Susceptibility

Optimal Design Microwave Radiated Susceptibility Test System

A Discussion of a Susceptibility Test Set Up Which Can Achieve High Field Levels Using Low Power Amplifiers

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Commercial and in-house EMI test facilities desiring to provide compliance testing services under the effectivity of MIL-STD-461C and EMI sections of the commercial avionics environmental qualification specification RTCA/DO-160C must have a minimum 20 Volts/meter (V/m) capability from 10 kHz to at least 18 GHz. To compete in the entire market for test services, however, it is necessary to supply test capability to levels exceeding 20 V/m. Many military programs and, in the future, an increasing share of commercial avionics will require 200 V/m testing and even higher levels at spot frequencies. Above 1 GHz, this becomes expensive because of the high cost of amplifier gain-octave band product. For instance, a 200 Watt Traveling Wave Tube Amplifier (TWTA) covering a single octave band will run approximately $30,000. (The TWTA has become the signal source of choice for EMI testing above 1 GHz.) Acquiring the capability to generate field intensity levels above 20 V/m is often felt to be uneconomical because of the sharp rise in price between 20 W TWTAs sufficient for 20 V/m and higher power TWTAs. It is not generally recognized, however, that field intensities greatly in excess of 20 V/m can be transmitted from the lower power amplifiers, by careful test set up design and antenna selection. This article describes an optimal test set up utilizing efficient antennas that maximize the field intensity achievable from a given signal source (V/m/Watt). Technical issues are addressed first, then a parts list and cost breakdown is given.

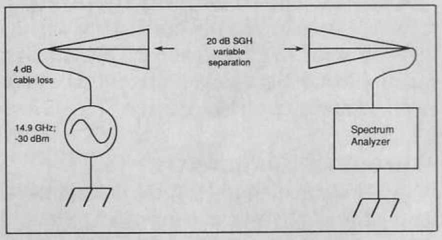

Figure 1. Test set up to determine actual vs. far field boundary.

Background

Potential purchasers of a microwave radiated susceptibility test capability should be aware of the variety of TWTA models available. The heart of a TWTA is the traveling wave tube (TWT). A small number of tube vendors provide a limited variety of tubes to all TWTA manufacturers. For most EMI test purposes, there are only two tube models of interest. These are the tubes built into the 10 or 20 W TWTAs, and the tubes built into the 100 to 250 W TWTAs. The tube type drives the amplifier price. Thus, there is little price differential between a 10 W or 20 W TWTA, or between a 100 W or 200 W TWTA. Within the last few years, 50 W TWTAs based on the lower power tubes have appeared on the market with prices about 10% higher than a comparable 20 W TWTA. Two-octave band TWTAs provide double the frequency range at a cost comparable to the single octave model. These are complementary measures which add to the value of the amplifier.

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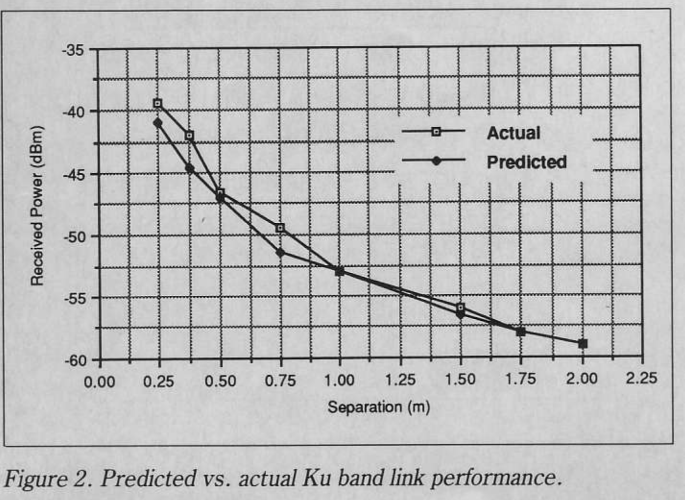

Figure 2. Predicted vs. actual Ku band link performance.

