 to 120 dB may be required when conducting interference coupling mechanism measurements.

18 Spectrum analyzer noise figure may be determined empirically as follows: With the RF input terminated, tune the analyzer to the frequency (or to sweep across the frequency range) where noise figure must be determined. Set spectrum analyzer input attenuation to zero. Set the IF bandwidth (sometimes called resolution bandwidth) to 1 MHz. Set the video bandwidth to 1 kHz. Set detection to either average, sample, or peak (the selection doesn’t matter because of the

Excessive gain in this stage does not improve system sensitivity or signal-to-noise ratio, but reduces system dynamic range; inadequate gain results in system noise figure exceeding that of the LNA.

C.1.2 Additional Hardware

In addition to the basic hardware already specified for RSEC measurements (spectrum analyzer; fast oscilloscope; optional discrete-component detector; RF front-end containing variable attenuation, tracking bandpass preselection, and low-noise preamplification; and 1-m parabolic reflector antenna with appropriate mount), some additional hardware may be highly desirable.

NTIA/ITS engineers who perform spectrum measurements often utilize an omni antenna and pair it with a second spectrum analyzer as an auxiliary monitoring system. This auxiliary monitors the energy from the radar fundamental during the entire time that the spectrum is being measured. The purpose is to ensure that radar fundamental power does not vary during the measurement.[19]

C.2 Software Requirements

NTIA/ITS engineers have found that all measurements associated with the RSEC can be greatly augmented in terms of speed, efficiency, reliability, and accuracy through the use of software to control measurement equipment and to record data. And for the spectrum measurement portion of RSEC testing, software is a virtual necessity.

Unfortunately, as of the time that this report is being written, no software for RSEC measurement control or data recording has ever been commercially produced. NTIA/ITS engineers have developed all of the software described here. The software that they have written is not proprietary, but currently works with only a limited set of commercially available hardware and a custom-built RF front-end box.

The measurement system software is used to perform the following tasks:

1) Perform measurement system calibrations and store the results;

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narrowness of the video filter compared to the IF filter). Observe the level of the noise trace. Subtract -114 dBm from this level. The result is the noise figure of the spectrum analyzer.

[19] Although radar fundamental power is nominally very stable, it can happen that radar modes are changed without warning during a measurement, leading to a change in radiated power. Furthermore, radars having a nominally fixed center frequency are sometimes switched to another frequency without warning during a measurement. And, in cases in which a radar antenna has been aimed directly at the measurement system (“boresighted”), the radar antenna sometimes drifts in azimuth during the measurement. Without an auxiliary monitoring system to watch for these sorts of changes in the radar transmitter’s behavior, much time can be wasted on a useless measurement.

2) Perform automated radar emission spectrum measurements, correct results from calibration tables, and store the results;
3) Store results from manually operated instrumentation during other RSEC measurements, including antenna patterns and pulse parameters.

C.2.1 Stepped Measurement Algorithm

If there is a single key to the acquisition of radar emission spectra suitable for RSEC compliance verification, it is the combination of the RF front-end design (Section 4.2.1 and this appendix) and the software implementation of the specialized algorithm described in this section. Without this hardware-software combination, a broadband, wide-dynamic range radar spectrum measurement is not practical. With this combination, the radar spectrum measurement becomes relatively easy, and very practical.

The software solves two final problems with the radar spectrum measurement: (1) how to obtain the peak power from the radar beam every time it scans across the position of the measurement system; and (2) how to run the measurement with the proper amount of RF attenuation at each measured frequency.[20]

The key to solving these problems is to *not* sweep the measurement system's tuned frequency during the measurement. Instead, the measurement system is always tuned to a single frequency at a time (that is, is operated with a frequency span of zero hertz). The spectrum analyzer is effectively made to operate like a slow-motion oscilloscope, but one with an RF tuner installed. This process is called *stepping*. RSEC spectrum measurements cannot be performed in other than a stepped-measurement mode.

The stepped-spectrum measurement algorithm operates as follows. At each measured frequency, the spectrum analyzer is tuned to a zero-hertz frequency span, and the sweep time is set to a value slightly longer than the beam-scanning period of the radar. For repetitively scanned radar beams, this is trivial: if an air traffic control radar, for example, has a 4.75 second rotation period, then the sweep time is set to 5 seconds. For radars with non-repetitive beam scanning periods, empirical observations at the measurement location will reveal the amount of time required to obtain peak values, as described further in Sections 8 and 9 of this report. Typically, no radar requires a sweep time exceeding one minute before the beam again scans across the measurement location.

With the system fixed-tuned to the frequency that is to be measured, the RF attenuation can be verified to ensure that its value is appropriate to keep the radar peak power within the dynamic range of the measurement system. If it is not, then either the software or the operator adjusts RF

[20] The RF attenuation must be adjusted across the measured spectrum, so as to keep the received radar signal's amplitude within the instantaneous dynamic range of the measurement system. For example, 70 dB attenuation may be required when tuned to the radar fundamental, 30 dB may be required when tuned 100 MHz from the fundamental, and 0 dB may be required when tuned more than 300 MHz from the fundamental.

attenuation appropriately. In practice, an experienced operator can adjust attenuation with a simple keyboard input on a frequency-by-frequency basis, with no delay to the speed of the overall measurement. Software adjustments may work by monitoring the radar signal level relative to measurement system noise and overload levels.

Because the spectrum analyzer sweep time (the step interval, or *dwell*) has been set to exceed the beam-scanning interval of the radar, it is ensured that one or more (usually a series of twenty or more) maximum-power pulses will be recorded on the spectrum analyzer trace during the dwell period. Thus, the measurement system software need only retrieve the peak value from the spectrum analyzer trace at each step, correct it for calibration factors, and store it in order to complete the measurement of radar peak power at the frequency in question.

Since each measured frequency takes one radar beam-scan interval, the amount of time required for the entire spectrum measurement is just the number of data points multiplied by the scanning interval of the radar. But how many points should be measured? There is no reason to measure points that are separated in frequency by less than the IF bandwidth of the measurement system, nor should the frequency interval between measured points greatly exceed this interval, lest significant behavior in the spectrum be missed. Thus, the interval between points should ideally be equal to the IF bandwidth of the measurement system.

For example, an air-search radar with a 10-second rotation period and a 1-µs pulse width should ideally be measured with an 11 second dwell interval and a 1 MHz bandwidth, with 1 MHz between measured steps. It will require about 40 minutes to measure 200 MHz of this radar spectrum. As slow as this process may appear, NTIA/ITS engineers have found no faster or more effective method for measuring radar spectra for RSEC compliance.

While this algorithm might in principle be implemented manually, it would be so tedious as to put the entire measurement at risk due to operator fatigue. It has been the experience of NTIA/ITS engineers that this algorithm needs to be implemented through software for control of the measurement system, automatic calibration corrections, and data recording.

C.2.2 Overall Measurement Algorithm and Flowchart

The overall procedure for an RSEC measurement is provided here in the form of a flowchart and associated notes. This description is intended to provide a coherent overview of the interrelated steps and procedures that are individually described in greater detail elsewhere in this report. Figure C-3 contains the overall procedure flowchart.

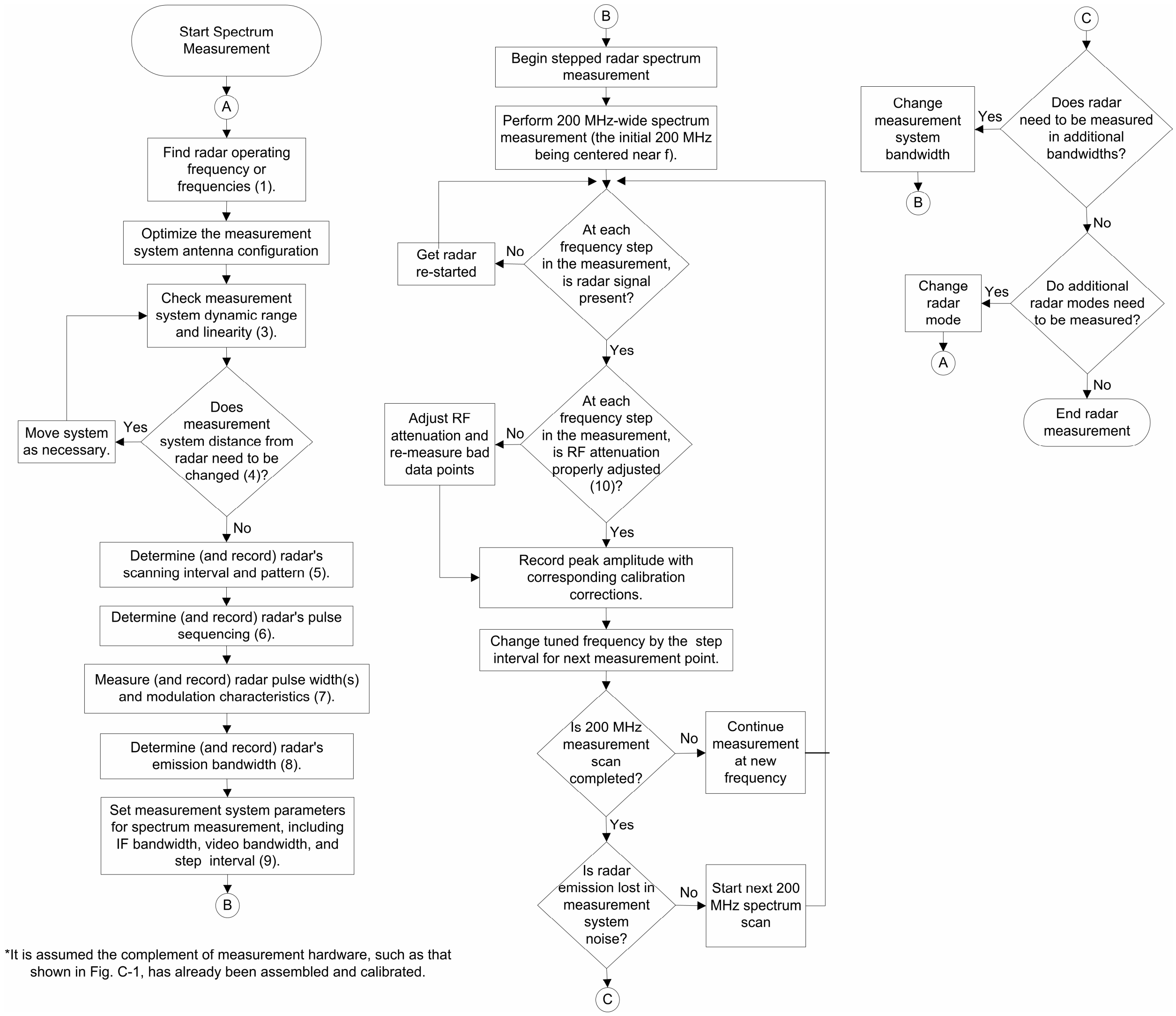


Figure C-3. RSEC measurement procedure flowchart.

The following notes are numbered in correspondence with various steps in the measurement process portrayed in Figure C-3.

(1) Find radar operating frequency or frequencies. The measurement system antenna is pointed approximately at the radar. The measurement system RF front end and spectrum analyzer (or any instrument used in place of a spectrum analyzer) is adjusted to sweep across the frequency range of the operational band of the radar. Measurement system parameters are nominally set as shown in Table C-1.

With the measurement system thus adjusted, spectrum is swept repetitively across the radar band, and the peak radar emission spectrum envelope will gradually (but only partially) fill in over a period of a few minutes. The peak spectrum envelope will normally fill in sufficiently to approximately indicate all the fundamental frequencies that are being radiated by the radar.

After these frequencies have been approximately identified in this manner, and have been noted by measurement personnel, then the measurement system is used to determine each of those frequencies with more precision. To do this, the measurement system is tuned to each approximately identified frequency on an individual basis. At each identified frequency, the measurement system is center-tuned to that frequency, and the frequency span range of the measurement system is set to 50 MHz. Then the measurement system data trace display mode is cleared and a new maximum-hold series of sweeps are undertaken. The result is a more detailed spectrum picture of each radar fundamental frequency. The final result of the measurement at each fundamental radar frequency is a maximum-hold data trace that shows the fundamental frequency with an accuracy of 1 MHz. The resulting set of frequencies is noted for later use in the measurement of the radar spectrum.

Table C-1. Measurement System Parameters for Determination of Radar Fundamental Frequency or Frequencies.

Measurement system parameter	Parameter setting
IF bandwidth	1 MHz
Video bandwidth	Equal to or greater than 1 MHz
Detection mode	Positive peak
Frequency sweep range	Operational band of the radar
Frequency sweep rate	Maximum allowed for the combination of measurement bandwidth and frequency sweep range
Trace display mode	Maximum hold
Front end attenuation	Sufficient to prevent measurement system overload (adjusted empirically)

(2) Optimize the measurement system antenna configuration. With the measurement system tuned to one of the radar fundamental frequencies, and with the measurement system bandwidth and detection modes set as described in Table C-1, the frequency sweep range should now be set to zero hertz, so that the measurement system is displaying a time-domain picture of the radar beam scanning pattern. Then, the measurement system sweep time should be adjusted to an amount of time that is substantially longer than a single radar beam-scan interval. For example, if the radar beam-scanning interval is 5 seconds, then the measurement system sweep time should be set to a value of perhaps 60 seconds. The data display trace mode should be set to refresh itself with each trace, rather than the maximum hold mode used earlier.

