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Bandwidth Dependence of Emission Spectra of Selected Pulsed-CW Radars

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BANDWIDTH DEPENDENCE OF EMISSION SPECTRA OF SELECTED PULSED-CW RADARS

Frank H. Sanders[1]

This technical memorandum describes measurements of the radiated emission spectra of selected maritime radiolocation radar transmitters in multiple bandwidths. The results support published criteria for selection of measurement bandwidths for emission spectra of non-FM pulsed-CW radars. This result complements the radar spectrum engineering criteria (RSEC) measurement procedures described in NTIA Report TR-05-420.

Key words: radar emission measurement bandwidths; radar emission measurement techniques; radar emissions; radar spectrum engineering criteria (RSEC); spectrum measurements

1 INTRODUCTION

Radar transmitter out-of-band and spurious emissions (together called unwanted emissions) are limited by regulations. Some emission masks (such as the NTIA radar spectrum engineering criteria (RSEC)) are specified in terms of amplitude suppression relative to the peak power produced at the radars' fundamental frequencies (e.g., spurious emission suppression must be at least 60 dB below the fundamental power). Mask-compliance limits are computed on the basis of theoretically perfect emissions plus a margin that allows for realistic transmitter performance.

Compliance with radar emission masks is determined through measurements. 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. This presents a problem for determining radar emission mask-compliance by measurements.

An ideal peak-detected spectrum measurement result for a non-FM pulsed-CW radar transmitter is shown in Figure 1. Power measured at the fundamental frequency (far left) varies as $20 \log(B_m)$, but maximizes when B_m exceeds the values recommended in published literature [1-2] and reproduced in Table 1. In contrast, the measured power in the rest of the spectrum (the unwanted-emission region) climbs arbitrarily high as B_m increases. As a result, the difference between power values measured at the fundamental frequency versus other frequencies (reading between the left and right sides of Figure 1) *decreases* if B_m is greater than the values recommended in Table 1.

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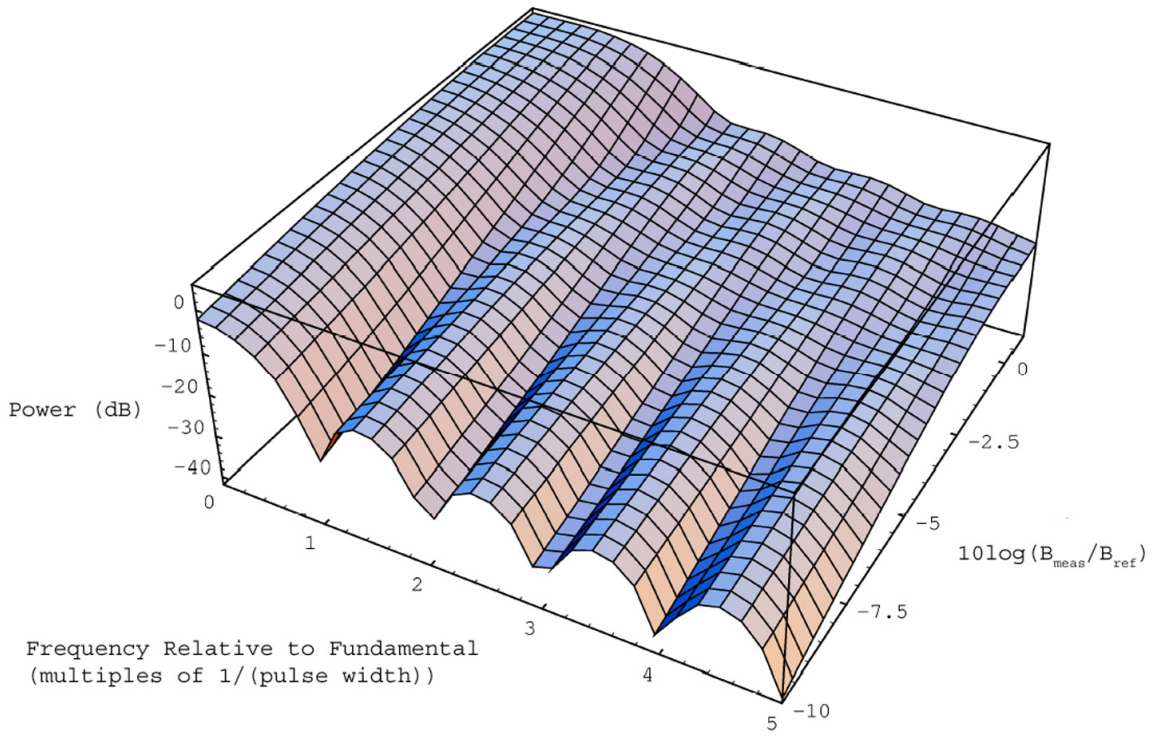

Figure 1. Graphical theoretical representation of the measured power at a radar fundamental frequency versus power measured at other frequencies as measurement bandwidth changes. The modeled radar emission modulation is non-FM pulsed-CW.

This report addresses this issue by describing spectrum measurements on two maritime radiolocation (surface search and navigation) radars in the band 2,900-3,100 MHz and three maritime surface search radars in the band 8,500-10,500 MHz. The purpose of the measurements was to observe the variation of unwanted emission levels of these radars relative to the measured fundamental level as a function of B_m, so as to provide a check on the validity of B_m values recommended for measurement of emissions from non-FM pulsed-CW radars shown in Table 1.

Table 1. Published Emission Spectrum Measurement Bandwidth, B_m (from [1-2])

Radar Modulation Type	**RSEC Measurement Bandwidth (B_m)**
Non-FM pulsed-CW and phase-coded pulsed	$B_m \leq (1/t)$, where t = emitted pulse duration (50% voltage) or phase chip (sub-pulse) duration (50% voltage)
FM-pulsed (chirped)	$B_m \leq (Bc/t)^{1/2}$, where Bc = frequency sweep range during each pulse and t = emitted pulse duration (50% voltage)
CW	B_m = 1 kHz
FM/CW	B_m = 1 kHz
Phase-coded CW	$B_m \leq (1/t)$, where t = emitted phase-chip duration (50% voltage)
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 measurement.