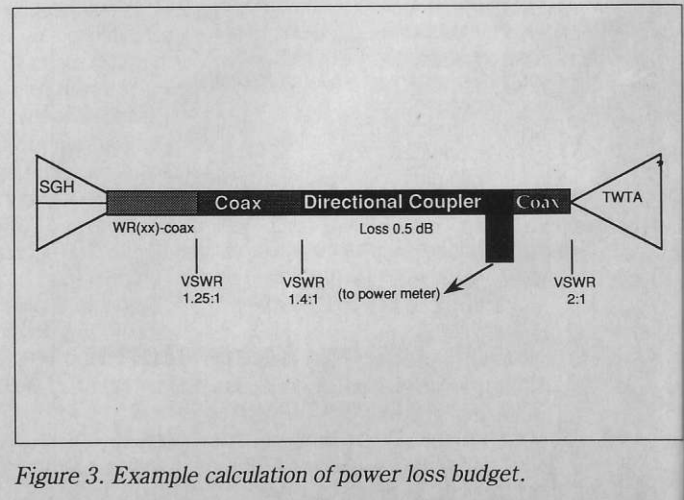

Figure 3. Example calculation of power loss budget.

Band (GHz)	Wave-guide/ coax VSWR/ loss (dB)	Coax Switch #1 VSWR/ loss (dB)	C.S. #1 loss (dB)	C.S. #2 VSWR /loss (dB)	C.S. #2 loss (dB)	directional coupler VSWR /loss (dB)	d.c loss (dB)	TWTA VSWR /loss (dB)	Total Loss (dB)
1.12-1.7	1.25/0.05	1.2/0.04	0.2	1.2/0.04	0.2	1.15/0.02	0.2	2/0.5	1.25
1.7-2.6	1.25/0.05	1.2/0.04	0.2	1.2/0.04	0.2	1.15/0.02	0.2	2/0.5	1.25
2.6-3.95	1.25/0.05	1.3/0.08	0.3	1.3/0.08	0.3	1.15/0.02	0.2	2/0.5	1.53
3.95-5.85	1.25/0.05	1.3/0.08	0.3	---------	----	1.15/0.02	0.2	2/0.5	1.15
5.85-8.2	1.25/0.05	1.3/0.08	0.3	---------	----	1.20/0.04	0.2	2/0.5	1.17
8.2-12.4	1.25/0.05	-------	----	---------	----	1.25/0.05	0.3	2/0.5	0.90
12.4-18	1.50/0.18	-------	----	---------	----	1.35/0.10	0.5	2/0.5	1.28

Table 1. Power Loss Calculations

Freq. Band (GHz)	Mid-band Freq. (GHz)	Antenna Aperture (inches)	Antenna-UUT separation (meters)	Far Field (meters)	**Field Strength (Volts/meter)**
1.12-1.7	1.38	12	0.90	0.86	**70**
1.7-2.6	2.1	8	0.60	0.58	**100**
2.6-3.95	3.2	4.72	0.32	0.31	**200**
3.95-5.85	4.8	2.89	0.32	0.17	**200**
5.85-8.2	6.9	2.02	0.32	0.13	**200**
8.2-12.4	10.0	1.58	0.32	0.11	**200**
12.4-18	14.9	0.93	0.32	0.06	**200**

Table 2. Field Intensity vs. Transmitted Power for 10 dBi SGH

Assuming a 1-18 GHz 20 V/m capability, achieved with 20 Watt TWTA's and conventional EMI test antennas (log-conicals, double ridge guide horns/horn fed dishes), a group of new test set ups are described that facilitate the generation of field intensities ranging from 70 V/m at 1 GHz to 200+ V/m at 3 GHz and higher frequencies. The extra required passive microwave equipment is relatively inexpensive: approximately $12,000. Thus the cost of upgrading from 20 V/m to 70 V/m over the frequency range 1-18 GHz, and to 200 V/m or greater above 3 GHz is about that of one 20 Watt octave band TWTA. Furthermore, because the necessary items are passive, reliability and portability are enhanced (relative to larger, heavier, more powerful amplifiers, which are less reliable than the 20 Watt TWTAs).

