Step Frequency Ground Penetrating Radar Characterization and Federal Evaluation Tests

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Research, Development, and Technology
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FOREWORD

The objective of this report is to provide a comprehensive emissions characterization and evaluation of a step frequency ground penetrating radar (SF GPR) system. These study results will help officials determine whether SF GPR can be operated safely, that is, without interfering with other tools, in a proposed configuration that may include frequency notching in specific frequency bands. The final system configuration results present evidence that the SF GPR system will work without interfering with other systems. This report provides detail and raw data for all the tests so that decisionmakers may make their own evaluations of the data.

Joseph Peters
Director, Office of Operations
Research and Development

TECHNICAL REPORT DOCUMENTATION PAGE

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16. Abstract
A step frequency ground penetrating radar (SF GPR) system was characterized and evaluated to determine whether it can be operated safely in a proposed configuration that may include frequency notching in specific frequency bands. This emission testing was conducted with possible notching configurations turned on and then turned off to allow for both scenarios to be evaluated. Testing work focused on emissions characterization measurements suitable for computer analysis of potential interference with relevant systems. After initial testing was completed, needs for follow-up testing were defined. This follow-up testing was completed, and results are included in this report.

Results from initial emissions testing showed that the SF GPR met National Telecommunications and Information Administration (NTIA) criteria for most frequencies, but some emissions frequencies still exceeded NTIA criteria. In addition, unintentional emissions below 140 MHz were observed to exceed intentional emission criteria at many frequencies. System adjustments were performed, and follow-up emissions testing was conducted using a final system configuration. The final system configuration met NTIA criteria for intentional emissions as described in the report. Unintentional emissions below 140 MHz were characterized to allow them to be evaluated as needed.

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SI* (MODERN METRIC) CONVERSION FACTORS

APPROXIMATE CONVERSIONS TO SI UNITS

Symbol	When You Know	Multiply By	To Find	Symbol
		LENGTH		
in	inches	25.4	millimeters	mm
ft	feet	0.305	meters	m
yd	yards	0.914	meters	m
mi	miles	1.61	kilometers	km
		AREA		
in^2	square inches	645.2	square millimeters	mm^2
ft^2	square feet	0.093	square meters	m^2
yd^2	square yard	0.836	square meters	m^2
ac	acres	0.405	hectares	ha
mi^2	square miles	2.59	square kilometers	km^2
		VOLUME		
fl oz	fluid ounces	29.57	milliliters	mL
gal	gallons	3.785	liters	L
ft^3	cubic feet	0.028	cubic meters	m^3
yd^3	cubic yards	0.765	cubic meters	m^3
		NOTE: volumes greater than 1000 L shall be shown in m^3		
		MASS		
oz	ounces	28.35	grams	g
lb	pounds	0.454	kilograms	kg
T	short tons (2000 lb)	0.907	megagrams (or "metric ton")	Mg (or "t")
		TEMPERATURE (exact degrees)		
^oF	Fahrenheit	5 (F-32)/9 or (F-32)/1.8	Celsius	^oC
		ILLUMINATION		
fc	foot-candles	10.76	lux	lx
fl	foot-Lamberts	3.426	candela/m^2	cd/m^2
		FORCE and PRESSURE or STRESS		
lbf	poundforce	4.45	newtons	N
lbf/in^2	poundforce per square inch	6.89	kilopascals	kPa

APPROXIMATE CONVERSIONS FROM SI UNITS

Symbol	When You Know	Multiply By	To Find	Symbol
		LENGTH		
mm	millimeters	0.039	inches	in
m	meters	3.28	feet	ft
m	meters	1.09	yards	yd
km	kilometers	0.621	miles	mi
		AREA		
mm^2	square millimeters	0.0016	square inches	in^2
m^2	square meters	10.764	square feet	ft^2
m^2	square meters	1.195	square yards	yd^2
ha	hectares	2.47	acres	ac
km^2	square kilometers	0.386	square miles	mi^2
		VOLUME		
mL	milliliters	0.034	fluid ounces	fl oz
L	liters	0.264	gallons	gal
m^3	cubic meters	35.314	cubic feet	ft^3
m^3	cubic meters	1.307	cubic yards	yd^3
		MASS		
g	grams	0.035	ounces	oz
kg	kilograms	2.202	pounds	lb
Mg (or "t")	megagrams (or "metric ton")	1.103	short tons (2000 lb)	T
		TEMPERATURE (exact degrees)		
^oC	Celsius	1.8C+32	Fahrenheit	^oF
		ILLUMINATION		
lx	lux	0.0929	foot-candles	fc
cd/m^2	candela/m^2	0.2919	foot-Lamberts	fl
		FORCE and PRESSURE or STRESS		
N	newtons	0.225	poundforce	lbf
kPa	kilopascals	0.145	poundforce per square inch	lbf/in^2

*SI is the symbol for the International System of Units. Appropriate rounding should be made to comply with Section 4 of ASTM E380.
(Revised March 2003)

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LIST OF ABBREVIATIONS

3D	Three-dimensional
ASR-11	Airport surveillance radar release 11
dB	decibel
dBm	decibels relative to 1 milliwatt
EIRP	Equivalent isotropic radiated power
FAA	Federal Aviation Administration
FCC	Federal Communications Commission
FHWA	Federal Highway Administration
GHz	Gigahertz (10^9 hertz)
GPS	Global positioning system
GPS L1	Global positioning system down link frequency 1
kHz	Kilohertz (10^3 hertz)
MHz	Megahertz (10^6 hertz)
MMIC	Monolithic microwave-integrated circuit
NTIA	National Telecommunications and Information Administration
NTIA SPS	NTIA Spectrum Planning Subcommittee
RBW	Resolution bandwidth
SF GPR	Step frequency ground penetrating radar
VBW	Video bandwidth
SARSAT	Search And Rescue Satellite-Aided Tracking
RF	Radio frequency
RMS	Root mean squared
USDOT	United States Department of Transportation

EXECUTIVE SUMMARY

Step frequency ground penetrating radar (SF GPR) technology offers unprecedented subsurface three-dimensional (3D) imaging capabilities. Subsurface material deterioration, void imaging, and precise material and geometry measurements of civil infrastructure are all accurately and efficiently carried out using this specialized technology. Through previous evaluations and reports, the Federal Highway Administration (FHWA) has determined that SF GPR can be applied to subsurface infrastructure evaluation problems to meet needs in the national interest.[1,2] In addition to infrastructure applications described in these reports, it is notable that land mines, runway pavements, and buried historic sites can be imaged using SF GPR technology.

Due to SF GPR operating principles, system emissions testing is required to support an FHWA/United States Department of Transportation (FHWA/USDOT) application for a National Telecommunications and Information Administration (NTIA) Stage 3 (developmental) and NTIA Stage 4 (operational) certificate of spectrum support under NTIA rules for out-of-band operations. This testing is described in this report along with a proposed coordination procedure between NTIA and system users to ensure appropriate system operation. Results of the emissions testing indicate that the system can operate safely without violating emissions criteria in Annex K of the *Manual of Regulations and Procedures for Federal Radio Frequency Management*.[3]

SF GPR emissions tests were conducted by Federal Aviation Administration (FAA) staff at the FAA Technical Center in New Jersey during the week of March 9, 2009. The emissions tests used a standardized test configuration across a measurement spectrum from 50 MHz to 6 GHz. These tests characterized SF GPR emissions relative to an emissions mask defined by NTIA rules (described in detail in the background section of this report). Tests included general measurements that covered the full range of operating frequencies of the SF GPR and detailed emission measurements in narrow frequency ranges corresponding to specific Federal systems identified by NTIA. Based on initial results from these SF GPR emissions tests, needs for follow-up testing were defined. Follow-up data are included in appendix C of this report. The data were collected by a Federal Communications Commission (FCC)-certified emissions test laboratory after final tuning changes were made to reduce emissions at specific frequencies. This test laboratory also produced a test report based on collected emissions data (see appendix E).

INTRODUCTION

Potential interference testing of an FHWA/USDOT SF GPR system was conducted by FAA staff at the FAA Technical Center in New Jersey during the week of March 9, 2009. The testing was designed to evaluate whether SF GPR can be operated safely in a proposed configuration that may include frequency notching in specific frequency bands. Testing was conducted with all notches turned on and then with all notches turned off to allow for both scenarios to be evaluated. Testing focused on emissions characterization measurements suitable for computer analysis of potential interference with relevant systems.

Data from SF GPR emissions testing described and summarized in this report are expected to be used to determine whether FHWA/USDOT SF GPR meets NTIA criteria. An initial data analysis is provided in this report. Electronic test data are also provided with this report to the NTIA Spectrum Planning Subcommittee (SPS) for further analysis by individual Federal agencies as needed.

In addition, follow-up SF GPR emissions test data were collected in September 2009 at an FCC-certified laboratory after the SF GPR was fine-tuned to reduce emissions at specific frequencies (based on results from the initial March 2009 emissions tests). Data from this follow-up testing are presented in appendix C, and a test report produced by the certified test laboratory is presented in appendix E.

OBJECTIVE

Initially, SF GPR emission characterization measurements were conducted to achieve the following primary objectives:

- Evaluate SF GPR capabilities to meet SPS requirements for operation under NTIA rules for out-of-band operations.
- Measure emissions from a proposed SF GPR configuration with the frequency spectrum notching off and analyze data to evaluate potential interference issues relative to critical Federal systems.
- Measure emissions from a proposed SF GPR configuration with the frequency spectrum notching on and analyze data to evaluate potential interference issues relative to critical Federal systems.
- Measure emissions relative to individual notches anticipated to be implemented based on proximity to relevant facilities.

Data collected at the FAA Technical Center in March 2009 indicated that follow-up measurements were needed to achieve the objectives listed above (with minor revisions) and to evaluate the SF GPR in greater detail at low frequencies.

The revised objectives for the follow-up measurements were as follows:

- Evaluate SF GPR capabilities to meet SPS requirements for operation under NTIA rules for out-of-band operations.
- Measure emissions from a proposed SF GPR configuration with the frequency spectrum notching off and analyze data to evaluate potential interference issues relative to critical Federal systems.
- Measure emissions from a proposed SF GPR configuration with the frequency spectrum notching on and analyze data to evaluate potential interference issues relative to critical Federal systems. Three options for frequency spectrum notching configurations were defined and tested, A1, A2, and A3, and are presented in the background section.
- Collect detailed emissions data at frequencies from 50 to 200 MHz to evaluate system performance in this low frequency range.

In addition, a coordination procedure was proposed to provide a framework for system users to operate SF GPR responsibly under NTIA rules. The proposed coordination procedure is described in detail in appendix A.

BACKGROUND

This section provides a brief description of SF GPR technology, system emission characteristics, and emissions limits under NTIA rules.

Capabilities of FHWA/USDOT SF GPR are made possible by efficient techniques used to transmit and receive radar energy and subsequently store and process the corresponding data. Proposed SF GPR output signal characteristics are presented in figure 1.

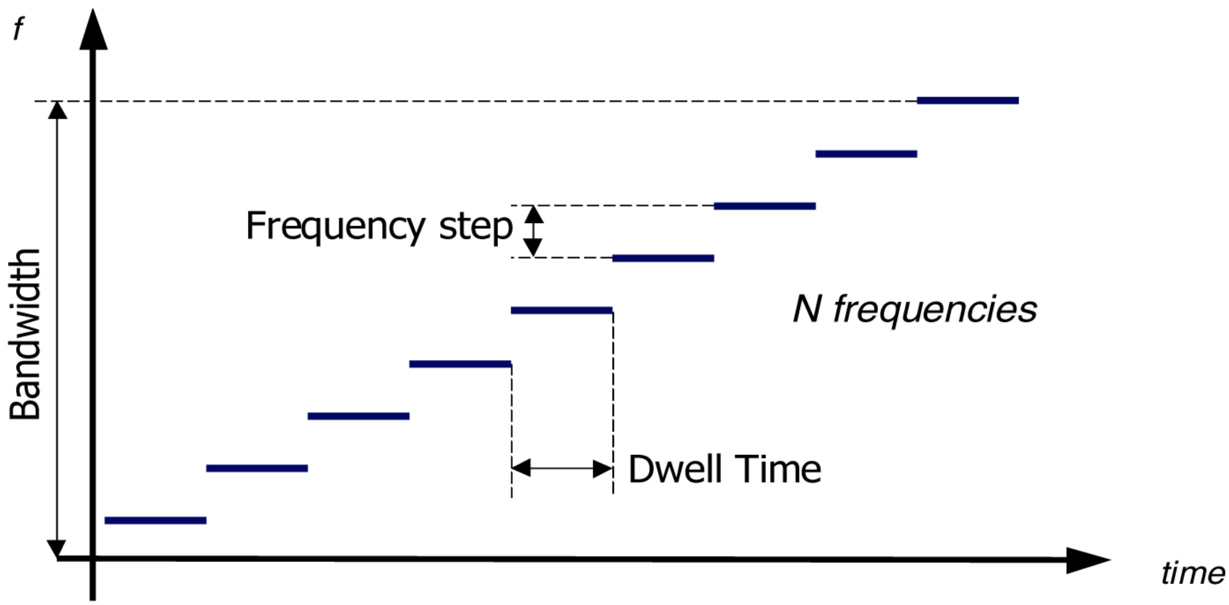


Figure 1. Chart. SF GPR emissions and their characteristics.

SF GPR signal output consists of continuous sine waves transmitted at a series of discrete frequencies during programmed dwell times. Frequency domain data collected by the receiver antenna are subsequently transformed into the time domain for display as range profiles and are later processed with data from many antenna array elements to produce tomographic images.

In order to accurately image subsurface defect and deterioration features such as cracks and voids in concrete, asphalt, and other civil engineering materials, SF GPR must have high range resolution and cross-range resolution capabilities. SF GPR resolution is directly dependent on the operating bandwidth of the system. Broad frequency availability is necessary to achieve the high resolution required to image features such as cracks, voids, and reinforcing steel. Operating parameters of the SF GPR system under test include the following:

- Frequency step = 2 MHz.
- Dwell time = 2.5 μs.
- Bandwidth = 140–3,000 MHz.
- Cycle time (single antenna element cycling through all frequencies) = 3.58 ms.

EMISSIONS MASK

Providing adequate bandwidth to accurately image features such as subsurface cracks, voids, and reinforcing steel is anticipated to require a system that complies with the recommended emission mask presented in table 1 and table 2. The tables specify maximum back lobe emissions because SF GPR equipment is operated with the antenna directed at the ground; unintentional emissions into the air will always be back lobe emissions. For instances where an SF GPR was used on a bridge deck that vehicles traveled under, calculations were made to determine the attenuation of the radar energy that propagated through the bridge deck. The internal report *Step Frequency GPR (SF GPR) Transmission Loss Calculations Through a Typical Concrete Bridge Deck* (SPS-16371/1) provides transmission loss calculations for a typical concrete bridge deck, showing that emissions transmitted through the bridge deck are reduced below back lobe emission levels (see appendix F).

Table 1. Maximum back lobe equivalent isotropic radiated power (EIRP) levels for both peak and average power (1-MHz resolution bandwidth).[3]

Frequency (MHz)	Peak EIRP (dBm)	Average EIRP (dBm)
< 140	-60.7	-93.7
140–216	-25.7	-58.7
216–960	-23.2	-56.2
960–1,610	-32.3	-65.3
1,610–1,990	-20.3	-53.3
1,990–3,000	-18.3	-51.3
> 3,000	-53.3	-86.3

In addition to the radiated emission limits specified in table 1, SF GPR was programmed to suppress emissions according to the limits in table 2.

Table 2. Emissions suppressed in specified bandwidths.[3]

Frequency (MHz)	Average EIRP (dBm) in 1 kHz Bandwidth
1,164–1,240	-75.3
1,559–1,610	-75.3

In addition to the recommended emissions mask in table 1 and table 2, notches that may be implemented in the recommended SF GPR emissions mask are summarized in table 3 through table 5. These notches correspond to frequencies of critical Federal systems that the NTIA SPS requested to include in SF GPR emissions testing. These frequencies are candidates for notching from the SF GPR emissions spectrum. One notch configuration, A1, was tested during initial testing, and all three notch configurations, A1, A2, and A3, were tested during follow-up testing. Regarding the practical implementation of notching configurations, they were accomplished by not transmitting at specific frequencies in the SF sequence (always generated sequentially within the SF GPR system). Therefore, the cycle time of the system remained constant for notched and unnotched configurations.

Table 3. Frequency notch configuration A1.

Frequency Range (MHz)	Purpose
161–174	Land mobile operations
328.6–335.4	Aeronautical radionavigation operations
406–406.1	SARSAT (Search And Rescue Satellite-Aided Tracking)
406.1–420	Land mobile operations
608–614	Radio astronomy
960–1,215	Aeronautical radionavigation operations
1,240–1,370	Aeronautical surveillance radars
1,559–1,610	Aeronautical radionavigation operations/global positioning system downlink frequency 1 (GPS L1)
1,400–1,427	Radio astronomy
1,660.5–1,668.4	Radio astronomy
2,025–2,110	Meteorological satellite
2,200–2,290	Aeronautical telemetry/space ground link sub/ satellite earth stations
2,290–2,300	Deep space network facility
2,700–2,900	Next generation weather/airport surveillance radar release 11(ASR-11)
2,900–3,000	Maritime radar

Table 4. Frequency notch configuration A2.

Frequency Range (MHz)	Purpose
328.6–335.4	Aeronautical radionavigation operations
406–406.1	SARSAT
608–614	Radio astronomy
960–1,215	Aeronautical radionavigation operations
1,240–1,370	Aeronautical surveillance radars
1,559–1,610	Aeronautical radionavigation operations/GPSL1
1,400–1,427	Radio astronomy
1,660.5–1,668.4	Radio astronomy
2,025–2,110	Meteorological satellite
2,200–2,290	Aeronautical telemetry/space ground link sub/ satellite earth stations
2,290–2,300	Deep space network facility
2,700–2,900	Next generation weather/ASR-11

Table 5. Frequency notch configuration A3.

Frequency Range (MHz)	Purpose
328.6–335.4	Aeronautical radionavigation operations
406–406.1	SARSAT
608–614	Radio astronomy
1,240–1,370	Aeronautical surveillance radars
1,559–1,610	Aeronautical radionavigation operations/GPSL1
1,400–1,427	Radio astronomy
1,660.5–1,668.4	Radio astronomy
2,025–2,110	Meteorological satellite
2,200–2,290	Aeronautical telemetry/space ground link sub/ satellite earth stations
2,290–2,300	Deep space network facility
2,700–2,900	Next generation weather/ASR-11

TEST DESIGN

SF GPR emissions characterization testing was conducted using the configuration shown in figure 2 and figure 3 and pictured in figure 4 and figure 5. The side view in figure 2 illustrates the maximum 9.84-ft (3-m) distance that was maintained between the SF GPR array under test and the emission measurement antennas. A biconic antenna was used to measure frequencies in the 50–299-MHz range, a log periodic antenna was used to measure frequencies in the 300–2,000-MHz range, and a horn antenna was used to measure frequencies in the 2,001–3,000-MHz range. Detailed make and model information for the test equipment is provided below. Figure 2 illustrates the seven angles that the SF GPR antenna array was aligned with for each test configuration to determine the orientation corresponding to maximum emissions. Due to antenna array symmetry, angles from 0 to 180 degrees were representative. As the test plan required, the antenna array was always directed at the ground and was suspended 10 inches (254 mm) above a standard sand pit.

Emission measurement equipment included the following:

- Agilent Technologies E4440 power spectrum analyzer.
- A.H. Systems, Inc. biconic antenna, model SAS-542, S/N 769 (9.84 ft (3 m)).
- A.H. Systems, Inc. log periodic antenna, model SAS-510-2, S/N 1053 (9.84 ft (3 m)).
- A.H. Systems, Inc. double ridge guide horn antenna, model SAS-571, S/N 549 (9.84 ft (3 m)).
- Electronic Cable Specialists cable P/N 310801 (two each at 6 ft (1.83 m) and one at 12 ft (3.66 m)).
- 3D Radar/Curtiss-Wright SF GPR system, model Geoscope GS3F.

The SF GPR system consists of a laptop computer, a rack mountable radar control unit, a 26.24-ft (8-m)-long cable bundle, and an antenna array that has 23 antenna elements (see figure 6).

The SF GPR emission characterization test procedure follows:

1. Measure ambient emissions to establish a baseline (50–6,000 MHz).
2. Position the SF GPR antenna array in each of the seven orientation angles (see figure 2).
3. Measure emissions from the SF GPR array using each of the three emission measurement antennas (biconic, log periodic, and horn) using the unnotched SF GPR emission spectrum for peak and root mean squared (RMS) measurements (50–6,000 MHz).
4. Determine SF GPR antenna array orientation corresponding to maximum emissions for the unnotched SF GPR emission spectrum configuration.

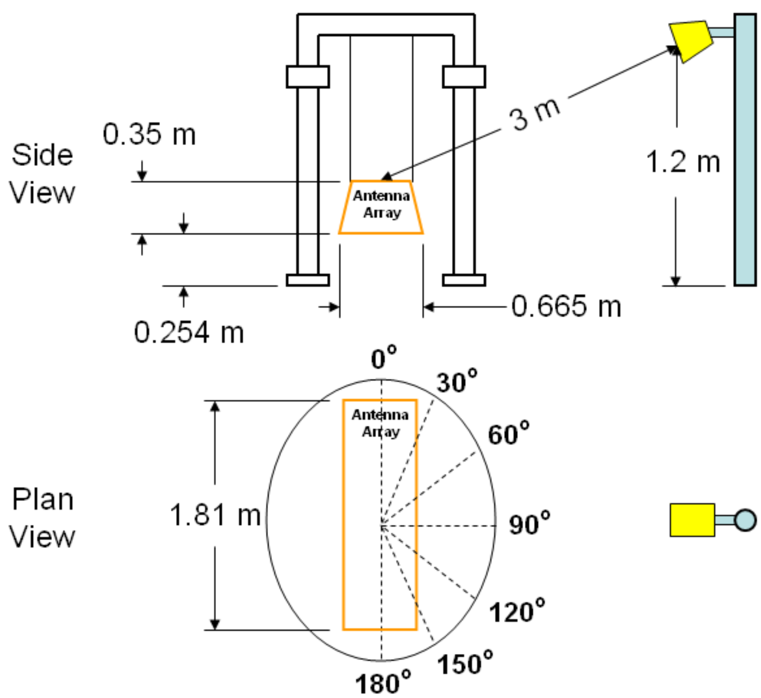
5. Measure the peak and RMS for the notched SF GPR emission spectrum with the SF GPR antenna array orientation corresponding to maximum emissions using each of the three emission measurement antennas (biconic, log periodic, and horn).

6. Collect the complete general measurement set by collecting data corresponding to the test matrix (see figure 15 and figure 16 in appendix B).

7. Make measurements to characterize SF GPR emissions in frequency bands corresponding to critical Federal systems. Make measurements for maximum emissions orientations of the SF GPR antenna array according to the test matrix (see figure 17 and figure 18 in appendix B).

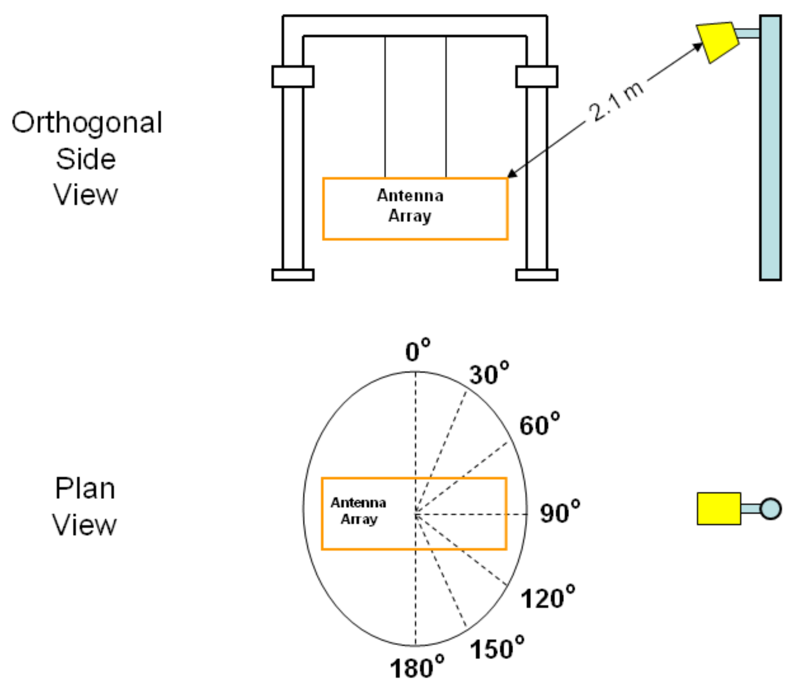
Maximum SF GPR emissions corresponding to the worst case orientation of the SF GPR antenna array relative to the emissions measurement antenna were determined by comparing emission measurement plots for each unnotched measurement configuration in the frequency range of interest and selecting the configuration corresponding to the maximum emissions.

Another set of measurements was made using the same procedure previously defined, but for these measurements, the number of active antenna array elements in the SF GPR array varied. These measurements were made in the event that Federal agencies would analyze emission characteristics when a subset of antenna array elements is active. The original test scenario, using all antenna array elements, represents worst case emissions. Therefore, the supplemental measurements are only expected to be used for a deeper analysis of SF GPR emission characteristics if needed.



1ft = 0.305 m

Figure 2. Diagram. SF GPR emissions characterization test configuration.



1ft = 0.305 m

Figure 3. Diagram. Orthogonal position of antenna array relative to figure 2.

Figure 4. Photo. SF GPR testing at the FAA Technical Center.

Figure 5. Photo. SF GPR test site at the FAA Technical Center.

