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Spectrally Flat Antenna Designs and Reshaped TEM Horns

– Applications to CW and Pulse Testing –

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Abstract

Wideband continuous wave (CW) and pulse illuminators can be a valuable aid in designing and evaluating the electromagnetic (EM) shielding of aircraft, buildings, ships, and other test objects and in maintaining the hardness protection throughout the system's lifetime. For such an application, the CW radiators need to have a spectral output that is as flat as possible over 2-3 decades of frequency. This is achievable in many instances by loading the antenna with resistors and/or ferrites, and there are a variety of options available that can help us design a radiating structure that is best for a given application. There are also several concepts for modifying TEM horns so they can be used for pulse transmission without differentiating the waveform. These have only been explored in the laboratory so far, but the results indicate that further study would be worthwhile. This paper reviews some of these concepts for both CW and transient radiators with references to the original work.

Acknowledgement

This work is the result of the efforts of a great many individuals, whose work over the span of 40 years helped lay the foundation for the technology we have today. This includes the Defense Threat Reduction Agency (DTRA), Oklahoma City Air Logistics Center, Patuxent River Naval Air Station, Naval Surface Weapons Center Dahlgren, and the Air Force Research Laboratory.

Preface

Beginning in 1984, the Air Force Weapons Lab and the Oklahoma City Air Logistics Center began the development of low-level continuous wave (CW) test methods for evaluating the integrity of electromagnetic shields on military aircraft. Measurement tools were developed and demonstrated, and found to be useful not only for hardness maintenance and hardness surveillance (HM/HS) of in-service aircraft, but also very useful during the development and assembly process, especially if the specifications are written in an unambiguous, measurable form.

Around 1988, the Defense Nuclear Agency (DNA), now DTRA, also began the development of CW technology, beginning with deployment of the CW Measurement System (CWMS) as an adjunct to the Transportable EMP Simulator (TEMPS), for use in testing ground-based communication facilities and ground vehicles.

CW illumination, of course, does not replace threat-level EMP simulation for qualifying a system, but for measuring the integrity of the shield and shielding components over the full frequency range, it is more accurate. Because of the narrowband characteristics of the CW measurement process, the dynamic range is much larger than that achieved with transient testing. However, as we know, CW testing does not induce enough voltage on the circuits to trigger any non-linear devices, so only linear effects can be measured. This must be taken into account if measuring current or voltage induced on individual wires. On cable bundles, the effect if not so marked, especially if there are ground wires, coax, or twisted shielded pairs included in the bundle. Cable shield currents are not affected by the internal wires, of course.

Any interference with outside receivers can be completely eliminated by not transmitting on assigned frequency bands (skip bands). Peak input power to the antenna is usually on the order of 100W. Radiated output power is on the order of a few watts, just enough to give us 1 V/m under the antenna. This is indeed inefficient, but that sacrifice is necessary in order to get the 3 to 4 decades of frequency range required for an EMP test system.

Over the past two decades, the use of electromagnetic shielding for protection of electronic systems from the adverse effects of EMI, EMC, EMP, HIRF, and HPM has increased significantly, in commercial as well as military systems. The measurement techniques described herein were originally designed for measuring the shielding of military aircraft against the nuclear electromagnetic pulse (EMP), but the measurement techniques are applicable to EM shielding in general and can be used to measure system protection against other EM phenomena within their band of operation. The equipment is readily available and costs significantly less than that required for high-level pulse testing, and it can easily be made transportable. The antennas are lightweight, inexpensive, and easy to fabricate.

1. Introduction.

References [1-4 and 21-23] are very interesting papers on wideband antennas that are applicable to today's problems, though they're not new. They present concepts, based on the work of Motohisha Kanda at NIST in Colorado Springs, Tapan Sarkar and his students at Syracuse University, Kurt Shager at Georgia Tech, and Giri & Gallon from Pro-Tech that can be used to broaden and flattening the spectral output of common antenna designs or allow us to design new ones for either CW or pulse operation. Kanda's papers describe broadband sensors, but through reciprocity, the concepts work for transmitting antennas, as well, as we remember from Hallen [5].

Many of us are familiar with using the Wu-King tapered resistive profile on dipole antennas to achieve non-resonance and broadband performance [6-7], but in their referenced papers, Kanda, Baum, and the others also address loaded loops, hybrids, and loaded TEM horns. We will review some of those here.

In addition, the papers by Wohlers and by Giri and Gallon present approaches to the design of horns from work that began in 1971 and continued into the 1980s. By reshaping the plates, they are able to make horns that are 1) lower impedance than a bicone and 2) can be used in either CW or pulse mode [19-23]. This offers a potential alternative design for electromagnetic pulse (EMP) Threat-Level Simulators (TLS), and in the opinion of the authors, should be further investigated.

Resistive loading can be applied to a LLCW antenna using the same method that was used on the Ellipticus, which is using ferrite rings and resistors [18]. The Ellipticus antenna is made of solid-jacket Heliax® cable, so the ferrite rings are simply slipped onto the antenna and held in place with tie-wraps or shrink tubing. The ferrites on the Ellipticus only need to work at the lower frequencies where the wavelength is on the order of the size of the antenna, below about 25 MHz, that is, when the antenna is performing as a loop. So, the ferrites only need to be active in that range. For other antennas, higher frequency ferrites may be required.

2. Dipole Antennas.

2.1. Wu-King Taper.

There were several papers written and directed by Carl Baum in 1969-73 for the design and construction of first the RES I Flying Dipole and later the VPD antennas. The Wu-King (W-K) taper was developed by T.T. Wu and R.W.P. King at Harvard University in 1965 [6-7].[1] The concept was to apply resistive loading to the antenna with the resistance increasing geometrically toward the end in such a way that the current was damped before reaching the end of the dipole. In this way, the antenna becomes non-resonant and has a

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[1] Historical Note: The development of the W-K taper was originally motivated by the need to measure and simulate the strange and new wideband transient phenomenon called EMP, something that was thrust upon us by the Starfish Test in 1962. Using this formula, AFWL built the Radiating EMP Simulator (RES I) Flying Dipole, a 200' pulse antenna driven by a 2 MV Marx generator. It was carried by a Chinook helicopter over the missile silos in Montana and the Dakotas during the early '70s, as shown in Figure 1.

flat radiating or receiving transfer function. It can thus be used for continuous wave or broadband transient radiation. If the antenna is not loaded in this manner, the wave will reflect from the end and set up a standing wave (resonance), which shows up in the time domain as undershoots or oscillations on the radiated waveform and in the frequency domain as a series of notches. However, what we need is a smooth frequency response that is as flat as possible. Figure 2 shows the shape of the resistive taper. The paper by Wright and Prewitt [8] addresses a large dipole antenna, probably one of the RES series of designs. The ones by Baum and Kehrer [9, 14-15] and Maloney and Smith [10, 11] address the design of the Vertical Dipoles (VPD II, NAVES, and EMPRESS II).