The advantages in capital outlay are significant: each 20 Watt TWTA costs about $10,000, while a 200 Watt TWTA costs about $30,000. Thus, to cover 1-18 GHz, a savings of $70k-$100k may be realized, depending on the amplifier manufacturer and models available. Therefore the return on investment is much greater and there is an impressive competitive advantage relative to a facility which prices services similarly but has a much greater investment in test equipment. There are only two disadvantages to the proposed design. The first is economic, and the second political.

(1) The tradeoff between using a low power amplifier vs. a high power amplifier, other than initial investment, reliability, and portability, is in the illuminated spot size. The described low power amplifier set up, other things equal, illuminates a spot diameter about 1/3 the size of that of the higher power amplifier. This is very theoretical. Note the use of the phrase "other things equal." In reality, a typical set up using a single broadband horn to cover multioctave bands is always operating in the near field at frequencies an octave or greater above its low frequency cut-off so that it is not clear what spot size is illuminated. Also, since the gain of a horn increases with the square of the frequency, the spot size will continually diminish with increasing frequency.

The decision here is economic: for a greater initial investment, an acceptance of reduced portability and reliability, a larger spot diameter (theoretically, other things equal) can be illuminated. With the 20 Watt TWTA's illuminated spot diameter at 70 V/m can be as large as 0.4 m, whereas the 200 Watt TWTA will illuminate a 1.3 meter diameter. The lower power set up will require multiple antenna positions to scan a large unit under test (UUT) arrangement. The tradeoff is initial investment vs. test time, i.e. fixed vs. variable costs.

(2) The political aspect of this problem relates to the MIL-STD-462 and RTCA/DO-160 dicta that a radiated test set up maintain a one meter separation between antenna and UUT. This is not the most economical test set up, nor is it technically justifiable. The technically correct antenna-UUT separation criteria is that UUT be plane wave illuminated with a minimum illumination spot diameter of $\lambda/2$. The far field of an aperture type antenna is given by

$$r_{separation} \geqslant \frac{2D^2}{\lambda} \qquad (1)$$

where D is the largest antenna aperture and λ is the wavelength.

Selection of the optimum antenna can keep this distance below one half meter

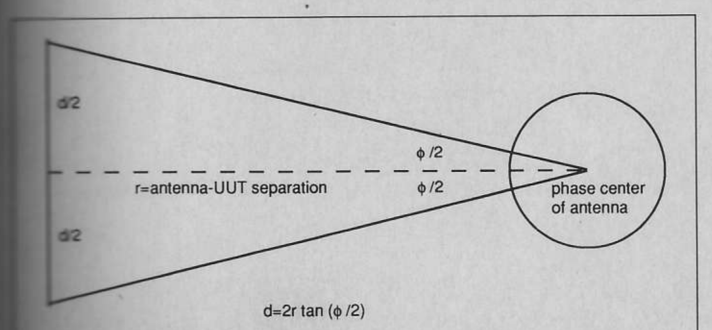

Figure 4. Illuminated Spot Diameter.