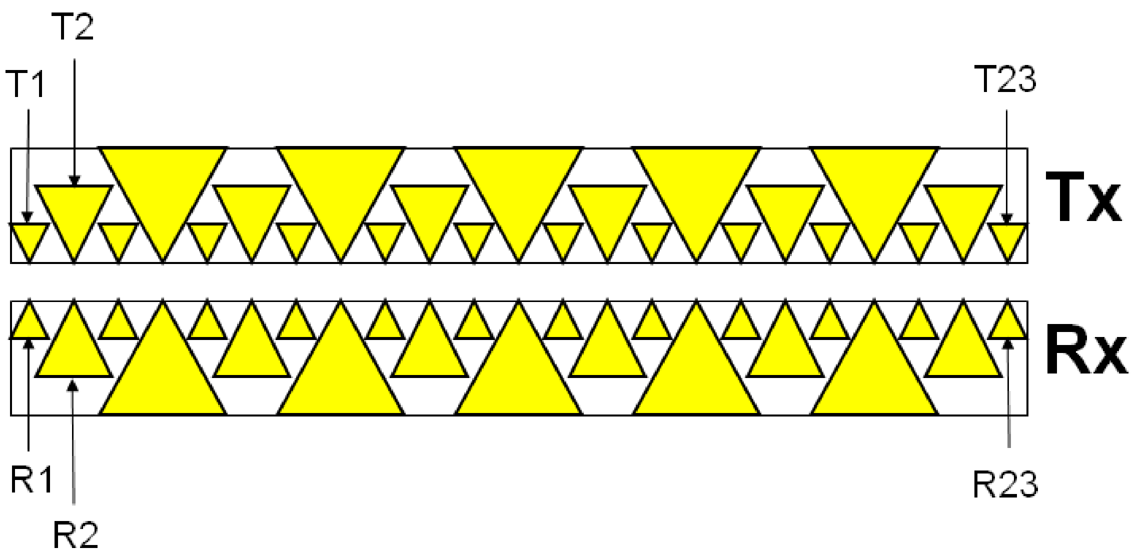


Figure 6. Diagram. Antenna array with a bank of 23 transmitter elements and 23 receiver elements.

Additional follow-up emission measurements were made using procedures described in the test report in appendix E. The minimum distance between the SF GPR antenna array and the measurement antenna was 6.88 ft (2.1 m), as illustrated in figure 3. This distance often corresponded to the orientation where maximum emissions were measured.

ANALYSIS

The analysis procedure for the SF GPR emissions characterization data followed equations defined in NTIA Annex K.[3] The analysis steps are as follows:

1. Determine the orientation of maximum emissions for each measurement and use this measurement data for subsequent analysis.

2. Calculate EIRP values at each frequency using the following equations. Equation 1 defines field strength as a function of field strength plus adjustments. Equation 2 further refines the definition of field strength as a function of field strength adjusted by the antenna factor and cable loss in terms of a unit length. Equation 3 converts from units in terms of unit length back to units in terms of decibels relative to 1 mW.

$$\text{Field Strength (dB}\mu\text{V)} = \text{Field Strength (dBm)} + 107 \quad (1)$$

$$\text{Field Strength (dB}\mu\text{V/m)} = \text{Field Strength (dB}\mu\text{V)} + \text{Antenna Factor} + \text{Cable Loss} \quad (2)$$

.

$$\text{EIRP in dBm} = \text{Field Strength (dB}\mu\text{V/m)} - 95.2 \quad (3)$$

RESULTS

Measured emission data were collected to determine whether SF GPR emissions levels were below the emissions mask that was proposed in the background section of this report. General measurements were used to make an overall assessment of emission levels using a resolution bandwidth (RBW) of 1 MHz and a video bandwidth (VBW) of 3 MHz. More detailed measurements were made in narrow frequency ranges corresponding to critical Federal systems using appropriate RBW and VBW settings. The operating spectrum for the SF GPR was 140–3,000 MHz, while the measured spectrum used for the emission measurements was 50–6,000 MHz.

This section provides a summary of general measurement results to illustrate system compliance with the proposed emissions mask. In instances where measurements indicate frequencies at which the system did not meet NTIA criteria, information is provided to describe ambient phenomena that were often present. To further address any noncompliant phenomena observed, supplemental follow-up data from an FCC-certified laboratory are provided in appendix C. Figure 19 through figure 36 provide follow-up data collected after final system tuning was complete. The three notch configurations, A1, A2, and A3, were tested during the follow-up testing in September 2009, while only one notch configuration, A1, was tested during the initial testing in March 2009.

Figure 7 through figure 10 correspond to measured emissions from the SF GPR when its emissions were unnotched. Figure 11 through figure 14 correspond to measured emissions responses from the SF GPR when its emissions were notched. Measured responses from the SF GPR with notched emissions were typically compliant with a few isolated exceptions.

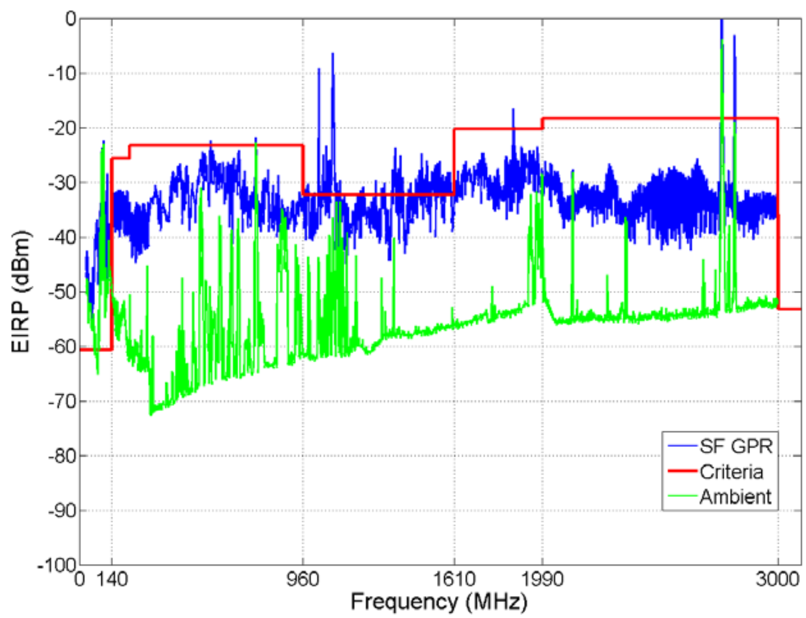


Figure 7. Graph. EIRP peak measurement values for horizontal measurement antenna orientation and maximum transmitter emission orientation without emission notching.

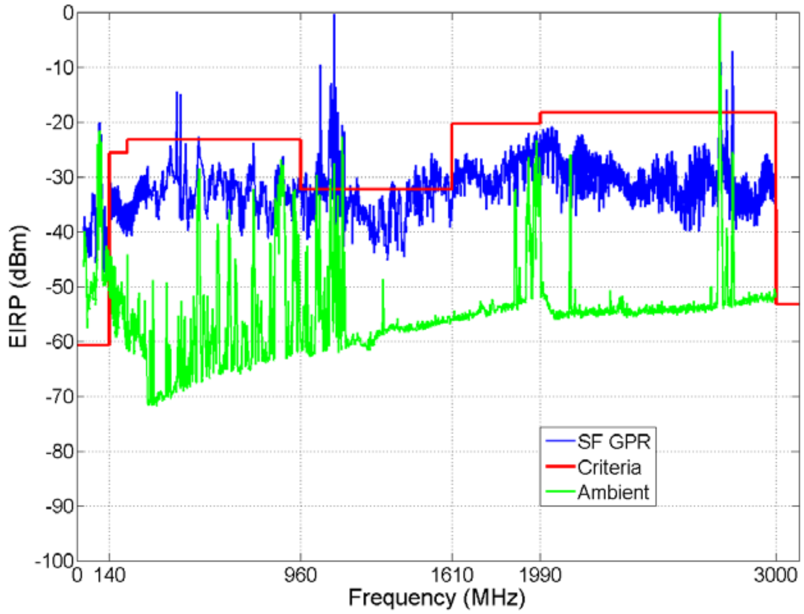


Figure 8. Graph. EIRP peak measurement values for vertical measurement antenna orientation and maximum transmitter emission orientation without emission notching.

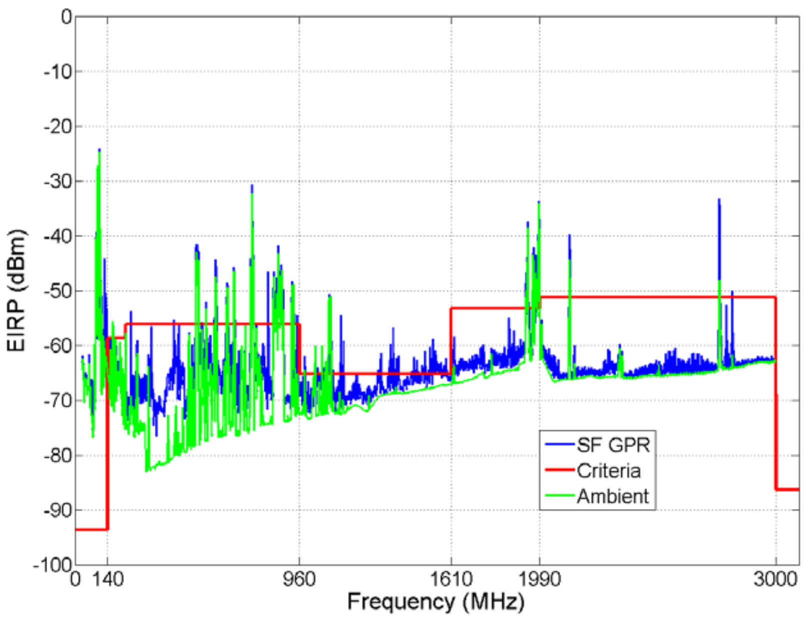


Figure 9. Graph. EIRP RMS measurement values for horizontal measurement antenna orientation and maximum transmitter emission orientation without emission notching.

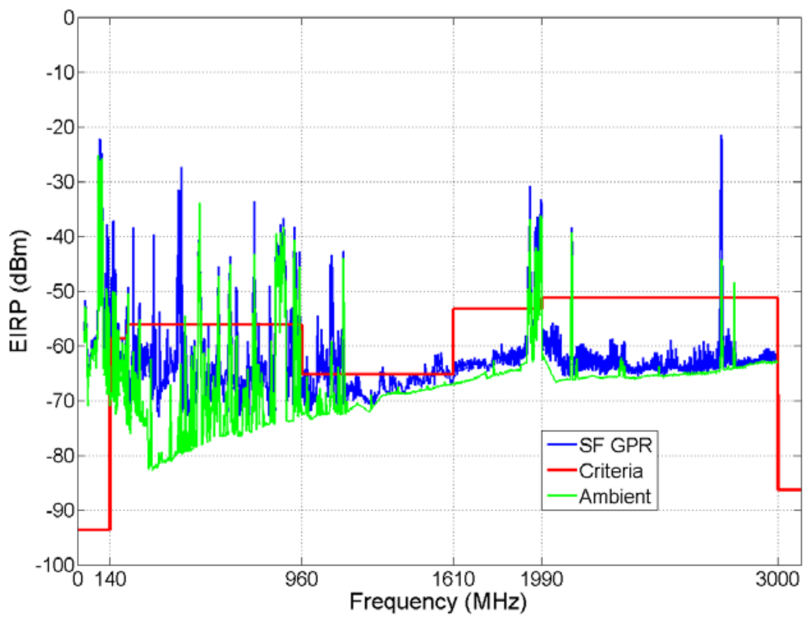


Figure 10. Graph. EIRP RMS measurement values for vertical measurement antenna orientation and maximum transmitter emission orientation without emission notching.

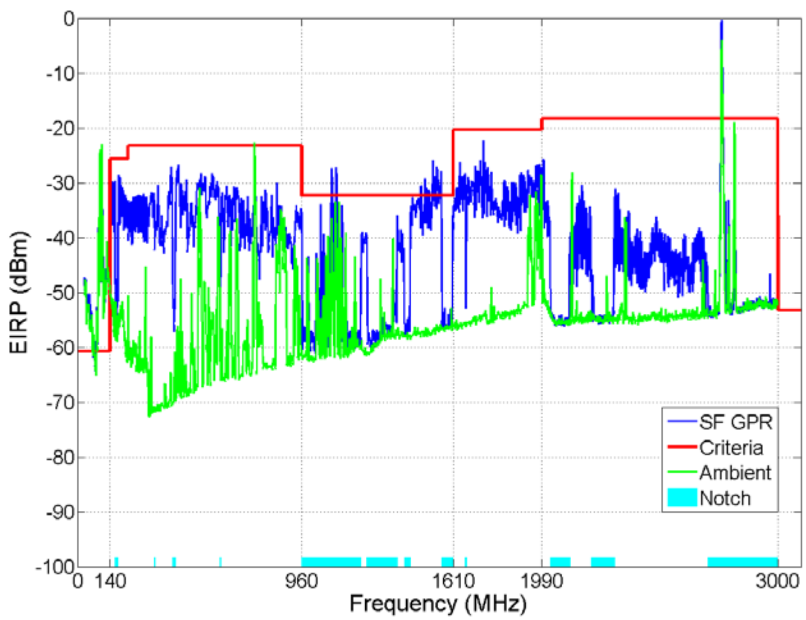


Figure 11. Graph. EIRP peak measurement values for horizontal measurement antenna orientation and maximum transmitter emission orientation with emission notching.

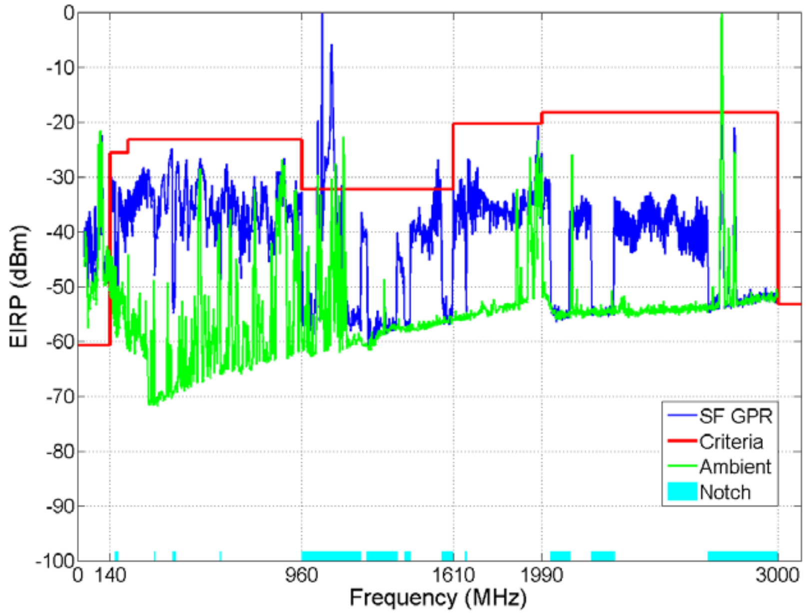


Figure 12. Graph. EIRP peak measurement values for vertical measurement antenna orientation and maximum transmitter emission orientation with emission notching.

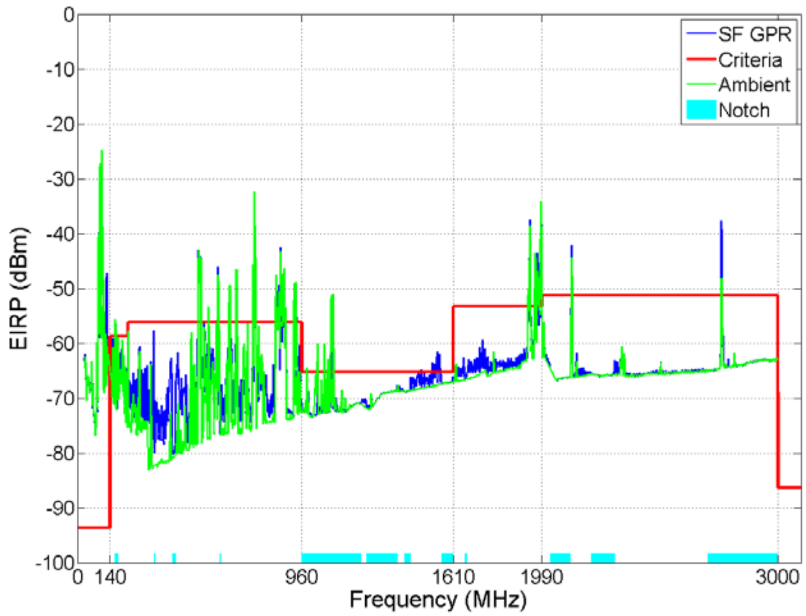


Figure 13. Graph. EIRP RMS measurement values for horizontal measurement antenna orientation and maximum transmitter emission orientation with emission notching.

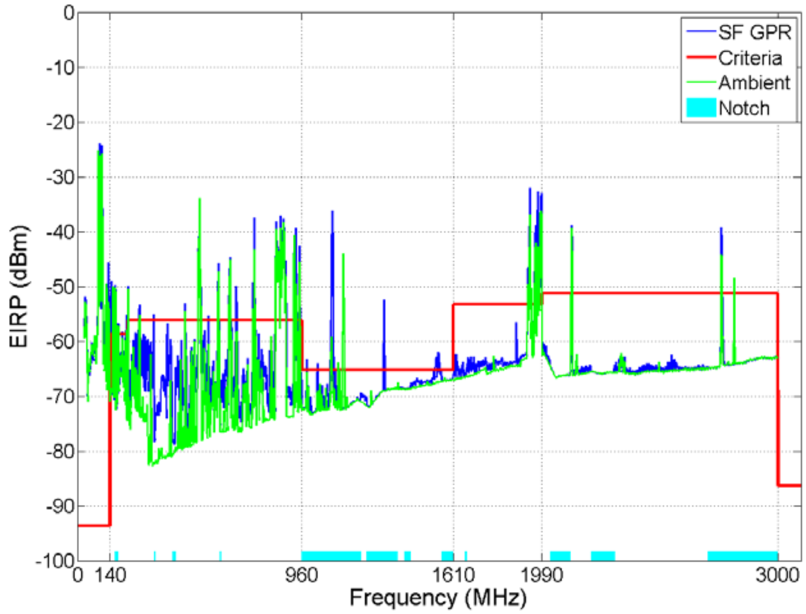


Figure 14. Graph. EIRP RMS measurement values for vertical measurement antenna orientation and maximum transmitter emission orientation with emission notching.

Unnotched SF GPR responses exhibited several frequencies that exceeded compliance criteria in the original emissions data from March 2009, while original notched emissions data rarely exceeded emission criteria. Emissions data collected during follow-up testing after system tuning in September 2009 illustrated that system performance met NTIA criteria in both notched and unnotched operating configurations with only a few exceptions. In instances where exceptions occurred in follow-up data and emissions exceeded NTIA criteria, the reasons were addressed (provided in this section).

Emissions data collected for the proposed compliant operating configuration (see figure 11 through figure 14) were obtained using the following methodologies corresponding to each figure. Data presented in figure 11 show the EIRP level received by emissions measurement antennas oriented horizontally while measuring peak emissions from the SF GPR with a notched emissions spectrum. Data in figure 12 show the EIRP level received by emissions measurement antennas oriented vertically while measuring peak emissions from the SF GPR with a notched emissions spectrum. Data in figure 13 show the EIRP level received by emissions measurement antennas oriented horizontally while measuring RMS emissions from the SF GPR with a notched emissions spectrum. Data in figure 14 show the EIRP level received by emissions measurement antennas oriented vertically while measuring RMS emissions from the SF GPR with a notched emissions spectrum.

In figure 11, (which generally illustrates compliant peak measurements), there are values that are a small number of decibels above the threshold criteria of 1,530 and 1,560 MHz. Other values exceeding the criteria corresponded to locations where significant ambient measurement values are present. In figure 12, peak measurements are also typically compliant. Frequencies of approximately 1,555 MHz are a small number of decibels above the threshold criteria. Frequencies in the 1,040-MHz range that exceed criteria correspond to substantial ambient emissions. Figure 13 and figure 14 present RMS data that are generally compliant as well.

Several SF GPR measurement peaks correspond to ambient measurement spikes in figure 13 and figure 14 and therefore do not indicate compliance issues. In the frequency range of 1,500–1,550 MHz, there are RMS values that are a small number of decibels above the threshold criteria.

Appendix C provides additional SF GPR data that were collected at an FCC-certified laboratory after attenuation adjustments were programmed into the system in an effort to bring the remaining system emissions into compliance. Figure 19 through figure 34 illustrate that the peak and RMS emissions greater than 140 MHz had few emissions that did not meet NTIA criteria for the adjusted configuration used during the additional emission measurements in September 2009. Below 140 MHz, peak values exceeded compliance criteria at several frequencies primarily due to unintentional emissions caused by radio frequency (RF) switches in the SF GPR. Unfortunately, there is not a practical way to reduce these unintentional emissions using current SF GPR technology. Detailed measurements are provided in figure 35 and figure 36 to illustrate low frequency phenomena occurring between 50 and 200 MHz. A clear transition between the characteristics of intentional emissions above 140 MHz can be observed relative to unintentional emissions below 140 MHz.

The following list provides potential reasons why SF GPR emissions exceeded NTIA criteria for some tested frequencies in September 2009 test data (follow-up data plots corresponding to these listed descriptions are provided in appendix C):

- The test report in appendix E indicates that during emission measurements, some SF GPR antenna array elements were as close as 6.88 ft (2.1 m) from the measurement antenna when it was rotated into the 90-degree position (see figure 2). For frequencies between 960 and 1,600 MHz (far field frequencies for this scenario), the free space loss should be related to the distance by 20*log(R). Therefore, the correction factor for a 6.88-ft (2.1-m) distance versus a 9.84-ft (3-m) standard distance is 20*log(2.1/3) = 3.1 dB. This correction factor can be applied to data from 960 to 1,600 MHz for figure 19 to figure 34. Most emission issues in this frequency range are addressed by this correction. This correction factor applies to SF GPR emission measurements made at the FAA Technical Center as well.

- Ambient emissions exceeded NTIA criteria at several localized frequencies between 50 and 3,000 MHZ in RMS data presented in figure 27 through figure 34. These ambient emissions accounted for localized features that exceeded NTIA criteria in SF GPR data in figures 26 through 33.

- Isolated peaks that exceeded NTIA criteria in figure 23, figure 25, figure 26, figure 28, figure 30, and figure 34 appear to be related to intermittent ambient phenomena that occurred during SF GPR emission measurements. This hypothesis is supported by measurement results obtained using similar measurement configurations that do not include these isolated peaks.

- Unintentional peak and RMS emissions below 140 MHz exceeded NTIA criteria, as shown in figure 35 and figure 36. These unintentional emissions were caused by monolithic microwave-integrated circuit (MMIC) switching devices, and they occurred each time the antenna array switched between antenna array elements. These emissions were a side effect of the operation of the MMIC devices within the SF GPR and were common in all RF solid state switches.

Data collected in narrow frequency bands corresponding to critical Federal systems were not analyzed for this report because this data are anticipated to be evaluated individually by appropriate Federal agencies. The original measurement data from this test are available in electronic form to accompany this report. Figure 17 and figure 18 in appendix B provide the data file matrix corresponding to critical Federal system data collected in March 2009. The data file matrix describing all other data files collected in March 2009 is provided in figure 15 and figure 16 in appendix B. Procedures for data file import are provided in appendix D.

SUMMARY

SF GPR emissions characterization testing has been performed to measure emissions of FHWA/USDOT technology relative to criteria established by the NTIA. Testing was conducted using standardized equipment at the FAA Technical Center in New Jersey. Measurements were carried out in a standardized GPR test geometry. Results show that the SF GPR was largely compliant with the proposed emissions mask when notches were implemented (with exceptions noted in the results section of this report). In the few frequency ranges where FAA Technical Center measurement data indicated that there were compliance issues, emissions were reduced to meet NTIA criteria by adjusting the system attenuation to frequencies above 140 MHz during follow-up measurements at an FCC-certified laboratory. Below 140 MHz, an MMIC switching device in the SF GPR produced emissions that exceeded NTIA criteria during measurements and during follow-up measurements at an FCC-certified laboratory. There was no practical method for reducing the unintentional SF GPR emissions below 140 MHz, but it was notable that NTIA emissions criteria were substantially below typical ambient signal levels in this range.

As described above, emission measurement data were collected for SF GPR emissions over a broad range of frequencies at and around the operating frequencies of the SF GPR equipment being tested. In addition, detailed emissions data were collected over significantly narrower bandwidths corresponding to critical Federal systems. The general data were analyzed and described in this report, while the detailed Federal system data will be provided to appropriate agencies in electronic form (along with this report).

RECOMMENDATION

SF GPR technology was characterized in this study via standardized methods relative to emissions criteria established by the NTIA. This technology has been demonstrated to be an effective tool for evaluating civil infrastructure materials and structures, as well as many other Federal applications in the national interest, such as land mine and unexploded ordinance detection. The results from SF GPR testing show that this technology meets proposed NTIA criteria for all of the configurations evaluated during follow-up testing in September 2009 for intentional emissions above 140 MHz. Unintentional emissions below 140 MHz may require a waiver at some frequencies.

Emissions measurement data were collected to evaluate general emissions over a broad range of frequencies that the SF GPR operates in. In addition, detailed emissions data were collected over significantly narrower bandwidths corresponding to critical Federal systems. General test data were analyzed and described in this report, while detailed Federal system data will be provided to appropriate agencies in electronic form (along with this report).

A proposed coordination procedure for operational use of SF GPR has also been developed and is summarized in appendix A. The proposed coordination procedure requires SF GPR users to register their systems with NTIA and also requires that they notify NTIA if SF GPR operations are going to take place at an airport facility.