In the W-K taper, the resistance is proportional to 1/(h-|x|), as shown in (1),

$$R(x) \propto \frac{1}{(h-|x|)} \tag{1}$$

where h = antenna half length
x = distance along the antenna from its center.

The resistive taper that was developed by Wright and Prewitt [8] and Baum [9] for the RES I “Flying Dipole” EMP Simulator antenna shown in Figure 2.

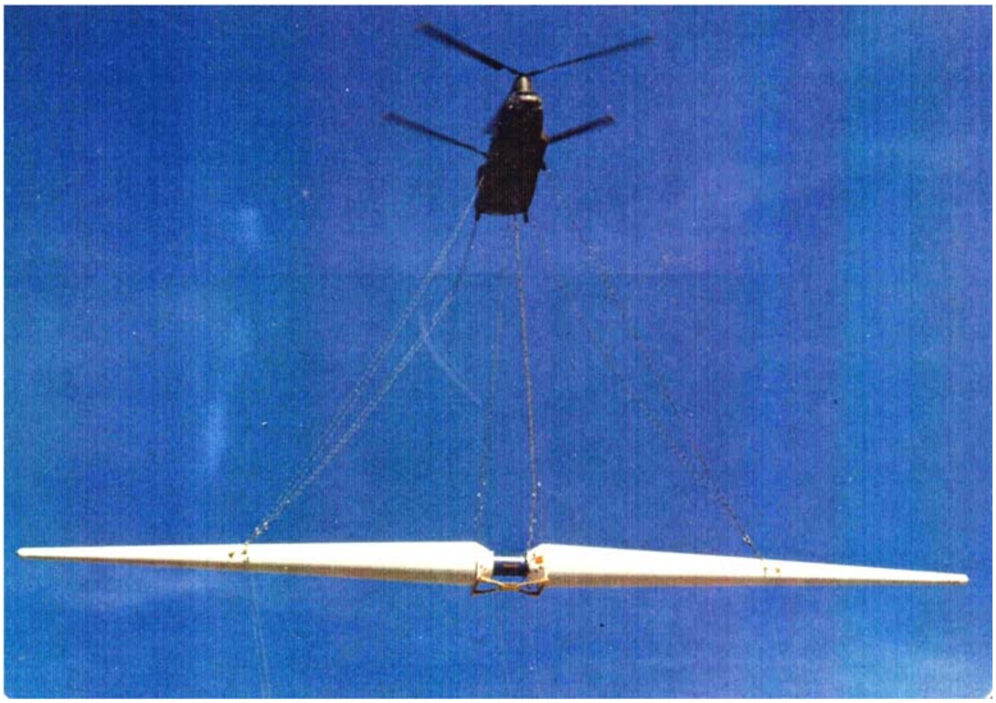


Figure 1. The RES-I Flying Dipole EMP Simulator had a W-K resistive taper on each side.

The antenna, which was designed to radiate only100 MHz EMP, contained discrete rings of resistive material spaced 5m apart. For 1 GHz performance, the resistors/inductors will, of course, need to be smaller and closer together.

For lumped loads that are spaced 5 m apart, the profile looks like that shown in Figure 2.

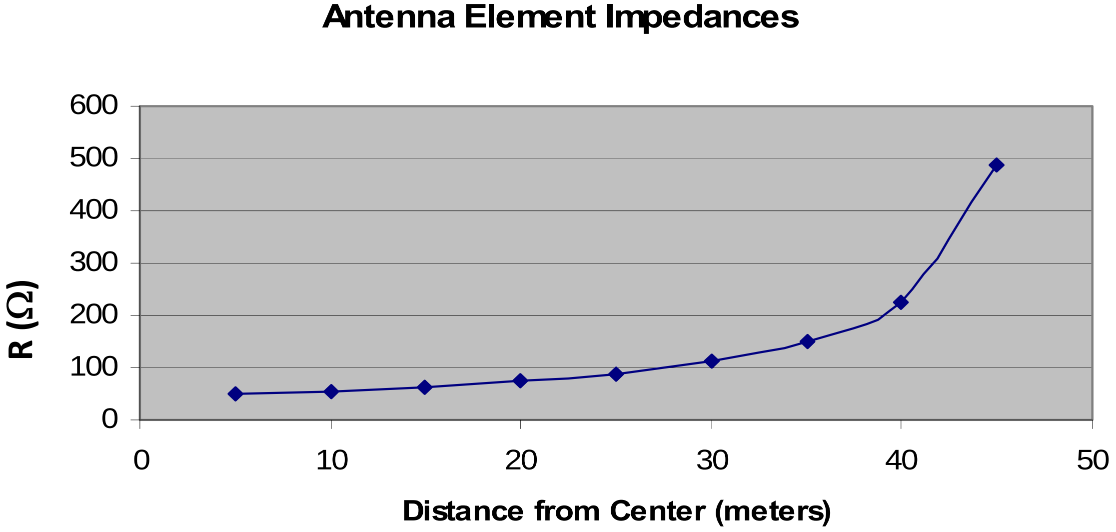


Figure 2. W-K resistive loading profile used on the Flying Dipole [8].

The impedance of the W-K taper, at the drive point, can be adjusted to match the impedance of the source (50 Ω or 100 Ω or whatever).

Figure 3 shows the measured receiving transfer function (RTF) of the small laboratory dipole antenna, defined as

$$RTF(f) = \ h_{eff}(f) = \frac{V_{OC}(f)}{E_{INC}(f)} \tag{2}$$

where V_{OC} is the open-circuit voltage at the antenna terminals

E_{INC} is the incident electric field.

$h_{eff}(f)$ is the effective height of the antenna.

The results can be scaled up by the wavelength and the size of the antenna. As shown in Figure 3, from Kanda, the variation in the amplitude of the receiving transfer function measurements on their laboratory model was on the order of only 3-4 dB [1].