2 APPROACH

The pair of 2,900-3,100 MHz maritime radars used in these measurements were provided by the government of Japan and were measured jointly by Japan and the United States (NTIA) at the Table Mountain radio quiet zone facility north of Boulder, CO. Two of the 8,500-10,500 MHz radars were also provided by Japan and were likewise measured jointly at Table Mountain. The third 8,500-10,500 MHz radar was the property of NTIA and was measured at Table Mountain on a different occasion. The 2,900-3,100 MHz radars were designated S-Band Radars 1 and 2, and the 8,500-10,500 MHz radars were designated X-Band Radars 1, 2, and 3, respectively.

The radars were set up with antenna heights of about 3 m above the ground. The measurement antenna was a 1-m parabolic unit mounted about 4 m above the ground. Radiated measurements were performed in conformance with published procedures [1-2]. The measurement system block diagram is shown in Figure 2. The S-Band radars and X-Band Radars 1 and 2 were all measured in two bandwidths; X-Band Radar 3 was measured in four bandwidths. Pulse widths of these radars are shown in Table 2.

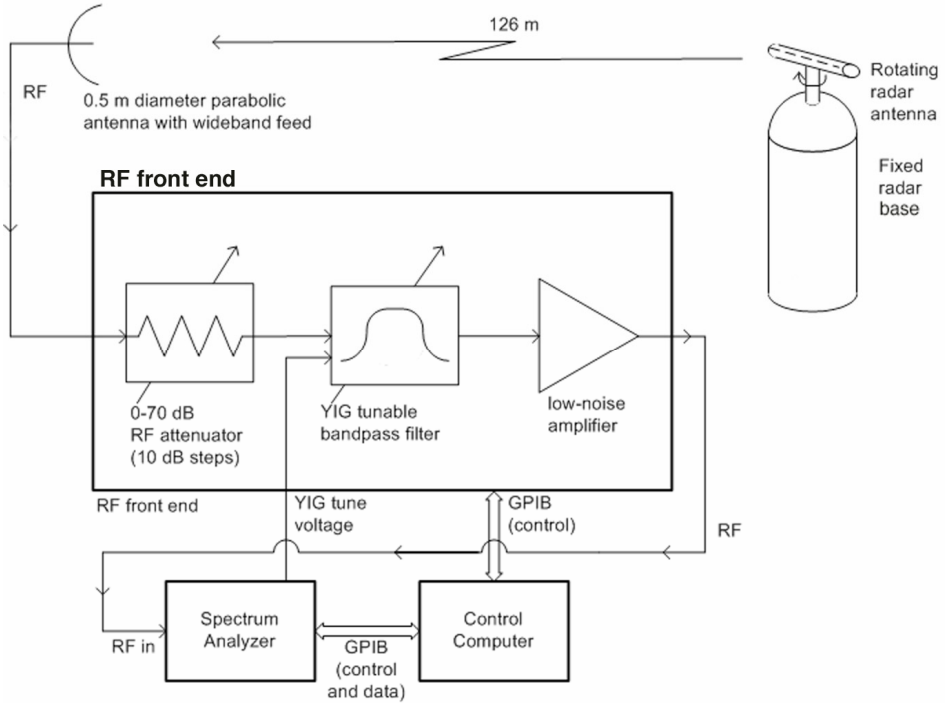

Figure 2. Block diagram of the radar emission measurement system. The spectrum analyzer was an Agilent E-4440A; the RF front end was custom-built by NTIA/ITS.

Table 2. Emission Characteristics of Radars in this Study

Radar Designator	Pulse width, t (ns)	Maximum recommended measurement bandwidth, 1/t from [1-2] (MHz)
S-Band Radar 1	60	16.7
S-Band Radar 2	70	14.3
X-Band Radar 1	70	14.3
X-Band Radar 2	60	16.7
X-Band Radar 3	80 and 800	12.5 and 1.25, respectively

3 RESULTS AND ANALYSIS

The results for S-Band Radars 1 and 2 are shown in Figures 3-6. The results for X-Band Radars 1 and 2 are shown in Figures 7-10. Because the bandwidths used for the measurements on these radars were always equal to or less than (1/pulse width), as specified in Table 1, the resulting spectra maintain the same ratios between the power measured at the fundamental frequencies and the power measured in the out of band and spurious parts of the spectra. This is demonstrated in Figures 4, 6, 8, and 10, where the maximum measured power levels at the radar fundamental frequencies are normalized and the emission spectra are observed to overlie each other.

The measured emission spectra for short-pulse and long-pulse radar modes of X-Band Radar 3 are shown in Figures 11 and 12. Measurement system internal noise occurs as flat floors at frequencies between 7,300-8,000 MHz and 11,000-11,200 MHz.

Figure 13 shows measured power at the X-Band Radar 3 fundamental frequency (approximately 9410 MHz) as a function of measurement IF bandwidth. The data in this figure confirm that the radar fundamental power varies as 20 log(B_m) for values of B_m that are equal to or less than (1/t), where t is the radar pulse width.

Figure 14 shows the spectra of X-Band Radar 3 normalized to the same power level at the fundamental frequency in short-pulse (80-ns) mode. In this mode, the 80 ns 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 bandwidths that were used, including 8 MHz.

Figure15 shows the spectra of X-Band Radar 3 normalized to the same power level at the fundamental frequency in long-pulse (800-ns) mode. In this case, the 3-dB emission bandwidth is predicted to be 1.25 MHz. The 300-kHz and 1-MHz spectra are identical to each other, because these bandwidths (which are less than (1/t)=1.25 MHz) meet the requirements of Table 1. But the 20 log(B_m) progression ceases for B_m values of 3 MHz and 8 MHz; consequently these spectra show higher levels of unwanted emissions relative to the power measured at the fundamental. This effect could cause the radar spectrum to (falsely) appear to fail to meet an emission mask limit if it were measured in these bandwidths for that purpose. Thus such bandwidths would be incorrect choices for emission mask compliance measurements in the long pulse mode, even though they would be acceptable choices for this radar in the short pulse mode.

The data in Figure 14 demonstrate an additional benefit that accrues from using measurement bandwidths that match the values of Table 1: the greatest dynamic range occurs in the spectrum measurements when the bandwidth limits of Table 1 are used. This effect is observed in the offsets of the measurement system noise floors of the normalized data traces between 7300-8000 MHz in that figure. Achieving wide measurement dynamic range is an important consideration in emission mask compliance requirements that may specify unwanted emission suppression levels of 80 dB relative to the maximum power at the fundamental frequency, and which therefore require at least 90 dB of dynamic range in the measurement system. Use of the best-matched measurement bandwidth is an easy and effective way to boost dynamic range without incurring extra engineering costs on the measurement system.