Frequency Band (GHz)	Mid band Freq. (GHz)	Antenna/UUT separation (meters)	3 dB spot diameter (meters/inches)	λ/2 at Midband Frequency (meters/inches)
1.12-1.7	1.38	0.90	0.84/33.00	0.109/4.30
1.7-2.6	2.1	0.60	0.56/22.00	0.071/2.80
2.6-3.95	3.2	0.32	0.30/11.75	0.047/1.85
3.95-5.85	4.8	0.32	0.30/11.75	0.031/1.20
5.85-8.2	6.9	0.32	0.30/11.75	0.022/0.86
8.2-12.4	10.0	0.32	0.30/11.75	0.015/0.60
12.4-18	14.9	0.32	0.30/11.75	0.010/0.40

Table 3. Illuminated Spot Size Determination for 10 dBi (50 degree beamwidth) SGH

Band (GHz)	Mid band Freq (GHz)	Wave-guide/ coax VSWR/ loss (dB)	directional coupler VSWR/ loss (dB)	d.c loss (dB)	TWTA VSWR/ loss (dB)	Total Loss (dB)	Power at Horn (20 Watt at TWTA)	**E-field @ $2D^2/\lambda$ (V/m)**	Spot Dia-meter (meter/ inches)	$\lambda/2$ (meters/ inches)
1.12-1.7	1.38	1.25/0.05	1.15/0.02	0.2	2/0.5	0.77	16.75	**82**	0.80/31	0.10/4.3
1.7-2.6	2.1	1.25/0.05	1.15/0.02	0.2	2/0.5	0.77	16.75	**122**	0.54/21	0.07/2.8
2.6-3.95	3.2	1.25/0.05	1.15/0.02	0.2	2/0.5	0.77	16.75	**229**	0.29/11.4	0.05/1.9
3.95-5.85	4.8	1.25/0.05	1.15/0.02	0.2	2/0.5	0.77	16.75	**417**	0.16/6.25	0.03/1.2
5.85-8.2	6.9	1.25/0.05	1.20/0.04	0.2	2/0.5	0.79	16.65	**544**	0.12/4.8	0.02/0.9
8.2-12.4	10	1.25/0.05	1.25/0.05	0.3	2/0.5	0.90	16.25	**635**	0.10/4	0.015/0.6
12.4-18	14.9	1.50/0.18	1.35/0.10	0.5	2/0.5	1.28	14.89	**1114**	0.05/2.2	0.01/0.4

Table 4. Maximum Far Field Intensities

over most of the microwave band. A non-technical, legalistic interpretation of MIL-STD-462 would frown on this approach. This is a serious issue for a commercial test facility. The author has submitted a recommendation to the military Tri-Service committee currently revising MIL-STD-462 that the one meter antenna-UUT separation requirement be restated as a guarantee that the UUT is in the far field of the antenna and a specified illumination spot size of at least $\lambda/2$ be maintained. The author made a similar recommendation to the Radio Technical Commission for Aeronautics (RTCA) for the RTCA/DO-160C, section 20 High Intensity Radiated Field (HIRF) revision, which was not incorporated.

At least one commercial EMI test facility (Genisco, now NTS, Rancho Dominguez, California) decided to use the $2D^2/\lambda$ criteria instead of a one meter separation for 200 V/m 18-40 GHz testing. This was done by necessity, since the highest power available TWTA covering these bands at the time was 15 Watts. A logical case can be made for doing the same at lower frequencies.

Technical Considerations

One of the most overlooked issues in radiated susceptibility testing is far field illumination of the UUT. For accuracy and repeatability it is of paramount importance that the circuit under test be illuminated by a spot diameter the lesser of the actual circuit dimension or $\lambda/2$. The designer of a radiated susceptibility facility must also consider:

(1) antenna selection

(2) power loss management, i.e., transmission line optimization

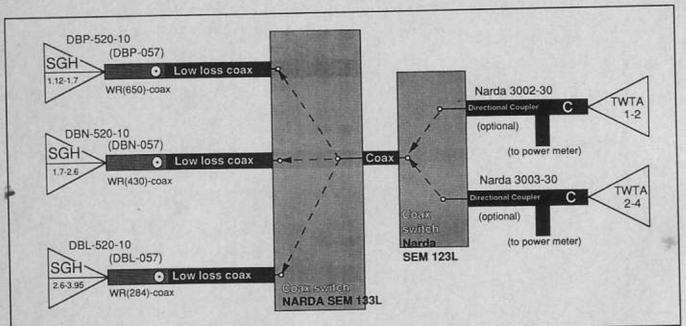

Figure 5. Test Set Up, 1.12 GHz to 3.95 GHz.