This measurement study has shown that SF GPR technology meets NTIA criteria and that an efficient coordination mechanism can be implemented that provides safety through a registration process and limited usage based on proximity to airport facilities. FHWA/USDOT has also shown that operational use of SF GPR technology will have critical implications for a variety of important subsurface evaluation applications in the national interest.

APPENDIX A: DRAFT LANGUAGE FOR SF GPR COORDINATION

SF GPR coordination with the NTIA is anticipated to be accomplished by registering entities that own SF GPR systems. The registration process will be used to define the entity responsible for the system, to provide a list of qualified system users, and to provide detailed technical specifications for each registered system. After registration, system users will receive a letter from NTIA defining coordination procedures that they are required to follow. If system users are operating an SF GPR in a location that is on airport facility grounds controlled by FAA, they must notify NTIA via a coordination form. The notification for SF GPR work on airport facility grounds should take place at least 3 days prior to SF GPR operation. If the operation of an SF GPR occurs off airport facility grounds, a valid NTIA registration for the system is required, but no notification is necessary to operate the system.

APPENDIX B: INDEX OF DATA FILES

This appendix shows an index of data files with a description of relevant files that are provided electronically in American Standard Code of Information Interchange (ASCII) format for Federal agencies to evaluate, with instructions for import into Microsoft Excel®, MatLab, MathCad, or other data processing software/programs.

Test #	Frequency (MHz)	Antenna	RBW	VBW	QP Amb (dBm)	Az	El	Pol	Ambient Datafile (Peak)	Ambient Datafile (RMS)	Notch Off Datafile (Peak)	Notch Off DataFile (RMS)	Notch On Datafile (Peak)	Notch On DataFile (RMS)	QP Notch off	QP Notch on
A0	30 - 300	Biconic	1MHz	3 MHz	-96	0	*	V	378	379	381	380	417	416	-84	-95
A30		3 ft. 9 in.				30		V			382	383				
A60						60		V			385	384				
A90						90		V			386	387				
A120						120		V			395	394				
A150						150		V			392	393				
A180						180		V			396	398				
B0	30 - 300	Biconic	1 MHz	3 MHz	-96	0	*	H	414	415	413	412				
B30						30		H			410	411				
B60						60		H			409	408				
B90						90		H			406	407	418	419	-83	-96
B120						120		H			405	404				
B150						150		H			402	403				
B180						180		H			400	399				
C0	300 - 2000	LPA ant	1MHz	3 MHz	-113	0	*	V	457	456	458	459				
C30						30		V			461	460	491	490	-82	-96
C60						60		V			462	463				
C90						90		V			465	464				
C120						120		V			466	467				
C150						150		V			469	468				
C180						180		V			470	471				
D0	300 - 2000	LPA ant	1MHz	3 MHz	-113	0	*	H	486	487	485	484				
D30						30		H			482	483				
D60						60		H			481	480	488	489	-82	-90
D90						90		H			478	479				

Figure 15. Screen shot. General measurement data summary table (part 1 of 2).

Test #	Frequency (MHz)	Antenna	RBW	VBW	QP Amb (dBm)	Az	El	Pol	Ambient Datafile (Peak)	Ambient Datafile (RMS)	Notch Off Datafile (Peak)	Notch Off DataFile (RMS)	Notch On Datafile (Peak)	Notch On DataFile (RMS)	Datafile QP
D120						120		H			477	476			
D150						150		H			474	475			
D180						180		H			473	472			
E0	2000 - 3000	Horn	1 MHz	3 MHz		0	*	V	420	421	423	422			N/A
E30	Preamp on					30		V			424	425	454	455	
E60						60		V			426	427			
E90						90		V			429	428			
E120						120		V			430	431			
E150						150		V			433	432			
180						180		V			434	435			
F0	2000 - 3000	Horn	1 MHz	3 MHz		0	*	H	450	451	449	448	453	452	
F30	Preamp on					30		H			446	447			
F60						60		H			445	444			
F90						90		H			442	443			
F120						120		H			441	440			
F150						150		H			438	439			
F180						180		H			437	436			N/A

Figure 16. Screen shot. General measurement data summary table (part 2 of 2).

Test #	Federal System	Frequency Band	Receiver BW	RBW	VBW	Sweep Time	Az	Pol	Ambient Datafile (Peak)	Ambient Datafile (RMS)	Notch Off Datafile (Peak)	Notch Off DataFile (RMS)	Notch On Datafile (Peak)	Notch On DataFile (RMS)	DataFile QP
A	general measurement	50 MHz - 300 MHz	Biconic ant	10 kHz	30 kHz		*	V							
B	general measurement	50 MHz - 300 MHz	Biconic ant	10 kHz	30 kHz		*	H							
C	general measurement	300 - 700 MHz	LPA ant	100 kHz	300 kHz		*	V							
D	general measurement	300 - 700 MHz	LPA ant	100 kHz	300 kHz		*	H							
E	general measurement	700 MHz - 6300 MHz	Horn antenna	1 MHz	3 MHz		*	V							N/A
F	general measurement	700 MHz - 6300 MHz	Horn antenna	1 MHz	3 MHz		*	H							N/A
1	ILS Marker Beacon	70- 80 MHz	65.2 kHz/100 kHz	10 kHz	30 kHz		30	V	373	372	370	371			N/A
2	VHF VOR	108-118 MHz	8 Hz/10 Hz	10 kHz	30 kHz		150	V	367	366	369	368			N/A
3	ILS	Localizer: 108.1-111.95 MHz	8 Hz/10 Hz	10k Hz	30 kHz						covered by #2				N/A
4		Glideslope: 325-340 MHz	8 Hz/10 Hz	10 kHz	30 kHz		30	V	334	333	331	332	335	336	N/A
5	VHF Comm	118-138 MHz	16 kHz	10 kHz	30 kHz		120	V	365	364	362	363			N/A
5a	**VHF Comm**	**118-138 MHz**	**16 kHz**	**10 kHz**	**30 kHz**		**180**	**H**			**530**	**531**			
6	VHF Digital Link System	118-137 MHz	16 kHz								covered by #5				N/A
7	LAAS VHF Data	108-118 MHz	16 kHz								covered by #5				N/A
8	AN/PRC-117 Communications System	50-88 MHz	25 kHz/30 kHz	30 kHz	100 kHz		120	V	358	359	361	360			N/A
8a		50-88 MHz		**30 kHz**	**100 kHz**		**180**	**V**			**532**	**533**			
9		117 - 138 MHz		10 kHz	30 kHz		120	V	104	103	covered by #5				N/A
10		138-151 MHz		10 kHz	30 kHz		90	H	105	106	136	137	108	107	N/A
11		138-151 MHz		10 kHz	30 kHz		90	H	105	106	136	137	108	107	N/A
12		138-151 MHz		10 kHz	30 kHz		90	H	105	106	136	137	108	107	N/A
13		150-160 MHz		10 kHz	30 kHz		120	V	114	115	131	130	117	116	N/A
14		162-174 MHz		10 kHz	30 kHz		90	H	113	112	139	138	110	111	N/A
15		162-174 MHz		10 kHz	30 kHz		90	H	113	112	139	138	110	111	N/A
16		225-300 MHz		10 kHz	30 kHz		150	V	374	375	377	376	118	119	N/A
17		300-400 MHz		10 kHz	30 kHz		150	V	143	142	343	344			N/A
18		400-420 MHz		10 kHz	30 kHz		150	V	339	340	342	341	338	337	N/A
19	Motorola XTL 1500, XTL 2500, XTL 5000 Land mobile system	138-144 MHz	12.5 kHz (and 25 kHz)	10 kHz	30 kHz										N/A
20		148-149.9 MHz		10 kHz	30 kHz						covered by 10 - 18				N/A
21		150.05-150.8 MHz		10 kHz	30 kHz										N/A
22		162.0125-173.2 MHz		10 kHz	30 kHz										N/A
23		173.4-174 MHz		10 kHz	30 kHz										N/A
24		380-399.9 MHz		10 kHz	30 kHz										N/A
25		406.1-420 MHz		10 kHz	30 kHz										N/A
26	Universal Access Transceiver	970 - 990 MHz	2 MHz/3 MHz	3 MHz	8 MHz		180	V	348	347	345	346	349	350	N/A
27	DME Interrogator	950-1250 MHz	650 kHz/1 MHz	1 MHz	3 MHz		30	V	354	353	355	356	351	352	N/A
28	DME	1025-1150 MHz	0.8 MHz/ 1MHz	1 MHz	3 MHz						covered by # 27				N/A
29	ATC Radio Beacon System	1070-1110 MHz	9 MHz/10 MHz	8 MHz	50 MHz		30	V	218	219	221	220	241	242	N/A
30	ATC Radio Beacon System	1010-1050 MHz	5.5 MHz/3 MHz	3 MHz	8 MHz		30	V	178	179	181	180	227	228	N/A
31	ASR-4	1240-1400 MHz	690 kHz/1 MHz	1 MHz	3 MHz		30	H	185	184	182	183	230	229	N/A
32	ASR-4		420 kHz/300 kHz	300 kHz	1 MHz		30	H	186	187	189	188	231	232	N/A
32a	**ASR-4**	**1240-1400 MHz**	**420 kHz/300 kHz**	**300 kHz**	**1 MHz**		**120**	**H**			**536**	**537**	**538**	**539**	
33	Search and Rescue Satellite Land User Terminal	1540-1550 MHz	800 kHz/1 MHz	1 MHz	3 MHz		180	H	190	191	193	192			N/A

Figure 17. Screen shot. Federal system data summary table (part 1 of 2).

Test #	Federal System	Frequency Band	Receiver BW	RBW	VBW	Sweep Time	Az	Pol	Ambient Datafile (Peak)	Ambient Datafile (RMS)	Notch Off Datafile (Peak)	Notch Off DataFile (RMS)	Notch On Datafile (Peak)	Notch On DataFile (RMS)	DataFile QP
34	Global Positioning System	1164-1188 MHz	1 MHz	1 MHz	3 MHz		60	V	202	203	205	204	233	234	N/A
35		1215-1240 MHz		1 MHz	3 MHz		30	H	217	216	214	215			N/A
35a		**1215-1240 MHz**		**1 MHz**	**3 MHz**		**120**	**H**			**477**	**476**			
36		1555-1615 MHz		1 MHz	3 MHz		180	H	197	196	194	195	237	238	N/A
37		1164-1188 MHz	1 kHz	1 kHz	3 kHz		60	V	209	208	206	207	235	236	N/A
38		1215-1240 MHz		1 kHz	3 kHz		30	H	210	211	213	212			N/A
38a		**1215-1240 MHz**		**1 kHz**	**3 kHz**		**120**	**H**			**534**	**535**			
39		1555-1615 MHz		1 kHz	3 kHz		180	H	198	199	201	200	239	240	N/A
40	Meteorological Aids	1668-1700 MHz	0.150 MHz/100	100 kHz	300 kHz		30	H	226	225	222 and 223	224	N/A	N/A	N/A
41	Meteorological Satellite	2025-2110 MHz	5.8 MHz	6 MHz	50		60	H	251	252	281	282	245	249	N/A
41a			**5.8 MHz**	**6 MHz**	**50**		**180**	**V**			**552**	**553**	**540**	**541**	
42			34 MHz (DSN)	8 MHz	50		60	H	254	253	284	283	247	248	N/A
42a			**34 MHz (DSN)**	**8 MHz**	**50**		**180**	**V**			**554**	**555**	**542**	**543**	
43			5.6 MHz (Processed Data Relay)	6 MHz	open						covered by 41				N/A
44			1.2 MHz Low Rate	1 MHz	3 MHz		60	H	255	256	285	286	258	257	N/A
45			0.050 MHz Command	30 kHz	100 kHz		60	H	262	261	287	288	259	260	N/A
45a			**0.050 MHz Command**	**30 kHz**	**100 kHz**		**180**	**V**			**556**	**557**	**544**	**545**	
46			0.060 MHz Weather Info	100 kHz	300 kHz		60	H	263	264	289	290	266	265	N/A
46a			**0.060 MHz Weather Info**	**100 kHz**	**300 kHz**		**180**	**V**			**558**	**559**	**546**	**547**	
47			0.060 MHz DCP								covered by 46				N/A
48	Space Ground Link Subsystem Earth Station Receiver	2200-2290 MHz	1 MHz/1 MHz	1 MHz	3 MHz		150	H	275	276	279	280	278	277	N/A
49	Satellite Earth Station Receivers	2200-2290 MHz	1.5 to 360 MHz	1 MHz	3 MHz						covered by 48				N/A
50	Deep Space Network Earth Station Receiver	2290-2300 MHz	1 MHz/1 MHz	1 MHz	3 MHz		60	V	270	269	291	292	267	268	N/A
51	Aeronautical Telemetry Ground-Based Receiver	2360-2390 MHz	25 MHz	8 MHz	open		0	H	271	272	293	294	274	273	N/A
51a	**Aeronautical Telemetry Ground-Based Receiver**	**2360-2390 MHz**	**25 MHz**	**8 MHz**	**50 kHz**		**180**	**V**			**550**	**551**			
52	ASR-9	2700-2900 MHz	653 kHz/ 1MHz	1 MHz	3 MHz						covered by 54				N/A
53	ASR-11		1.1 MHz/ 1 MHz	1 MHz	3 MHz						covered by 54				N/A
54	Next Gen Weather Radar	2700-3000 MHz	600 kHz/ 1MHz	1 MHz	3 MHz		180	V	295	296	298	297	305	306	N/A
55	Maritime Radar	2900-3100 MHz	4 MHz	3 MHz	10 MHz		180	V	302	301	299	300	303	304	N/A
56	Radar Altimeters	4200-4400 MHz	Pulsed 25 MHz	8 MHz	open		0	V	307	308	310	309	N/A	N/A	N/A
57			FMCW 90 kHz/ 100 kHz	100 kHz	300 kHz		0	V	314	313	311	312	N/A	N/A	N/A
58	Microwave Landing System	5030-5091 MHz	150 kHz/100 kHz	100 kHz	300 kHz		0	V	315	316	318	317	N/A	N/A	N/A
59	Terminal Doppler Weather Radar	5600-5650 MHz	0.910 MHz/ 1MHz	1 MHz	3 MHz		0	V	322	321	319	320	N/A	N/A	N/A
60	General	3000 - 6300 MHz		1 MHz	3 MHz		0	V	326	325	323	324	N/A	N/A	N/A
61	General	3000 - 6300 MHz		1 MHz	3 MHz		90	H	327	328	330	329	N/A	N/A	N/A
62	General	5000 - 6300 MHz		1 MHz	3 MHz								N/A	N/A	N/A

Figure 18. Screen shot. Federal system data summary (part 2 of 2).

APPENDIX C: GRAPHS SHOWING FOLLOW-UP MEASUREMENTS

This section provides graphs of the emission data from the SF GPR antennas and contrasts them to the background ambient emissions from the rural environment and to the maximum emissions criteria. In cases where there was emissions notching, the notch frequencies are provided on the bottom axis of the graphs.

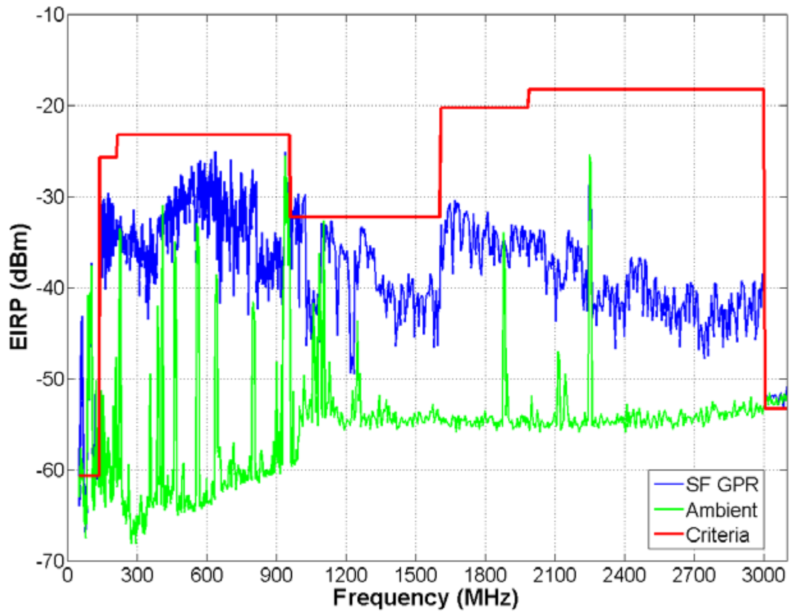


Figure 19. Graph. Outdoor peak emission measurement with horizontal polarization without notching.

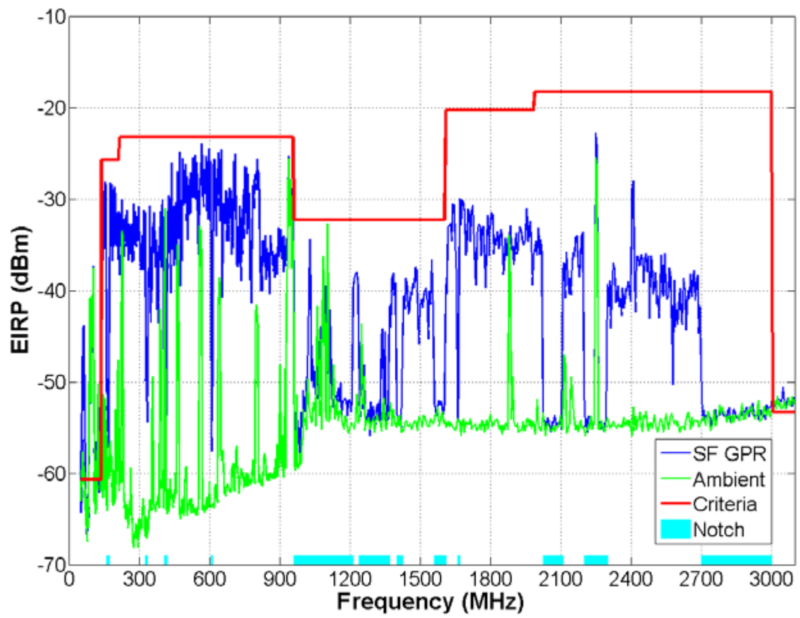


Figure 20. Graph. Outdoor peak emission measurement with horizontal polarization with A1 notch configuration.

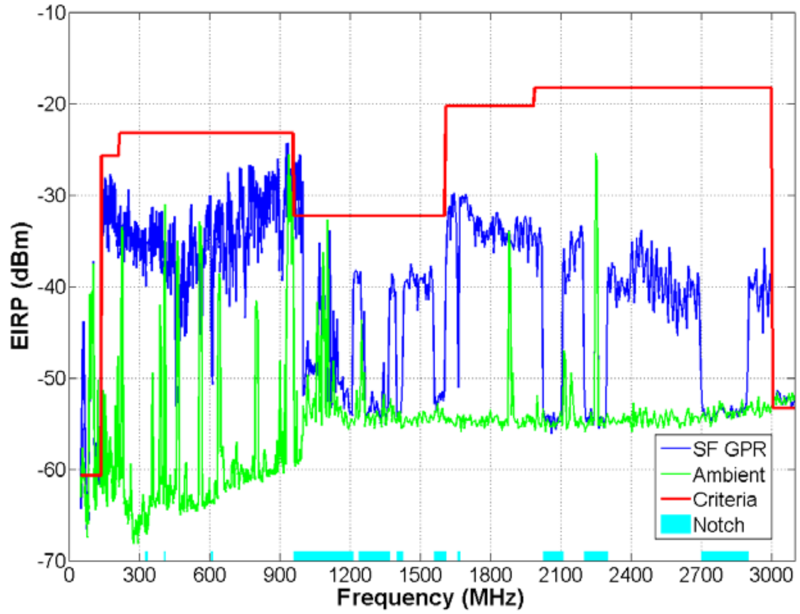


Figure 21. Graph. Outdoor peak emission measurement with horizontal polarization with A2 notch configuration.

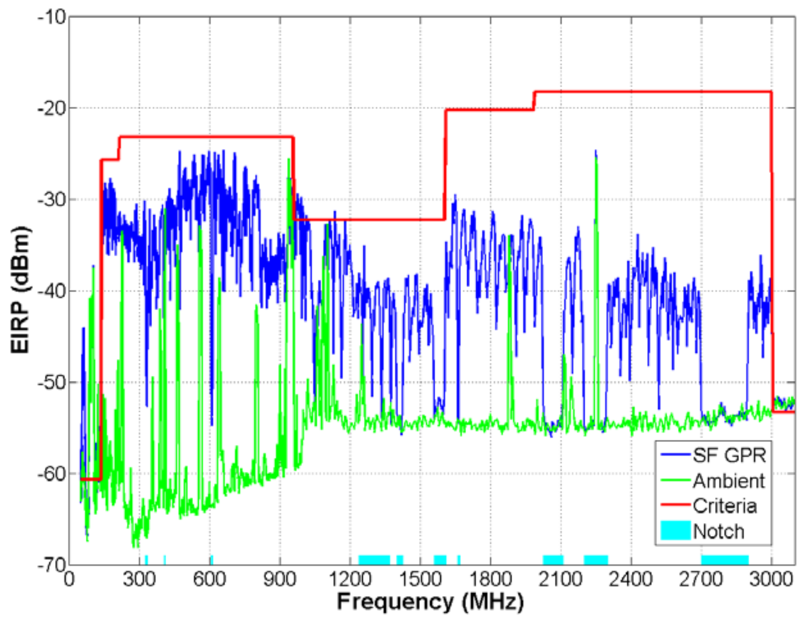


Figure 22. Graph. Outdoor peak emission measurement with horizontal polarization with A3 notch configuration.

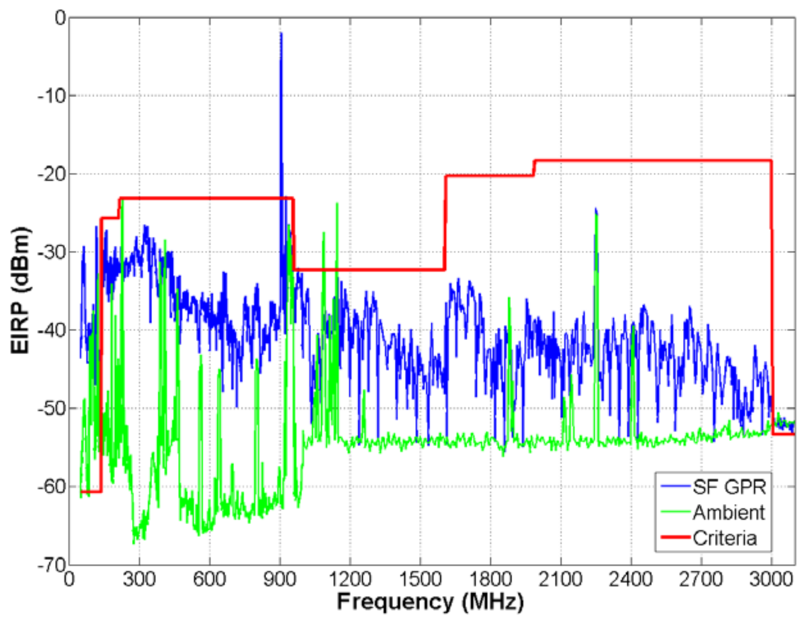


Figure 23. Graph. Outdoor peak emission measurement with vertical polarization without notching.

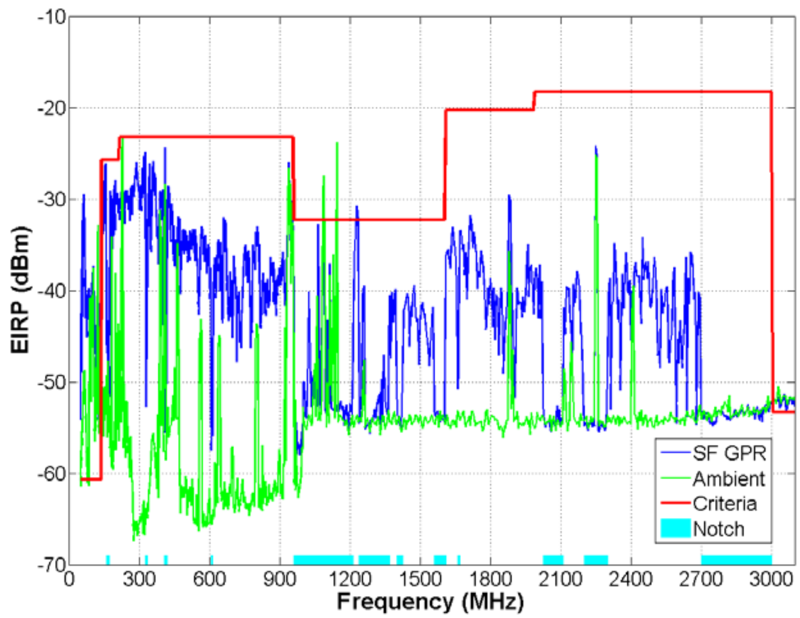


Figure 24. Graph. Outdoor peak emission measurement with vertical polarization with A1 notch configuration.