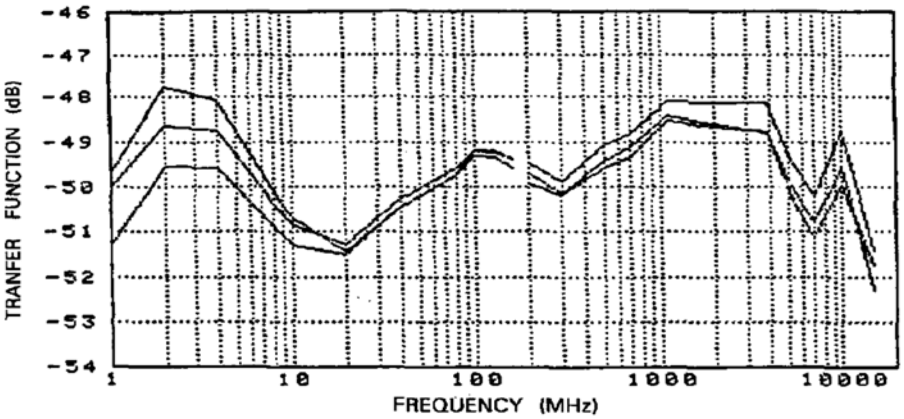


Figure 3. Measured transfer function of a laboratory-sized loaded dipole.
Note that the variation is < 3dB.

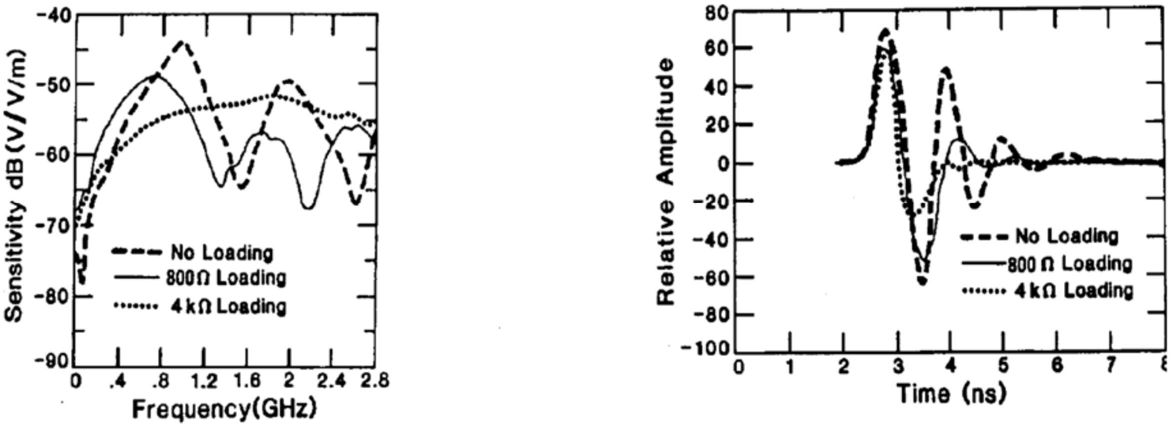
This approach could be applied to any dipole. In their papers, Kanda and Sarkar show how it can also be applied to conic antennas and TEM horns (conic sections).

3. Loop Antennas. In [1] and [2], Kanda treats the subject of a loaded loop antenna as well as other methods to raise the impedance (E/H) up to 377Ω, eliminate resonances, and at the same time broaden and flatten the spectrum. He presents several possible approaches.

3.1. Resistive loading at one point. A resistive load exists across the gap at the point where the loop is driven just by the presence of the power amplifier. Using a wideband transformer or balun, however, the value can be adjusted to get the best frequency response.

3.2. R-C Compensated. This might be an easy way to improve the performance of existing loop antennas at minimal cost. The resistive loading R serves to reduce the Q of the loop and thereby broaden its spectrum. The capacitance C can be used to shift the resonant frequency, f_0, so as to operate on the desired part of the curve. In the example shown by Kanda, there is a C across the feed gap and another RC on the opposite side.

3.3. Distributed resistive load. The resistive load might be uniformly distributed along the length of the antenna, as it is in the HPD or Ellipticus in order to make the loop non-resonant. The disadvantage, of course is that it will require more power to drive it. Figure 4 shows a comparison between the radiated field spectra and transient waveforms produced by 3 different loading values [1].



a. Frequency response.

b. Time-domain response.

Figure 4. Time and frequency plots of the effect of distributed loading on a loop [1]. The dotted line illustrates the behavior when it is loaded until it is non-resonant.

4. Hybrid Antennas. A hybrid antenna is one that combines the features of both a loaded dipole and a loaded loop in order to expand the bandwidth of the antenna and maximize the uniformity of the field across the test object, which is located inside the loop [12-15]. Unlike the radiating antennas described above, the hybrid antennas are designed to create a near uniform field in the center of the loop, which becomes the working volume. The original design calculations were done for a full loop in free space, but the practical application has always been that of a half loop (or ellipse) over a ground plane.

Dr. Baum created the hybrid concept and employed continuous resistive loading in order to

a. Create a near uniform field in the center of the loop.
b. Damp the current and raise the electric field in order to achieve a wave impedance of E/H = 377 Ω at the lower frequencies (late times) in order to properly excite the test object with the same wave impedance as would be found in an EMP plane wave.
c. Damp the end-to-end resonance of the structure.
d. Damp any reflections from the ground or test object to minimize “simulator/test object interaction.”

At early times (high frequencies, short wavelengths), the antenna behaves like a biconical transmission line. At the mid frequencies, it looks like a dipole with a gap in the center. Then, at the late times of an EMP pulse (lower frequencies, longer wavelengths), the antenna with its image in the ground plane operates as a continuous loop. The aircraft is always in the near field of the antenna at low frequencies, but the resistors serve to correct the wave impedance to 377 Ω, so the aircraft under test will respond as if it were being illuminated by a plane wave EMP instead of that of a near magnetic field (all H and no E).

4.1. TORUS EMP Simulator. The hybrid concept was first applied to the Transient Omnidirectional Radiating Unidistant and Static (TORUS) EMP simulator, which was made by the AFWL in the late 1970s [12-13]. It was a transportable, ground-based simulator designed for use in testing missile sites in the northern US.

TORUS was a half-toroidal shaped antenna with uniform resistive loading that could be driven by a 5 MV pulse generator or a repetitive pulse generator. The high frequency components were radiated by a biconic structure at the apex, and the intermediate and low-frequency components by the toroidal loop. At the lower frequencies in the MHz range, the test object will always be in the near field of the antenna, meaning that the wave impedance of the loop, $Z_O = E/H$, will always be very low (all H and very little E). Therefore, in order to cause the test object to respond as if it were in an EMP field, Dr. Baum loaded the antenna with resistors. The resistors 1) reduce the current (and hence the H field) and 2) create a voltage across each resistor to increase the E field. The loading in Ω/m is designed such that the impedance in the center of the working volume is 377Ω at the low frequencies, as described in [12-13]. An example sketch is seen in Figure 5. It can also be seen in the "Little HPD" antenna at the EMP test site at White Sands Missile Range (WSMR), as shown in Figure 6.