With this done, the measurement system antenna pointing angle should be gradually adjusted in azimuth, while the maximum received power from the radar is observed at each repetition of the radar beam-scan. The process is continued until the azimuth angle that maximizes the measured power from the radar is identified; the measurement antenna azimuth is then locked at that position. Next, the measurement antenna elevation angle is gradually adjusted in the same manner as the azimuth was earlier adjusted, until the optimal elevation pointing angle is determined. The measurement antenna pointing angle has been optimized at this point in all dimensions, and the antenna should be locked into this position.

Care needs to be taken during this pointing-angle process to ensure that the measurement antenna pointing angle is optimized on its main beam, and not on a sidelobe. To be sure of this, it is recommended that the measurement antenna pointing angle be varied enough during the adjustments to observe the measurement antenna sidelobes on either side of its main beam.

With the optimal measurement antenna pointing angle fixed, the next step is to determine the polarization that optimizes received signal strength from the radar. This is done by measuring the radar emission with a variety of polarizations and observing the measured power at each polarization. Typical alternative polarizations available to measurement personnel in their antennas are: horizontal, vertical, left-hand circular, and right-hand circular. Polarization is typically varied by either operating a polarization switch on a measurement antenna feed assembly, or else by mechanically changing measurement antenna feeds. The measurement polarization setting that maximizes received power from the radar is used for the measurement, and should be noted by measurement personnel.

(3) Check measurement system dynamic range and linearity. This step in the measurement process ensures that the measurement system distance from the radar is adequate to achieve a large enough dynamic range to check for RSEC compliance, and furthermore that the measurement system is not being overloaded by radar emissions.

In general, the measurement needs to achieve a total dynamic range that is at least 10 dB more than the –X dB level of the RSEC spectrum envelope. For example, if the radar needs to meet an ultimate suppression level of –80 dB, then the total dynamic range that is needed in the measurement will be about 90 dB.

A problem that is commonly encountered in wide-dynamic range measurements is overload of the measurement system due to the high field-strength environment in which the measurement system must be operated. Two types of overload may occur. One type may occur because the total measurement system RF front end attenuation is inadequate to keep the peak measured radar fundamental-frequency energy below the saturation point of the measurement system. The other type of overload is due to feed-through of radar energy directly into the measurement system amplifiers or detector, bypassing the measurement antenna and front end filtering. Prior to commencement of a spectrum measurement, these types of overload should be verified as not occurring.

To perform all of these checks and verifications, the measurement system should first be tuned to whichever frequency was previously identified as producing the highest measured emission power level. The frequency span of the measurement system is set to zero hertz, with positive peak detection and the widest available measurement bandwidth selected. The sweep time should be set the same as it was for the adjustment of the antenna pointing angle (i.e., substantially longer than a single radar beam scanning interval). In this configuration, the maximum measured power from the radar transmitter is being monitored at one of the radar fundamental frequencies by the measurement system.

RF attenuation in the measurement system RF front end should be adjusted to a high enough value to keep the maximum measured value from the radar well below the measurement system saturation level (1-dB compression point). If saturation does occur even when maximum RF attenuation is invoked, then the measurement system is too close to the radar and will need to be moved further away.

If the measurement system is not saturated when maximum RF front end attenuation is invoked, then the next step is to check for feed-through: that is, radar energy feeding into the measurement system without passing through the measurement antenna. This is accomplished by disconnecting the measurement antenna and replacing it with a terminator. When this is done, the amount of energy feeding into the measurement system past the antenna will be observed on the data display trace. With the terminator in place instead of the antenna, the amount of power measured on the display should drop many tens of decibels, preferably 60 dB or more. If such a drop is not observed, then feed-through may be a serious problem for the measurement system. Further use of the approach of disconnecting measurement system components and terminating their input ports will allow determination of the location of the feed-through problem in the measurement system.

If feed-through is a problem, then some part of the measurement system needs to be better isolated from the incident radar energy. This may be done in more than one way. One approach is to improve the shielding of the RF front end and/or the measurement system inside the measurement vehicle, depending upon where the radar energy is feeding into the measurement system. Implementation of this approach will likely involve a significant amount of time and engineering effort.

Other, more ad hoc approaches may be implemented at field locations. If the feed-through problem is occurring in the RF front end, then the front end may be moved inside the shielded enclosure of the measurement system vehicle, although this may require a somewhat longer RF line connection from the measurement antenna to the front end input, with concomitantly higher overall measurement system noise figure.

If the feed-through problem is occurring within equipment located inside the measurement vehicle, then it may be possible to eliminate the feed-through by moving the vehicle to a location behind a building or heavy foliage, and to extend the measurement antenna on a mast to a height above the building or foliage, while keeping the vehicle shielded behind the obstruction.

(4) Does measurement system distance from radar need to be changed? If feed-through is occurring and none of the measures described above eliminates this problem, then the only remaining course of action is to move the measurement system to a larger distance from the radar, such that the threshold for feed-through coupling is no longer exceeded.

If feed-through is not occurring, but the measured power level at the radar fundamental frequency exceeds the saturation point of the measurement system when all available front end RF attenuation has been invoked, then the measurement system must likewise be moved to a larger distance from the radar, until such saturation does not occur.

If the measurement system is located at such a distance from the radar that the received power levels are too low to permit enough dynamic range in the measurement to determine compliance with the –X dB ultimate suppression level (e.g., if the –X dB level is –80 dB but the maximum power being received from the radar will only allow measurement of 70 dB of dynamic range in the spectrum), then the measurement system needs to be moved closer to the radar. The decrease in distance must be enough to increase the received signal power from the radar enough to observe roughly the –X dB level plus an additional 10 dB (e.g., if the –X dB level is –80 dB, then the spectrum needs to be measured with at least 90 dB of total dynamic range).

(5) Determine (and record) radar's scanning interval and pattern. This process is described in detail in Sections 5 and 6. An abbreviated description of the process of determining radar scan interval, spectrum measurement step time, and antenna pattern is provided here.

The measurement system is tuned to the radar fundamental frequency (or to one of the fundamental frequencies, if there is more than one). The frequency range (or span) for sweeping is set to zero hertz. IF bandwidth is set to the widest value available, so long as it is less than twice the spacing between the selected radar fundamental frequency and an adjacent fundamental frequency, (e.g., if the radar has additional fundamental frequencies spaced 10 MHz above and below the fundamental, then the bandwidth should be less than 20 MHz). Detection is set to positive peak. The measurement system data trace mode is set to acquire a single sweep at a time. The sweep time is set to about 60 seconds (or possibly a somewhat longer interval, for some very long-range radars, such as space search or strategic early warning systems).

The radar emission is observed in this mode for a long enough period of time to establish the time intervals between maximum-amplitude occurrences of power. For simple radar beam-scanning techniques (such as might be encountered with a single-frequency system with a mechanically rotated, 360-degree azimuth scanning antenna and no elevation scanning), this interval will likely be fixed. For sector-scanned radars, there will be two observed intervals: a short, then a long, then a short, then a long, etc. This pattern results from the measurement system being off-axis from the center-line azimuth of the radar's sector scan. The effect will not be seen if the measurement system happens to be positioned precisely on the center of the radar's range of sector scan azimuths.

For more sophisticated radars, the interval between occurrences of the maximum received power level may be somewhat irregular. Examples include radars that scan a beam in elevation while they are moving the beam in azimuth; radars that employ multiple frequencies, and radars that employ fully electronic beam steering techniques. Even for such radars, however, there will normally exist a maximum length of time that is allowed to elapse before the radar scans in any given direction on any given frequency. This interval can be taken as the radar's 'scan interval,' for the purpose of the measurement.

The scan interval for any radar is determined by observing many occurrences of the maximum received power level and noting any repetition that seems to occur in the pattern of these occurrences. Some repetition in interval will be observed for virtually any radar. When such an interval seems to be observed, the sweep time of the measurement system is set to a value slightly longer than that interval. Then, many (ten or more) of those intervals need to be observed sequentially with the measurement system. If the radar consistently sends maximum power to the measurement system within that interval, then this interval can be taken as the effective scan rate for the measurement. If, conversely, the radar sometimes does not send maximum power to the measurement system within that interval, then the interval needs to be lengthened, and then a series of observations should be repeated. This process continues until the observation interval that has been selected consistently results in at least one maximum-power event from the radar. For the purpose of spectrum measurements, this time interval is the radar's 'scan' interval.

The scan interval that is determined from these observations is used to set the 'step' time for the radar spectrum measurement. The step time is the interval that will be used for data points collected in the radar emission spectrum. The step time needs to be about ten to twenty percent longer than the radar scan interval. For example, if the radar has a scan interval of 4.75 sec, then 5 sec is a reasonable step interval. Similarly, if the radar has a 10-sec scan interval, then a step interval of 11 sec is reasonable.

When the step interval has been set, at least one data trace should be acquired and recorded showing one complete radar scan pattern. This measurement is the effective radar antenna pattern as measured at the location of the measurement system. Additional patterns recorded at additional locations can be used to eliminate multipath features in the radar antenna pattern measurement.

(6) Determine (and record) radar's pulse sequencing. This process is described in detail in Section 4. No additional description is provided here. With the measurement system configured for the previous measurement of antenna pattern, the measurement bandwidth and pulse sequencing are measured as described in detail in Section 4.

(7) Measure (and record) radar pulse width(s) and modulation characteristic(s). This process is described in detail in Section 3. With the measurement system configured for the previous measurements of antenna pattern and pulse sequencing, the measurement bandwidth is set and the pulse sequence measured as described in detail in Section 3.

(8) Determine (and record) radar's emission bandwidth. With the radar beam scanning interval having been determined (as described in detail in Sections 5 and 6 and summarized in Note (6), above), the effective emission bandwidth is determined next. This process of making a bandwidth progression measurement is described in detail in Section 5.

(9) Set measurement system parameters for spectrum measurement, including IF bandwidth, video bandwidth, and step interval. The measurement system should now be ready to begin the spectrum measurement, and the parameter values to be used for the measurement should be known. The IF bandwidth should be set as described in Table 2 (and should be consistent with the empirically determined emission bandwidth of the radar as described in the bandwidth progression measurement of Section 5). The video bandwidth should be set equal to or greater than the IF bandwidth. The step time should be set to the value determined previously. The detection should be set to positive peak. Initial RF attenuation needs to be adjusted to keep the radar energy within the dynamic range of the measurement system at the initial frequency of the measurement.

(10) At each frequency step in the measurement, is RF attenuation properly adjusted? It is important that the RF attenuation at the front end of the measurement system be consistently adjusted from one frequency step to the next to ensure that the received peak power from the radar remains within the instantaneous dynamic range of the measurement system. It is also important to remain vigilant against the possibility of any sort of direct feed-through of radar energy into the measurement system, bypassing the measurement antenna.

To accomplish these goals, the radar measurement personnel should watch the maximum received power from the radar relative to both the noise floor and the saturation level of the measurement system. This is done by watching the radar maximum level on each data trace from each frequency step, and noting how close it is to noise and saturation levels. If, on any given step, the radar signal level approaches within 10 dB of either level, then RF attenuation should be either reduced (as the noise floor is approached) or increased (as the saturation point is approached). A suggested amount of change in RF attenuation per step is 10 dB. Such a routine can also be implemented as an automatic feature in measurement control software.

C.2.3 Data Units, Graphing and Recording

The RSEC specifies spectrum limits relative to measured peak power at the radar fundamental frequency or frequencies. Thus, it is adequate that measured spectrum power levels be recorded in decibels relative to an arbitrary power value within the measurement system circuitry. For example, NTIA/ITS engineers record spectrum data in units of dBm in 50 ohm circuitry.

If for some reason the radar emission spectrum needs to be specified in terms of incident field strength or EIRP from the transmitter, then the dBm values in the measurement circuitry may be converted through the use of gain tables for the measurement antenna.

For time-domain data, amplitudes may be measured in terms of relative detected voltage (and may be converted to dBm if necessary). Time is typically recorded in microseconds for easy insertion into the RSEC equations [1, Chapter 5].

It is the experience of NTIA/ITS engineers that RSEC spectrum data should be graphed in real time, point-by-point, as each dwell interval is completed. This allows examination of the measured spectrum for sharp discontinuities that may indicate attenuation errors or unanticipated changes in the radar’s transmitter mode.

All data should be recorded electronically in real time, preferably with accompanying hardcopies. Data back-ups are important, as it may prove impossible to revisit a measurement at a later date. Pulse characterization data should be captured from an oscilloscope and recorded electronically, with appropriate back-up.