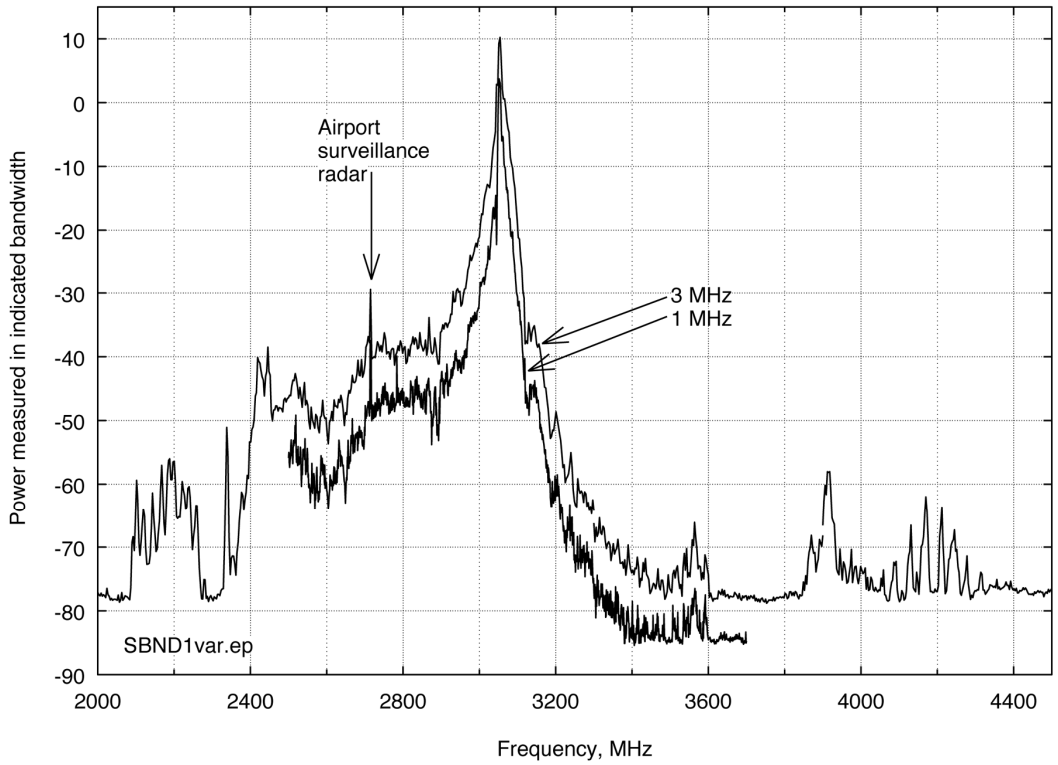

Figure 3. S-Band Radar 1 measured in 1-MHz and 3-MHz bandwidths.

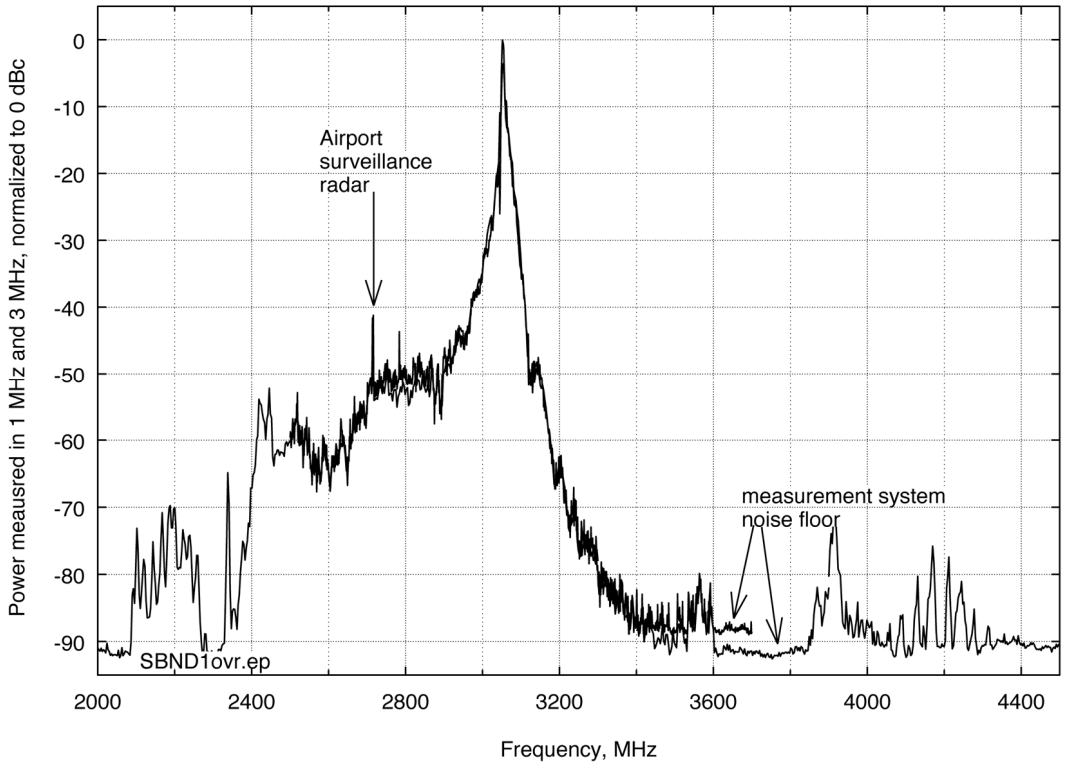

Figure 4. S-Band Radar 1 emission spectra with the 1-MHz and 3-MHz data normalized to 0 dB at the fundamental. Either bandwidth could be used for an emission mask measurement, but the 3-MHz data could be collected three times faster than 1-MHz data.