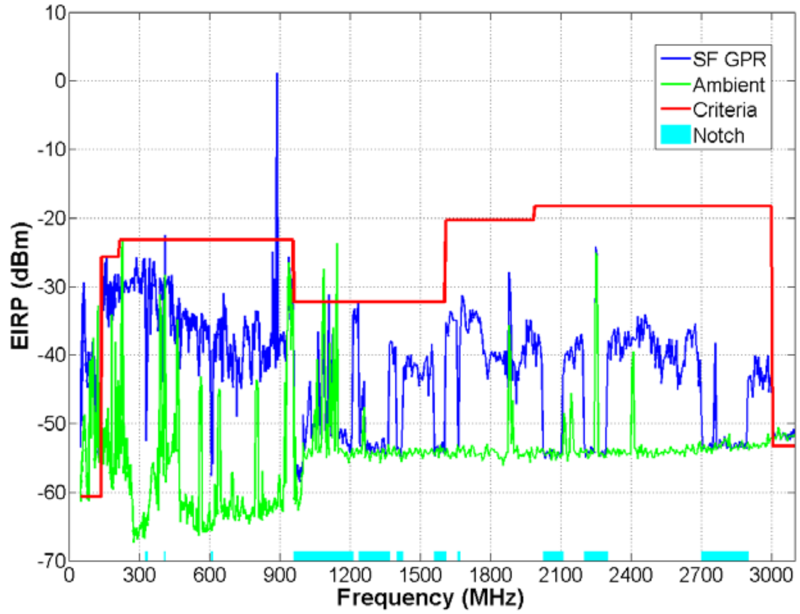


Figure 25. Graph. Outdoor peak emission measurement with vertical polarization with A2 notch configuration.

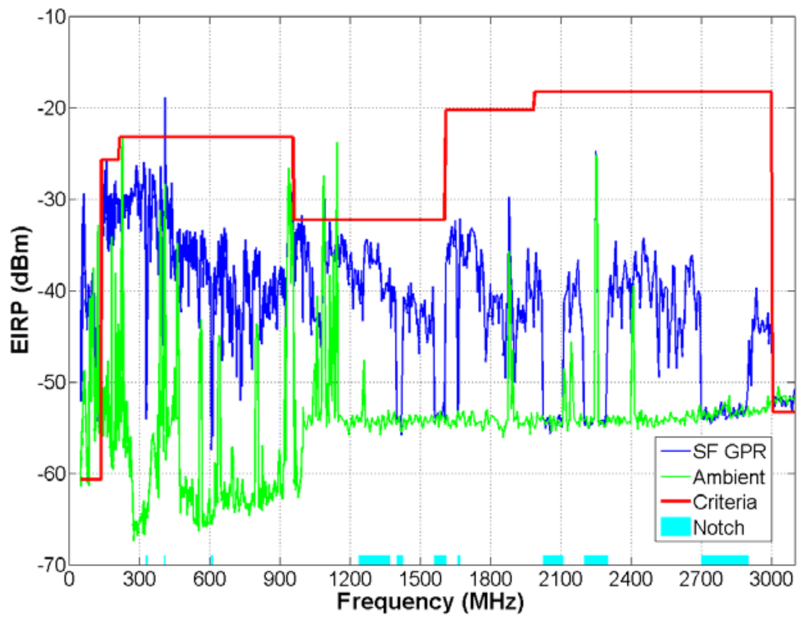


Figure 26. Graph. Outdoor peak emission measurement with vertical polarization with A3 notch configuration.

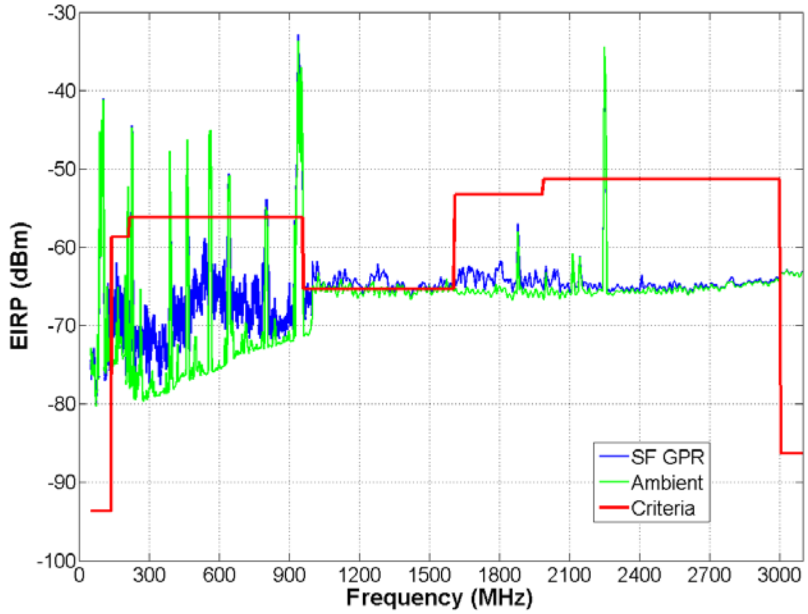


Figure 27. Graph. Outdoor RMS emission measurement with horizontal polarization without notching.

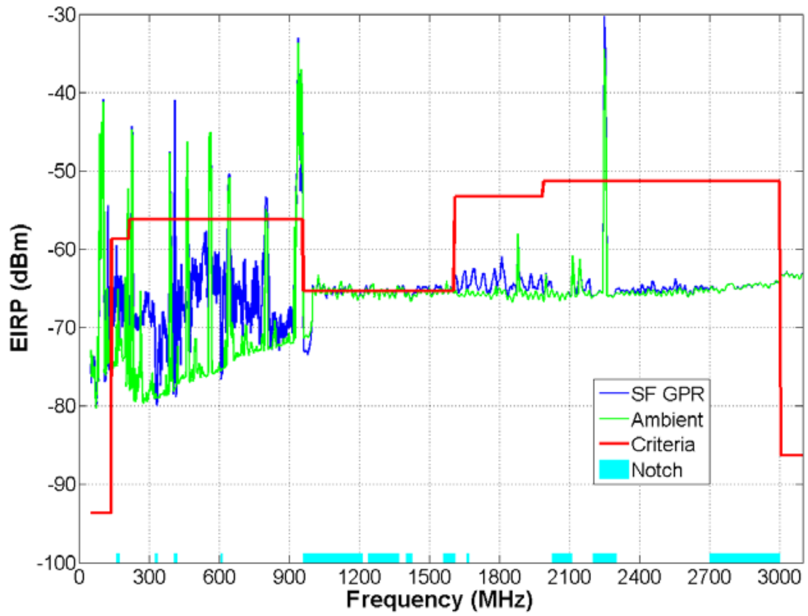


Figure 28. Graph. Outdoor RMS emission measurement with horizontal polarization with A1 notch configuration.

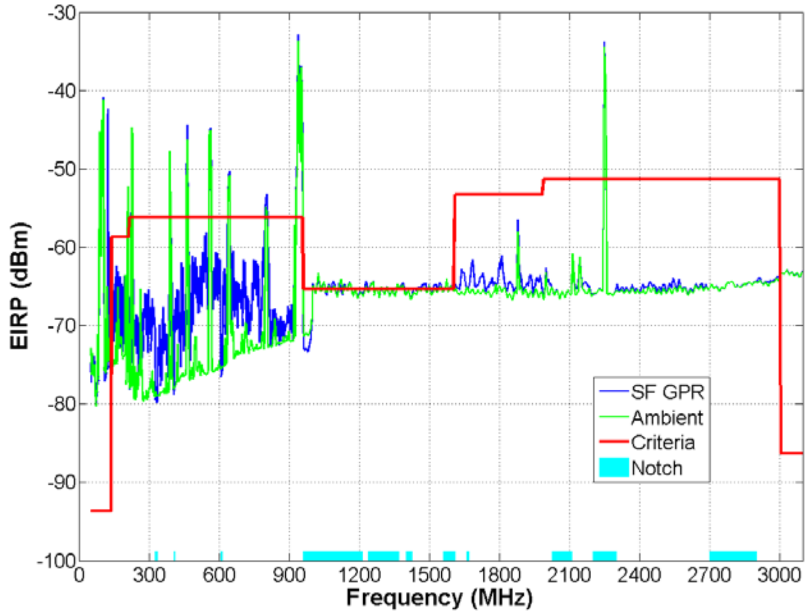


Figure 29. Graph. Outdoor RMS emission measurement with horizontal polarization with A2 notch configuration.

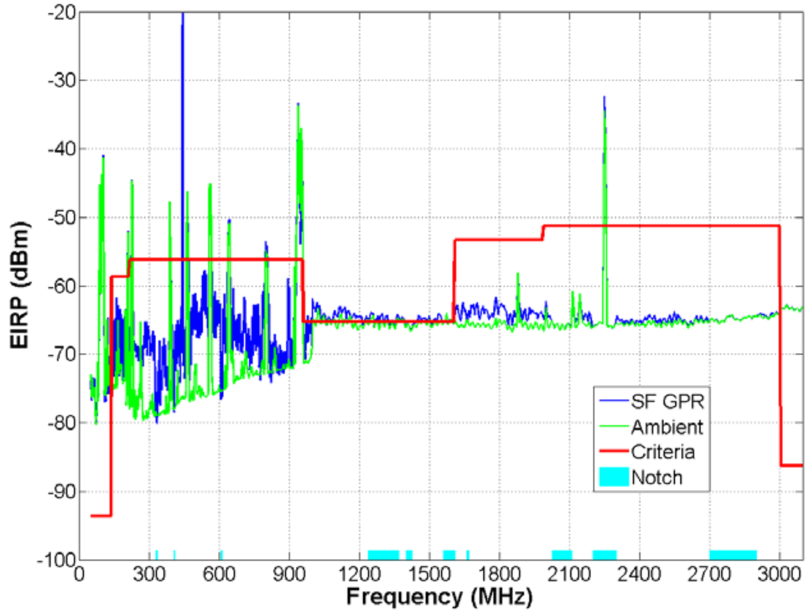


Figure 30. Graph. Outdoor RMS emission measurement with horizontal polarization with A3 notch configuration.

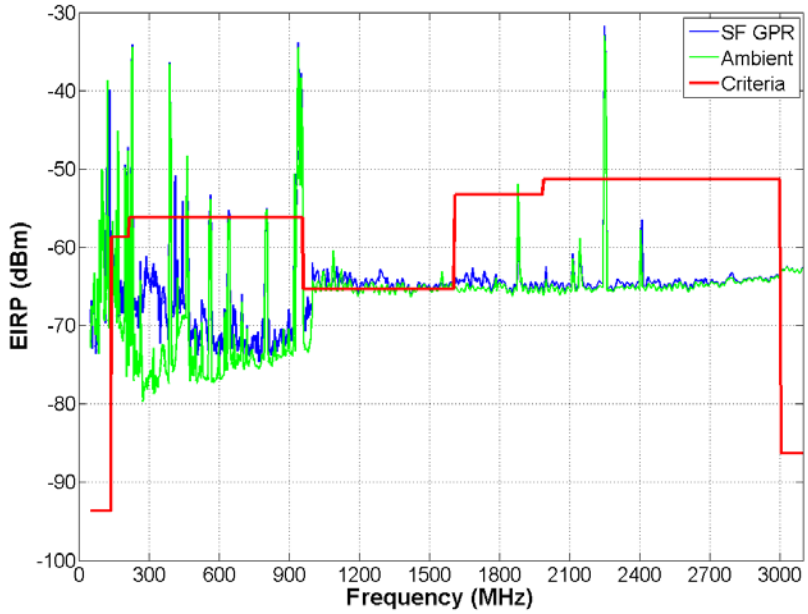


Figure 31. Graph. Outdoor RMS emission measurement with vertical polarization without notching.

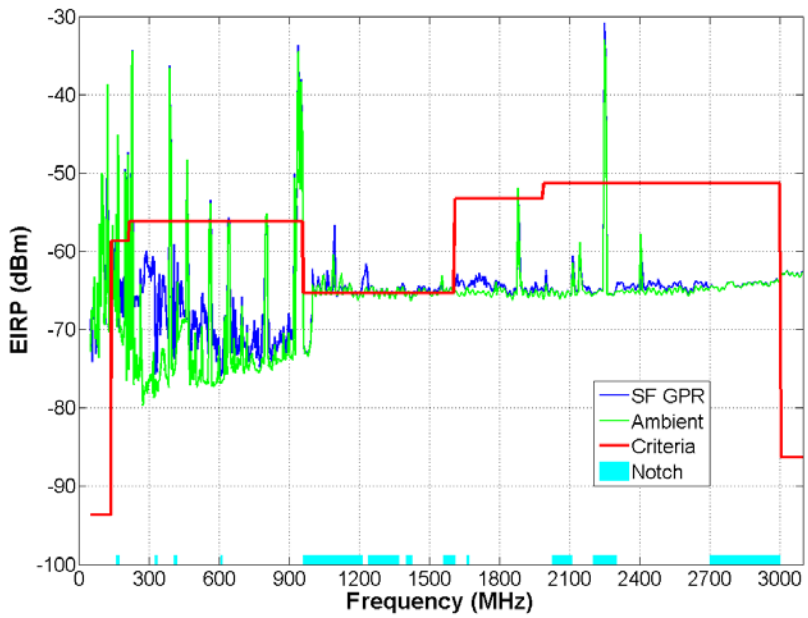


Figure 32. Graph. Outdoor RMS emission measurement with vertical polarization with A1 notch configuration.

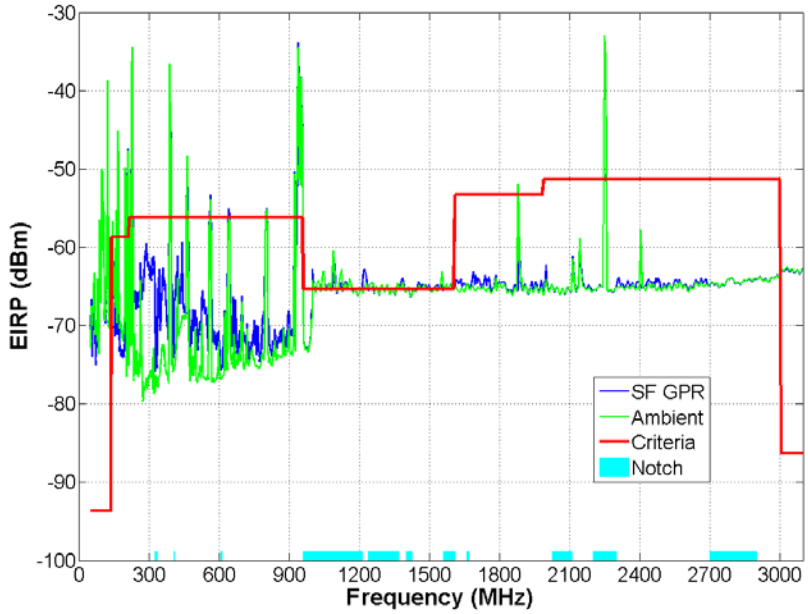


Figure 33. Graph. Outdoor RMS emission measurement with vertical polarization with A2 notch configuration.

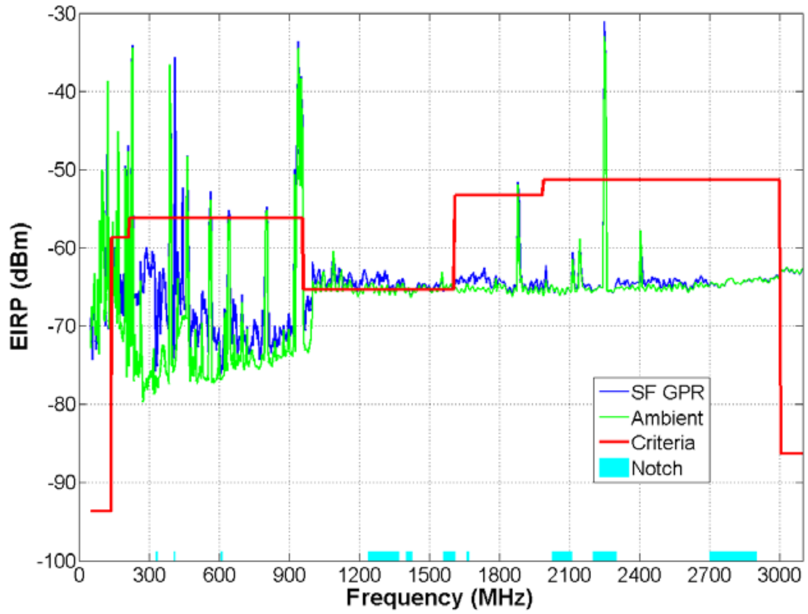


Figure 34. Graph. Outdoor RMS emission measurement with vertical polarization with A3 notch configuration.

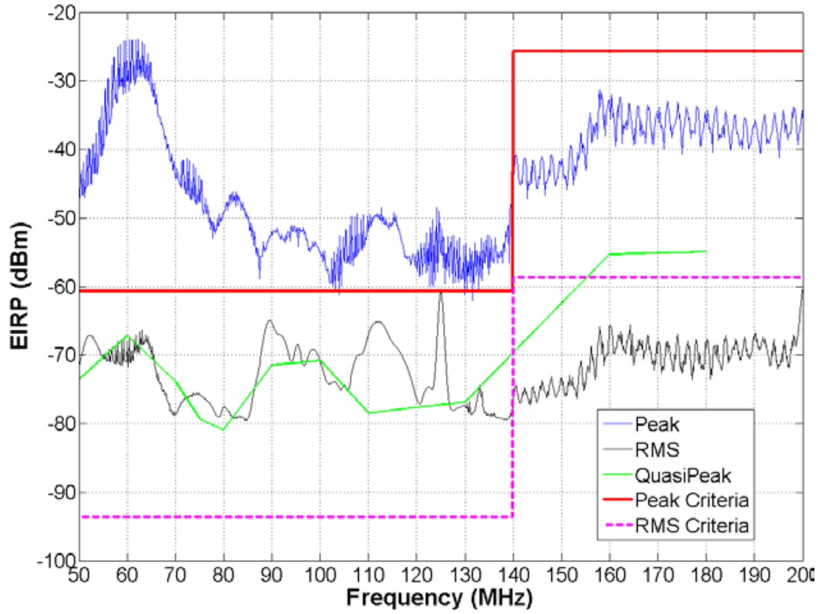


Figure 35. Graph. Indoor emission measurements using vertically polarized measurement antenna at low frequencies.

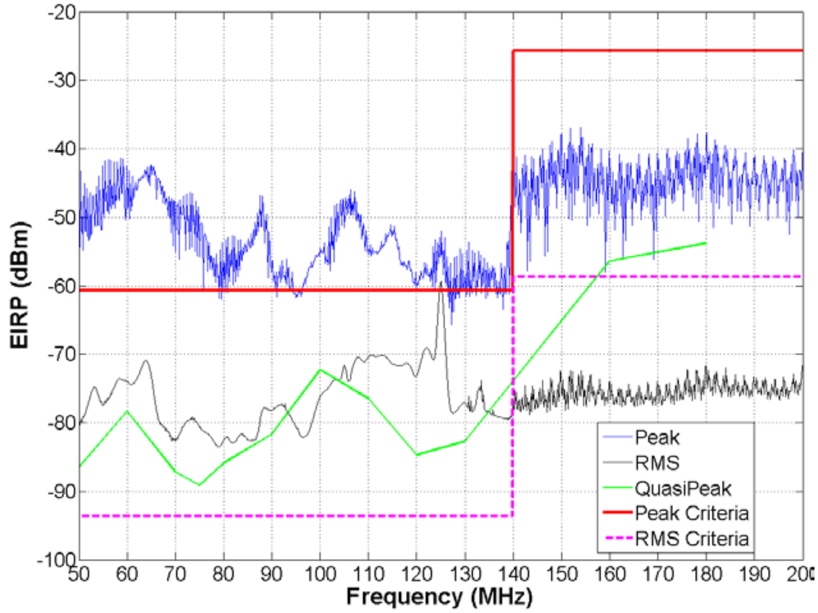


Figure 36. Graph. Indoor emission measurements using horizontally polarized measurement antenna at low frequencies.

APPENDIX D: DATA IMPORT PROCEDURES

The following section shows example data import procedures for SF GPR emissions characterization data.

ASCII data files are all named using the convention "TRACE###" where "###" is a three-digit number indicating the test number associated with the file. Antenna gain curves and cable loss factors are provided with the data files.

MICROSOFT EXCEL® PROCEDURE

1. Go to the Data menu.
2. Import External Data.
3. Import Data.
4. Select Tab Delimited Data.
5. Press "Next."
6. Press "Finish."

MATLAB PROCEDURE

```
%---reading header info---------
fileID=fopen('G:\FAATestReportWork\FAANTIAtest2009\Trace381.csv','r');

for i = 1 : 15
	header{i}=fgetl(fileID);
end
[junk,temp0]=strtok(header{11},',');
Npoints=str2num(temp0);
fclose(fileID);

DataOffset=16;

%---Example Data File-----------
fileID=fopen('G:\FAATestReportWork\FAANTIAtest2009\Trace418.csv','r');

for i = 1: Npoints+DataOffset-1
	traceA{i}=fgetl(fileID);
end

fclose(fileID);

for m= DataOffset : Npoints+DataOffset-1
```

```
        [junk,temp1]=strtok(traceA{m},',');
        freq(m)=str2num(junk);    %13
        RXpwr(m)=str2num(temp1(1:end));
end

freqBiconic=freq(DataOffset:end);
RXpwrBiconic=RXpwr(DataOffset:end);
```

APPENDIX E: CERTIFIED LABORATORY TEST REPORT: FOLLOW-UP TEST

The following certified laboratory test report contains supporting documentation and results of the testing performed for the research initiative in this report. The authors of this current study have not edited or changed the test report in this appendix except to remove more than one instance of company logo within the document and to format the report.

Test report no. : 133876/2

Item tested : B1823CH

Type of equipment : 3d-radar Geoscope

Client : 3d-Radar AS

Nemko is granted accreditation by
Norwegian Accreditation under
registration number TEST 033.
FCC test firm registration # 994405

Federal Highway Administration/Department of Transportation

Step Frequency Ground Penetrating Radar

Characterization and federal Compliance Tests

2009-10-27

Authorized by : ....

Geir Antonsen
Technical Verificator

CONTENTS

GENERAL INFORMATION

TESTHOUSE INFO

Name:	Nemko A/S
Address:	Nemko Kjeller Instituttvn 6, Box 96 N-2027 Kjeller, NORWAY
Telephone:	+47 64 84 57 00
Fax:	+47 64 84 57 05
E-mail:	comlab@nemko.com
FCC test firm registration #:	994405
Number of Pages:	90

CLIENT INFORMATION

Name:	3d-Radar AS
Address:	Klæbuveien 196 B, N-7037 Trondheim, Norway
Telephone:	+ 47 72 89 32 02
E-mail	egil@3d-radar.com

Contact:

Name:	Egil Eide
Phone:	+ 47 72 89 32 02
E-mail:	egil@3d-radar.com

MANUFACTURER (IF OTHER THAN CLIENT)

Name:	>
Address:	>
Telephone:	>
Fax:	>

Contact:

Name:	>
Phone:	>
E-mail:	>

TEST INFORFMATION

TESTED ITEM

Name :	3d-Radar Geoscope
Model/version :	B1823CH
Serial number :	6052
Hardware identity and/or version:	-
Software identity and/or version :	-
Frequency Range :	140 MHz – 3 GHz
Type of Power Supply :	12 V dc
Desktop Charger :	No

Description of Tested Device(s)

Step frequency Geo Radar.

TEST ENVIRONMENT

Normal test condition at the test sites

Temperature:	Outdoor: 10 - 15 °C, Indoor: 22,1 - 22,6 °C
Relative humidity:	38,2 %
Normal test voltage:	237,3 – 240,0 V ac

The values are the limit registered during the test period.

TEST PERIOD

Item received date: 2009-09-10
Test period: 2009-09-10 – 2009-09-11

STANDARDS AND REGULATIONS

Federal Highway Administration/Department of Transportation
Step Frequency Ground Penetrating Radar Characterization and Federal compliance Tests
July 2, 2009

TEST ENGINEER(S)

Egil Hauger

ADDITIONAL INFORMATION

Test Methods

Described in the relevant basic standards.

Test Equipment

List of used test equipment, see clause 7.

THIS TEST REPORT APPLIES ONLY TO THE ITEM(S) AND CONFIGURATIONS TESTED.

TESTED BY : ____ **DATE:** **2009-10-20**

Test Engineer

OTHER COMMENTS

GENERAL:

The outdoor test was performed in rural area with no surroundings reflecting objects, see photo on fig 29 to 31.
The indoor test was performed in a semi-anechoic chamber with dimensions 22 × 13 × 9,5 meters (l × w × h m), see photo on fig 32.

EUT (EQUIPMENT UNDER TEST):

EUT size 2,5x0,75x0,75 m
See photo fig 30 to 33.

LIST OF PORTS:

Signal ports:	Signal cable Internal antenna
Power ports:	12 V dc

EMISSION MEASUREMENTS

OUTDOOR TEST

Test set up:

The outdoor measurements were performed in rural area with no reflecting objects in the surroundings, see photo on fig 29 to 31. The weather was dry with temperature around 12-15 ^{o}C. The ground was sand with some smaller stones.
The test equipment was more that 5 m away from the radar.

All tests were stored as data file with frequency and EIRP in dBm.

Effective radiated power was calculated using Friis free space transmission formula with a distance of 3 m. This equals the formula presented in the test specification:

EIRP (dBm) = dBµV/m – 95,2

Test antennas used:

50 – 200 MHz:	Biconic antenna
200 – 1000 MHz:	Log.periodic antenna
1000 – 6000 MHz:	Horn antenna

All antennas were calibrated by National Physical Laboratory NPL UK.
The conversion factors converting the measured values to EIRP in dBm including cables and pre.amplifier were calibrated before the test and stored in the test equipment.

Measurement instruments set up: Resolution bandwidth 1 MHz
Video bandwidth 3 MHz
Sweep time 15 sec
Detector Peak and RMS

All test files with frequency and EIRP are enclosed.

Some of the files with the most interesting frequency spectra are converted to Excel and shown below.
See fig 1 to 13.