C.3 Measurement Hardware and Software (More Detailed Descriptions)

Block diagrams of the type of measurement system required for RSEC emission spectrum measurements are shown in Figures C-1 and C-2. The first element to be considered in the system is the receive antenna. The receive antenna should have a broadband frequency response, at least as wide as the frequency range to be measured. A high-gain response (as achieved with a parabolic reflector) is usually also desirable. The high gain value permits greater dynamic range in the measurement; the narrow antenna beamwidth provides discrimination against other signals in the area; the narrow beamwidth minimizes problems with multipath propagation from the radar under measurement; and spectrum data collected with a parabolic antenna require a minimum of post-measurement correction, as discussed in the next paragraph. The antenna feed polarization is selected to maximize response to the radar signal. Circular polarization of the feed is a good choice for cases in which the radar polarization is not known *a priori*. The antenna polarization may be tested by rotating the feed (if linear polarization is used) or by exchanging left and right-hand polarized feeds, if circular polarization is being used.

Corrections for variable antenna gain as a function of frequency should be considered. Antenna gain levels are usually specified relative to that of a theoretically perfect isotropic antenna, in units of dBi. The effective aperture of an isotropic antenna decreases as 20log(f), where f is the frequency being measured. This means that, if the measurement antenna has a constant effective aperture (that is, has an isotropic gain that increases as 20log(f)), no corrections for variable antenna gain need be performed. This requirement is met by a theoretically perfect parabolic reflector antenna, and is one of the reasons that such an antenna is preferred for a broadband radar spectrum measurement. Conversely, to the extent to which the gain of the measurement antenna deviates from a 20log(f) curve (including a less-than-ideal parabolic antenna), the resulting measurements must be corrected for such deviation.

The cable connecting the measurement antenna to the measurement system should also be considered. A length of low-loss radio frequency (RF) cable (which will vary depending upon the circumstances of measurement system geometry at each measurement radar site) connects the antenna to the RF front-end of the measurement system. As losses in this piece of line attenuate the received radar signal, it is desirable to make this line length as short, and as low-loss, as possible.

The RF front-end is one of the most critical parts of the entire measurement system. It performs three vital functions. The first is control and extension of measurement system dynamic range through the use of variable RF attenuation. The second is bandpass filtering (preselection) to prevent overload of amplifiers by high-amplitude signals that are not at the tuned frequency of the measurement system. The third is low-noise preamplification to provide the maximum sensitivity to emissions that may be as much as 130 dB below the peak measured level at the radar fundamental. Each of these sections in the RF front end is considered below.

The RF attenuator is the first element in the front-end. It provides variable attenuation (e.g. 0–70dB) in fixed increments (e.g. 10 dB/attenuator step). Use of this attenuator during the measurement extends the dynamic range of the measurement system by the maximum amount of attenuation available (e.g. 70 dB for a 0–70 dB attenuator).

The key to using the RF front end attenuator with effectiveness in a radar measurement is to tune the measurement system in fixed-frequency increments (e.g., 1 MHz), called steps, rather than to sweep across the spectrum, as is more conventionally done with manually controlled spectrum analyzers. At each fixed-frequency step, the attenuator is adjusted to keep the radar peak power within the dynamic range of the other elements in the measurement system (often the front-end amplifier and the spectrum analyzer log amplifier are the limiting elements). With the front-end RF attenuator properly adjusted at each step, a measurement of the radar power at that frequency is performed. In this way, a nominal 60 dB dynamic range for the measurement system is extended by as much as 70 dB, to a total resulting dynamic range of 130 dB (or, more realistically, 110–120 dB in operational systems). To minimize measurement time, this attenuator and the stepped-frequency measurement algorithm that it necessitates can be controlled by computer.

The next element in the front end, the tunable bandpass filter preselector, is necessary if it is needed to measure low-power spurious emission levels at frequencies that are adjacent to much higher-level fundamental emissions (e.g., 130 dB below fundamental). For example, it may be necessary to measure spurious emissions from an air traffic control radar at 2900 MHz that are at a level of –120 dBm in the measurement circuitry, while the fundamental emission level is at + 10 dBm and is only 150 MHz away in frequency (at 2750 MHz). The measurement system requires an unattenuated low-noise amplifier (LNA) to measure the spurious emission at 2900 MHz, but the amplifier will be overloaded (and thus gain-compressed) if it is exposed to the unattenuated fundamental emission at 2750 MHz. For this reason, attenuation that has frequency dependence is required in the front-end at a position before the LNA input. In practice, this tunable bandpass filtering is effectively provided by varactor technology (below 500 MHz) and by yttrium-iron-garnet (YIG) technology (above 500 MHz). The applicable filters may be procured commercially, and should be designed to automatically track the tuned frequency of the measurement system.

The final element in the RF front-end is an LNA. An LNA is installed as the next element in the signal path after the preselector. The low-noise input characteristic of the LNA provides high sensitivity to low-amplitude spurious radar emissions, and its gain allows for the noise of the rest of the measurement system (e.g., a length of transmission line and a spectrum analyzer) to be overdriven. This means that the noise figure of the LNA dominates the overall system noise figure.

Considerations for the sensitivity and dynamic range of the measurement system, as well as for typical spectrum analyzer noise figures, are the same as those stated in section C.1.1.

Another option for LNA configuration is one in which LNAs are cascaded. The first LNA is placed between two stages within the YIG or varactor bandpass preselector filter. It has a low noise figure, but only enough gain to allow for the insertion loss of the second YIG stage. A second LNA is placed immediately after the YIG. This option will provide a somewhat lower overall system noise figure because the second stage of the YIG is allowed for by the first LNA. However, this option may require more advanced design and engineering modifications to the preselector filter than an administration may deem practical.

A third option for the measurement system LNA configuration, and one not requiring any redesign or retrofitting of the front end preselector filter, is to place a lower-gain LNA in the front end and a second LNA at the spectrum analyzer signal input. The first LNA is selected to have very low noise figure and just enough gain to allow for the RF line loss and the noise figure of the spectrum analyzer LNA. The spectrum analyzer LNA, in turn, is selected for a gain characteristic that is just adequate to allow for the spectrum analyzer's noise figure in the appropriate frequency range of the radar measurement. This set of two cascaded LNAs may be more easily acquired than a single, extremely high-performance LNA. Regardless of the configuration of the LNAs, the cascaded gain must be computed at each LNA input to insure that the input linear range of each component is not exceeded.

The remainder of the RF measurement system is expected to be essentially a commercially available spectrum analyzer. Any spectrum analyzer which can receive signals over the frequency range of interest, and which can be computer-controlled to perform the stepped-frequency algorithm, can be used. As noted above, the high noise figure of currently available spectrum analyzers must be allowed for by low-noise preamplification if the measurement is to achieve the necessary sensitivity to observe most spurious emissions.

The measurement system can be controlled via any computer which has a bus interface (GPIB or equivalent) that is compatible with the computer controller and interface card(s) being used. In terms of memory and speed, modern PC-type computers are quite adequate. The measurement algorithm (providing for frequency stepping of the spectrum analyzer and the preselector, and control of the front-end variable attenuator) must be implemented through software. Some commercially available software may approach fulfillment of this need, but it is likely that the measurement organization will need to write at least a portion of their own measurement software. While the development of software requires a significant resource expenditure, practical experience with such systems has shown such an investment to be worthwhile if radar emission measurements are to be performed on a frequent and repeatable basis.

Data may be recorded on the computer's hard drive or on a removable disk. Ideally, a data record is made for every 100-200 measurement steps, so as to keep the size of data files manageable, and to prevent the loss of an excessive amount of data if the measurement system computer or other components should fail during the measurement.

With the radar antenna beam scanning normally, and with the measurement system set up as described above, the first data point is collected. A data point consists of a pair of numbers: measured power level and the frequency at which the power level was measured. For example, the first data point for the above measurement might be –93 dBm at 2000 MHz. The data point is collected by monitoring the radar emission at the desired frequency, in a frequency span of 0 Hz, for an interval (step time) slightly longer than that of the radar antenna rotation period, or for a longer step time for complex radar systems. This time-display of the radar antenna beam rotation will be displayed on the spectrum analyzer screen. The highest point on the trace will normally represent the received power when the radar beam was aimed in the direction of the measurement system. That maximum received power value is retrieved (usually by the control computer, although it could be written down manually), corrected for measurement system gain at that frequency, and recorded (usually in a data file on magnetic disk).

The second measurement point is taken by tuning the measurement system to the next frequency to be measured. This frequency is optimally equal to the first measured frequency plus the measurement bandwidth (e.g., if the first measurement was at 2000 MHz and the measurement bandwidth were 1 MHz, then the second measured frequency would be 2001 MHz). At this second frequency, the procedure is repeated: measure the maximum power received during the radar beam rotation interval, correct the value for gain factor(s), and record the resulting data point.

This procedure, which consists of stepping (rather than sweeping) across the spectrum, continues until all of the desired emission spectrum has been measured. The stepping process consists of a series of individual amplitude measurements made at predetermined (fixed-tuned) frequencies across a spectrum band of interest. The frequency change between steps is optimally equal to the measurement system IF bandwidth. For example, measurements across 200 MHz of spectrum might use 200 steps at a 1-MHz step interval and a 1-MHz IF bandwidth. The step interval may be set wider in the spurious emission domain to expedite the overall measurement. However, at frequencies that are integral multiples (e.g., 2, 3, 4) of the fundamental radar emission, the maximum step interval should again be about equal to the measurement system IF bandwidth.

The measurement system remains tuned to each frequency for a specified measurement interval. The interval is called step-time, or dwell. The dwell time for each step is specified by the measurement system operator, and is normally slightly longer than the radar beam scanning interval.

Computer control of the measurement system is desirable if this process (step, tune, measure, correct for gain, and repeat) is to be performed with efficiency and accuracy. In order to correctly measure the peak of the fundamental emission it may be required to use a smaller step interval of the order of half or less of the measurement bandwidth over this region.

The stepped time technique is required to enable the insertion of RF attenuation at the front-end of the measurement system as the frequencies approach the center frequency (and any other peaks) of the radar spectrum. This ability to add attenuation on a frequency-selective basis makes it possible to extend the dynamic range available for the measurement to as much as about 130 dB, if a 0–70 dB RF attenuator is used with a measurement system having 60 dB of instantaneous dynamic range. This is of great benefit in identifying relatively low-power spurious emissions. To achieve the same effect with a swept-frequency measurement, a notch filter could be inserted at the center frequency of the radar, but there would be no practical way to insert a notch filter for all the other high-amplitude peaks that might occur in the spectrum.

It is *important* to provide adequate bandpass filtering at the front-end of the measurement system, so that strong off-frequency signal components do not affect the measurement of low-power spurious components.

These measurements may be performed without the radar antenna being rotated, provided that the directions of both maximum fundamental emission and any unwanted emission are known.

C.3.1 Clear Channel Advisor for HF Radar Emission Spectrum Measurements

For HF radars, ionospherically propagated transmissions can travel large distances, and so much of the spectrum that is measured by the test antenna will, in general, be exposed to external signals. It is therefore important to have a device advising of occupied channels, preferably one that can capture this data and give some indication of the signal strength. The spectrum measuring system can be used for this, or an independent receiving system. This data can be used to reconcile any unwanted emissions that may have been caused by external sources. It should also be used to detect a clear channel for the testing within the in-band B_{-40} and OOB domains.

C.4 Dynamic Range of the Measurement System

The measurement system should be able to measure levels of unwanted emissions [1, Chapter 5] and as diagrammed in Figure C-4. To obtain a complete picture of the spectrum especially in the spurious emissions domain, it is recommended to be able to measure levels of emissions 10 dB below the ultimate suppression level [1, Chapter 5].

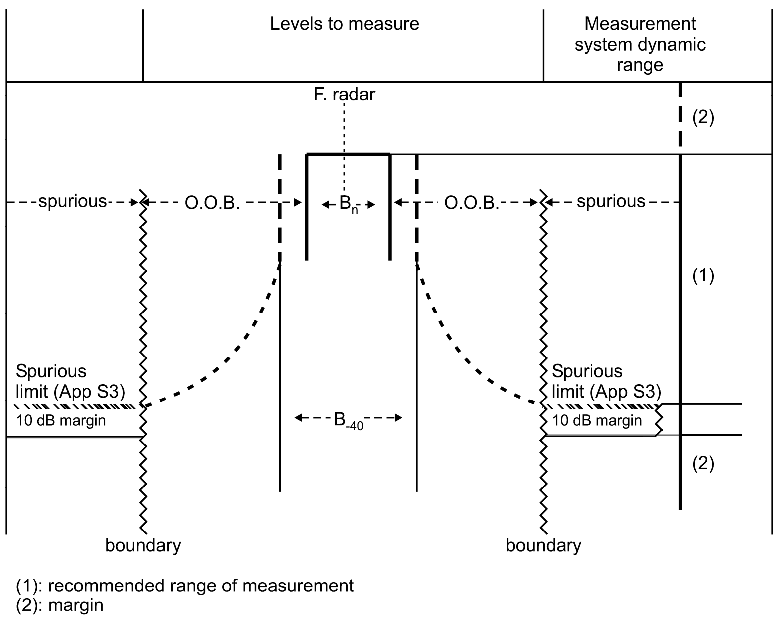


Figure C-4. Diagram of out-of-band and spurious emission suppression levels required by the RSEC. It should be noted that Recommendation ITU-R SM.329 recommends under category B more stringent limits than those given within Appendix S3 in some cases. This should be taken into account when evaluating the required range of measurement and the recommended dynamic range of the measurement system.