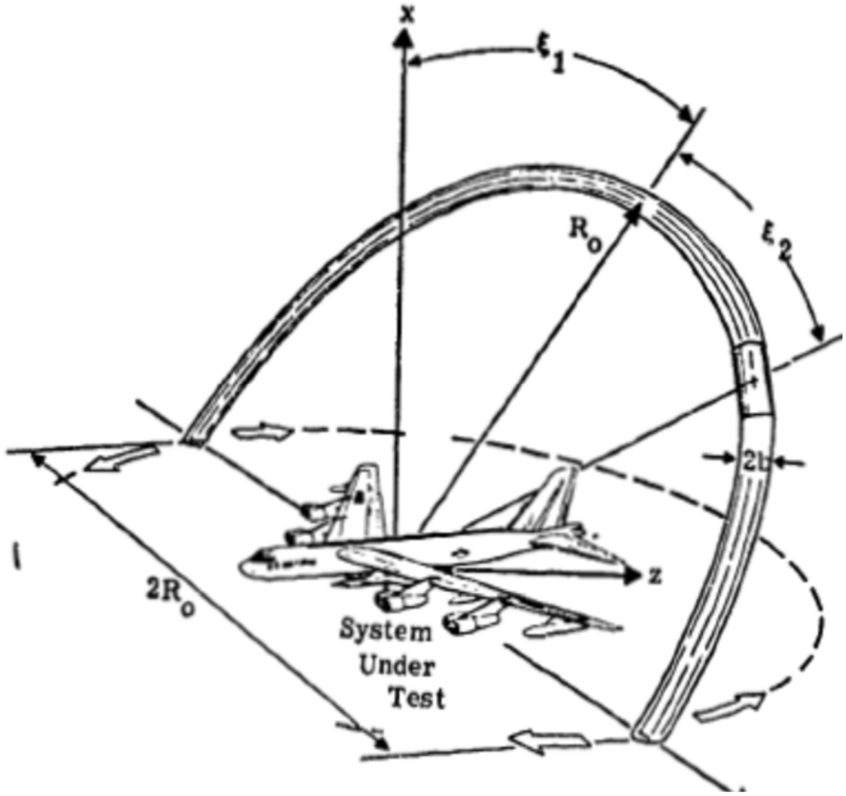


Figure 5. TORUS EMP Simulator Concept.

We also note that the concept allows for the pulser to be placed anywhere around the antenna and the antenna can be tilted over, which allows for a large variety of incidence angles and polarizations.

Figure 6. Little HPD at White Sands.

4.2. The ATHAMAS I (HPD) EMP Simulator. The second application of this concept was to the ATHAMAS I EMP simulator, more commonly known as the Horizontally Polarized Dipole (HPD) shown in Figure 7. This is a misnomer, of course, because it is not technically a horizontally polarized dipole, but a hybrid. However, the name stuck, so that's what it is commonly called, even today.

The ATHAMAS I is really just a flattened version of the TORUS. The original concept developed for aircraft was in fact a TORUS, but it was reshaped into an ellipse in order to keep the pole height below the restrictions set by the local FAA for the airport. This also had the advantage of bringing the pulse generator closer to the aircraft and thus increasing the field level.

The equations for calculating the resistive loading are the same as those developed by Baum for the TORUS [12-13]. The primary parameter is the area of the loop, so the equations apply just as well to the elliptic shape of the ATHAMAS I.

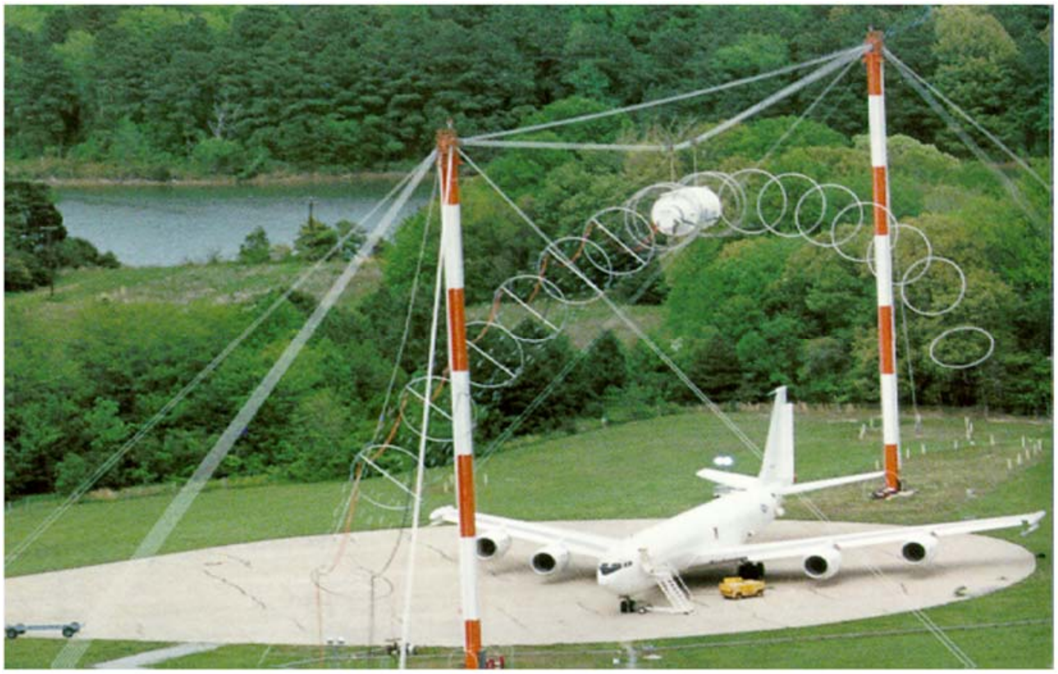


Figure 7. The ATHAMAS I or Horizontally Polarized Dipole (HPD) Elliptic EMP Simulator at Patuxent River NAS, MD.

4.3. Ellipticus CW Simulator. The Ellipticus CW illuminator, shown in Figure 8, was designed as a counterpart to the HPD. It has the same shape and same resistive loading profile as HPD, but is smaller, being only 20m high at the center instead of the 30m height of HPD. However, for most aircraft that are about 100-120' long, such as the E-6, KC-135, B-52, etc., it is quite adequate and has been shown to predict the EMP response of the test aircraft to with a few dB [16-18].