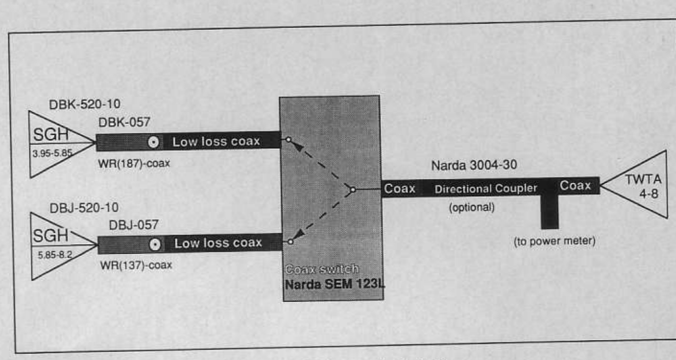

Figure 6. Test Set Up, 3.95 GHz to 8.2 GHz.

(3) susceptibility signal modulation requirements
(4) achievable field intensities
(5) illuminated spot diameter
(6) risk assessment

Technical Issue 1: Antenna Selection. The following analysis demonstrates that for microwave radiated susceptibility test purposes, maximizing the field intensity at the UUT is not simply a matter of finding the highest gain horn.

$$P_d = \frac{P_t G}{4\pi r^2} \tag{2}$$

$$P_d = \frac{E^2}{377} \tag{3}$$

Equations 1 - 3 determine the required power (P_t - Watts) at the antenna terminals for a given desired power density (P_d -Poynting vector - Watts/meter^2) or field intensity (E - Volts/meter) at a distance from the antenna (r - meters) which is in the far field of the antenna with gain G. Horn gain is a function of the ratio of physical aperture to the square of the wavelength:

$$G = G\left(\frac{D^2}{\lambda^2}\right) \tag{4}$$

If the field intensity is to be maximized, subject to the constraint that the UUT is plane wave or far field illuminated, then the antenna - UUT separation will be just at

$$r = 2\left(\frac{D^2}{\lambda}\right) \tag{5}$$

Substitution of (1) and (4) into (2) and (3) yields

$$P_d = \frac{E^2}{377} = \frac{(P_t)\,\alpha\left(\frac{D^2}{\lambda^2}\right)}{4\pi\left(\frac{2D^2}{\lambda}\right)^2} \tag{6}$$

where $\alpha D^2/\lambda^2$ is the gain of the horn, α a constant. Simplification results in:

$$P_d = \frac{E^2}{377} = \frac{P_t\alpha}{16\pi D^2} \tag{7}$$

If the gain and far field dependence upon aperture dimension are accounted for when evaluating (2), then it can be seen from (7)

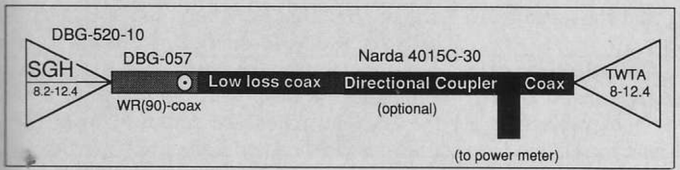

Figure 7. Test Set Up, 8 GHz to 12.4 GHz.

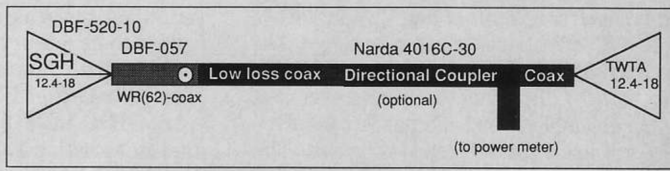

Figure 8. Test Set Up, 12.4 GHz to 18 GHz.

that it is important to not maximize, but minimize the horn gain. This is because the gain and hence the power density are proportional to the square of the aperture dimension, but the path loss is proportional to the fourth power of the aperture dimension.