APPENDIX D: RSEC MEASUREMENT SYSTEM CALIBRATION

D.1 Calibration Overview

The measurement system is calibrated by disconnecting the antenna from the rest of the system, and attaching a noise diode to the RF line at that point. A 25 dB excess noise ratio (ENR, where ENR = (effective temperature, ^{o}K, of noise diode/ambient temperature, ^{o}K)) diode should be more than adequate to perform a satisfactory calibration, assuming that the overall system noise figure is less than 20 dB. The technique is standard Y-factor measurement with comparative power measurements made across the spectrum, once with the noise diode on and once with the noise diode off.

The noise diode calibration results in a table of noise figure values and gain corrections for the entire spectral range to be measured. The gain corrections may be stored in a look-up table, and are applied to measured data as those data are collected. The next section describes these procedures in more detail.

The measurement antenna is not normally calibrated in the field. Correction factors for the antenna (if any) are applied in post-measurement analysis.

D.1.1 Gain and Noise Figure Calibration Using a Noise Diode

Measurement system calibration should be performed prior to every radar emission spectrum measurement. As measurements are performed, gain corrections may be added automatically to every data point. For measurement system noise figures of 20 dB or less, noise diode Y-factor calibration (as described below) may be used. This appendix describes the theory and procedure for such calibration.

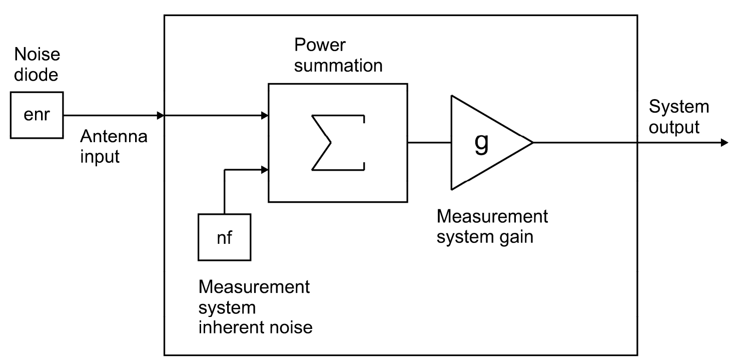


Figure D-1. Lumped component diagram of noise diode calibration.

The noise diode calibration of a receiver tuned to a particular frequency may be represented in lumped-component terms as shown in Figure D-1. In this diagram, the symbol Σ represents a power-summing function that linearly adds any power at the measurement system input to the inherent noise power of the system. The symbol g represents the total gain of the measurement system. The measurement system noise factor is denoted by nf, and the noise diode has an excess noise ratio denoted as enr. (In this appendix, all algebraic quantities denoted by lower-case letters, such as "g," represent linear units. All algebraic quantities denoted by upper case letters, such as "G," represent decibel units.)

Noise factor is the ratio of noise power from a device, n_{device}(W), and thermal noise, $\frac{n_{device}}{kTB}$ where k is Boltzmann's constant ($1.38 \cdot 10^{-23}$ J/K), T is system temperature in Kelvin, and B is bandwidth in hertz. The excess noise ratio is equal to the noise factor minus one, making it the fraction of power in excess of kTB. The noise figure of a system is defined as 10 log (noise factor). As many noise sources are specified in terms of excess noise ratio, that quantity may be used.

In noise diode calibration, the primary concern is the difference in output signal when the noise diode is switched on and off. For the noise diode = on condition, the power, P_{on}(W), is given by:

$$p_{on} = (nf_s + enr_d) \times gkTB \tag{D-1}$$

where nf_s is system noise factor and enr_d is the noise diode enr.

When the noise diode is off, the power, P_{off}(W), is given by:

$$p_{off} = (nf_s) \times gkTB \tag{D-2}$$

The ratio between P_{on} and P_{off} is the Y factor:

$$y = \left(\frac{p_{on}}{p_{off}}\right) = \frac{(nf_s + enr_d)}{nf_s} \tag{D-3}$$

$$Y = 10\log(y) = 10\log\left(\frac{p_{on}}{p_{off}}\right) = P_{on} - P_{off}$$

Hence the measurement system noise factor can be solved as:

$$nf_s = \frac{enr_d}{y-1} \tag{D-4}$$

The measurement system noise figure is:

$$NF_s = 10\log\left(\frac{enr_d}{y-1}\right) = ENR_d - 10\log(y-1) = ENR_d - 10\log\left(10^{Y/10} - 1\right) \tag{D-5}$$

Hence:

$$g = \frac{p_{on} - p_{off}}{enr_d \times kTB} \tag{D-6}$$

$$G = 10\log\left(p_{on} - p_{off}\right) - 10\log\left(enr_d \times kTB\right)$$

or

$$G = 10\log\left(10^{P_{on}/10} - 10^{P_{off}/10}\right) - ENR_d - 10\log\left(kTB\right)$$

In noise diode calibrations, the preceding equation is used to calculate measurement system gain from measured noise diode values.

Although the equation for NF_s may be used to calculate the measurement system noise figure, software may implement an equivalent equation:

$$nf_s = \frac{p_{off}}{gkTB} \tag{D-7}$$

$$NF_s = 10\log\left(p_{off}\right) - 10\log\left(gkTB\right) = P_{off} - G - 10\log\left(kTB\right)$$

And substituting the expression for gain into the preceding equation yields:

$$NF_s = P_{off} + ENR_d - 10\log\left(10^{P_{on}/10} - 10^{P_{off}/10}\right) \tag{D-8}$$

The gain and noise figure values determined with these equations may be stored in look-up tables. The gain values are used to correct the measured data points on a frequency-by-frequency basis.

Excluding the receive antenna, the entire signal path is calibrated with a noise diode source prior to a radar spectrum measurement. A noise diode is connected to the input of the first RF line in place of the receiving antenna. The connection may be accomplished manually or via an automated relay, depending upon the measurement scenario. The noise level in the system is measured at a series of points across the frequency range of the system with the noise diode turned on. The noise measurement is accomplished with the IF bandwidth set to 1 MHz and the video bandwidth set to 1 kHz. The noise diode is then turned off and the system noise is measured as before, at the same frequencies. The measurement system computer thus collects a set of P_{on} and P_{off} values at a series of frequencies across the band to be measured. The values of P_{on} and P_{off} are used to solve for the gain and noise figure of the measurement system in the equations above.

APPENDIX E: POSITIONING OF MEASUREMENT SYSTEM FOR RADIATED MEASUREMENTS

E.1 Measurement Environment Conditions

1. Regarding the measurement distance, the antenna pattern should be measured in the far field of the radar antenna. But the spectrum can be measured at distances at least as close as half the far field distance, as shown for example in Figure E-1. Variation of the peak received signal should be made less than 3 dB when the receiving antenna is moved $\lambda D/2H$ horizontally or vertically away from the point where maximum signal is received (H: height of the transmitting point, D: measurement distance, λ: transmitting wavelength).

2. Regarding the measurement site, it is preferable to locate the transmitting and receiving antennas in a fairly high position, such as on towers. Note that the height should be determined considering the vertical beam width of the radar and measurement antennas, and no reflective objects should be between the antennas.

For the purpose of performing radiated emission measurements on a radar, it is important to position the measurement system so that maximum power is coupled from the radar to the measurement system. This condition will achieve the highest possible dynamic range in the resulting emission spectrum data.

The question of near field and far field distances inevitably arises for radiated measurements. The terms ‘near field’ and ‘far field’ refer to changes in the radiation patterns of antennas as a function of distance from such antennas. Antenna patterns gradually approach a limiting case at infinite distances, but real-world measurements must be performed at finite distances. Therefore criteria have been developed for computation of distances at which radiation patterns are close enough to the limiting case to satisfy most engineering and scientific requirements. Two common criteria are $2D^2/\lambda$ and D^2/λ. But as noted, these criteria are intended for use in radiation pattern measurements, not spectrum measurements.

For RSEC measurements, the far-field limit may be taken as D^2/λ, where D is the radar antenna diameter and λ is the wavelength of the radar fundamental frequency. For a 2900-MHz radar with a 7-m antenna diameter, for example, the far-field distance will be 475 m. For a 420-MHz radar with an antenna diameter of 40 m, the far-field distance will be 2.25 km.

Pulse shape, modulation, and PRR measurements may be performed within the near field limit. Likewise, spectrum measurements may be performed at least as close as half of D^2/λ with only small differences from a measurement at D^2/λ, as shown in Figure E-1.

Antenna pattern measurements within the near field limit will be incorrect. Thus a distance of D^2/λ or greater is preferred when the measurement system is being positioned for an antenna pattern measurement.

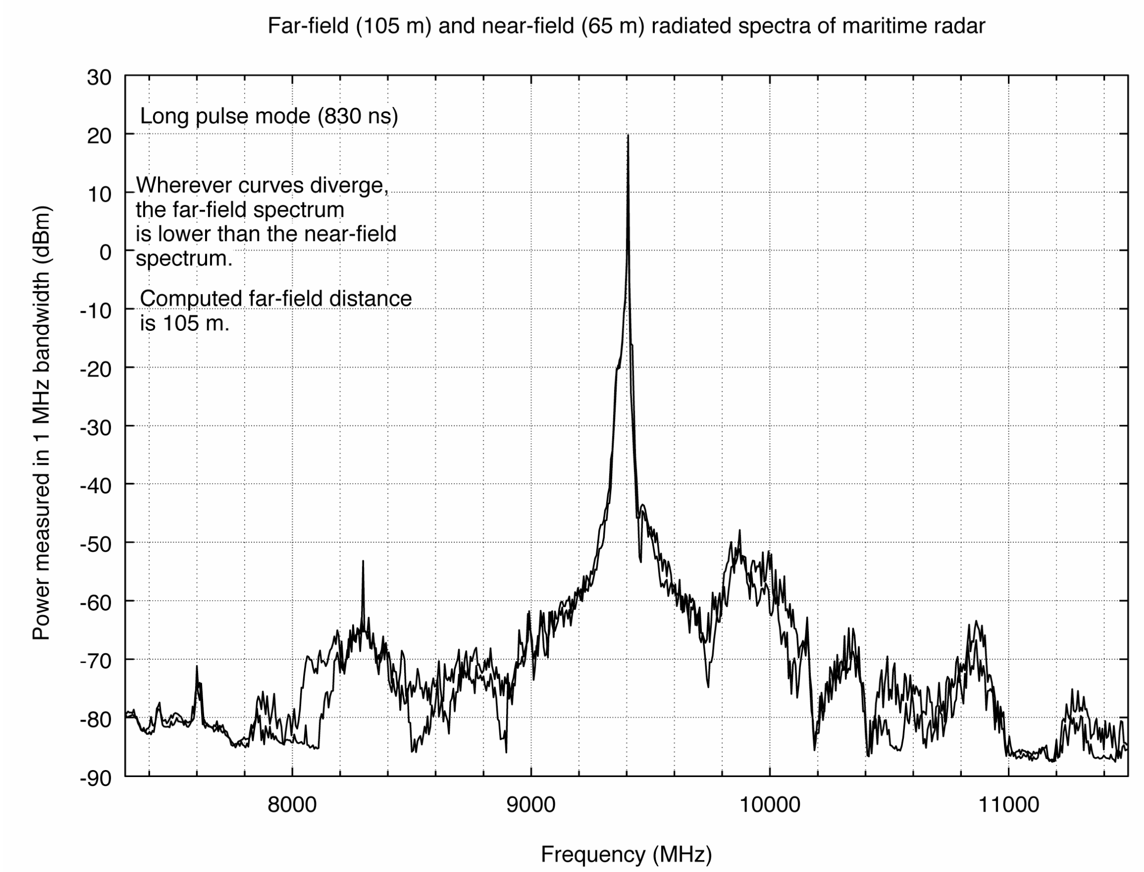


Figure E-1. Emission spectrum measurements of a maritime radar made at distances of 105 m (D^2/λ distance limit) and 65 m, well within that distance. Where the two spectra diverge, the far-field spectrum is lower than the near-field spectrum.

Because of the shape of typical radar beams, incident power at ground level does not continually increase as distance to the radar antenna decreases. Rather, there will usually be a distance at which incident power is maximized. Within this distance the power level drops because the measurement system is being moved underneath the radar antenna's highest-amplitude lobes. Outside this distance, the effect of $1/r^2$ geometric drop-off is experienced. The measurement system should be positioned at this maximum incident power point, unless it is within the near field limit of either the radar antenna or the measurement antenna.

The highest-amplitude location may be determined as follows, assuming that the measurement system is vehicularly mounted. A low-gain measurement antenna is mounted on the vehicular exterior, preferably on the roof. The antenna is connected to a spectrum analyzer which is tuned to the radar fundamental frequency. The spectrum analyzer span is set to zero hertz, the resolution bandwidth is set as wide as possible, and positive peak detection is used. The spectrum analyzer sweep time is set to a value that exceeds the time it will take to drive the vehicle from the radar transmitter to a location a few kilometers away. In practice, this will likely be about 300 sec.