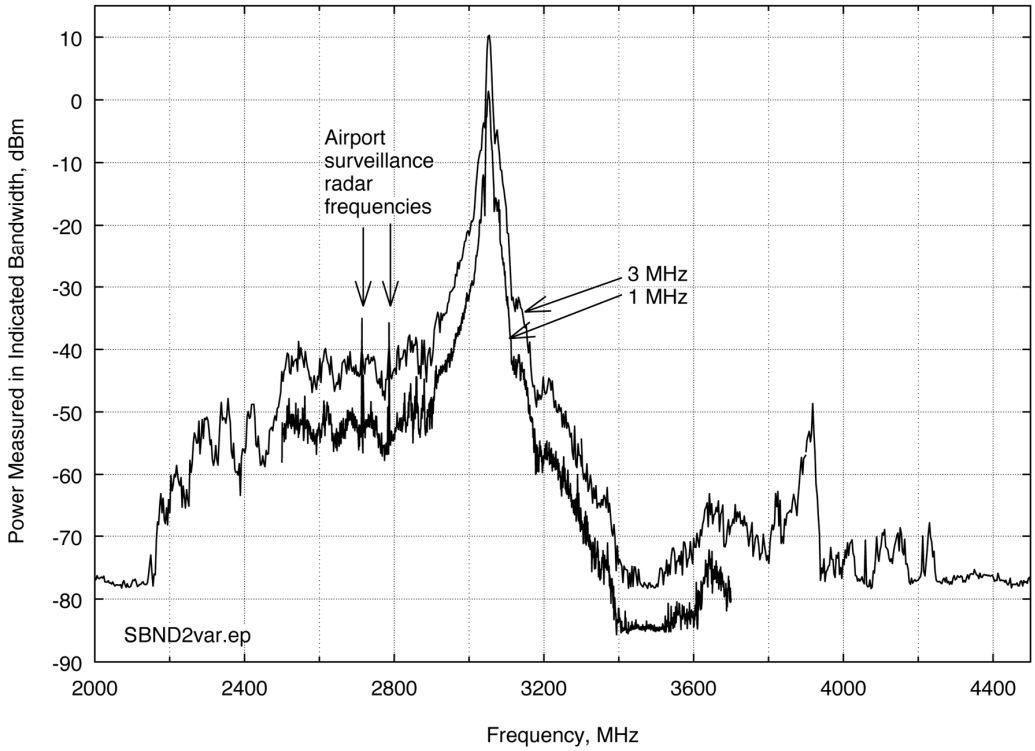

Figure 5. S-Band Radar 2 measured in 1-MHz and 3-MHz bandwidths.

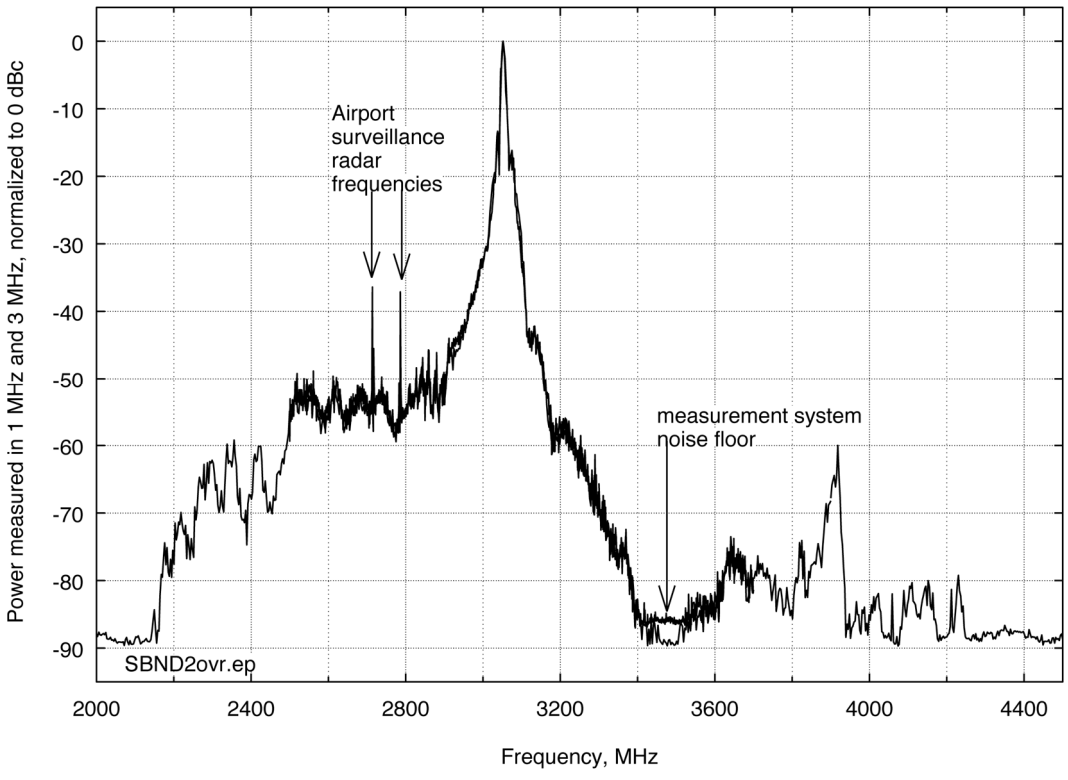

Figure 6. S-Band Radar 2 emission spectra with the 1-MHz and 3 MHz data normalized to 0 dB at the fundamental. Either bandwidth could be used for an emission mask measurement, but the 3-MHz data could be collected three times faster than 1-MHz data.