All standard gain horns (SGH) of equal gain are not created equal. For instance, gain as a function of aperture dimensions for Scientific Atlanta SGH is described fairly well by

$$G = \frac{10\ ab}{\lambda^2} \tag{8}$$

where a and b are the aperture dimensions. For the same gain, the DeMornay Bonardi type horns (now manufactured by Systron Donner Microwave Division) typically have smaller aperture dimensions. This is because the wave is launched differently in the two antennas. The DeMornay Bonardi type horns were selected for this application on that basis.

In order to ascertain how well the advertised far field gain was maintained as the separation from the antenna approached $2D^2/\lambda$, a two antenna test was performed as shown in Figure 1. Only 20 dB DeMornay Bonardi Ku band SGH were available. $2D^2/\lambda$ is achieved at 0.5 m at the mid band frequency of 14.9 GHz. The antennas were placed two meters apart and the received power noted. Then the antennas were moved towards each other and readings taken at various positions with no other changes made. The graph in Figure 2 shows theoretical square law vs. actual performance. Although there is a 2 dB anomaly at 0.75 meter separation, there is good performance from two meters to 0.5 meters, the far field boundary. Thus the advertised far field gain is achieved at the near/far field boundary.

Technical Issue 2: Transmission Line Optimization. In the above analysis, P_t is the power transmitted by the antenna. P_t is the signal source output attenuated by absorptive and reflective losses in the transmission line path. Evaluation of losses for the test set ups of Figures 5 - 8 is performed as below.

Common to all of these set ups is the power loss budget, that is, the amount of power lost between signal source (amplifier) and antenna. Absorptive losses are minimized by accounting for losses in each component between amplifier and antenna and controlling transmission line length. Loss components are any coax, the coax switch and directional couplers. A directional coupler's loss is inversely proportional to the attenuation of the measurement port; for this and other reasons attenuation of this port relative to the straight through path should be at least 20 dB and preferably 30 dB. Reflective losses are controlled by accounting for all interface VSWR between components.

Maximizing field intensity requires that the antenna is mounted to the amplifier RF output with a minimum of interconnecting transmission line. With such a connection it should in all cases be possible to limit line losses to 0.5 dB. However, for ease and speed in testing, the set ups shown in Figures 5 - 8 are designed such that each set up is permanent and can be brought into the test chamber on a wheeled wooden cart. Interconnects are limited to the TWTA's signal input (from outside the chamber), facility 60 Hz power for the TWTA, and control voltage for the coaxial switch (as applicable). Coaxial switches allow the complete TWTA(s) band(s) to be swept without removal/replacement of horns. The only chamber access necessary is for polarization and next TWTA set up.