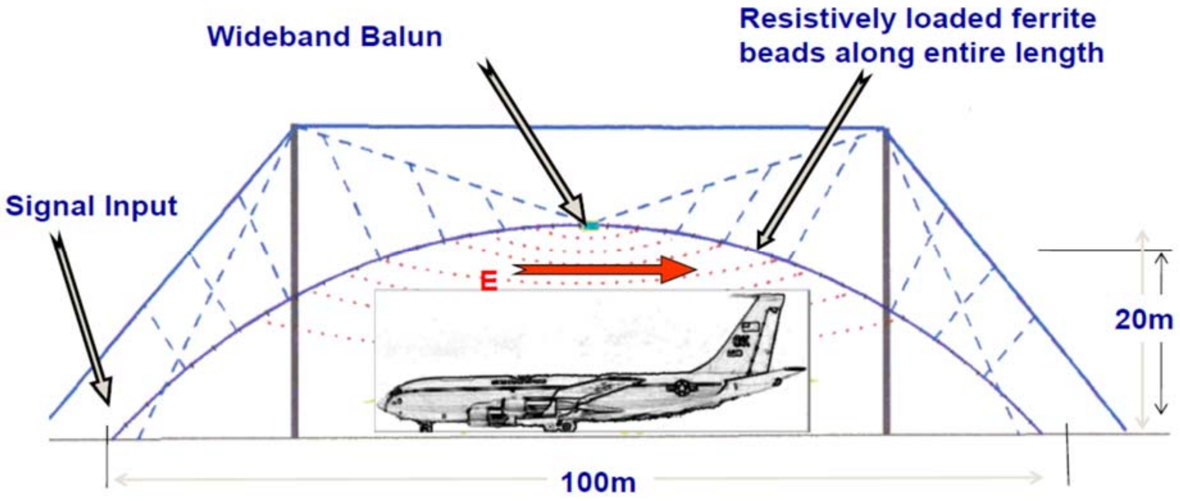


Figure 8. The Ellipticus CW Illuminator.

5. TEM Horns. A TEM horn consists of two metallic plates, each an isosceles triangle. The planes of each plate are separated by some angle β. The angle β and the angles α of the sides of the triangles determine the impedance of the horn, usually set to the same impedance as the transmission line feeding it.

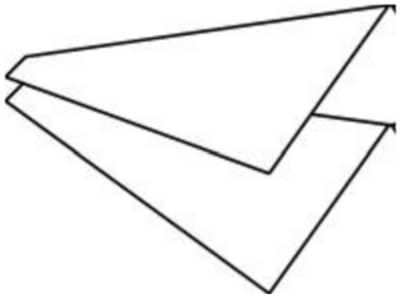


Figure 9. Basic TEM horn antenna.

To radiate an ultra-wideband transient signal, as would be desired for an EMP simulator, the basic TEM horn, as shown in Figure 9 is one that comes quickly to mind. However, this will not work, because the transmitting and receiving characteristics of a TEM horn are different. That is, in a TEM horn, the received voltage, $V_{OC}(\omega)$ follows the incident field as described in (3).

$$V_{OC}(\omega) = h_{eff}(\omega)\, E^{inc}(\omega) \tag{3}$$

In transmission, however, the aperture field is proportional to the applied voltage, but the far field is the derivative of the aperture field as shown in (4). That is, the reflections at the aperture end of the horn cause it to radiate a signal that is the first derivative of the driving voltage, which makes it unacceptable for use as an EMP simulator.

$$E^{rad}(\omega) \;\propto\; j\omega\, E_{aperture}(\omega) \tag{4}$$

Fortunately, this behavior can be modified by reshaping the plates and changing the shape of the output aperture so as to eliminate the rectangular aperture at the output of the horn that is causing the differentiation.

5.1. Resistively Loaded Horns. One way of overcoming the differentiating feature of a TEM horn is to introduce resistive loading. This is addressed by Sarkar and Kanda in [1-4] and by Shlager, et al, in [21-22]. The papers describe TEM Horns with a continuously tapered loading designed so that the impulse does not reflect off the end of the antenna (i.e. so that the antenna is non-resonant), which eliminates the need for a termination.

Motohisha Kanda (from NIST in Colorado Springs) explored this in the 1980s and tried out two methods. The first model was a horn made of a resistive sheet with uniform resistive loading (uniform in Ω/square across the entire plate). The second had a W-K resistive taper.

5.1.1. Uniformly Loaded TEM Horn. Figure 10 shows the measured transfer function of the TEM horn antenna with an evenly distributed loading taper. The improvement flatness of the receiving transfer function is easily seen.

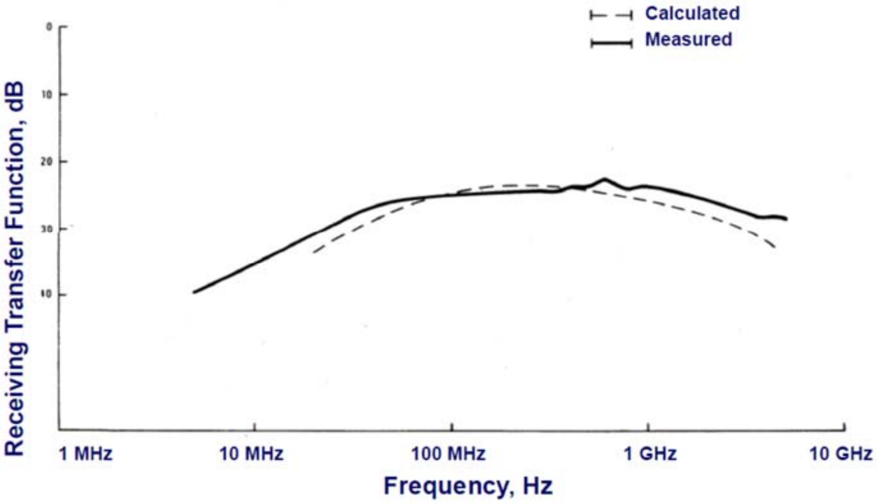


Figure 10. Receiving transfer function of a loaded TEM horn.

The receiving transfer function is defined as the ratio of the load voltage received at the antenna terminals divided by the incident field, as shown in (2).

5.1.2. TEM Horn with Tapered Loading. For very large horns, this might be improved upon by increasing the resistive loading toward the end of the horn in a fashion similar to the Wu-King taper described by (5).

$$Z(z) = \frac{Z_0}{1-\frac{z}{l}} \ \Omega/m, \ 0 \le z \le l \tag{5}$$

where Z_0 = resistance/unit length at the driving point

z = distance from the driving point, as shown in Figure 10.

l = length of the horn

This is illustrated in Figures 10 and 11.