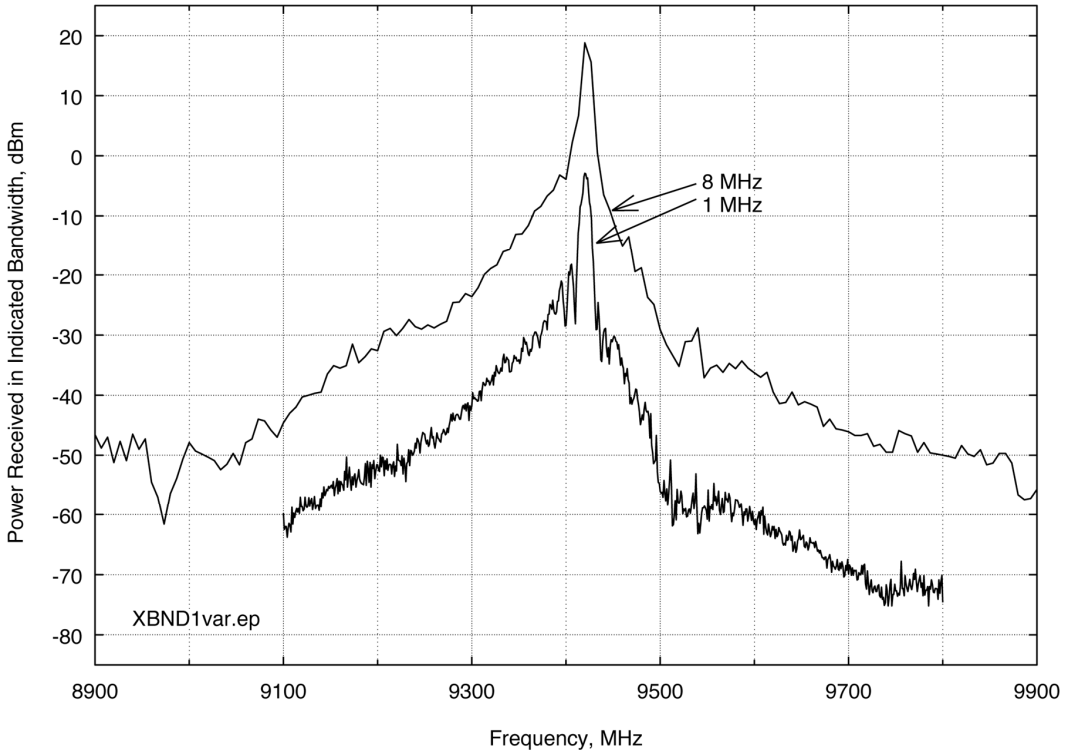

Figure 7. X-Band Radar 1 measured in 1-MHz and 8-MHz bandwidths.

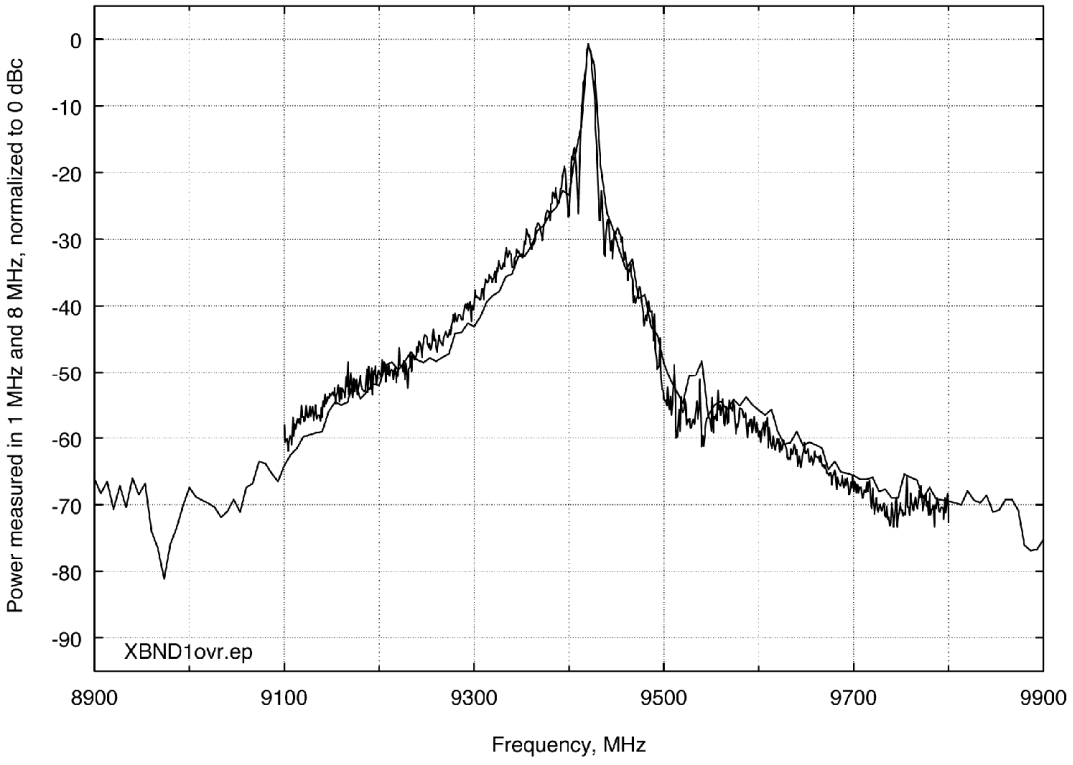

Figure 8. X-Band Radar 1 emission spectra with the 1-MHz and 8-MHz data normalized to 0 dB at the fundamental. Either bandwidth could be used for an emission mask measurement, but the 8-MHz data could be collected eight times faster than 1-MHz data.