Figure 3 shows an example setup. The losses figured left to right are: coax to

Table V: Parts List and Cost Breakdown for Passive Microwave Elements

ITEM	Manufacturer/Part Number	Quantity	Price	
Antennas: 10 dBi SGH	Systron Donner (old DeMornay Bonardi)			
	1.12-1.7 GHz: DBP-520-10	1		
	1.7-2.6 GHz: DBN-520 -10	1		
	2.6-3.95 GHz: DBL-520-10	1		
	3.95-5.85 GHz: DBK-520-10	1		
	5.85-8.2 GHz: DBJ-520-10	1		
	8.2-12.4 GHz: DBG-520-10	1		
	12.4-18 GHz: DBF-520-10	1		
			Antenna Subtotal:	~$6200
Waveguide to coax adapters:	Systron Donner or equivalent			
	1.12-1.7 GHz: DBP-057	1		
	1.7-2.6 GHz: DBN-057	1		
	2.6-3.95 GHz: DBL-057	1		
	3.95-5.85 GHz: DBK-057	1		
	5.85-8.2 GHz: DBJ-057	1		
	8.2-12.4 GHz: DBG-057	1		
	12.4-18 GHz: DBF-057	1		
			Adapter Subtotal:	~$2600
Low loss coax/coax fittings (as necessary)				not priced
Coaxial Switches: (not necessary but speeds test)	Narda SPDT (P/N SEM123L)	2		
	Narda SP3T (P/N SEM133L)	1		
			Switch Subtotal:	~$1000
Directional Couplers: (not necessary but facilitates quick and accurate calibration)	1-2 GHz: Narda 3002-30	1		
	2-4 GHz: Narda 3003-30	1		
	4-10 GHz: Narda 3004-30	1		
	7-12.4 GHz: Narda 4015C-30	1		
	12.4-18 GHz: Narda 4016C-30	1		
			Coupler Subtotal	~$2000
			Grand Total:	~$11800

Table 5. Parts List and Cost Breakdown for Passive Microwave Elements

waveguide adapter VSWR loss is 0.05 dB, directional coupler to coax VSWR loss is 0.12 dB, directional coupler resistive loss is 0.60 dB, TWTA output to coax VSWR loss is 0.50 dB. Thus the total power loss between amplifier and antenna is 1.27 dB.

See Table 1 for detailed loss figures. The table is derived from Figures 5 - 8 and manufacturers' published data. The losses may be compared to that assumed for Table 2, showing a positive safety margin in every case. As stated in the risk assessment paragraph, however, the low frequency set ups' margins are small enough that tolerances on manufacturer data must be small and parasitic losses due to coax interconnects must be minimized.

Technical Issue 3: Susceptibility Signal Modulation. Another reasonable assumption that aids in getting the most V/m/Watt out of the test set up in the microwave bands is that the only modulation schemes necessary are pulse, phase or frequency modulations, not audio signal amplitude. Amplitude modulation is not used in communications at microwave frequencies, and is therefore unnecessary. This frees up amplifier headroom and allows the amplifiers to be run at the edge of saturation, again assuring that the amplifier is used to its fullest capacity.

Technical Issue 4: Calculation of Microwave Field Intensity, 1.12 GHz - 18 GHz. Table 2 gives achievable field intensities with a 1.6 dB margin relative to 20 Watts while choosing an antenna-UUT separation either maximizing the field intensity or just achieving 200 V/m. That is, the field strengths are 1.6 dB below what is theoretically attainable from a 20 Watt source. 1.6 dB is greater than the maximum amplifier to antenna loss calculated in Table 1.

Technical Issue 5: Illuminated Spot Diameter. The illuminated spot diameter should in all cases be at least one half wavelength at the frequency of interest, in order to guarantee that the maximum power be coupled into the circuit under test from the field. The illuminated 3 dB spot diameters are derived from the antenna gain and the antenna-UUT separation as depicted in Figure 4.

Table 3 shows that the illuminated spot diameters resulting in the field intensities listed in Table 2 are in all cases at least six times what is necessary to worst case stress the UUT. There is a tradeoff between spot size and field intensity. Table 4 demonstrates the very high (far) field intensities possible with the test set ups if the coax switches are removed from the transmission line and if the horn aperture is set precisely $2D^2/\lambda$ from the UUT. These will be very useful for HIRF testing and RTCA/DO-160C, Section 20 testing in the very near future.

Technical Issue 6: Risk Assessment. It should be noted that at the lowest frequencies of interest, 1-3 GHz, there exists a smaller design margin than one might desire. Parts performance described by manufacturers' data as typical, with no tolerance specified, may need extra manufacturer supplied screening or incoming inspection.

Parts List and Cost Breakdown

Table 5 lists the passive components shown in Figures 5 - 8 by manufacturer and part number. Individual piece prices are not quoted at the request of the manufacturer. Subtotals and total prices are as of February 1991 and are subject to change.