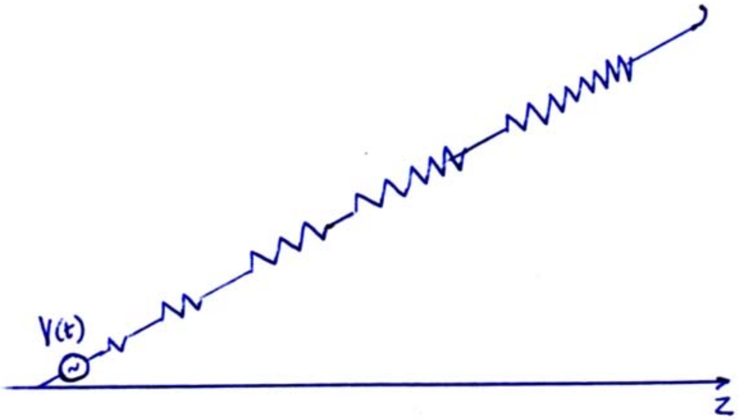


Figure 10. Resistively loaded horn with a W-K taper.

The tapered resistance was made of several interconnected resistive sheets that began with a low resistivity at the apex and increased to a very high value at the aperture. This is illustrated in Figure 11. The resistive profile used was similar to that used by Wu and King on dipoles. The resulting output waveform can be seen in Figure 13 from Shlager [22]. The reduction in the current along the length of the horn can be seen in Figure 12. In Figure 13, the reduction in the reflection from the open end of the horn, which causes the horn to radiate a differentiated waveform, is significantly reduced by the tapered loading.

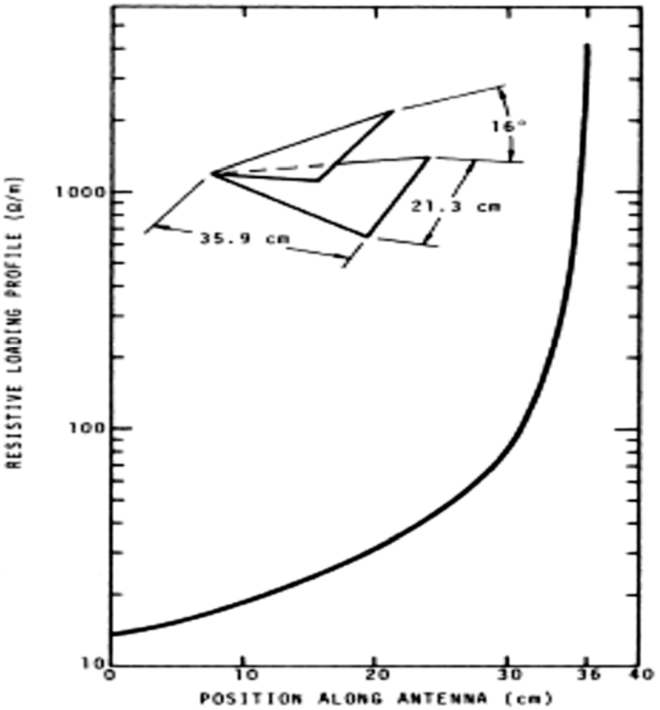


Figure 11. Example of the resistive taper on a horn in Ω/m [21].

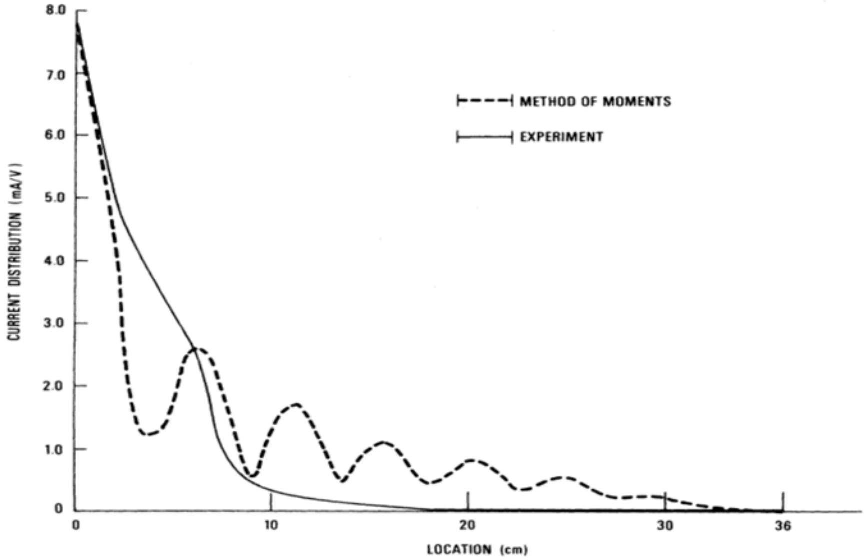
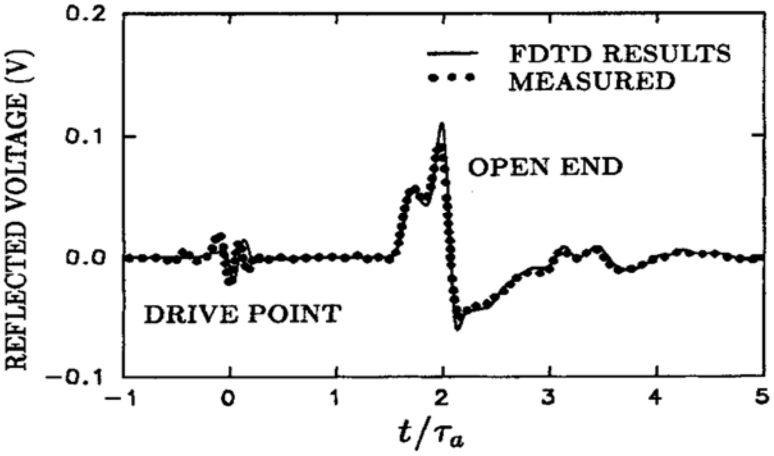
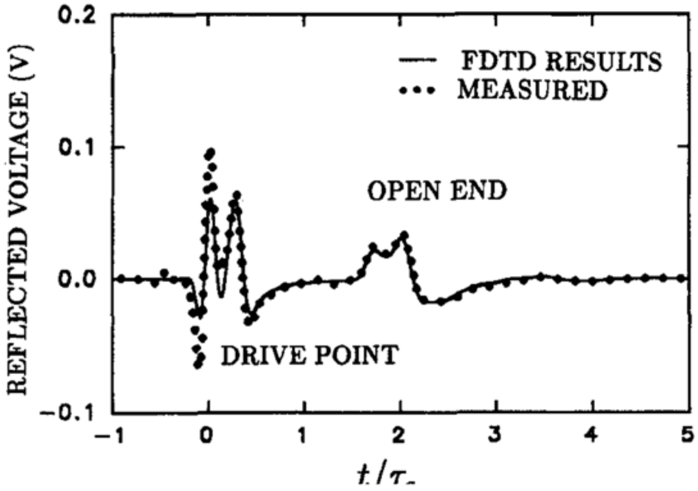


Figure 12. Current distribution on a resistively loaded TEM horn scale model.



a. Reflection from the aperture end of a metallic TEM Horn. .



b. Reflection from the aperture end with resistive loading.