Test file notation:

Test	Config	Freq	Ant	Az	Pol	File no Peak	File no RMS
A1	Ambient	50-200 MHz	Bicon	0	V	003	004
A2	No notching	50-200	Bicon	0	V	005	006
A3	Notch A1	50-200	Bicon	0	V	007	008
A4	Notch A2	50-200	Bicon	0	V	009	010
A5	Notch A3	50-200	Bicon	0	V	011	012
A6	Ambient	50-200	Bicon	90	H	002	001
A7	No notching	50-200	Bicon	90	H	019	020
A8	Notch A1	50-200	Bicon	90	H	018	017
A9	Notch A2	50-200	Bicon	90	H	015	016
A10	Notch A3	50-200	Bicon	90	H	014	013
A11	Ambient	200-1000 MHz	Log.per	0	V	032	031
A12	No notching	200-1000	Log.per	0	V	040	039
A13	Notch A1	200-1000	Log.per	0	V	037	038
A14	Notch A2	200-1000	Log.per	0	V	035	036
A15	Notch A3	200-1000	Log.per	0	V	033	034
A16	Ambient	200-1000	Log.per	90	H	021	022
A17	No notching	200-1000	Log.per	90	H	024	023
A18	Notch A1	200-1000	Log.per	90	H	025	026
A19	Notch A2	200-1000	Log.per	90	H	028	027
A20	Notch A3	200-1000	Log.per	90	H	029	030
A21	Ambient	1-6 GHz	Horn	0	V	041	042
A22	No notching	1-6	Horn	0	V	043	044
A23	Notch A1	1-6	Horn	0	V	046	045
A24	Notch A2	1-6	Horn	0	V	047	048
A25	Notch A3	1-6	Horn	0	V	050	049
A26	Ambient	1-6	Horn	90	H	080	079
A27	No notching	1-6	Horn	90	H	078	077
A28	Notch A1	1-6	Horn	90	H	075	076
A29	Notch A2	1-6	Horn	90	H	074	073
A30	Notch A3	1-6	Horn	90	H	071	072
A31	Ambient	1-3	Horn	0	V	059	060
A32	No notching	1-3	Horn	0	V	058	057
A33	Notch A1	1-3	Horn	0	V	055	056
A34	Notch A2	1-3	Horn	0	V	054	053
A35	Notch A3	1-3	Horn	0	V	051	052
A36	Ambient	1-3	Horn	90	H	062	061
A37	No notching	1-3	Horn	90	H	063	064
A38	Notch A1	1-3	Horn	90	H	066	965
A39	Notch A2	1-3	Horn	90	H	067	068
A40	Notch A3	1-3	Horn	90	H	070	069
A41	No notching	1,164-1,240 GHz	Horn	0	V	088	087

Test file notation:

Test	Config	Freq	Ant	Az	Pol	File no Peak	File no RMS
A42	No notching	1,559-1,610	Horn	0	V	085	086
A43	No notching	1,165-1,240	Horn	90	H	082	081
A44	No notching	1,559-1610	Horn	90	H	083	084

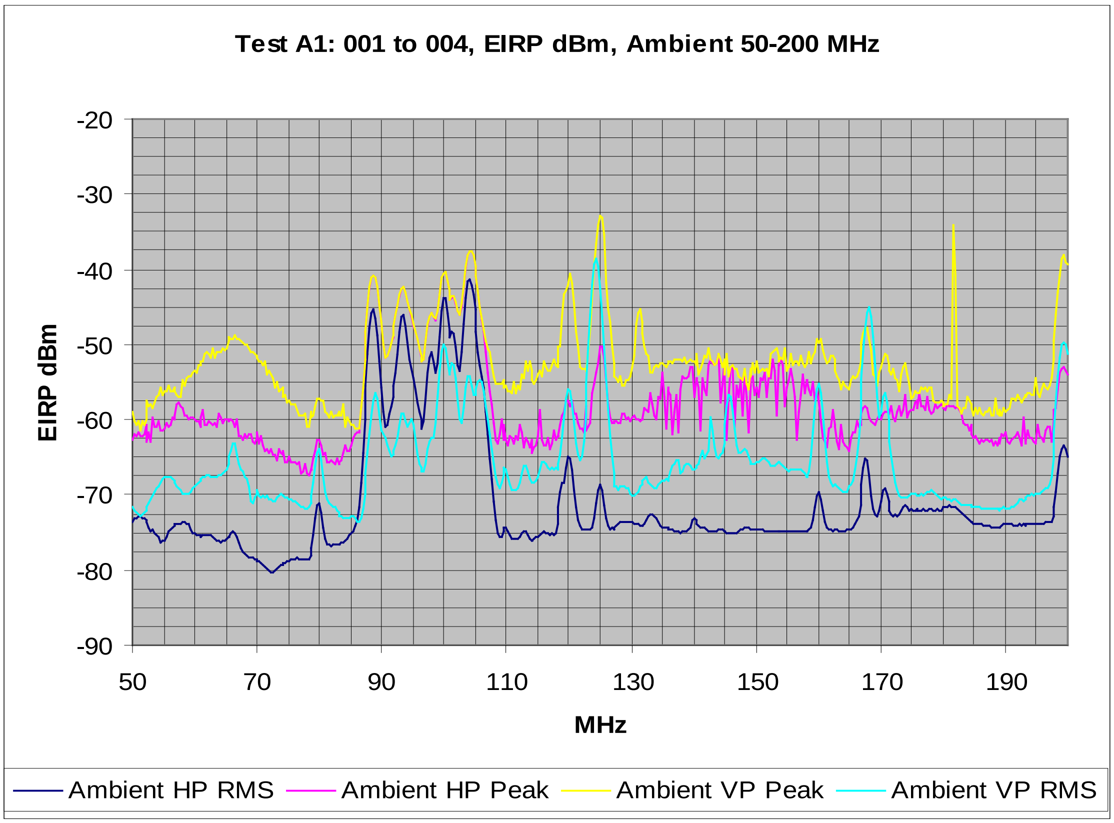
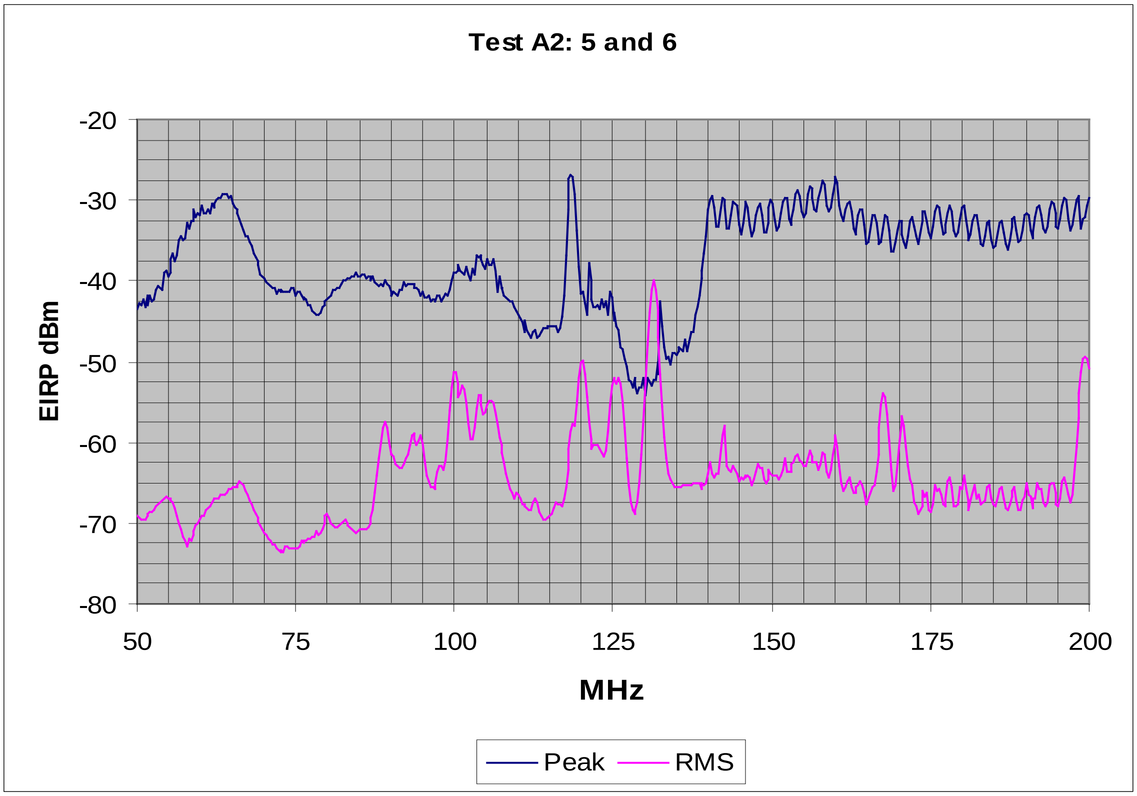
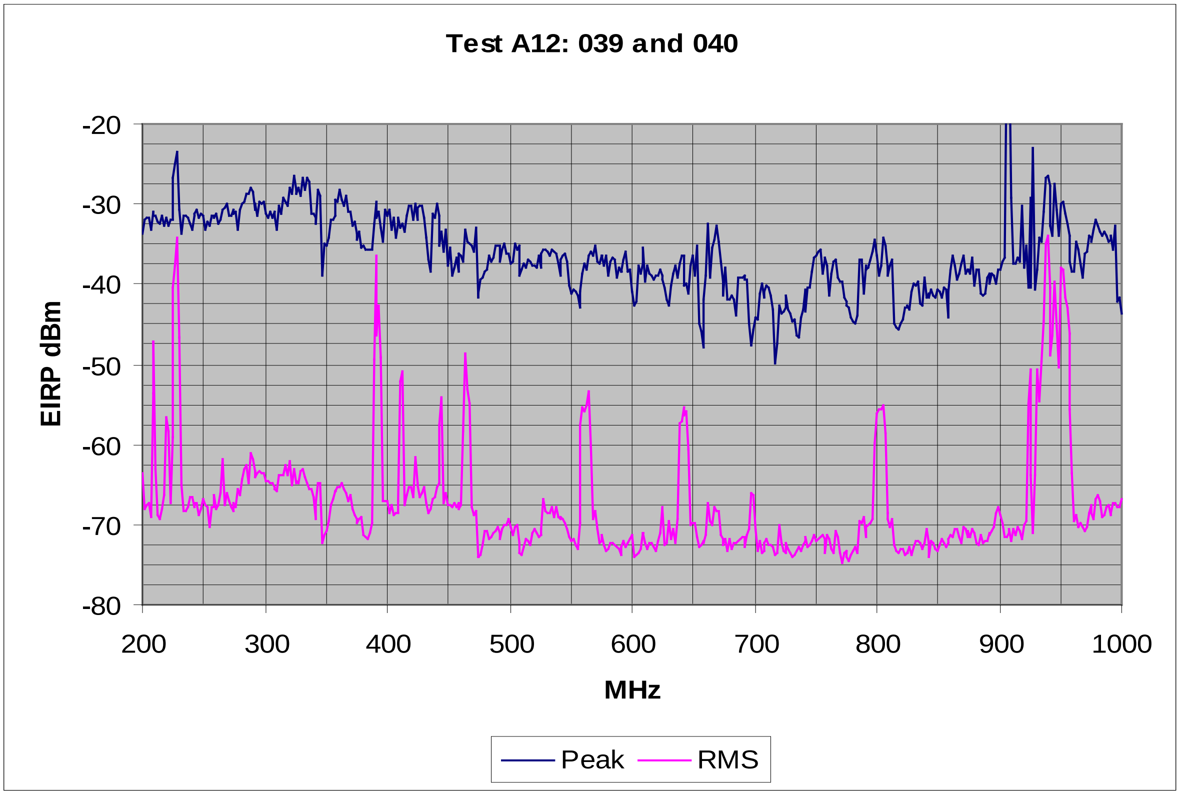


Fig 1



Test A2: 5 and 6
-20
-30
-40
-50
-60
-70
-80
EIRP dBm
50
75
100
125
150
175
200
MHz
Peak
RMS

Fig 2



Test A12: 039 and 040
-20
-30
-40
-50
-60
-70
-80
EIRP dBm
200
300
400
500
600
700
800
900
1000
MHz
Peak
RMS

Fig 3

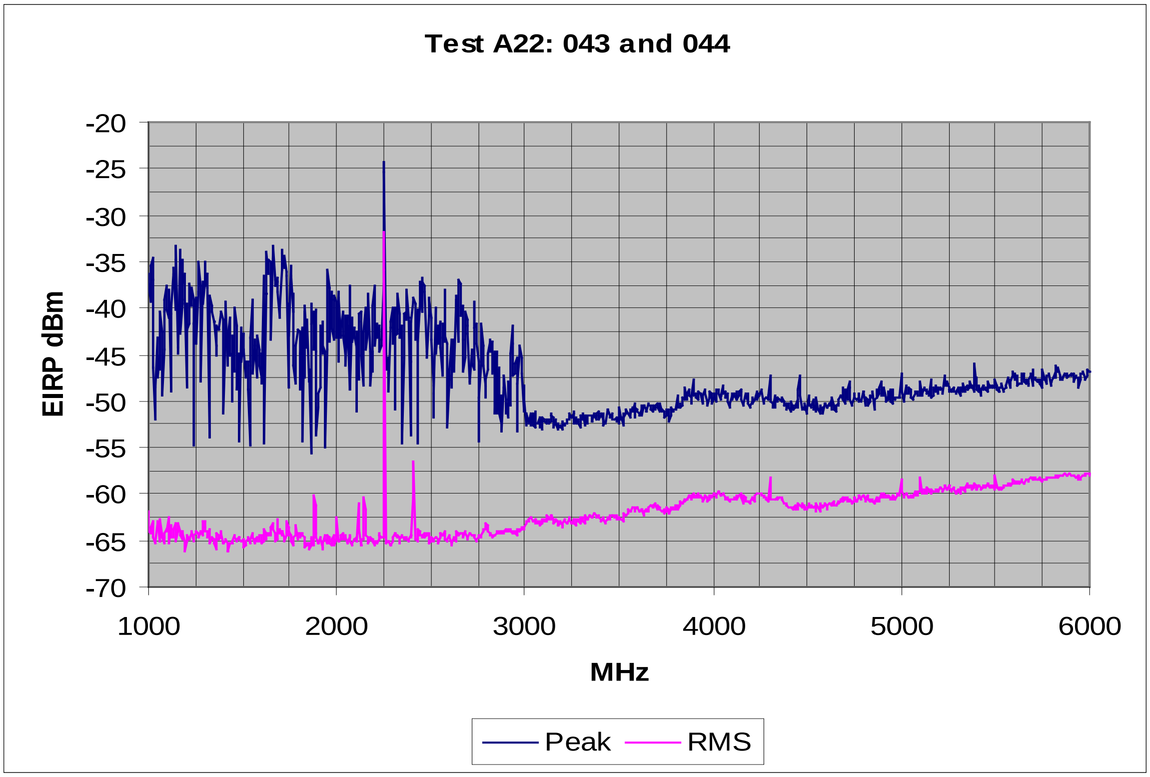

Test A22: 043 and 044
-20
-25
-30
-35
-40
-45
-50
-55
-60
-65
-70
EIRP dBm
1000
2000
3000
4000
5000
6000
MHz
Peak
RMS

Fig 4

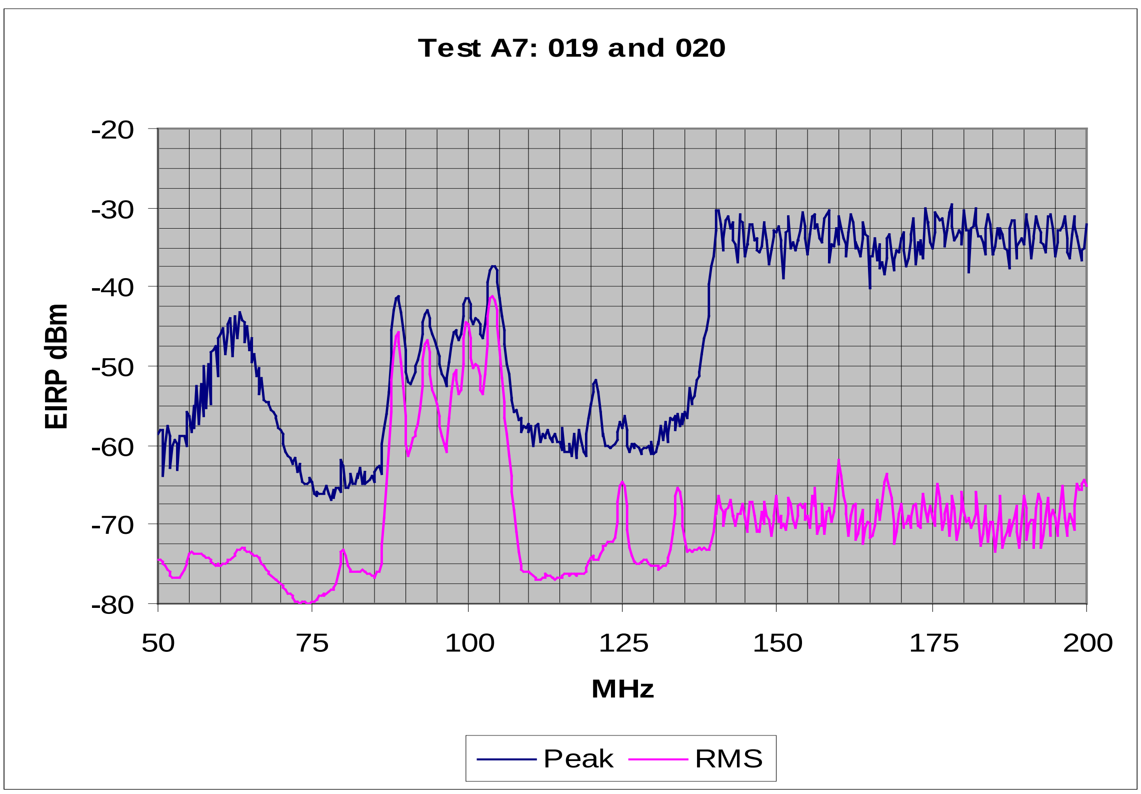

Test A7: 019 and 020
-20
-30
-40
-50
-60
-70
-80
EIRP dBm
50
75
100
125
150
175
200
MHz
Peak
RMS

Fig 5

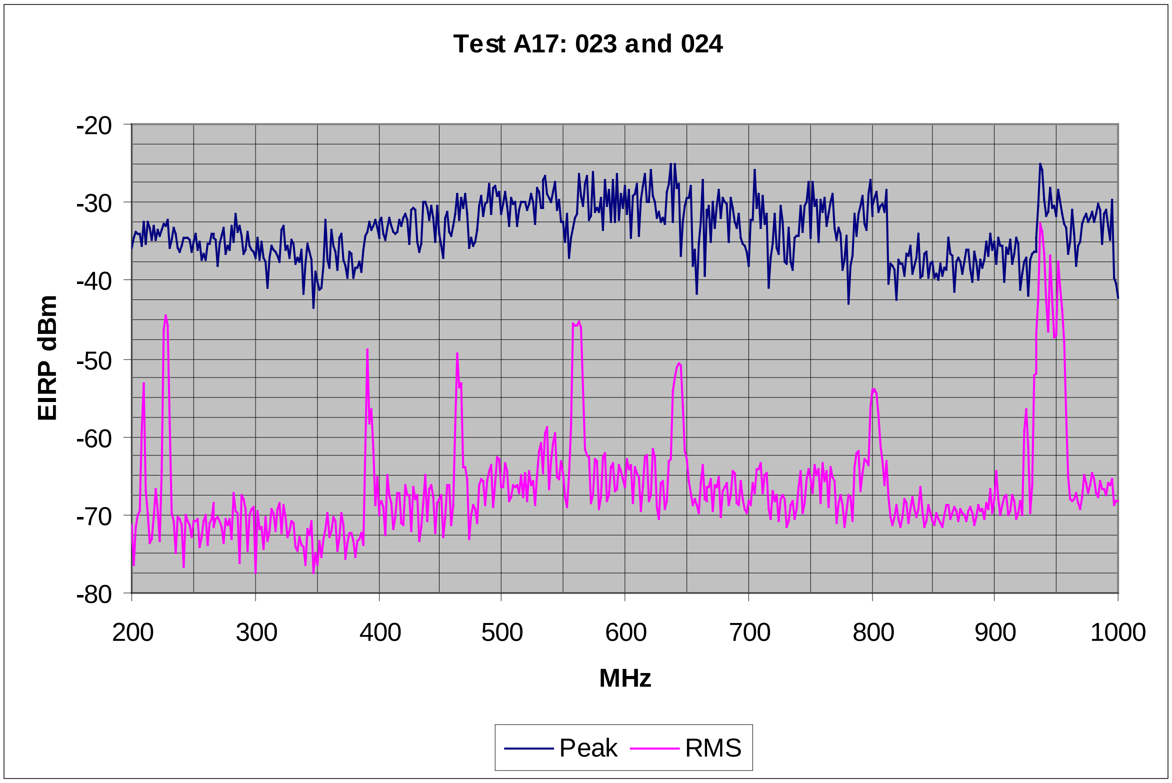

Test A17: 023 and 024
EIRP dBm
-20
-30
-40
-50
-60
-70
-80
200
300
400
500
600
700
800
900
1000
MHz
Peak
RMS

Fig 6

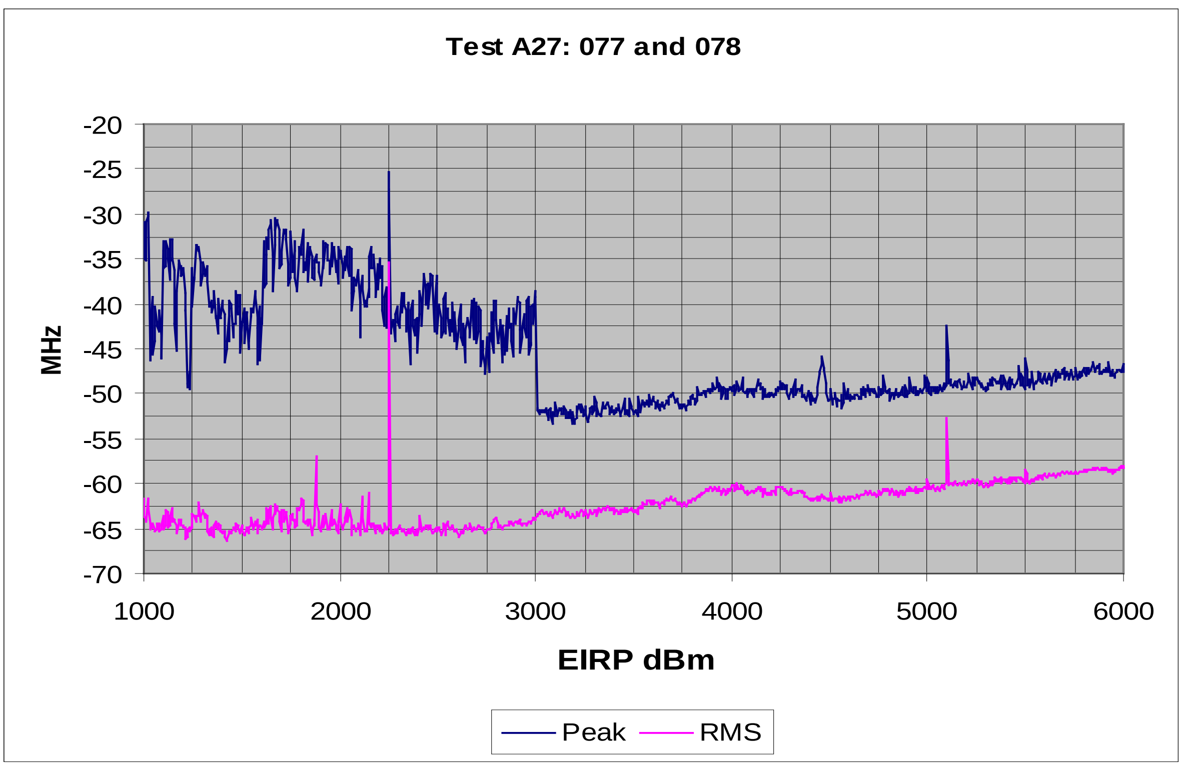

Test A27: 077 and 078
MHz
-20
-25
-30
-35
-40
-45
-50
-55
-60
-65
-70
1000
2000
3000
4000
5000
6000
EIRP dBm
Peak
RMS

Fig 7

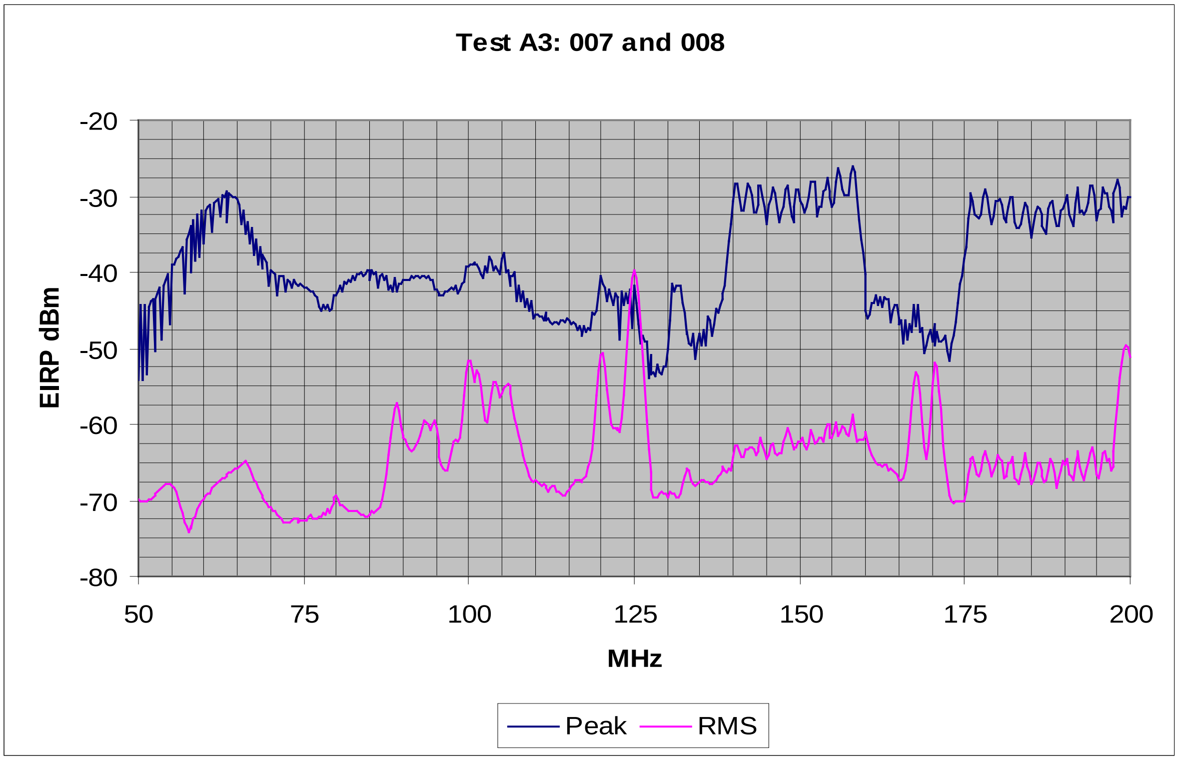

Test A3: 007 and 008
-20
-30
-40
-50
-60
-70
-80
EIRP dBm
50
75
100
125
150
175
200
MHz
Peak
RMS