The vehicle is initially positioned at the radar transmitter. As the spectrum analyzer sweep is triggered (manually), the vehicle begins to drive away from the radar. Every few seconds, the radar beam will sweep across the vehicle and the received power value will be observed. The received power level will gradually rise as the vehicle moves away from the radar. At some point, the received power level will no longer increase, and at longer distances from the radar the received power will decrease. The vehicular location where the maximum power was received should be noted by the vehicle's driver; this is the optimum location for the ensuing spectrum measurement.

As rough guidelines, the typical optimal distance from which to perform measurements on air search radars and weather radars is between 0.8 km to 1.2 km. Distances on the order of 0.1 km (100 meters) or less may be optimal for measurements of emissions from maritime surface search radars.

With the measurement vehicle properly positioned, the measurement system is configured for the full RSEC measurement as described in Appendix C. A constant-aperture (parabolic) antenna is substituted for the low-gain antenna used in the location survey. The measurement antenna should be raised as high as possible on a mast for air search radar measurements. For maritime radar measurements, the measurement antenna should be positioned at a height that maximizes the coupled power from the radar.

APPENDIX F: VARIATION IN MEASURED PULSE SHAPES ACROSS EXTENDED EMISSION SPECTRA

Since the pulse shape is related to the emission spectrum via the Fourier transform, the pulse shape can in principle be observed in complete detail only if the entire emission spectrum is convolved within the measurement bandwidth. But in practice, a measurement bandwidth that convolves a large number of the highest-amplitude emission lines near the fundamental frequency of a spectrum (ie., a bandwidth that equals or exceeds (1/pulse width)) will produce a pulse shape that nearly replicates the true pulse shape, as shown in Figure F-1 for a weather radar.

But using the same bandwidth at a frequency within the spurious portion of the emission spectrum, the convolved set of emission lines will not produce the pulse shape of Figure F-1a. Instead, this sub-set of emission spectrum lines will produce a double pulse shape such as that shown in Figures F-1b through F-1d. (These figures are off-tuned measurements made on the same radar as Figure F-1a). This phenomenon is referred to vernacularly as "rabbit ears." The spacing between the two spikes will be the same as the nominal pulse width. But between the two spikes low-amplitude noise will be observed. Depending upon the spurious frequency, the relative amplitudes of the leading-edge spike, trailing-edge spike, and center-pulse noise will vary.

This phenomenon has important implications for the RSEC spectrum measurement. The essential significance is that *the measurement bandwidth at which the measured peak power remains constant varies with frequency*. In section 5 a measurement of bandwidth progression shown in Figure 12 illustrates the point at which the measured peak power remains constant despite an increase in measurement bandwidth. At the fundamental, this point is about 1/t, where t is the pulsewidth. In the spurious portions of the spectrum, this bandwidth is much wider, usually about $1/t_r$, where t_r is the pulse's risetime. This variation has important consequences for the selection of appropriate bandwidth for the RSEC spectrum measurement, as discussed in Section 5 of this report and shown in Figures 16–17 of that section.

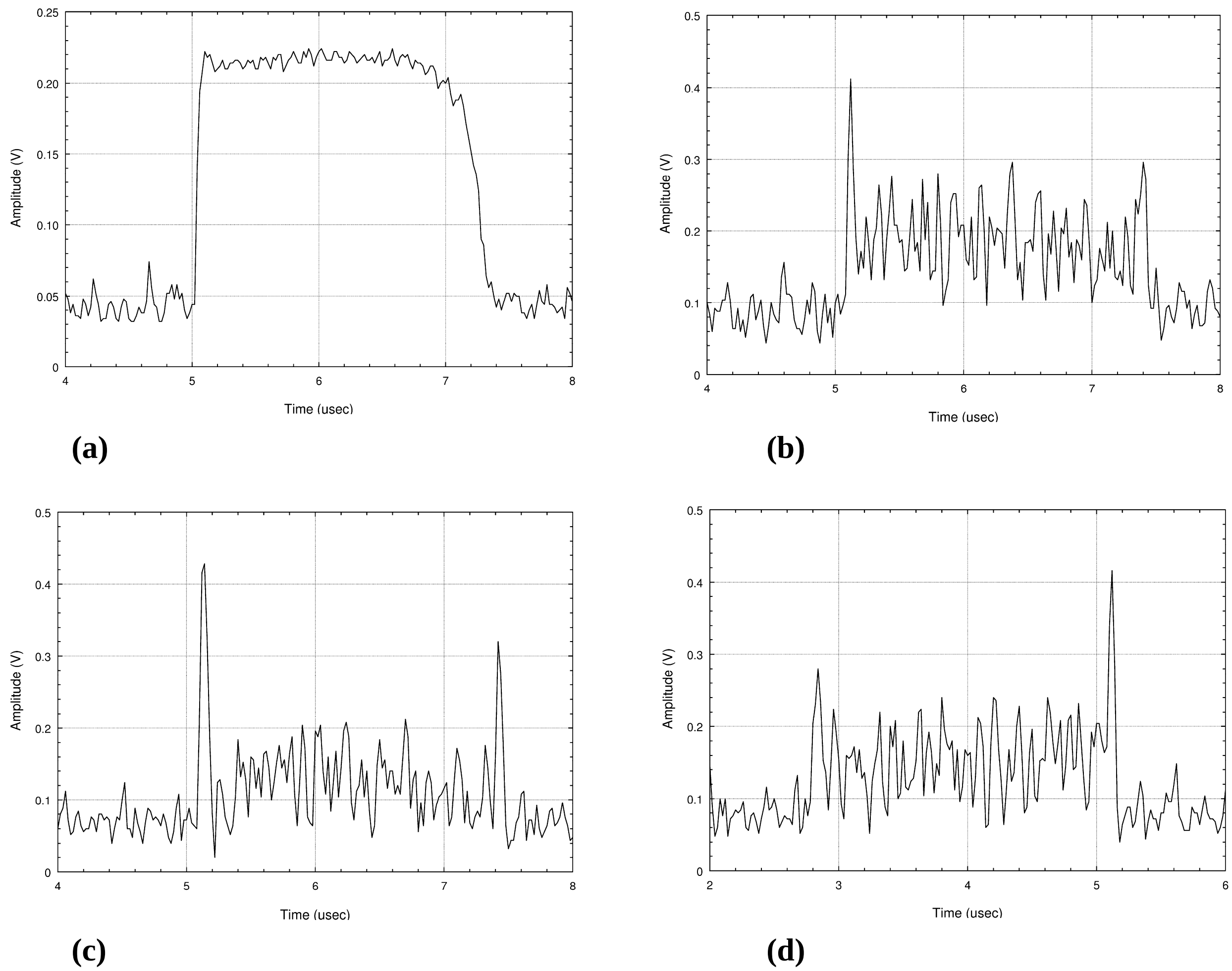


Figure F-1. A weather radar pulse envelope measured at nominal radar center frequency (a), and at three other frequencies in the out-of-band and spurious parts of the emission spectrum ((b) through (d)). Measurement bandwidth was 8 MHz. The emission lines convolved at the center frequency in the measurement bandwidth yield a good approximation of the full-bandwidth pulse envelope in the time domain. But the subsets of Fourier lines convolved in the same bandwidth at frequencies in the out-of-band spurious portions of the emission spectrum do not yield the nominal pulse envelope; instead they tend to produce high-amplitude features in the leading edge, trailing edge, or both. (Note however that total pulse duration of off-tuned detected pulses is constant, even though much of the structure is low-amplitude and noisy.)

APPENDIX G: VARIATION IN MEASURED SPURIOUS AMPLITUDES AS A FUNCTION OF MEASUREMENT BANDWIDTH

G.1 Introduction

Pulsed radar transmitters produce broadband spurious emissions at relatively high levels as compared to emissions from narrowband communication systems. As documented in [3], radar spurious emission levels are typically tens of decibels higher than theoretically predicted $sinc^2$ spectra of pulsed emissions. These emissions in the frequency domain probably correspond to short-term transient behavior in the time domain characteristics of the rising and falling edges of the radar pulses.

For spectrum management purposes, radar out-of-band and spurious emissions are limited in the U.S. by Government regulations such as the radar spectrum emission criteria (RSEC). RSEC spurious emission masks are specified in terms of amplitude suppression relative to the power produced at radars' fundamental frequencies [1] (e.g., suppression might be required to be at least 60 dB below the fundamental at frequencies of 100 MHz or more away from the fundamental). Mask-compliance limits are computed on the basis of a theoretically perfect pulsed emission plus a margin that allows for realistic performance of an economical transmitter design.

Compliance with emission masks is determined through measurements of emission spectra. The measured levels of radar unwanted emissions and fundamental-frequency emissions both vary as a function of measurement system bandwidth, B_m. But the variation with B_m differs between unwanted emissions and the fundamental-frequency emissions. Moreover, the variation of unwanted emission levels varies as a function of frequency as well as B_m. This presents a problem for radar emission mask-compliance measurements.

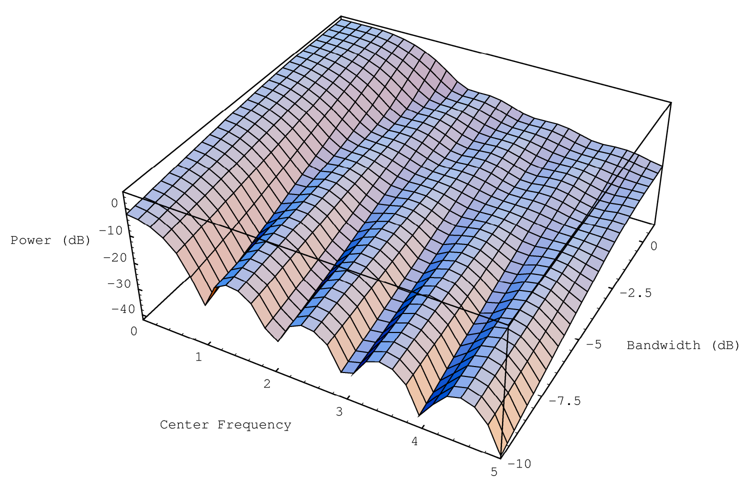


Figure G-1. Schematic representation of the measured power at a radar fundamental frequency versus power measured at other frequencies as measurement bandwidth changes. Units are arbitrary.

In a peak-detected power measurement, completely non-coherent (noise-like) emissions should vary as 10 $\log(B_m)$, while coherent emissions should vary as 20 $\log(B_m)$. Since the bandwidth progression coefficients of 10 and 20 represent limiting cases, radar spurious emissions should have a coefficient somewhere between these two values. But no study is known to have been undertaken to determine the actual coefficient for radars. An ideal peak-detected measurement is shown in Figure G-1. Power measured at the fundamental frequency (far left) first increases at a 20log rate, but maximizes when measurement bandwidth exceeds the values given in Table 2 of this report. But since the power in the rest of the spectrum climbs arbitrarily high as bandwidth increases, the difference between power values at the center frequency vs. other frequencies (reading between the left and right sides of this diagram) therefore *decreases* if measurement bandwidth is greater than the values of Table 2.

NTIA/ITS has begun to address this problem by performing emission spectrum measurements on a maritime surface search (navigation) radar. The purpose of the measurements has been to determine the actual variation of spurious emission levels of a radar relative to the measured fundamental level as a function of the measurement bandwidth, B_m. With this value known, NTIA will be better able to specify appropriate bandwidths for RSEC-compliance measurements, as well as any post-measurement correction factors that might be required.

G.2 Approach

A magnetron-based X-band maritime surface search radar was set up with an antenna height of approximately 4 m on a mast at a prairie location free of local obstructions. A measurement system contained in the RF-shielded enclosure of the NTIA Radio Spectrum Measurement System (RSMS) was positioned at a distance of 105 m from the radar. The RSMS received radar emissions via a 1-meter diameter parabolic dish antenna with a linear, matched-polarization log-periodic feed. Figure G-2 shows the radar transmitter and the RSMS during the measurement.