Figure 13. Reduction in differentiation at the aperture of the TEM horn with a resistive taper.

The advantages of a loaded TEM horn antenna for CW illumination are:

1. Flat spectral performance
2. Fixed phase center for all frequencies, i.e. It is non-dispersive.
3. In CW mode, it would function like the vertical CWMS, but would be directional.

The disadvantages are:

1. Field falls off as 1/r, which is a limitation if illuminating a ship from the end. Should be OK for side-on illumination of a ship, especially if there is an array of several antennas.
2. Functions well as a CW radiator, but will not work as a transient antenna, because the aperture differentiates the time-domain waveform, as demonstrated by Shlager, et al [22]. However, there is a way around this, as shown below.

5.1.3. Modified Plate Antennas. The shape of the plates can be modified to overcome the differentiating feature. *This has been demonstrated experimentally,* and offers an alternative for the design of the antenna of the Threat Level Simulator (TLS) currently being studied for testing ships. The objective is to 1) lower the impedance, which lowers the required voltage for a given radiated field level and 2) make the antenna directional in order to get more field on target. Two concepts have been published. The first was introduced by Wohlers in 1971 [19]. A description of this is also repeated in the papers by Theodorou, et al [20], Shlager [22], and Giri and Gallon [23]. Ian Gallon exposed his talent for British humor by referring to this antenna as a traveling wave impedance taper or TWIT. This is illustrated in Figure 14.

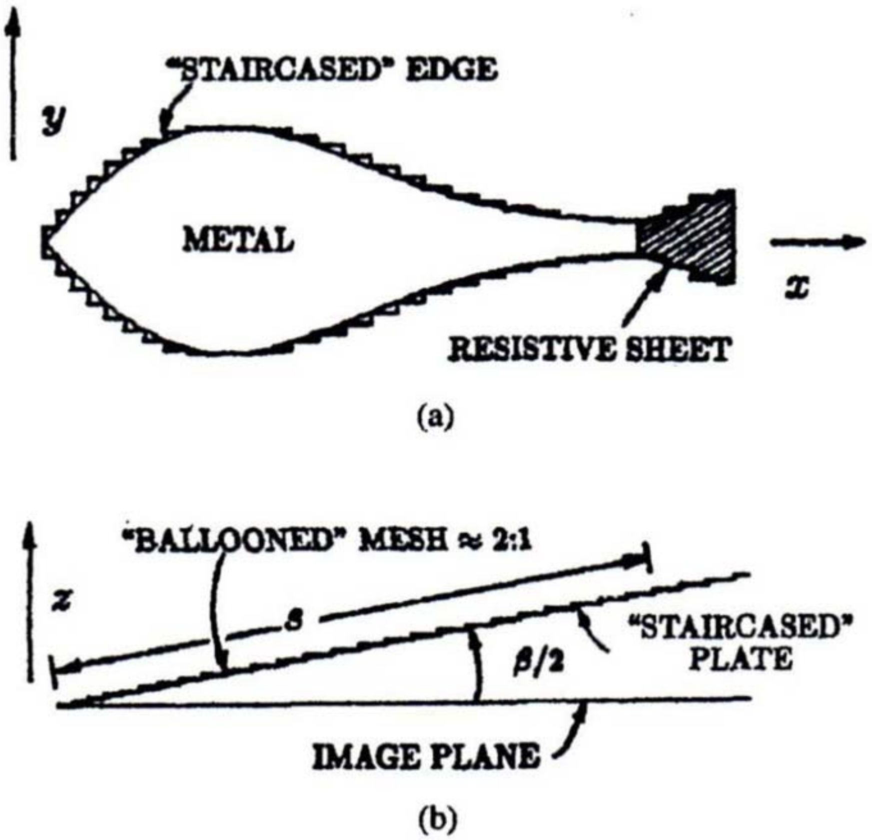
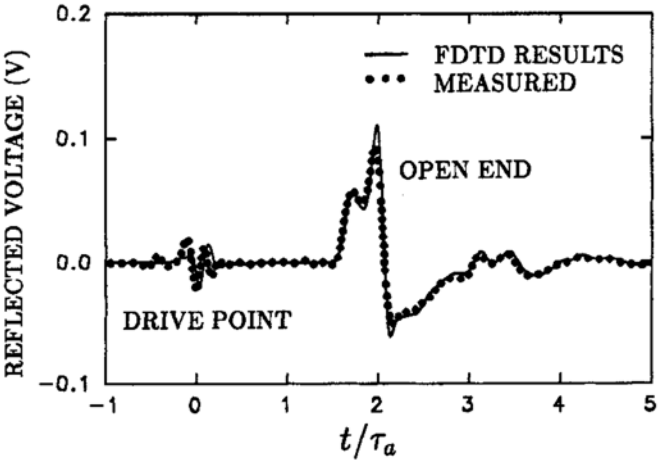
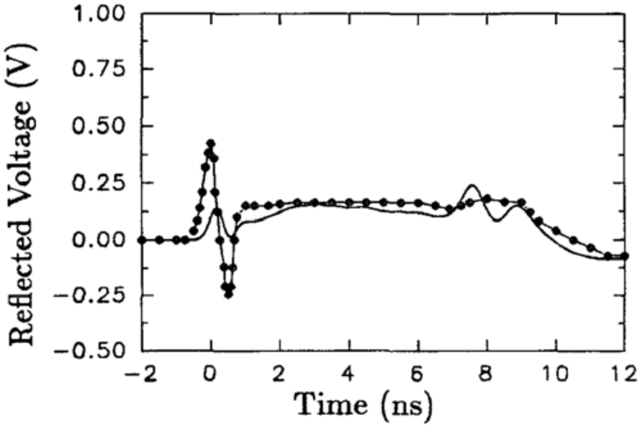


Figure 14. TEM horn shaped and loaded to match 377 Ω/square.