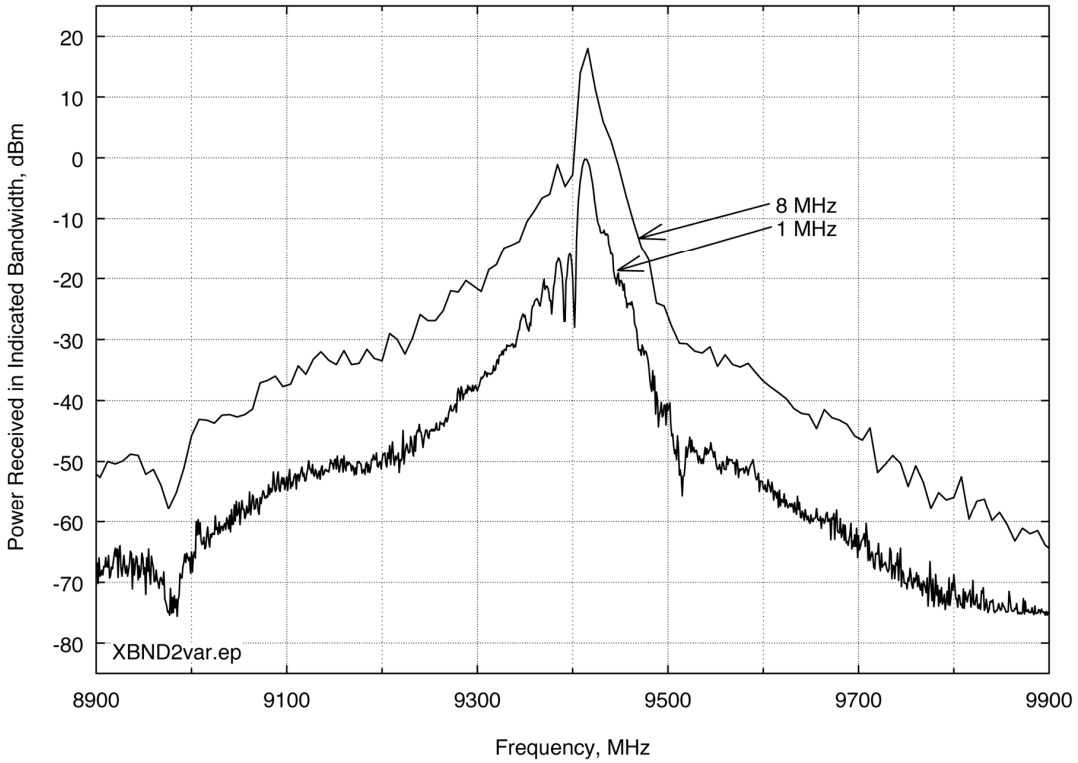

Figure 9. X-Band Radar 2 measured in 1-MHz and 8-MHz bandwidths.

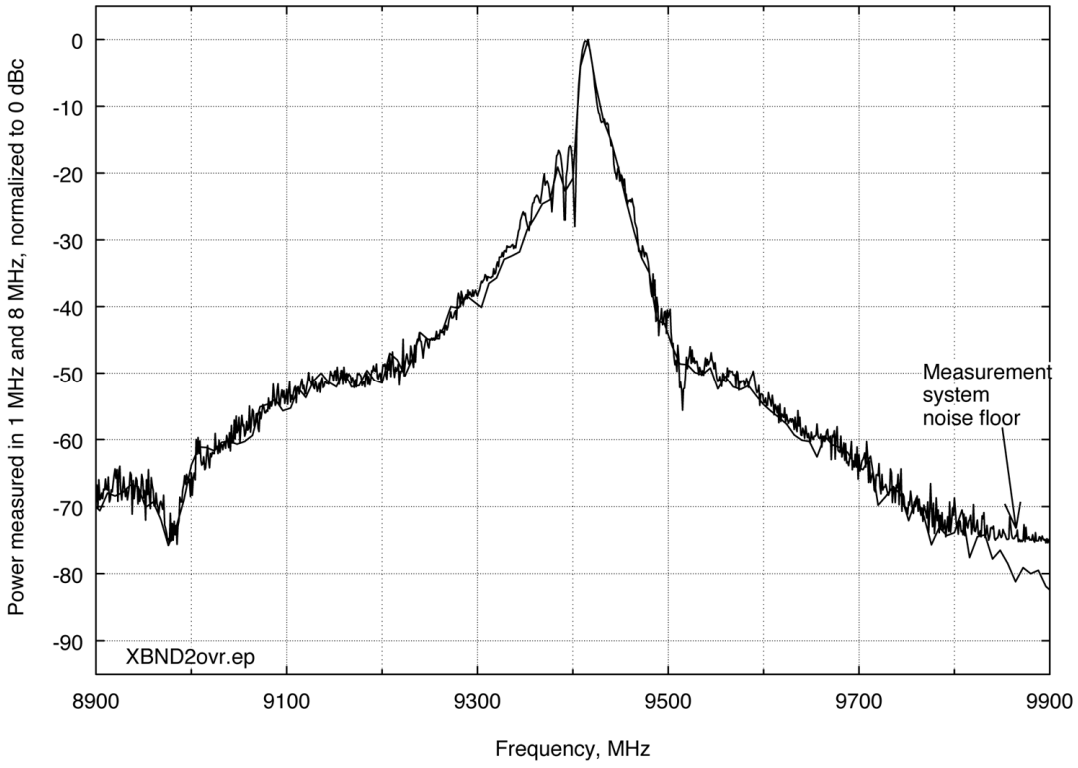

Figure 10. X-Band Radar 2 emission spectra with the 1-MHz and 8-MHz data normalized to 0 dB at the fundamental. Either bandwidth could be used for an emission mask measurement, but the 8-MHz data could be collected eight times faster than 1-MHz data.

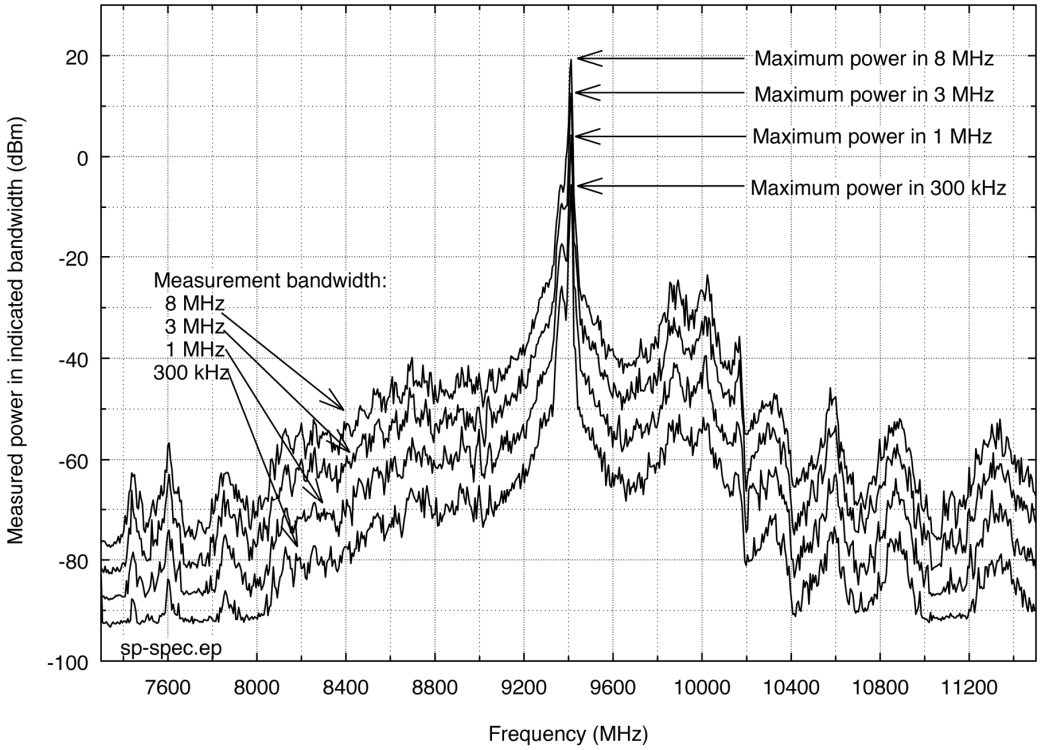

Figure 11. X-Band Radar 3 emission spectrum measured in four bandwidths with transmitter operating in short-pulse (80 ns) mode.