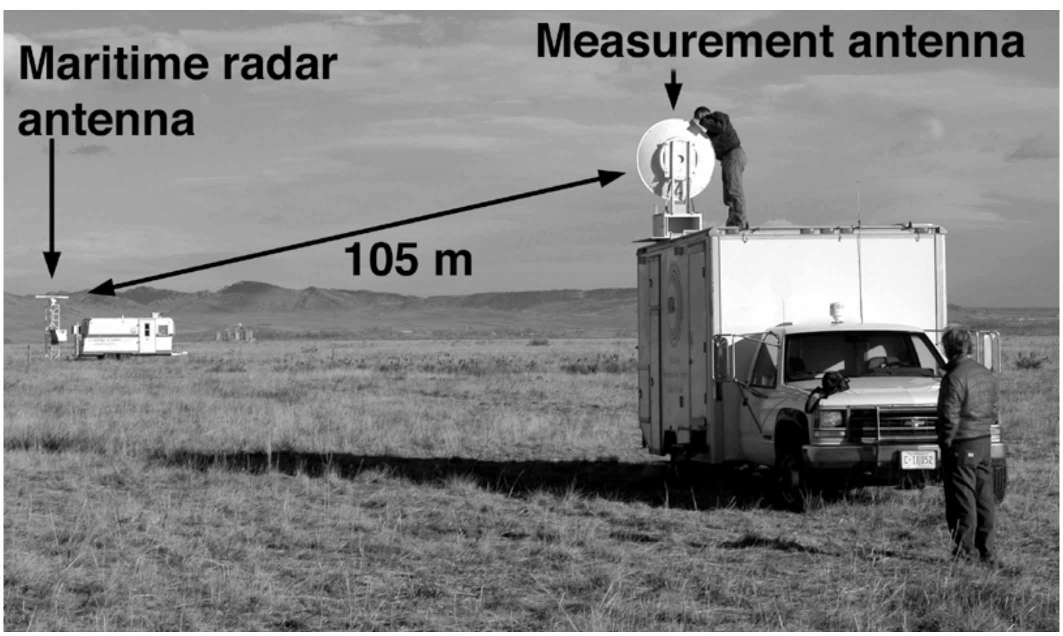


Figure G-2. Maritime radar and measurement system.

The measurement system is shown in block-diagram form in Figure G-3. Following the antenna, a variable (0–70 dB) attenuator was adjusted on a frequency-dependent basis to keep the received signal level from the radar within the dynamic range of the measurement system. That is, the attenuation level was zero when radar emissions were close to measurement system noise, but was gradually increased (in 10 dB steps) to as much as 70 dB as the measured frequency approached the radar fundamental. The attenuation was gradually decreased at frequencies above the radar fundamental, being finally reduced to zero at the upper end of the measured spectrum.

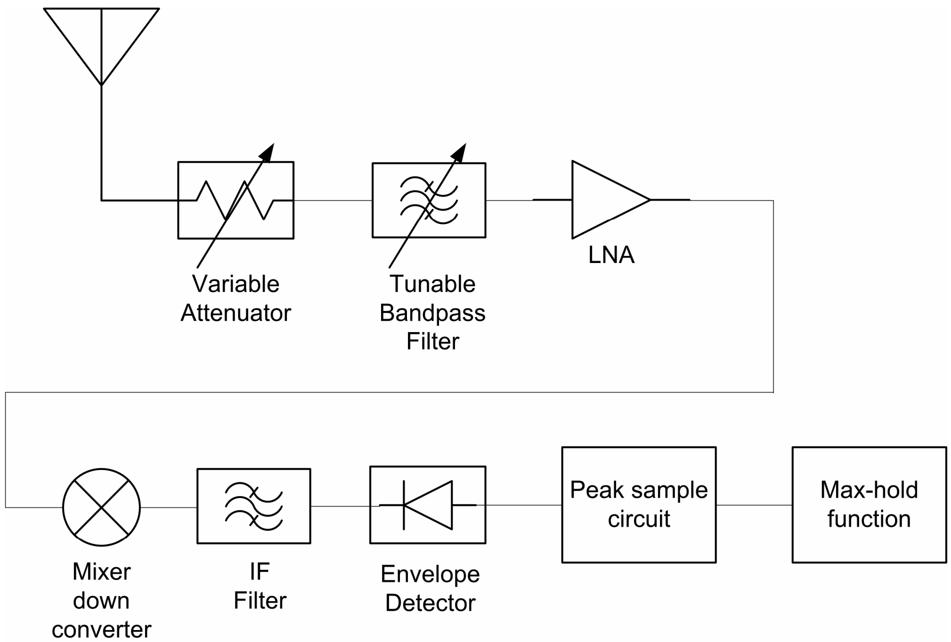


Figure G-3. Measurement system functional block diagram.

Following the attenuator, a tunable bandpass filter based on yttrium-iron-garnet (YIG) technology isolated the system’s broadband low-noise filter (LNA) from the high-power radar fundamental energy as the spectrum measurement progressed. The LNA provided the sensitivity required to measure out-of-band and spurious emission levels as much as 100 dB below the measured fundamental power level.

The LNA output was fed into a spectrum analyzer. The critical spectrum analyzer stages are shown in Figure G-3, including frequency downconversion; IF filtering; envelope and peak detection; analog-to-digital conversion; and final output to a data-recording computer.

As noted above, the requisite dynamic range of the measurement (about 100 dB) demanded that the RF attenuator setting be varied as a function of frequency. Therefore, the measurement system could not be operated in a swept-frequency mode. Instead, the measurement system was fixed-tuned to a single frequency with a single attenuator setting. A peak-detector circuit was operated at the single frequency for a period of time (3 sec) slightly in excess of the radar’s antenna rotation period (2.7 sec). This ensured that the radar beam maximum output would be sampled at each measured frequency.

With the emission amplitude measured at a single frequency, the measurement system was tuned to another frequency, the RF attenuator was adjusted (if necessary) and the measurement process was repeated for another 3 sec. This stepped-frequency measurement process was used to acquire all data presented in this paper.

With 100 dB dynamic range available in the measurement, the radar spectrum was measurable across 4.2 GHz of spectrum, from 7300 MHz to 11500 MHz. Because the out-of-band and spurious emissions are a continuum, lacking discrete carrier frequencies, those emissions could be sampled at arbitrary spacings between frequency steps. For this measurement, the step interval was set at 6 MHz, for a total of 700 steps (and 701 measured frequencies) across the range 7300-11500 MHz. Each spectrum run therefore required about 35 minutes for completion.

Because the 6 MHz step spacing could result in the omission of the radar fundamental frequency from the measured spectrum, a supplemental measurement was made at the radar fundamental for each spectrum. This ensured that radar peak power was accurately included in each spectrum output.

The radar can transmit multiple pulse widths, ranging from 80 nsec to 800 nsec. The radar spectrum was measured in two pulse modes (80 nsec and 800 nsec) in four IF bandwidths (where B_m=300 kHz, 1 MHz, 3 MHz, and 8 MHz). Thus a total of eight spectrum measurements were performed.

G.3 Results

The measured emission spectra for short-pulse and long-pulse radar modes are shown in Figures G-4 and G-5. Measurement system internal noise occurs as a flat floor at frequencies between 7300-8000 MHz, and as a flat area between 11000-11200 MHz. It is observed that the spurious emission levels are changing with a progression that is somewhere between 10 log and 20 log bandwidth, depending upon frequency.

Figure G-6 shows measured power at the radar fundamental frequency (approximately 9410 MHz) as a function of measurement IF bandwidth. The data in this figure confirm that the radar fundamental power follows a 20 log(B_m) rule for values of B_m that are equal to or less than (1/pulse width).

In the short-pulse mode, the 80 nsec pulse width results in a predicted fundamental-frequency 3-dB emission bandwidth of 12.5 MHz, which is wider than the maximum measurement IF bandwidth of 8 MHz. Consequently, the measured power increases as 20 log(B_m) for all points. But in the long-pulse mode of 800 nsec pulse width, the 3-dB emission bandwidth is predicted to be 1.25 MHz. As a result, the 20 log(B_m) progression breaks down for 3 MHz and 8 MHz B_m values.

Figure G-7 quantifies the decibel differences between spectra measured in successive values of B_m. These are shown as deviations from a 20 log progression, computed as follows:

$$\Delta = \left[\frac{P_x - P_y}{\log\left(B_x / B_y\right)} \right] - 20 \qquad \text{(G-1)}$$

where:

Δ = deviation from 20 log(B_m) progression;
$P_{[x,y]}$ = log power measured in B_x and B_y;
$B_{[x,y]}$ = measurement bandwidth;
[x,y] are subscripts for successive measurement IF bandwidths (e.g., 3 MHZ and 1 MHz).

The differences should lie between –10 (corresponding to a noise-like 10 log progression) and 0 (for the 20 log rule that coherent emissions should follow). Some points lie outside these bounds. Deviations outside this range could result from the interaction of spectrum peaks and valleys with a particular measurement bandwidth; uncertainty in measured values; or variation in shape factors between filters.

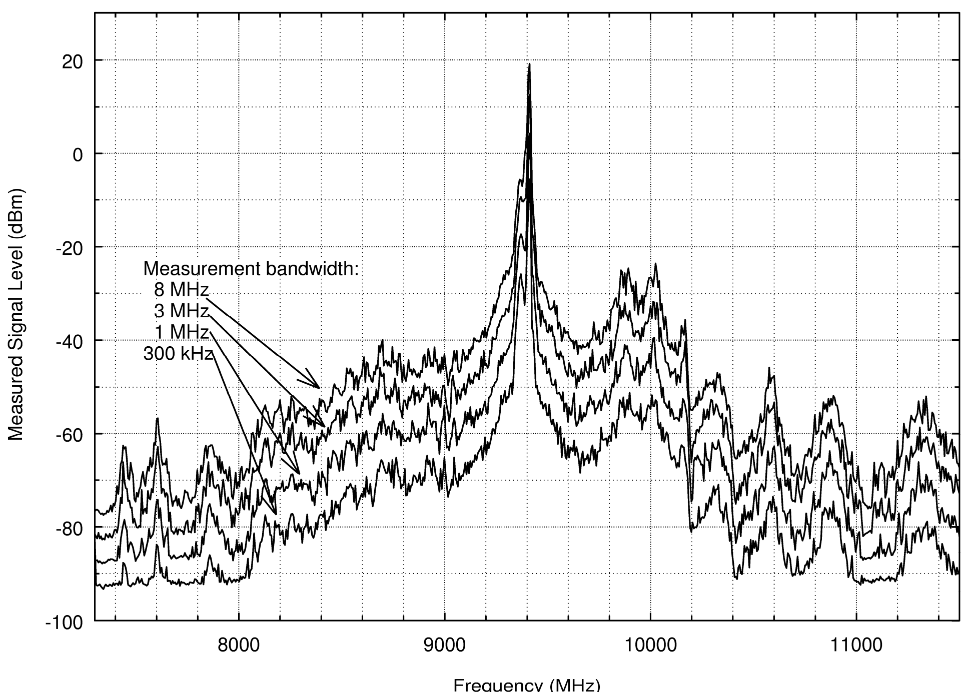


Figure G-4. Maritime radar emission spectrum measured in four bandwidths with transmitter operating in short-pulse mode.

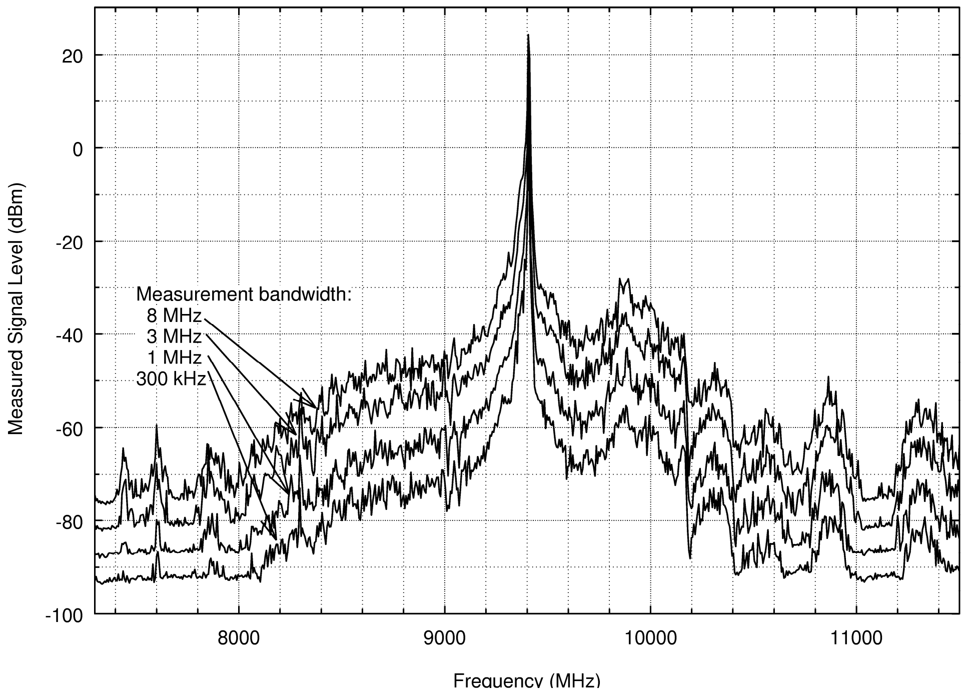


Figure G-5. Maritime radar emission spectrum measured in four bandwidths with transmitter operating in long-pulse mode.