Fig 8

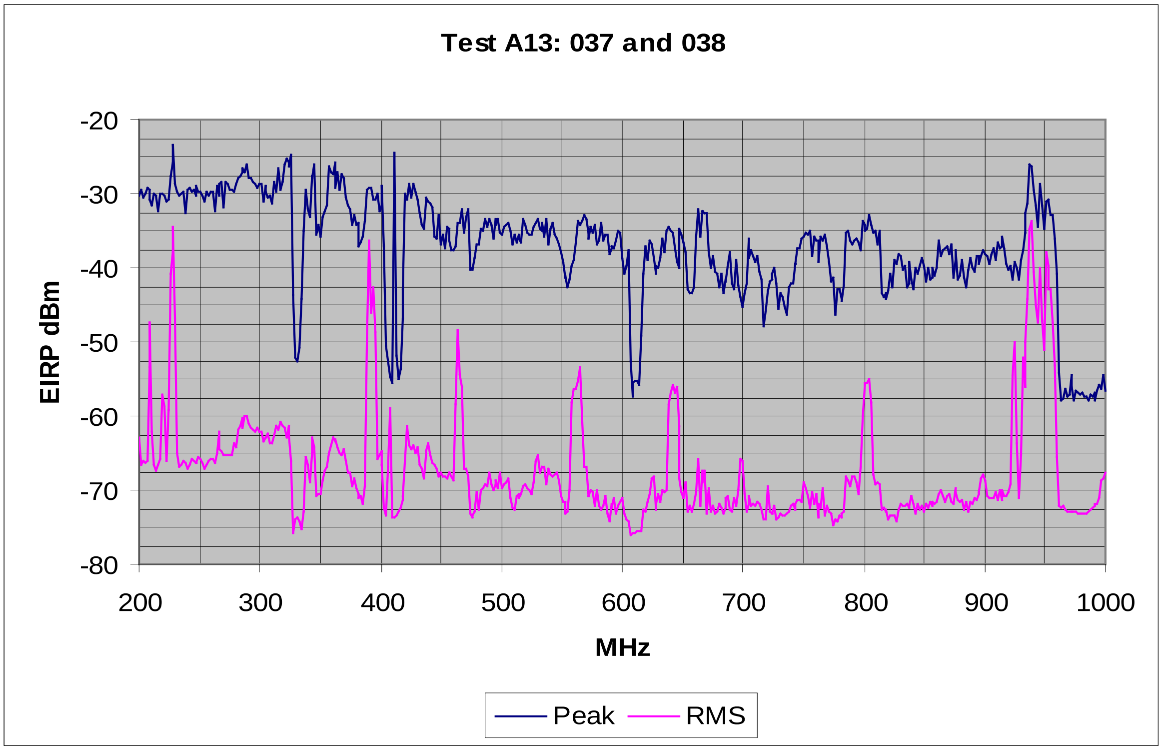

Test A13: 037 and 038
-20
-30
-40
-50
-60
-70
-80
EIRP dBm
200
300
400
500
600
700
800
900
1000
MHz
Peak
RMS

Fig 9

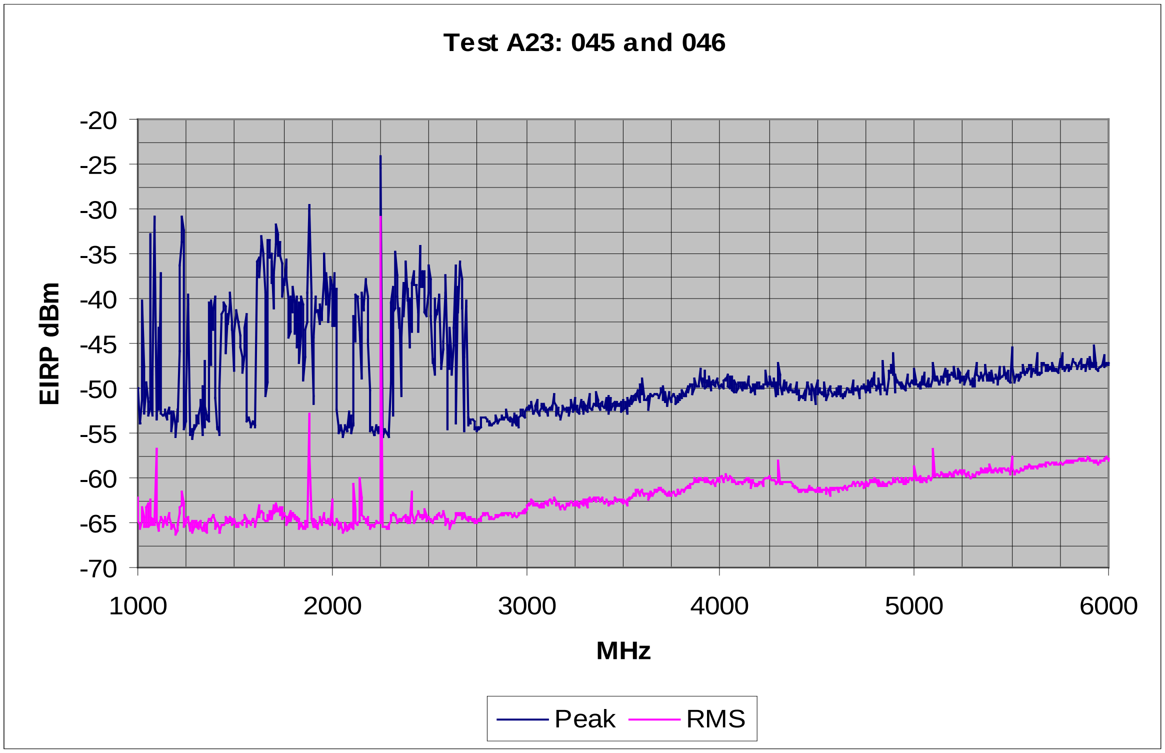

Test A23: 045 and 046
EIRP dBm
-20
-25
-30
-35
-40
-45
-50
-55
-60
-65
-70
1000
2000
3000
4000
5000
6000
MHz
Peak
RMS

Fig 10

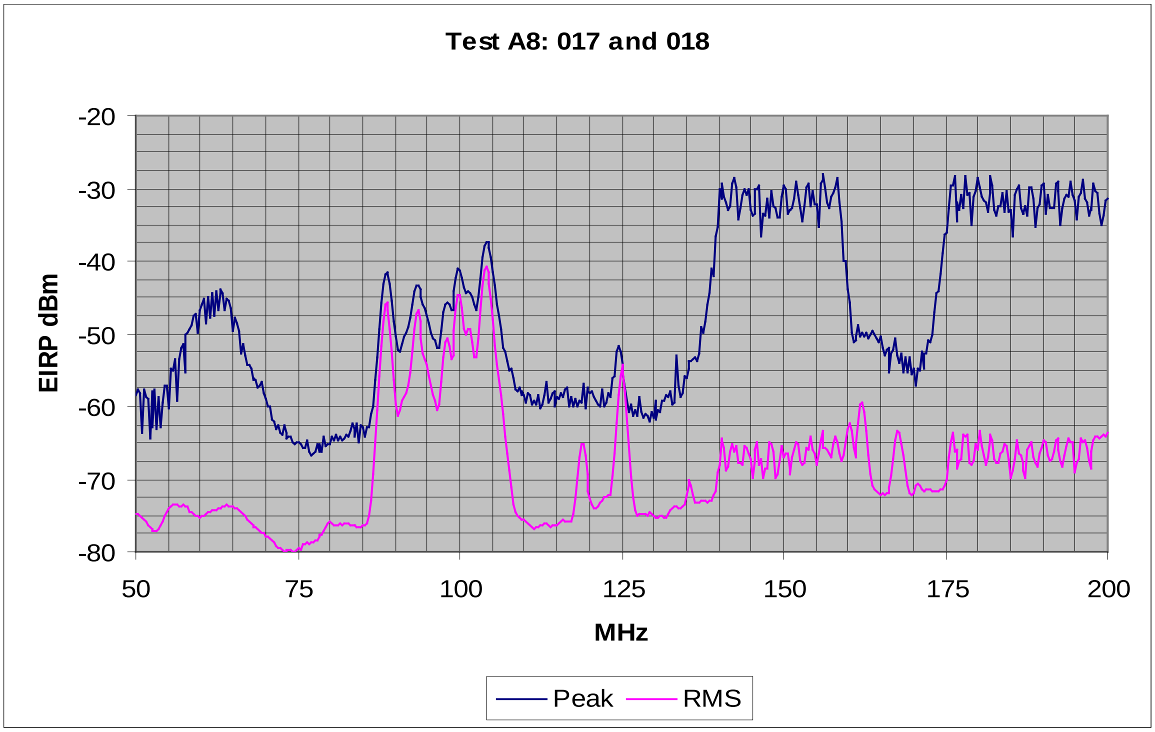

Test A8: 017 and 018
EIRP dBm
-20
-30
-40
-50
-60
-70
-80
50
75
100
125
150
175
200
MHz
Peak
RMS

Fig 11

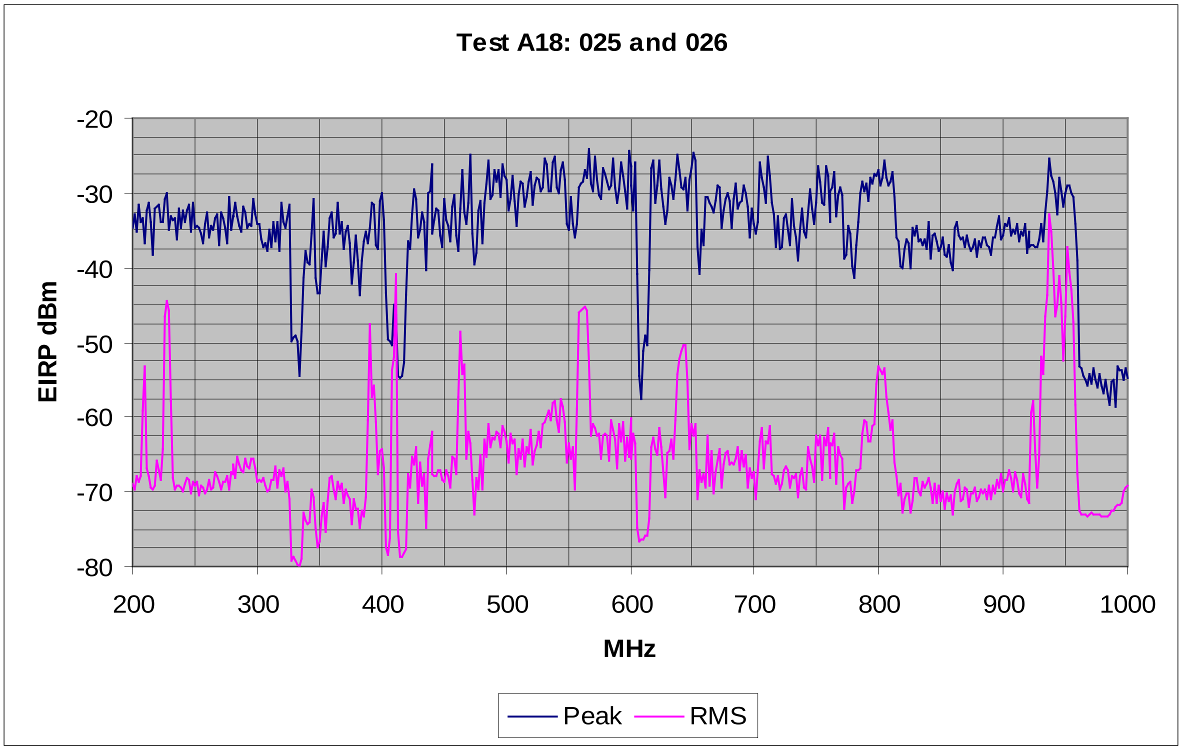

Test A18: 025 and 026
EIRP dBm
-20
-30
-40
-50
-60
-70
-80
200
300
400
500
600
700
800
900
1000
MHz
Peak
RMS

Fig 12

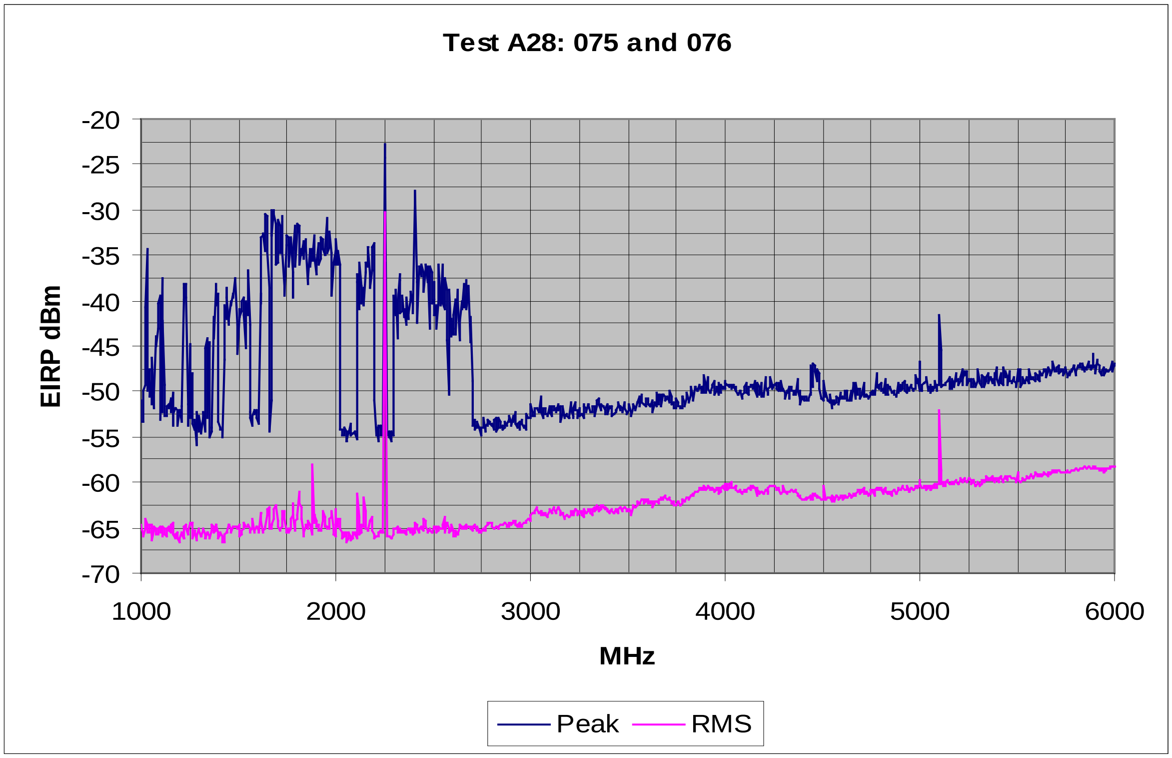

Test A28: 075 and 076
EIRP dBm
-20
-25
-30
-35
-40
-45
-50
-55
-60
-65
-70
1000
2000
3000
4000
5000
6000
MHz
Peak
RMS

Fig 13

INDOOR TEST

Test set up:

The test is performed in a semi anechoic chamber with a size of 22 × 13 × 9,5 meters (l × w × h).

The EUT was placed on a table with a height of 80 cm. on a turntable. Absorbers with ferrite tiles were placed below the table to prevent reflection from the floor. The receiver antenna height was 2 m, both with horizontal and vertical polarisation with a distance of 3 m to EUT. The EUT was rotated in 30 dgr step from 0 to 180 dgr., see photo on fig 32.

Quasi-Peak measurement with 3 m test distance:
120 kHz BW

Frequency MHz	EUT Az	Polarization HP/VP	Level dBm
50	0	VP	-73,6
60	0	VP	-67,2
60,95	180	VP	-62,2
70	0	VP	-73,9
75	0	VP	-79,3
80	0	VP	-80,9
90	0	VP	-71,5
100	0	VP	-70,8
110	0	VP	-78,5
120	0	VP	-77,6
130	0	VP	-76,9
158	0	VP	-54,7
160	0	VP	-55,3
160	180	VP	-54,8
180	0	VP	-54,9
180	180	VP	-54,5
50	90	HP	-86,5
60	90	HP	-78,3
70	90	HP	-87,2
75	90	HP	-89,1
80	90	HP	-85,9
90	90	HP	-81,7
100	90	HP	-72,3
110	90	HP	-76,5
120	90	HP	-84,7
130	90	HP	-82,7
160	90	HP	-56,4
180	90	HP	-53,8

Sveep measurement:

Test #	Configuration	Frequency Band	Antenna	RBW	VBW	Sweep Time	Az	Pol	Datafile (Peak)	Datafile (RMS)
B1	Ambient	50 MHz - 200 MHz	Biconic	1 MHz	3 MHz	15sec	-	V	100	101
B2	No notching	50 MHz - 200 MHz	Biconic	1 MHz	3 MHz	15sec	0	V	102	103
B3	No notching	50 MHz - 200 MHz	Biconic	1 MHz	3 MHz	15sec	30	V	104	105
B4	No notching	50 MHz - 200 MHz	Biconic	1 MHz	3 MHz	15sec	60	V	106	107
B5	No notching	50 MHz - 200 MHz	Biconic	1 MHz	3 MHz	15sec	90	V	108	109
B6	No notching	50 MHz - 200 MHz	Biconic	1 MHz	3 MHz	15sec	120	V	110	111
B7	No notching	50 MHz - 200 MHz	Biconic	1 MHz	3 MHz	15sec	150	V	112	113
B8	No notching	50 MHz - 200 MHz	Biconic	1 MHz	3 MHz	15sec	180	V	114	115
B9	Ambient	50 MHz - 200 MHz	Biconic	1 MHz	3 MHz	15sec	-	H	130	131
B10	No notching	50 MHz - 200 MHz	Biconic	1 MHz	3 MHz	15sec	0	H	128	129
B11	No notching	50 MHz - 200 MHz	Biconic	1 MHz	3 MHz	15sec	30	H	126	127
B12	No notching	50 MHz - 200 MHz	Biconic	1 MHz	3 MHz	15sec	60	H	125	124
B13	No notching	50 MHz - 200 MHz	Biconic	1 MHz	3 MHz	15sec	90	H	122	123
B14	No notching	50 MHz - 200 MHz	Biconic	1 MHz	3 MHz	15sec	120	H	120	121
B15	No notching	50 MHz - 200 MHz	Biconic	1 MHz	3 MHz	15sec	150	H	118	119
B16	No notching	50 MHz - 200 MHz	Biconic	1 MHz	3 MHz	15sec	180	H	117	116

See fig 14 to 28.

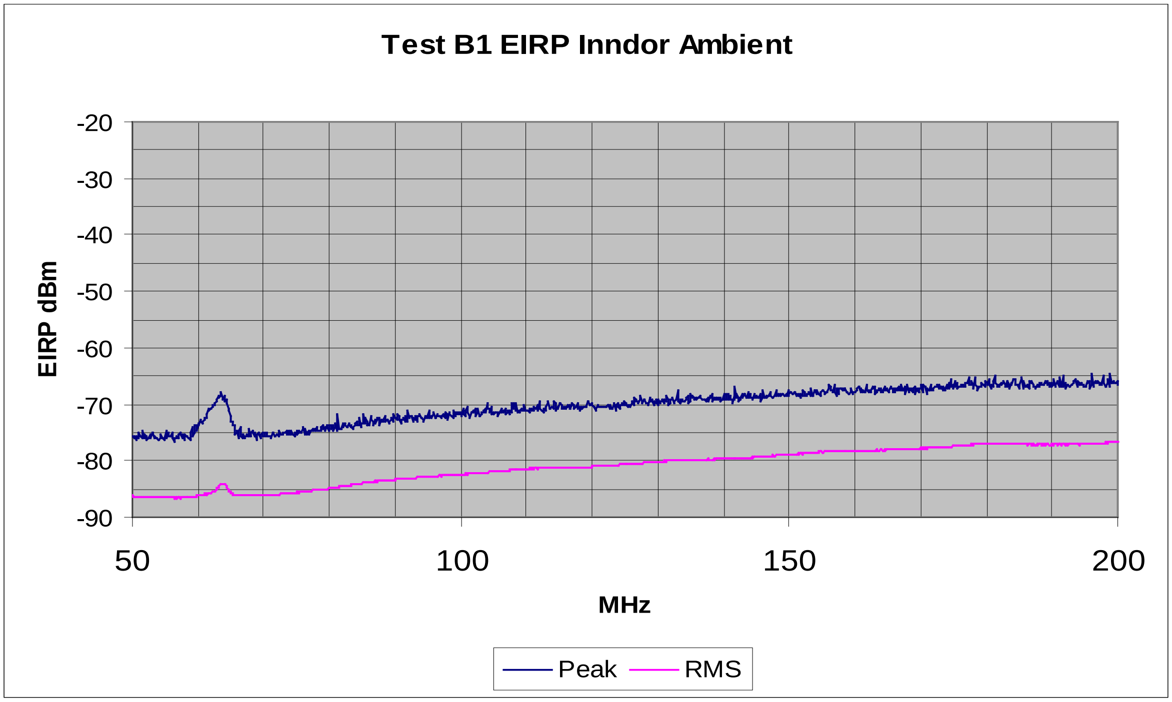

Test B1 EIRP Inndor Ambient
-20
-30
-40
-50
-60
-70
-80
-90
EIRP dBm
50
100
150
200
MHz
Peak
RMS