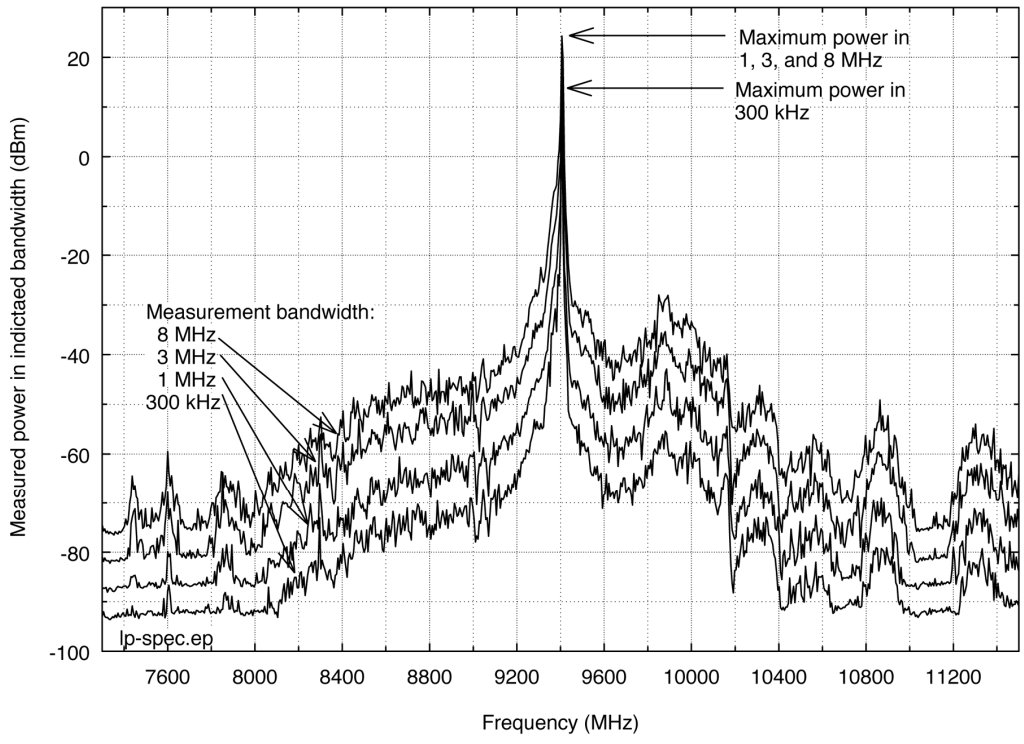

Figure 12. X-Band Radar 3 emission spectrum measured in four bandwidths with transmitter operating in long-pulse (800 ns) mode.

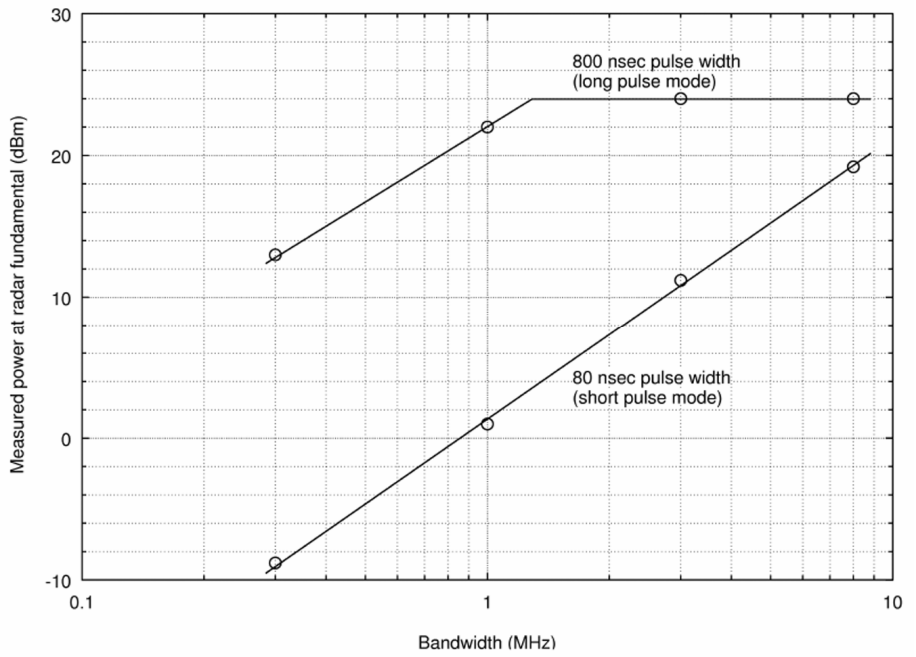

Figure 13. Measured power at the X-Band Radar 3 fundamental frequency as a function of bandwidth and pulse mode. In accordance with Table 1, any of the indicated bandwidths may be used to measure emissions in the short-pulse mode, but only bandwidths of about 1 MHz or less should be used to measure the long-pulse mode for verification of emission mask compliance.