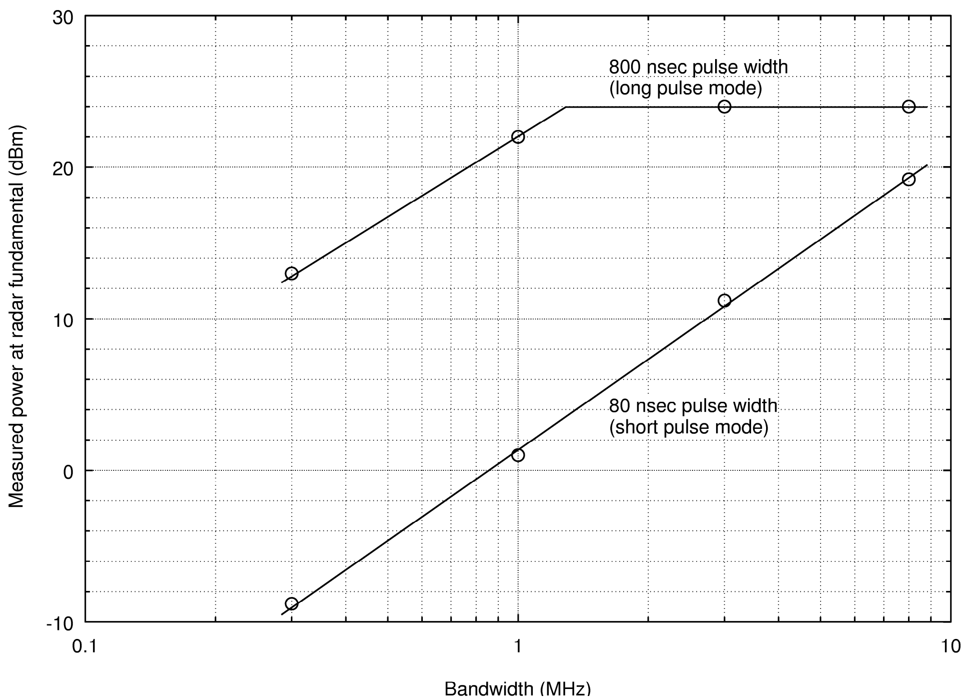


Figure G-6. Variation in measured power at the radar fundamental as a function of measurement bandwidth and pulse mode.

Some trends are clearly observed in the values for the curves in Figure G–7. The values of the deviation curves typically range between –4 and –2, corresponding to variation coefficients between 16 and 18. Neglecting the points that exceed zero, the extreme values range between –8 and 0, corresponding to variation coefficients between 12 and 20, respectively.

G.4 Summary and Conclusions

In summary, spurious and out-of-band emissions measured from a maritime navigation radar were found to typically vary at a value between 16 $\log(B_m)$ and 18 $\log(B_m)$. Extreme values ranged from a low of 12 $\log(B_m)$ to a high of 24 $\log(B_m)$.

These results indicate that the radar spurious emissions did not vary as would be predicted for thermal noise (10 log progression). Thus radar spurious emissions should not be characterized as "noise-like," at least for the radar measured in this study.

Radar emission spectrum measurements that are performed for the purpose of determining the suppression of out-of-band and spurious emissions relative to radar fundamental-frequency power will show a bandwidth dependent variation. Measurement of spectra in multiple bandwidths is recommended until this phenomenon is better understood.

It may be desirable for future emission masks to accommodate this effect. Such masks might include a recommended IF measurement bandwidth, and possibly a method for computing correction factors for measurements made in other bandwidths.

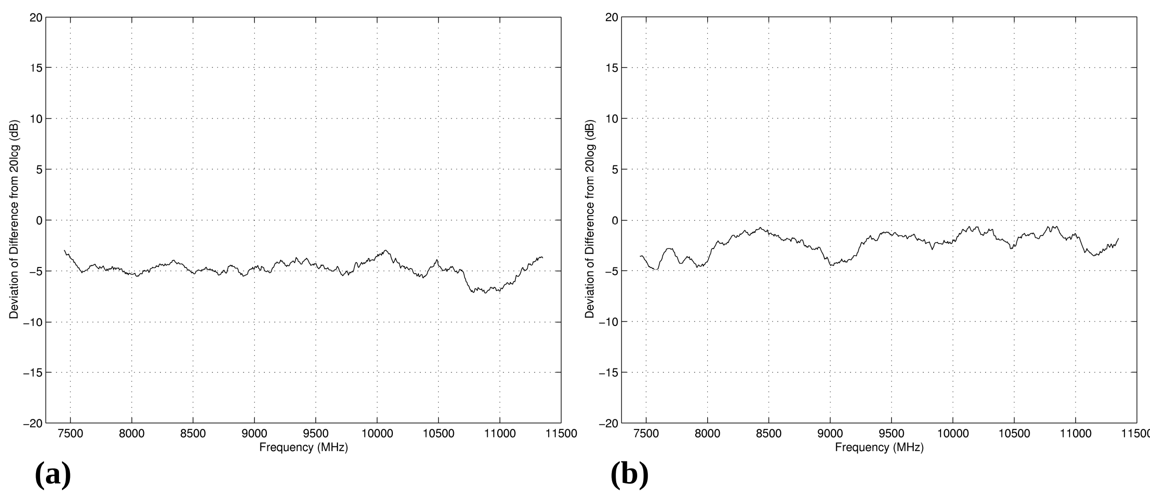
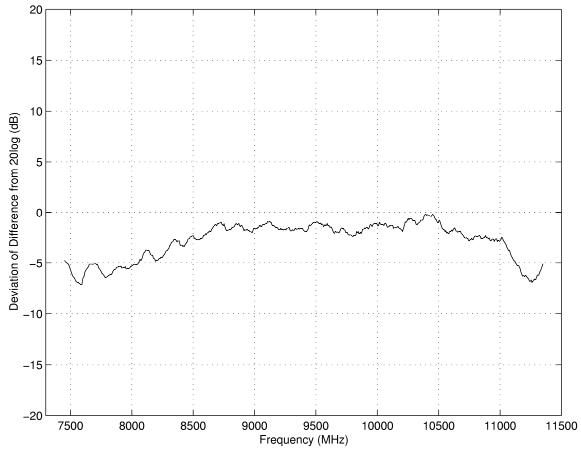
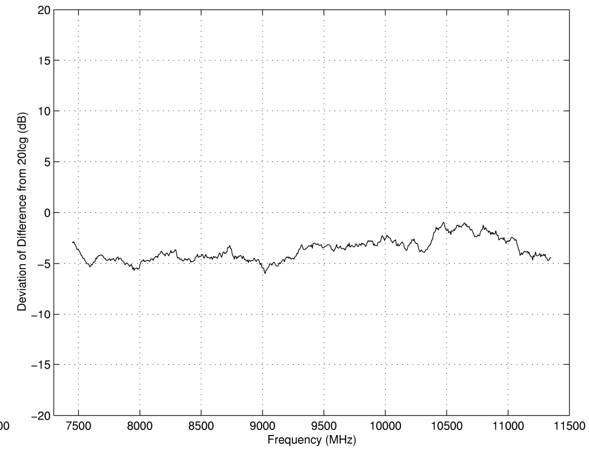


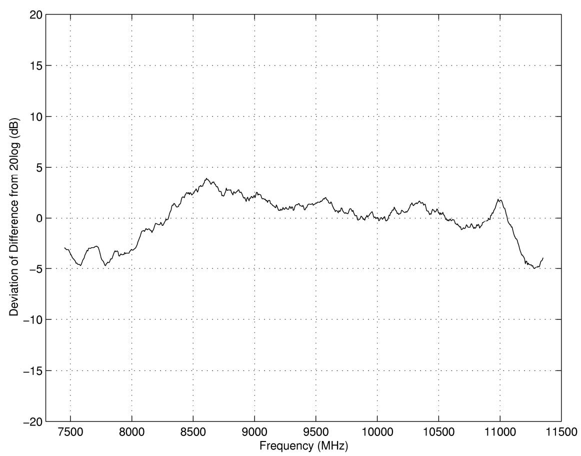
Figure G-7a. 8 MHz – 3 MHz smoothed difference, short pulse radar mode.
Figure G-7b. 3 MHz – 1 MHz smoothed difference, short pulse radar mode.

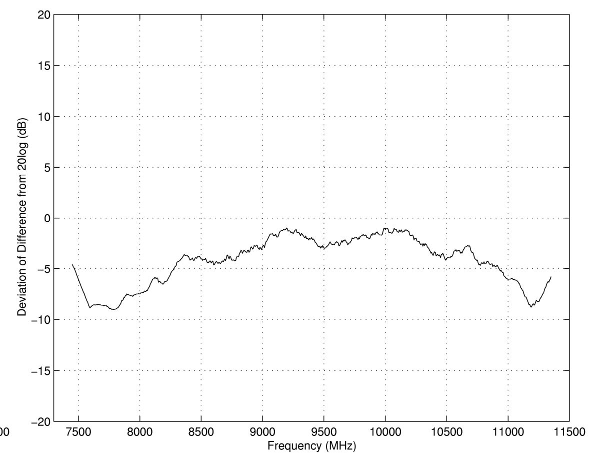




(c) **(d)**

Figure G-7c. 1 MHz – 300 kHz smoothed difference, short pulse radar mode.
Figure G-7d. 8 MHz – 3 MHz smoothed difference, long pulse radar mode.





(e) **(f)**

Figure G-7e. 3 MHz – 1 MHz smoothed difference, long pulse radar mode.
Figure G-7f. 1 MHz – 300 kHz smoothed difference, long pulse radar mode.

APPENDIX H: RADAR SPECTRUM ENGINEERING CRITERIA (RSEC) EMISSION MASK SPREADSHEET

H.1 Introduction

NTIA has developed an automated model to plot RSEC emission masks as a function of radar characteristics. The RSEC Emission Mask spreadsheet will plot the permitted emission limits for primary radar stations operating in the radiodetermination service as required [1, § 5.5]. Measured emission spectrum data can be imported into the spreadsheet for comparison with the RSEC emission limits. The RSEC emission mask spreadsheet is in Microsoft Excel© format. The program is available on the following website: http://ntiacsd.ntia.doc.gov/rsec. Comments and suggested improvements to the spreadsheet should be sent to Robert Sole at rsole@ntia.doc.gov. A user's guide for the program is given below.

H.2 System Requirements

The ITU-R emission mask spreadsheet requires Microsoft Excel 2000© or later version, and Microsoft Windows 98© or later operating system.

H.3 Opening Program

Start Microsoft Excel. Open the file ITU-R emission mask spreadsheet. When prompted, enable the macros. If not prompted to enable macros, then go to the Tools pull down menu, and select Macro-Security. In the Security level tab, choose Medium and press OK. Close the spreadsheet and re-open it. Upon re-opening the spreadsheet, you should be prompted to enable macros. Click on the NEW/Restart button to initialize the spreadsheet.

H.4 Importing Measured Emission Spectrum Data

Measured emission spectrum data may be imported into the program. If measured data are being used, they should be imported prior to providing the data in Table 1 since the Excel program determines some parameters in Table 2 from the measured emission spectra data. The imported emission spectrum data files must be in ASCII file format, Easy Plot© file format, or table entry. The ASCII file must include the emission spectrum data in two fields: 1) frequency in MHz, 2) measured emission spectrum data in absolute power (e.g.; dBW or dBm), or in dB relative to the maximum measured signal level. Note: if the data are in absolute power the program will normalize the data to dB relative to the maximum measured signal level.

The procedure for importing measured data into the spreadsheet is as follows.

A. Click on the **Get Data** button.

B. An **Emission Spectrum Data** window will pop up. Click on the **Read/Describe Emission Spectrum Data** button.

C. An **Emission Spectrum Input** window will pop up. Click on the **Read ASCII File** button if the emission spectrum data are in an ASCII file. Click on the **Read CSV File** button if the emission spectrum data are in an CSV file. Click on the **Read EP File** button if the emission spectrum data are in an Easy Plot© file. If the spectrum data are not in a file, and are available in a Table Entry form, click on **Table Entry**.

D. An **Open Emission Spectrum Data File** window will pop up. Go to the bottom of the menu and where it says "Files of type", use the pull-down menu to select "all files." Locate the file to be imported into the spreadsheet using the **Look in** pop-down button. Select the file to be imported, and click on **Open**.

E. Select an emission spectrum file to be loaded into the spreadsheet. Sample emission spectrum data are available. See H.13 below for information on sample emission spectrum data files.

F. Click on the **OK** button,

G. A window will come on the screen that says **Emission Spectrum Data** with the ability to select fixed frequency or frequency hopping. Select the appropriate radar mode. If you select fixed frequency, the window will display the Operating Frequency (F_O) based on the measured data. If you select the Frequency Hopping Mode, the Lowest Channel Frequency (F_L) and Highest Channel Frequency (F_H) windows will display the selected F_L and F_H frequencies based on the measured data. In cases where there are multiple operating (fundamental) frequencies, or the radar is a frequency hopping radar, the program may not select the appropriate Operating Frequency (F_O), or in the case of frequency hopping radar the Lowest Channel Frequency (F_L) and Highest Channel Frequency (F_H) for plotting the RSEC emission mask. If the appropriate F_O, F_L , or F_H values were not selected, type in the appropriate values. Then click the OK button. Measured data should now be visible on the spreadsheet. The Excel program will normalize the power level at the fundamental frequency (F_O) to 0 dB. Verify that the Fo data in Row 6 of the spreadsheet is in agreement with the plotted data. In the case of frequency hopping radars, the value for F_O in Row 6 should be midway between F_L and F_H.