In this design, the characteristic impedance ($\propto$ width of the plate) was smoothly varied from $Z_a = 50\ \Omega$ at the apex to 377 Ω at the aperture (open end). Then, resistive sheets with resistivity of $R_s = 100\ \Omega$/square were placed over the plates at the pointed open end to further reduce the reflections. The reduction in the voltage pulse reflected back into the feed line by the end of the antenna, as seen in Figure 15, is an indication of the reduction in the derivative. This design has real potential. It would desirable to see some better field measurements in the far field and a study to optimize the shape of the plate and resistivity of the sheet.



a. Reflection from the aperture of a metallic TEM horn.



b. End reflection from the open aperture of the TWIT
with the resistive sheet in place.

Figure 15. Measurements of the reduction in the voltage reflected from the open end of the TWIT antenna with resistive sheet loading.

Another concept suggested by Giri and Gallon in their paper [23], is illustrated in Figure 16. This concept has been analyzed numerically and does effectively reduce the differentiation of the output waveform.

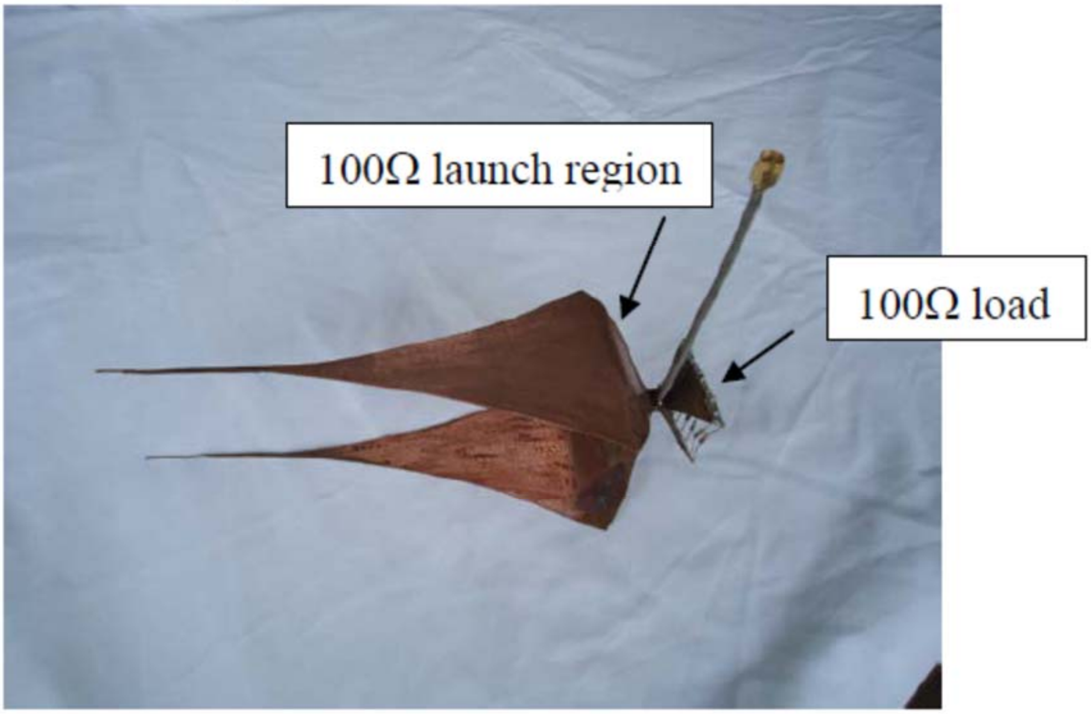


Figure 16. Scale model of a TEM horn designed to maintain a 50 Ω input impedance across a wide frequency range.

6. Summary. Wideband continuous wave (CW) and pulse illuminators can be a valuable aid in designing and evaluating the EM shielding of aircraft, buildings, ships, and other test objects and in maintaining the hardness protection throughout the system's lifetime. Broadband radiators, if designed properly, can have an almost flat spectral output over a range of 2-3 decades, and there are a variety of options available that can help us design a radiating structure that is best for a given application. There are also a number of ways that TEM horns can be modified so they will radiate EMP transient waveforms without the use of a termination, which offers an advantage in some situations.

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The EMP Notes can be downloaded from the University of New Mexico website at http://ece-research.unm.edu/summa/empseries.htm

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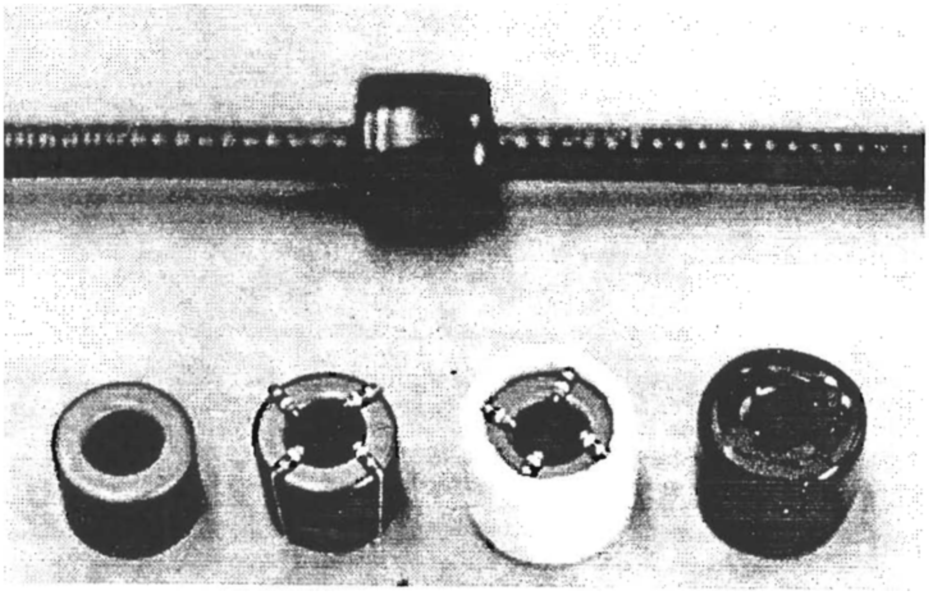
Appendix A. Adding Resistive Loading to an Antenna.

A.1. In-line resistors. Resistive loading taper can be installed into an antenna using in-line resistors as we find in the HPD, VPD, and the Vertical CWMS antenna.

A.2. Ferrite rings with resistors. Resistive loading can be installed on an antenna made of solid metal or coaxial cable by using ferrite rings and resistors, as is done on the Ellipticus (which is made out of solid jacket Andrews Heliax® cable). This is described in [18]. Figure A.1 shows the ferrite beads in various stages of assembly.



Left to right (bottom):

- Bare toroidal ferrite ring.
- Ring with four 39 Ω resistors.
- Wound with foam tape.
- Covered with UV-resistant heat shrink.

Figure A.1. Ferrite rings and resistors installed on the Ellipticus antenna (Heliax cable).