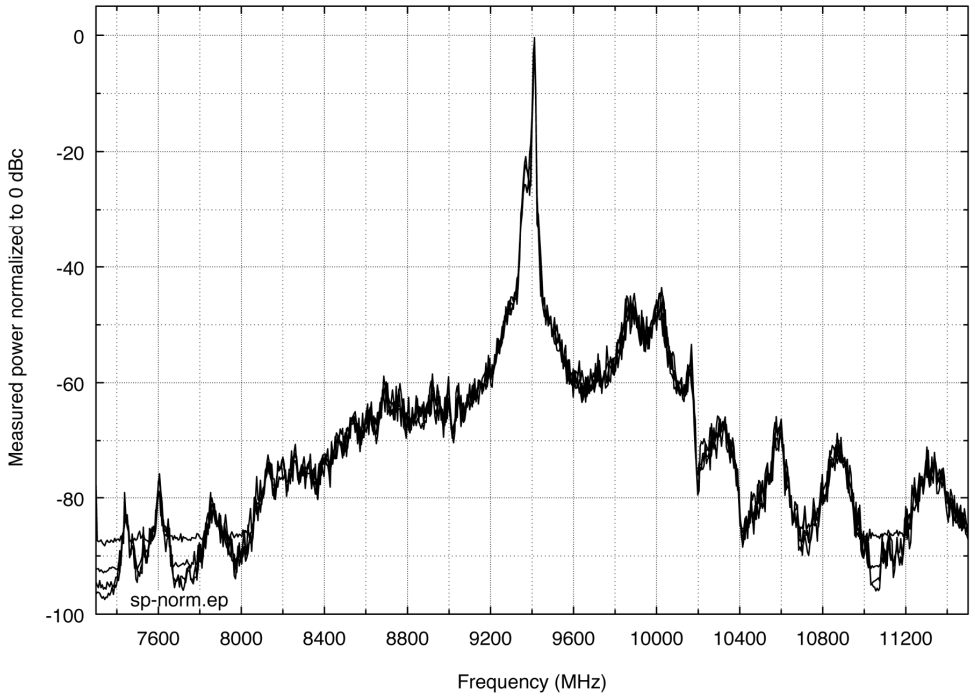

Figure 14. Normalized short-pulse emission spectra of X-Band Radar 3 as measured in 300 kHz, 1 MHz, 3 MHz, and 8 MHz (from Figure 11), with the fundamental frequency maxima of all four spectra set to 0 dB. The normalized spectra are nearly identical within the uncertainty of the measurement; any of these bandwidths may be used to correctly measure the radar spectrum.

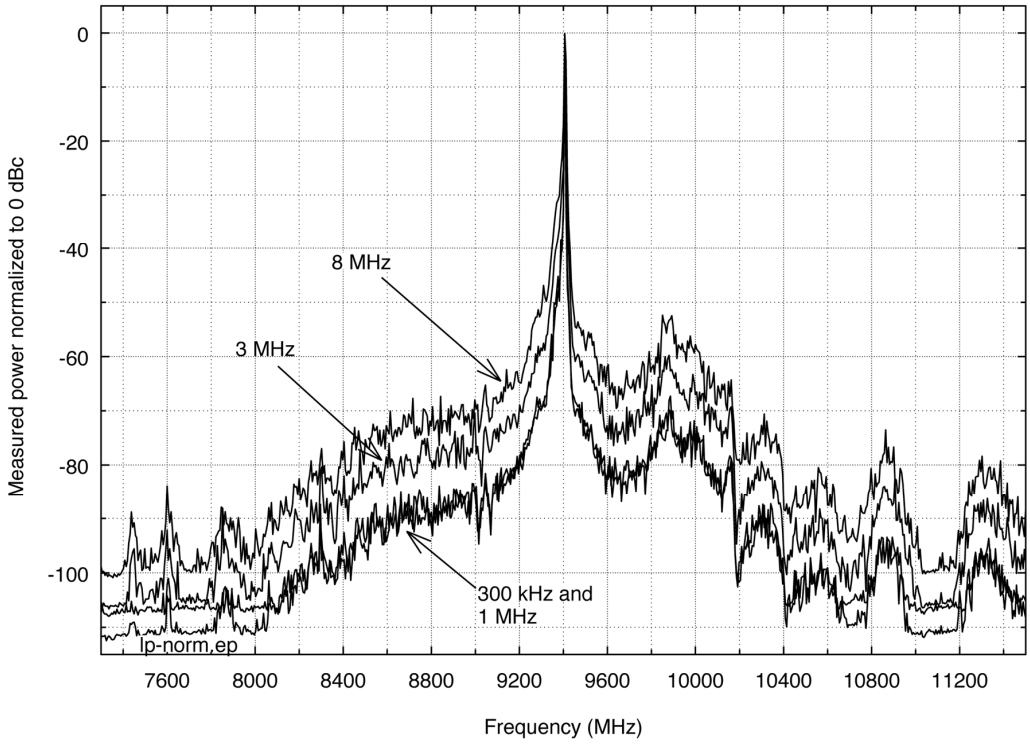

Figure 15. Normalized long-pulse emission spectra of X-Band Radar 3 as measured in 300 kHz, 1 MHz, 3 MHz, and 8 MHz (from Figure 12), with the fundamental frequency maxima of all four spectra set to 0 dB.

4 SUMMARY AND CONCLUSIONS

In summary, measurements of unwanted (spurious and out-of-band) emissions from five different non-FM pulsed-CW maritime radars are shown to yield the same results regardless of the value of B_m provided that B_m is less than (1/t), as recommended in Table 1. Time and effort can be saved in such measurements without sacrificing the accuracy of results if measurements are performed in the widest possible bandwidth that is still less than (1/t). For example, a measurement in 8 MHz will take 1/8 as long as a measurement in 1 MHz and will be just as accurate, provided that the radar pulse width is less than (1/(8 MHz)) = 125 ns.

When measurement bandwidths are wider than the values in Table 1 for non-FM pulsed-CW emissions, it is demonstrated that the measured levels of unwanted emissions are higher relative to the fundamental emission level than when they are measured in bandwidths that conform with the requirements of Table 1; such bandwidths should not be used for emission mask compliance measurements on such radars.

Maximum measurement dynamic range is demonstrated to occur when the measurement system bandwidth equals the bandwidth limits of Table 1. This is an important consideration when emission mask compliance requirements are 80 dB lower than the maximum power at the radar fundamental, and the measurement system must therefore achieve a dynamic range of at least 90 dB. Using the best-matched measurement bandwidth maximizes the measurement dynamic range without incurring extra engineering costs in the measurement system (such as reducing system noise with a higher-performance low-noise amplifier at the RF front end).

It is noted in passing that 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 that is not entirely predictable on theoretical grounds [1]. Therefore, measurement of emission spectra in multiple bandwidths, as shown for example in Figures 11 and 12, is recommended until this phenomenon is better understood.

5 REFERENCES

[1] F.H. Sanders, R.L. Hinkle, and B.J. Ramsey, "Measurement procedures for the radar spectrum engineering criteria (RSEC)," NTIA Report TR-05-420, Mar. 2005.

[2] ITU-R Recommendation M.1177-3, "Techniques for measurement of unwanted emissions of radar systems," International Telecommunication Union, Radiocommunication Sector, 2003.