H. If desired, the frequency scale of the measured data can be normalized to zero MHz/GHz at the radar Fundamental Frequency (F_O). Verify that the value for normalized data in Row 6 is correct. Click on the **Normalize to Fo** button in Row 34. The measured data will be normalized to Fo at zero hertz.

H.5 Changing Graph Title and X and Y Axes

Once the measured data have been imported into the spreadsheet, the Titles and the X and Y axes ranges on the measured data plot can be changed if necessary.

A. The graph titles, and X and Y axes titles can be changed by clicking on the **Set Graphs Titles** button. Make appropriate changes to the titles, and click on the **OK** button.

B. The scale range of the X and Y axes can be changed if necessary by pointing the mouse to the X or Y scale on the graph and right click when the Values (X or Y axis) window pop up. Then click on **Format Axis**. A **Format Axis** window will pop up. Click on the **Scale** tab, and change the axis values as required. Then click on the **OK** button. The measured data should now be in the desired format.

H.6 Select RSEC Criteria

Click on the RSEC Criteria button in row 3. A window will appear titled RSEC Criteria which provides information on Radar Description and Applicable Criteria. Determine the appropriate RSEC Criteria, and click on the RSEC button in Row 3 Column B. A pop-down list for RSEC Criteria A, B, C, D, and E will appear. Click on the appropriate criteria.

If RSEC Criteria D is selected, a window will pop up showing the congested areas for radars operating in the 2700-2900 MHz band. If the radar will be operated in a congested area, click on the **Congested** window, Row 8, and insert Y for yes in a congested area. Otherwise insert N for not in a congested area. This will change the required slope roll-off from the –40 dB bandwidth from 40 dB per decade to 80 dB per decade.

H.7 Radar Peak Power

Enter the radar peak power, Pp, in Row 7 of the spreadsheet. The pop-down window to the right lets you select appropriate units for specifying peak power. Click on the units then click on the pop-down window to change the units.

H.8 Table 1 – Pulse/Sub-Pulse Characteristics

Table 1 is provided to input the measured or calculated pulse/sub-pulse characteristics for determining the RSEC emission mask limits. The definition of the radar parameters in Table 1 are provided in the NTIA Manual [1, § 5.5]. Table 2 [1, § 5.5] shows the calculated RSEC emission mask parameters and other data needed for determining the RSEC emission mask for the radar parameters entered in Table 1 [1, § 5.5].

The Table 1 spread sheet will let you specify up to eight pulse/sub-pulse time waveform characteristics for multiple waveform radars. For multiple waveform radars, the RSEC emission mask limits are determined from the pulse type (waveform) which results in the maximum B(-40 dB) bandwidth. Use the following procedure for providing the pulse/sub-pulse waveform information in Table H-1.

A. The column labeled **Pulse Type** must have a value selected. Place the cursor at the small red triangle on the upper right side of the cell for guidance on selecting the proper pulse type. There are nine pulse/waveform modulation types to choose from. Type in the appropriate number. Once the pulse type is determined, fields in Table 1 that are not applicable to that pulse type will have an NA in them.

B. The column labeled **Pulse Width or Sub-Pulse Width** (t) must have data entered into it for the pulse/sub-pulse width in microseconds. Place the cursor on the small red triangle on the upper right side for guidance for determining the pulse width.

C. The column labeled **Pulse Rise/Fall Time** (t_r) must have data entered into it for the rise/fall time in microseconds. If the pulse/sub-pulse fall time (t_f) is less than the rise time (t_r), t_f is to be used in place of t_r for determining the emission bandwidth calculation. Place the cursor on the small red triangle on the upper right side for guidance for determining the pulse rise/fall time.

D. For frequency swept (chirped) pulses, the column labeled **Chirp Bandwidth** (B_c) must have data entered into it for the chirp range in MHz. Place the cursor on the small red triangle on the upper right side for guidance for determining the chirp bandwidth.

E. For CW radars, the column labeled **Total Frequency Deviation** (B_d) must have data entered into it for the frequency deviation range in MHz. Place the cursor on the small red triangle on the upper right side for guidance for determining the frequency deviation.

F. For phase coded pulses, the column labeled **Number of Chips per Pulse** (N) must have data entered into it for the total number of chips per pulse. Place the cursor on the small red triangle on the upper right side for guidance for determining the frequency deviation.

G. The column labeled **Pulse Repetition Rate** (PRR) must have data entered into it for the pulse repetition rate in pulses per second (PPS). Place the cursor on the small red triangle on the upper right side for guidance for determining the pulse repetition rate.

H. For frequency hoping radars, the columns labeled **Lowest Channel and Highest Channel Frequency** (F_L and F_H) must have data entered into them for the lowest and highest channel frequency of a frequency hopping radar deviation in MHz. The data for F_L and F_H should be added to these fields when **Pulse Types** 3, 4, and 8 are selected in Step A above. Check to determine if the data in these fields are correct. Place the cursor on the small red triangle on the upper right side for guidance for determining the appropriate values for F_L and F_H.

After the radar characteristics data have been completed in Table 1, the calculated parameters related to the RSEC Emission Limits Mask for each waveform are shown in Row 1 of Table 2.

H.9 Plotting RSEC Emission Mask

Review the calculated parameters related to the RSEC Emission Limits Mask data shown in Table 2. The RSEC Emission Mask can be plotted on the measured data using the following procedure.

A. The emission mask data that will be plotted over the measured data correspond to the Emission Mask Number shown in Column A of Table 2. If the radar mode has multiple pulse waveforms, review the B(-40 dB) bandwidths shown in Table 2 for the various pulse waveforms. Check the mask number shown in Row 38. If necessary, change the mask number in Row 38 to correspond to the Emission Mask number in Column A of Table 2, which has the maximum B(-40 dB) bandwidth. Click on the **Add/Del** button shown in Row 40. The emission mask will be added in the plot.

B. To delete the emission mask from the plot, click on the **Add/Del** button shown in Row 40. Check the mask number shown in Row 38. If necessary, change the mask number in Row 38 to correspond to the Emission Mask number that you want to delete shown in Column A of Table 2.

C. The slope from the B(-40 dB) bandwidth can be changed by clicking on the **Set S (slope)** button shown in Row 44. Check the mask number shown in Row 38. If necessary, change the mask number in Row 38 to correspond to the Emission Mask number that you want to change the slope of shown in Column A of Table 2.

D. The X dB Floor can be changed by clicking on the **X dB Floor** button shown in Row 42. A specific X dB floor value can be typed in, or the box titled **Proposed New X dB Floor** can be checked. Check the mask number shown in Row 38. If necessary, change the mask number in Row 38 to correspond to the Emission Mask number that you want to change in Column A of Table 2.

H.10 RSEC Mask Offset

The RSEC B(-40)dB bandwidth can be offset from the frequency of maximum emission level, and can be shifted to center the mask at the measured -40 dB level of the measured data. If there is a RSEC mask on the graph, click on the **Add/Del Mask** button. This will delete the indicated mask. To offset the RSEC mask, click on the **Mask Shift** button and type in the desired frequency shift in a positive or negative direction. Then click on the **Plot Mask Shift** button.

H.11 Plotting Additional Emission Masks

Additional emission masks with parameters other than the RSEC Emission Mask can be plotted on the measured data. To plot additional emission masks to the data plot, it is necessary to provide additional Pulse/Sub pulse characteristics data in another row of Table 1. This can be accomplished by clicking on the row in Table 1 that you want copied, and then click the **Copy**

Row button, rows 22-23. The RSEC Emission Mask data will appear in the corresponding row in Table 2. Change the appropriate parameter (e.g.; Slope dB/dec,) in the row of Table 2. Change the Mask Number in Row 38 to the appropriate row of Table 2. Click on the **Add/Del** button shown in Row 40. The additional emission mask will be added in the plot.

H.12 Printing the Spreadsheet

To print Graph, Table 1, and Table 2, click the appropriate buttons in rows 48, 50, and 52 respectively. Also, the graphs and Tables can be printed by clicking on the **Summary** button on line 3, and then clicking on the **Summary** tab at the bottom of the page. (Note: you must click on the **Summary** button on line 3 to import the data prior to clicking on the Summary tab at the bottom of the page.) From the **Summary** page, the spreadsheet can be printed, or copied to a text document.

H.13 Viewing Measurement Data and RSEC Emission Mask Data

To view the measurement data and RSEC emission mask data, click on the **Temp** tab at the bottom left of the Excel screen.

H.14 Sample RSEC Spreadsheet Data

A sample radar emission spectrum is provided below. The radar measured was an Aeronautical Radionavigation radar which operates in the 2700-2900 MHz band. Thus the emissions of the radar must comply with RSEC-D criteria. RSEC Emission Mask 1 is for a 40 dB per decade roll-off from the –40 dB bandwidth, and RSEC Emission Mask 2 is for an 80 dB per decade roll-off from the –40 dB bandwidth for designated congested areas.

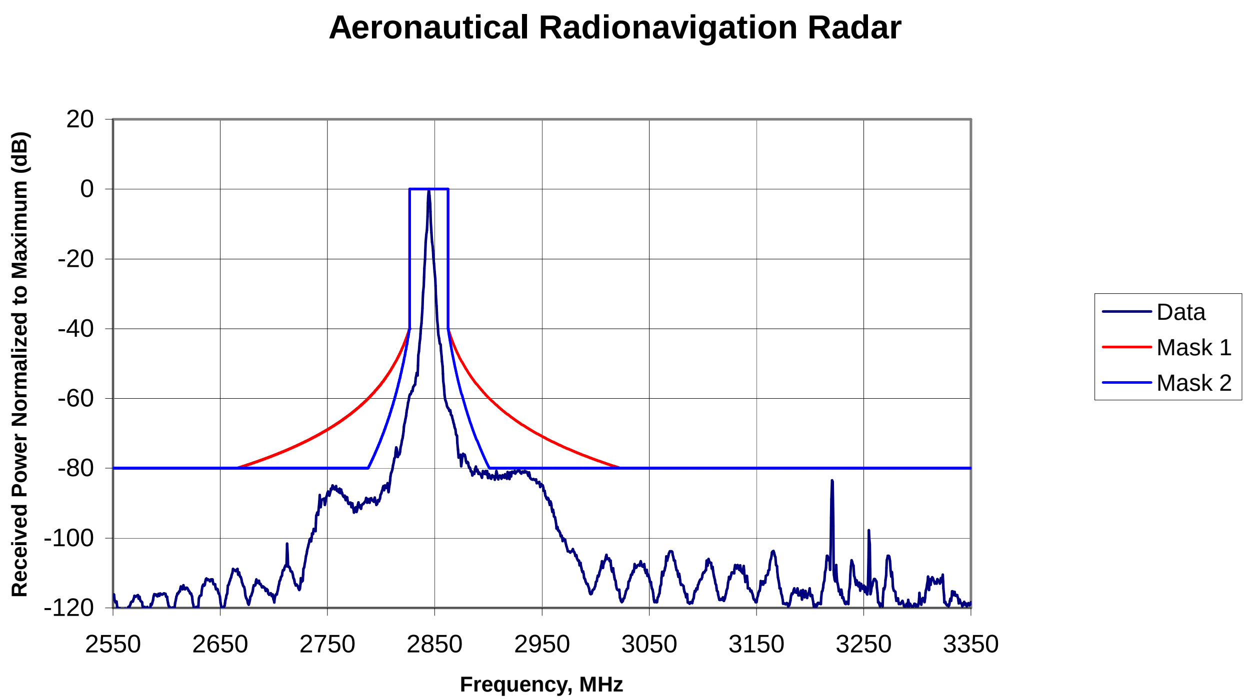
SAMPLE RSEC SPREADSHEET DATA

Aeronautical Radionavigation Radar

	RSEC-D	
F_0	2844.4	MHz
P_p	91.500	dBm

	(t) Pulse Width or Sub-Pulse Width (u sec)	(t_r) Pulse Rise/ Fall time (u sec)	(B_c) Chirp Band width (MHz)	(B_d) Frequency Deviation	(N) Number of Chips	(PRR) Pulse Repetition Rate (PPS)	(F_L) Lowest Channel Frequency (MHz)	(F_H) Highest Channel Frequency (MHz)
1	0.6	0.05	NA	NA	1	1040	NA	NA
2	0.6	0.05	NA	NA	1	1040	NA	NA

	(B_s) Frequency Hopping Range (MHz)	(P_t) Maximum Spectral Power Density (dBm/kHz)	(d)** Compress-sion Ratio (no units)	(PG) Processing Gain	$(B_n(-20))$ Necessary Bandwidth (MHz)	B(-40) Bandwidth (MHz)	(S)* Slope (dB/dec)	(X(dB)) Floor Level of Mask(dB)
1	0	27.195	NA	0.000	10.335	35.796	40	80
2	0.6	27.195	NA	0.000	10.335	35.796	80	80



Mask 1: , t=0.6, tr=0.05, Bc=NA, d=NA, Bc=NA, N=1, PRR=1040, FL=NA, FH=NA, Bs=0, Pt=27.233, PG=0., Bn(-20)=10.335, B(-40)=35.796, S=40., X(dB)=80.