Fig 14

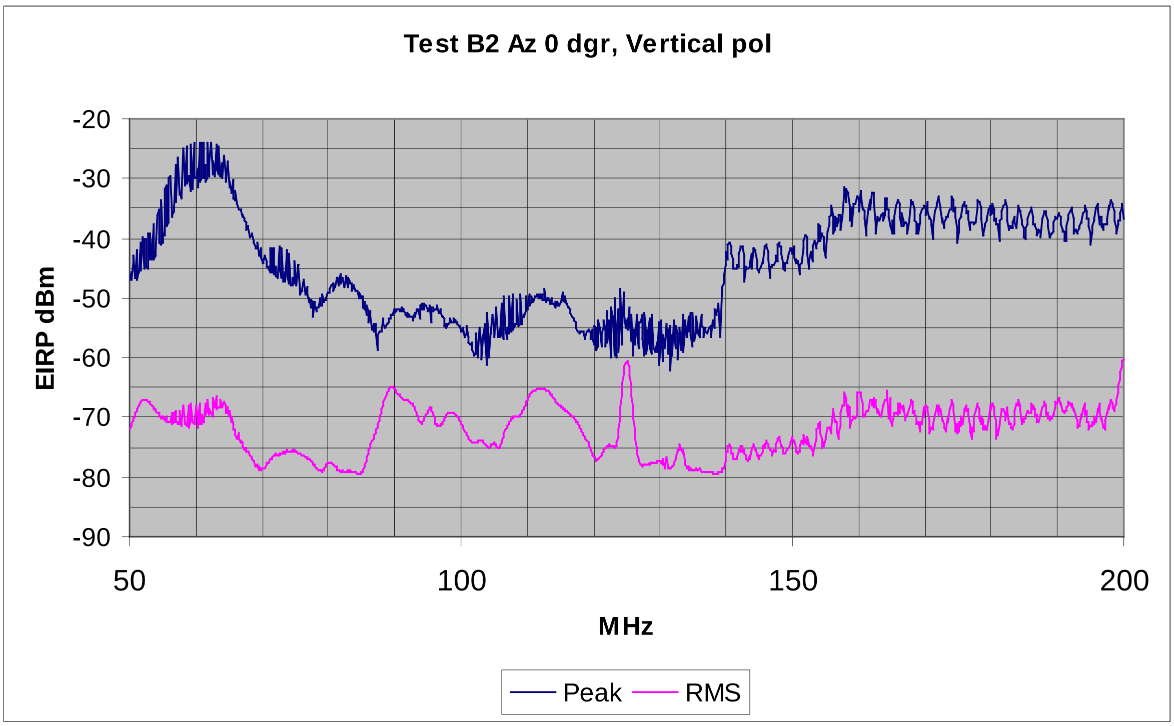
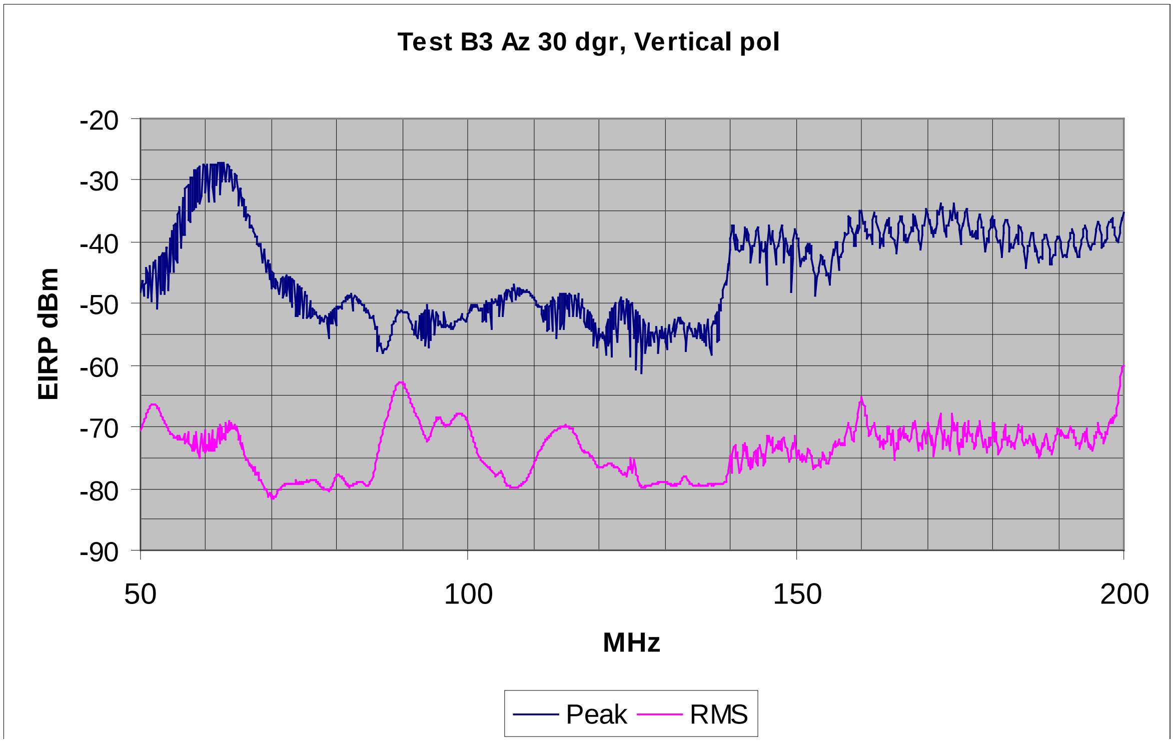
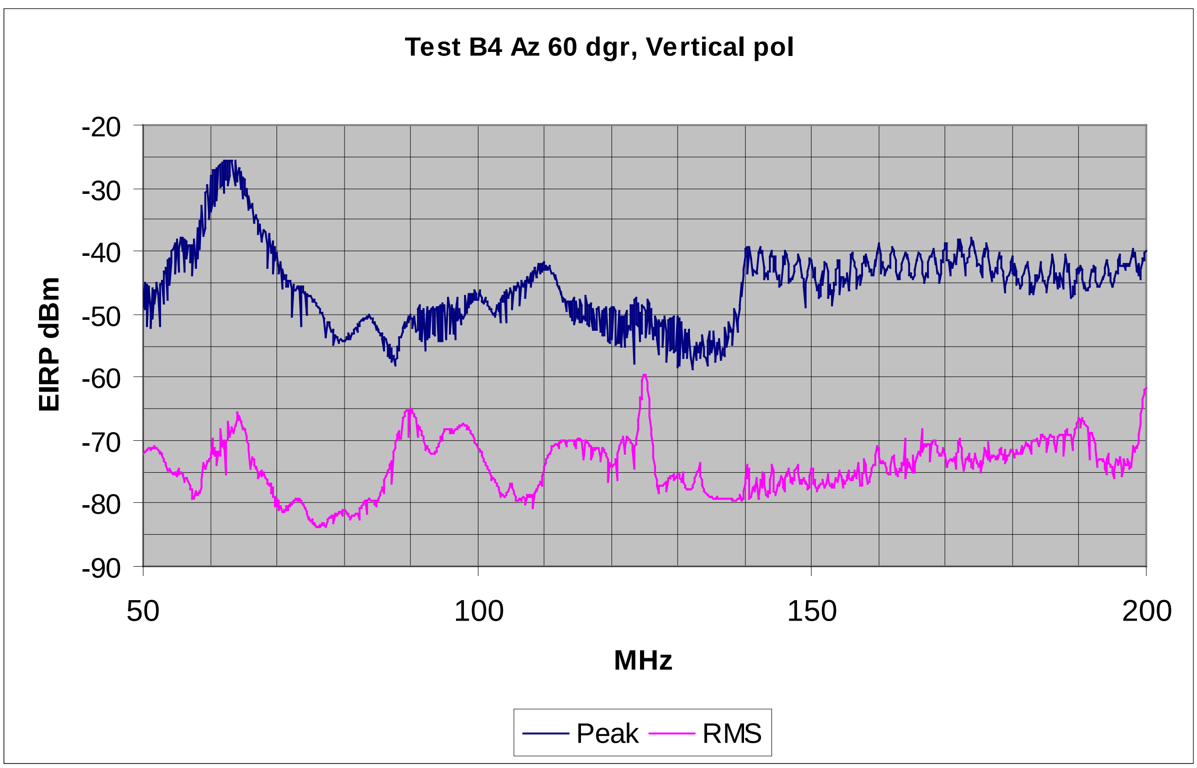

Test B2 Az 0 dgr, Vertical pol
-20
-30
-40
-50
-60
-70
-80
-90
EIRP dBm
50
100
150
200
MHz
Peak
RMS

Fig 15



Test B3 Az 30 dgr, Vertical pol
EIRP dBm
-20
-30
-40
-50
-60
-70
-80
-90
50
100
150
200
MHz
Peak
RMS

Fig 16



Test B4 Az 60 dgr, Vertical pol
EIRP dBm
-20
-30
-40
-50
-60
-70
-80
-90
50
100
150
200
MHz
Peak
RMS

Fig 17

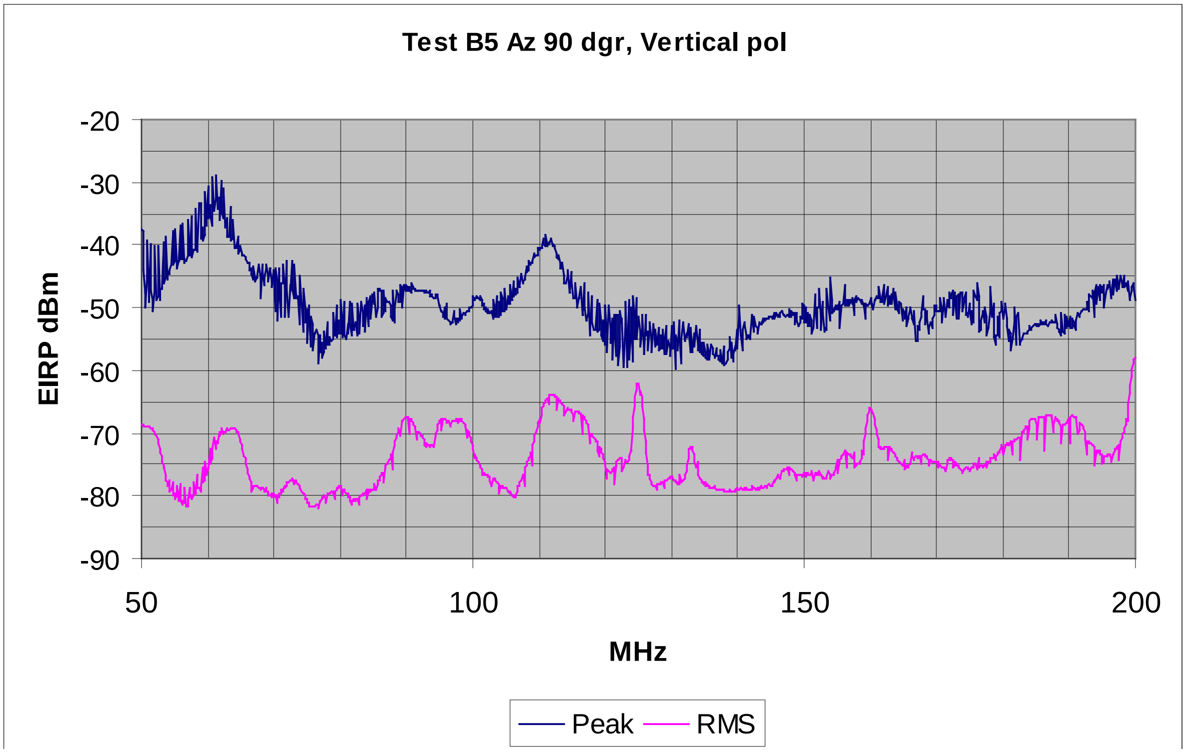

Test B5 Az 90 dgr, Vertical pol
EIRP dBm
-20
-30
-40
-50
-60
-70
-80
-90
50
100
150
200
MHz
Peak
RMS

Fig 18

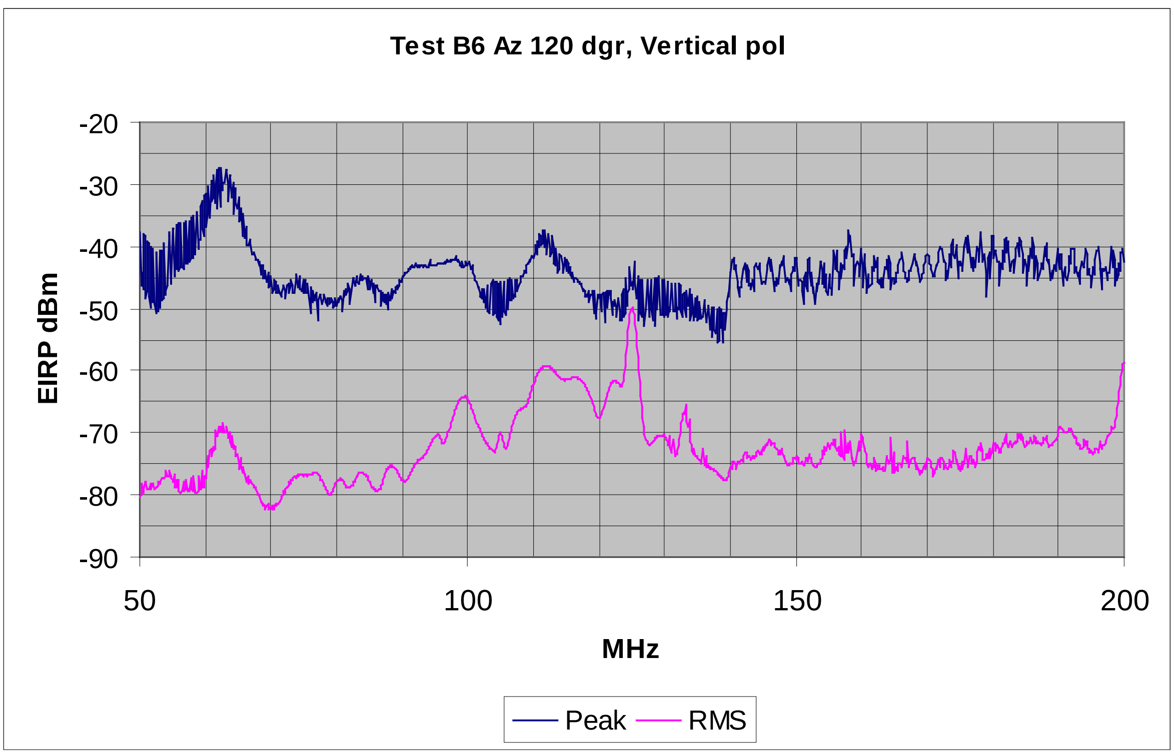

Test B6 Az 120 dgr, Vertical pol
EIRP dBm
-20
-30
-40
-50
-60
-70
-80
-90
50
100
150
200
MHz
Peak
RMS

Fig 19

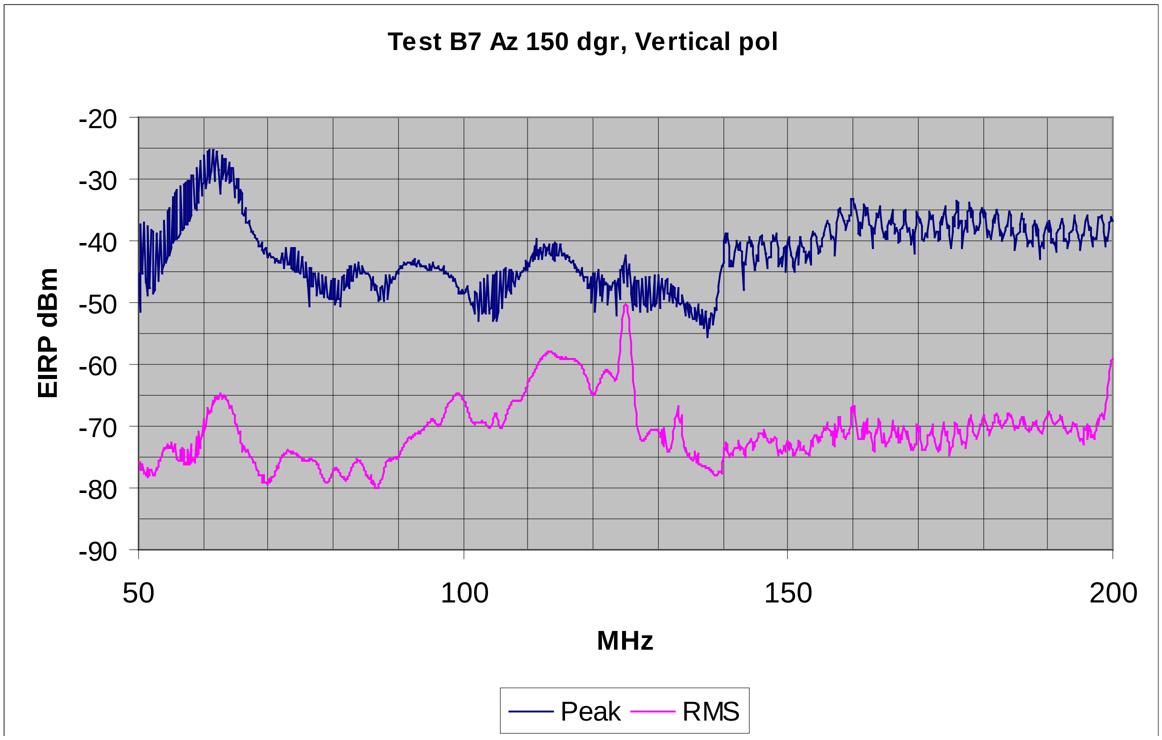

Test B7 Az 150 dgr, Vertical pol
-20
-30
-40
-50
-60
-70
-80
-90
EIRP dBm
50
100
150
200
MHz
Peak
RMS

Fig 20

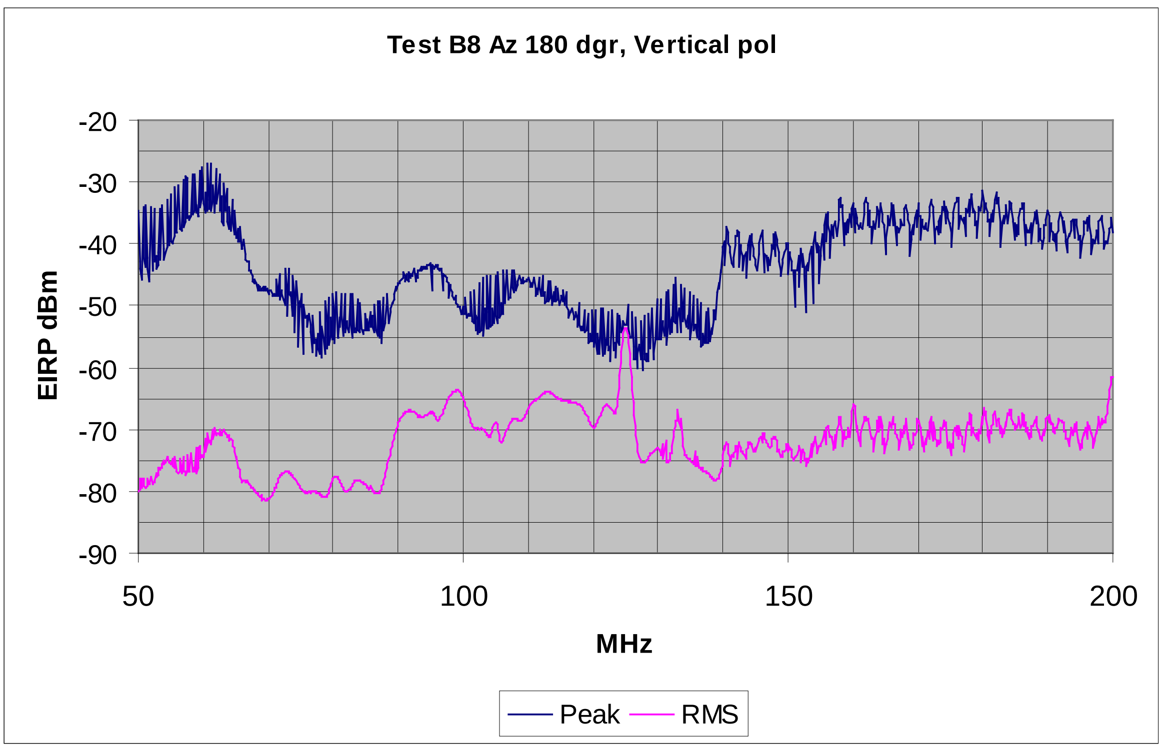
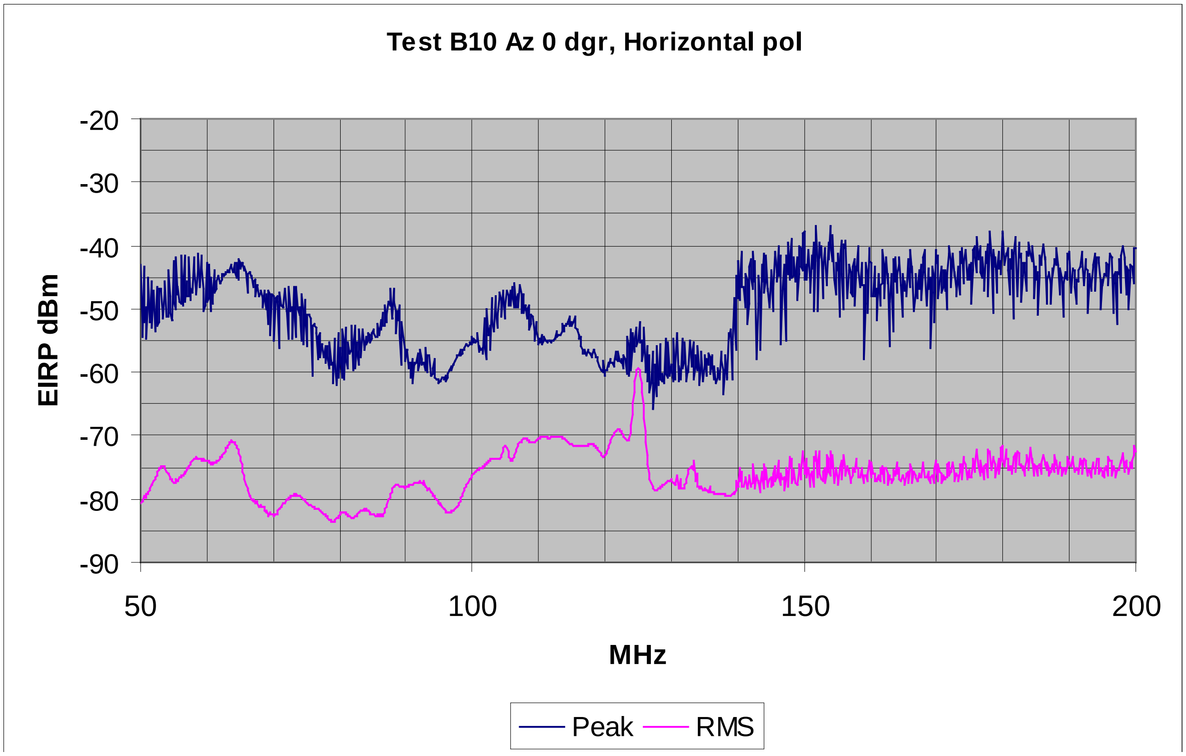
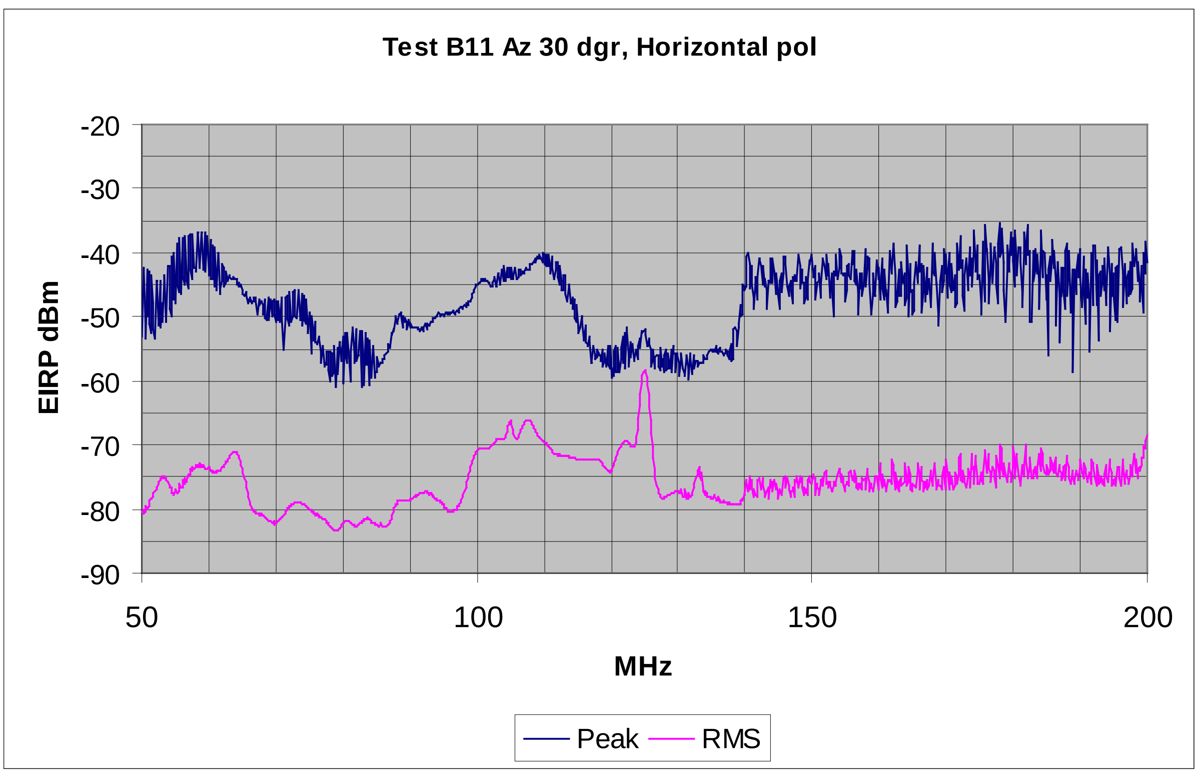

Test B8 Az 180 dgr, Vertical pol
-20
-30
-40
-50
-60
-70
-80
-90
EIRP dBm
50
100
150
200
MHz
Peak
RMS

Fig 21



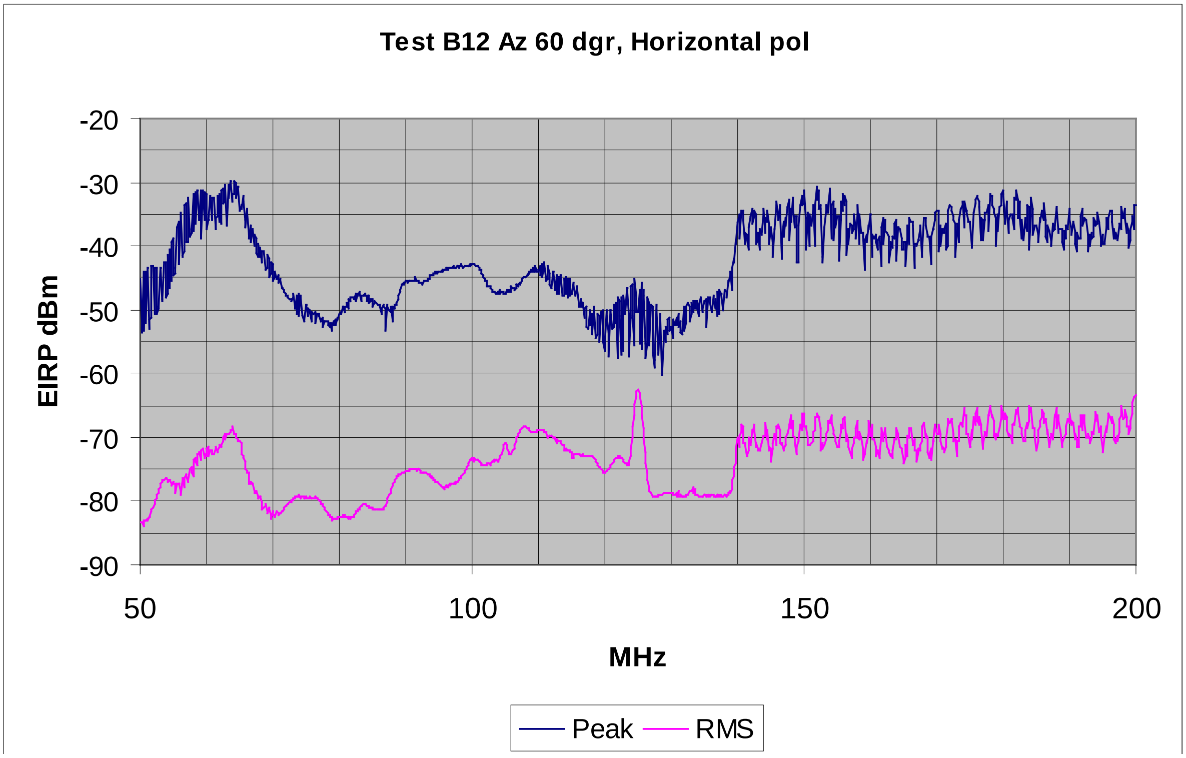
Test B10 Az 0 dgr, Horizontal pol
EIRP dBm
-20
-30
-40
-50
-60
-70
-80
-90
50
100
150
200
MHz
Peak
RMS

Fig 22



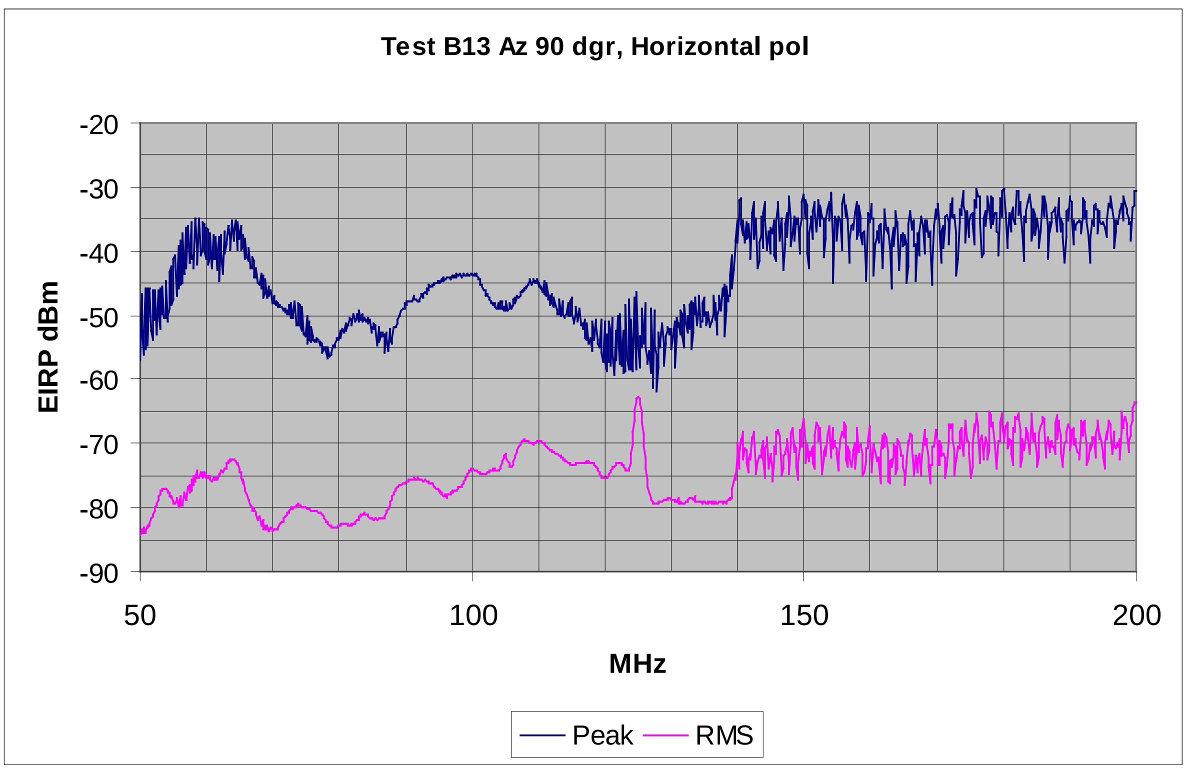
Test B11 Az 30 dgr, Horizontal pol
EIRP dBm
-20
-30
-40
-50
-60
-70
-80
-90
50
100
150
200
MHz
Peak
RMS

Fig 23



Test B12 Az 60 dgr, Horizontal pol
EIRP dBm
-20
-30
-40
-50
-60
-70
-80
-90
50
100
150
200
MHz
Peak
RMS

Fig 24



Test B13 Az 90 dgr, Horizontal pol
EIRP dBm
-20
-30
-40
-50
-60
-70
-80
-90
50
100
150
200
MHz
Peak
RMS

Fig 25

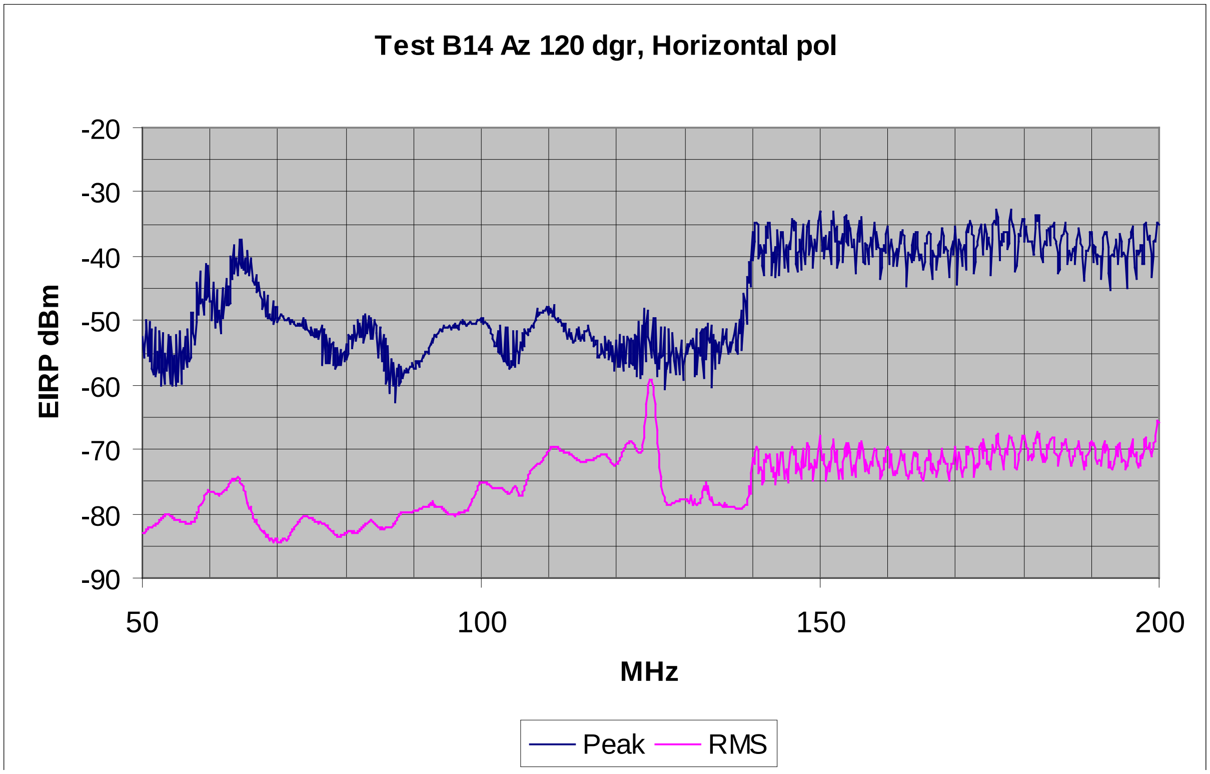

Test B14 Az 120 dgr, Horizontal pol
EIRP dBm
-20
-30
-40
-50
-60
-70
-80
-90
50
100
150
200
MHz
Peak
RMS

Fig 26

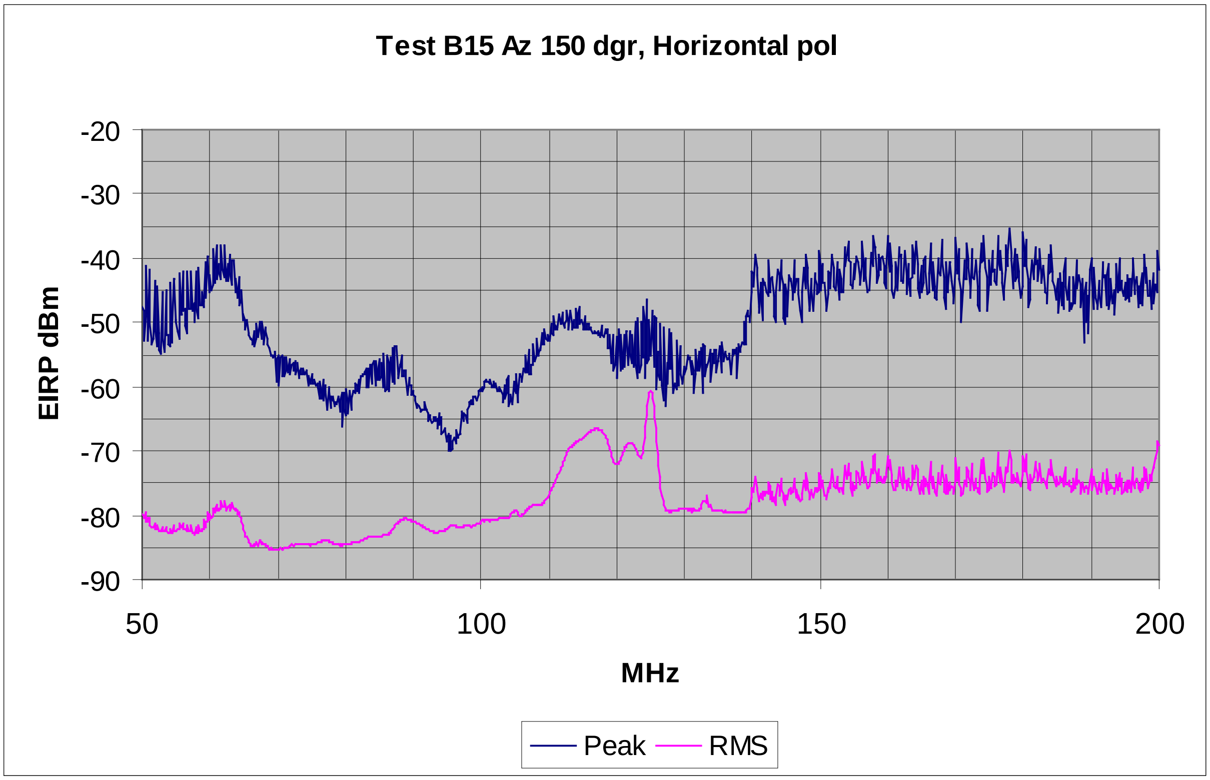

Test B15 Az 150 dgr, Horizontal pol
EIRP dBm
-20
-30
-40
-50
-60
-70
-80
-90
50
100
150
200
MHz
Peak
RMS

Fig 27

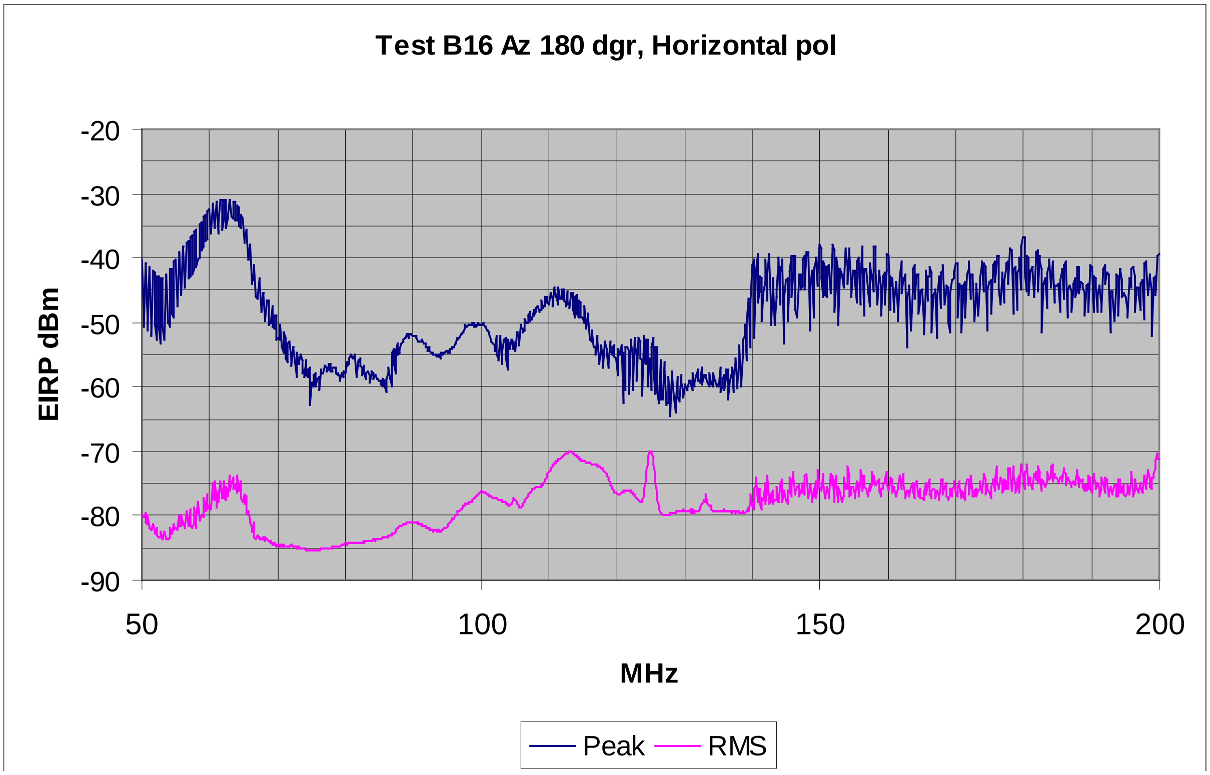

Test B16 Az 180 dgr, Horizontal pol
-20
-30
-40
-50
-60
-70
-80
-90
EIRP dBm
50
100
150
200
MHz
Peak
RMS

Fig 28

TEST EQUIPMENT AND ANCILLARIES USED FOR TESTS

To facilitate inclusion on each page of the test equipment used for related tests, each item of test equipment and ancillaries such as cables are identified (numbered) by the Test Laboratory.

No	Instrument/Ancillary	Type	Manufacturer	Ref. No.
1	Test receiver	ESN	R&S	LR 1237
2	Biconical antenna	3104C	EMCO	LR 1262
3	Log.per antenna	3146	EMCO	LR 1221
4	Horn antenna	3115	EMCO	LR 1330
5	Spectrum analyzer	FSP	R&S	LR 1551
6	Pre.amp	8447F	HP	TF 03305
7	Pre.amp	8449B	HP	TF 03475
8	Cable	Sucoflex 106 6 m	Suhner	

PHOTO OF EUT AND TEST SET UP

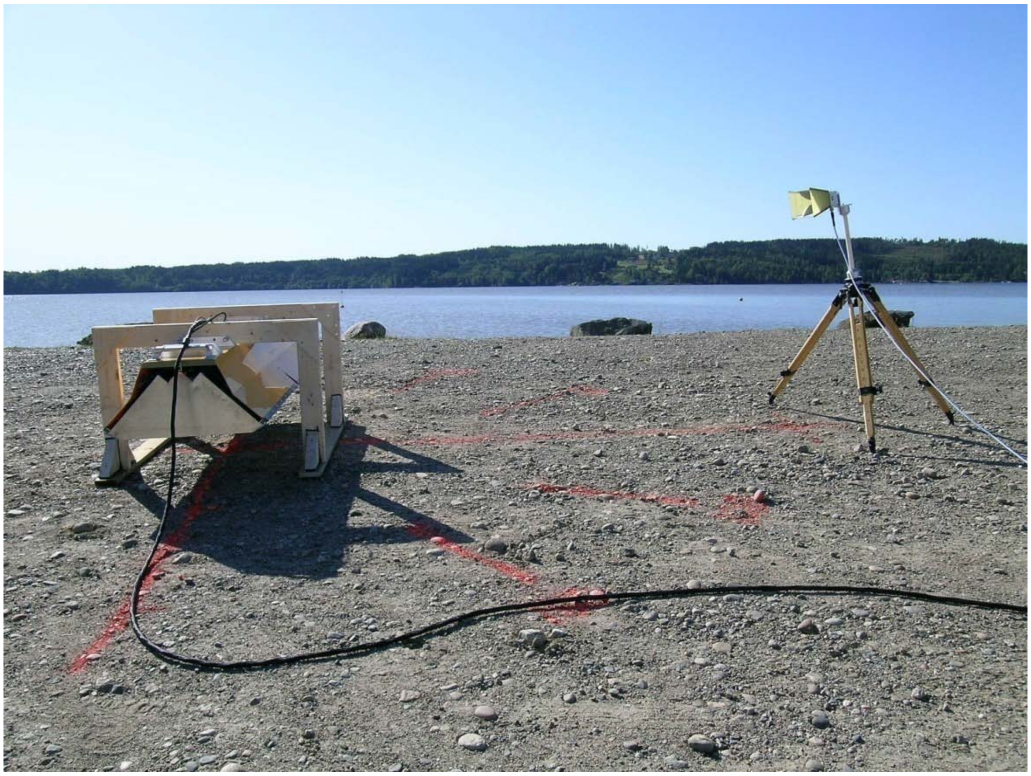


Fig 29 Test set up outdoor measurement

Fig 30 Test set up outdoor measurement

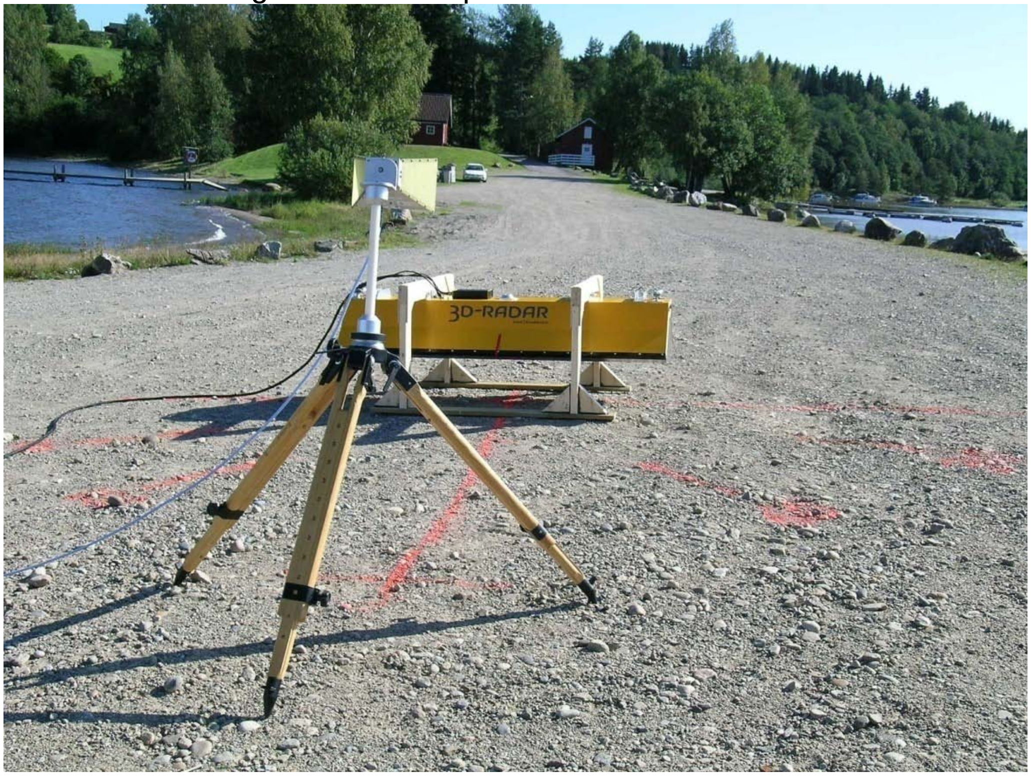


Fig 31 Test set up outdoor measurement

Fig 32 Test set up indoor measurement

APPENDIX F: STEP FREQUENCY GPR (SF GPR) TRANSMISSION LOSS CALCULATIONS THROUGH A TYPICAL CONCRETE BRIDGE DECK

The following report contains supporting documentation and results of the calculations performed for the research initiative in this report. Since it is an unpublished internal working paper, it would not be otherwise accessible as a reference to use for the current report. The report in this appendix has not been edited or changed in any way from its original form as a working paper that was submitted to the SPS of the Interdepartment Radio Advisory Committee (IRAC).

Note that the term $Loss_{spreading}$, is the same as the later abbreviated version $Loss_{spr}$ found in this appendix. The terms are mathematically equivalent. The definition was inadvertently left out of the original paper. They are both defined as the spreading loss in decibels. Since the paper is being reproduced unchanged, clarification is being provided in this foreword.

Step Frequency GPR (SF GPR) Transmission Loss Calculations Through a Typical Concrete Bridge Deck

February 15, 2007

The NTIA Spectrum Planning Subcommittee (SPS) Coast Guard representative requested additional documentation regarding Step Frequency GPR Transmission losses through a concrete bridge deck. This request was made to address potential interference concerns that could arise when a vessel crosses under a bridge deck while an SF GPR is being used to evaluate the bridge deck.

The total losses are computed based on the assumption that radar energy is transmitted through a concrete bridge deck superstructure with an average thickness equal to 1 foot and at a position 1 meter or more below the bridge deck, which is provided for reasonable clearance of the vessel underneath the bridge deck. These assumptions are consistent with United States Coast Guard 2005 CFR Title 33, Volume 1, Subchapter J – Bridges.

The following equation for losses was used to account for both transmission/attenuation losses and spreading losses [Daniels]:

$$Loss_{total} = Loss_{transmission+attenuation} + Loss_{spreading}$$

where: $$Loss_{trans} = 2*(20*\log_{10}(\frac{4Z_m Z_a}{\left|Z_m + Z_a\right|^2})) + Loss_{attenuation}$$

Z_a = *Characteristic impedance of air = 377 Ω*
Z_m = *Characteristic impedance of concrete = 160 Ω*
$Loss_{att}$ = *Attenuation loss in concrete = 3 dB/ft at Freq<1000 MHz*
$Loss_{att}$ = *Attenuation loss in concrete = 6 dB/ft at Freq≥1000 MHz*

$$Loss_{spr} = 20*\log_{10}(\frac{\lambda}{4\pi R})$$

$\lambda = Wavelength$
R = Radial distance from source

This equation for $Loss_{total}$ was used to compute losses corresponding to each range of frequencies used by the Step Frequency GPR system. Table 1 presents the results:

Freq (Hz)	λ	Spreading Loss (dB)	Total Loss (dB)
140000000	2.142857	-15.36433275	-21.36433275
178000000	1.685393	-17.45017208	-23.45017208
588000000	0.510204	-27.82931856	-33.82931856
1285000000	0.233463	-34.61983459	-43.61983459
1800000000	0.166667	-37.54722214	-46.54722214
1995000000	0.150376	-38.44063004	-47.44063004
2000000000	0.15	-38.46237195	-47.46237195
1202000000	0.249584	-34.03986139	-43.03986139
1585000000	0.189274	-36.44235737	-45.44235737

Table 1. Calculations for $Loss_{total}$ at representative Step Frequency GPR operating frequencies. Representative frequencies are selected as center frequencies within operating ranges defined in Tables 2 and 3.

Tables 2 and 3 describe emissions of the Step Frequency GPR within its operating range and include calculations for losses due to the concrete bridge deck compared with back lobe emission levels (subtracted from bore sight emission levels).

Frequency (MHz)	Peak EIRP (dBm)	Average EIRP (dBm)	Concrete bridge deck loss (dB)	Δ (bore sight - back lobe) (dB)
<140	-60.7	-93.7	21	5.0
140 – 216	-25.7	-58.7	23	10.1
216 – 960	-23.2	-56.2	34	14.1
960 – 1610	-32.3	-65.3	44	16.6
1610 – 1990	-20.3	-53.3	47	12.4
1990 – 2000	-18.3	-51.3	47	14.7
>2000	-53.3	-86.3	48	14.7

Table 2. Maximum back lobe EIRP levels for both peak and average power (1MHz resolution BW).

Frequency (MHz)	Average EIRP (dBm) in 1 kHz BW	Concrete bridge deck loss (dB)	Δ (bore sight - back lobe) (dB)
1164 – 1240	-75.3	43	11.7
1559 – 1610	-75.3	45	12.7

Table 3. Emissions suppressed in specified bandwidths.

Note that the fourth column of Table 1 corresponds to the third column of Tables 2 and 3. Also note that emissions are reduced more by concrete bridge deck losses than bore sight minus back lobe levels.

Reference:

Daniels, D.J., Surface Penetrating Radar, IEEE, December 1, 1996, pp. 300.

REFERENCES

1. Scott, M.L., Gagarin, N., Oskard, M., and Mills, M.K. (2005). "Step Frequency Ground Penetrating Radar Applications to Highway Infrastructure Measurement and System Integration Feasibility With Complementary Sensors," *Review of Progress in Quantitative Nondestructive Evaluation*, 1164–1170, Brunswick, ME.

2. Scott, M.L., Gagarin, N., Mills, M.K., and Oskard, M. (2006). *Step Frequency GPR Evaluation of the Natchez Trace Parkway: Pavement and Infrastructure Measurement and Assessment for FHWA Digital Highway Measurement Vehicle Applications*, Highway Geophysics Nondestructive Evaluation Conference, Saint Louis, MO.

3. National Telecommunications and Information Administration. (2008). "Technical Standards for Federal 'Non-Licensed' Devices," Annex K, *Manual of Regulations and Procedures for Federal Radio Frequency Management*, 1–42.

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