AN ULTRA PORTABLE MARX GENERATOR-BASED SOLUTION FOR MIL STD 461 E/F RS-105 TESTING

J.R. Mayes[ξ], M.B. Lara, W.C. Nunnally, M.G. Mayes, and J. Dowden

Applied Physical Electronics, L.C, PO Box 341149

Austin, Texas, USA

Abstract

A parallel-plate test cell is designed and implemented for EMP testing covered under MIL STD 461E/F, testing standard RS-105. The device is constructed to give a maximum crated footprint of approximately 4ft.x 8 ft., while being two-man portable, and set-up in less than one hour. The system is driven by a Marx generator and pulse-forming circuit which are designed for minimal maintenance, and maximum shot life. An integrated power electronics module contains an electronic pressure regulator, trigger module, dual-polarity high-voltage supplies, and battery, making the operation of the system safe and user-friendly by providing complete high-voltage isolation of the user via a fiber-optic hand-held remote control. Design and operational data from the tester are presented in this paper.

I. INTRODUCTION

A test apparatus is desired to test electronic assemblies and enclosures under MIL STD 461 E/F, RS-105 test procedure, to test for electronic vulnerability to an Electro Magnetic Pulse (EMP). The objective of this effort is to develop a test bed to meet the test standard for rack mount enclosures.

A maximum test volume of 24 in. x 24 in. x 16 in. is desired, with a system that is very simple to operate and is two-man portable for field testing.

A two-pass design process was taken. The first pass was built to closely implement the test standard's suggested configuration. While the completed structure met all of the specifications of the standard, the apparatus was difficult to operate; and while the system was portable, a forklift was required.

The first system was implemented as a solid-panel parallel plate structure, which brought problems with managing the homogeneity of the field within the test region, as well as managing the transient reflections throughout the structure. The pulse power driving the structure was also connected via RG-220, which created impedance transition issues, as well as problems with high voltage insulation.

A second system was designed and tested, building from experiences gained from the first system. The new structure was modified to mitigate the field and reflection problems, by implementing a rod-like structure to replace the solid sheet construction. A pulse power module was integrated into the structure, removing the RG-220 and the necessary coax-to-parallel plate transition.

The final system meets all of the test standard's specifications, while being highly portable and simple to use. Several systems are now in service to test military components.

This paper describes the two-pass design and testing process taken to develop the tested solution.

II. BACKGROUND

The MIL STD 461 E/F document details the RS-105 hardware requirements and definitions, as well as the test procedure. Figure 1 provides an overview of the hardware required for this test. This includes a TEM waveguide structure, a pulse generator and a Faraday cage for shielding the oscilloscope used for calibrating and diagnosing the electrical behavior of the system. The specification suggests a solid parallel plate TEM waveguide, sourced by a coaxial cable-connected pulse generator. A field probe is to be used to measure the field strength at various defined points within the test region; and a direct measurement is required between the pulse generator and the TEM structure for calibration and monitoring of the system.

Figure 2 is taken from the Mil-Standard document, and defines the layout and dimensional requirements of the system. The width of the waveguide should be at least twice the width of the EUT, and the length of the test region should be twice the length of the EUT. From Figure 1, this region is the constant dimension section, with the feed and load sections attaching on either side. The height, or the plate separation definition is not provided in Figure 2; however, the standard defines the specification as 3 times the height of the EUT.

A sample of the required waveform is provided in Figure 3. The electric field, within the test region, is characterized by a rise time between 1.8 and 2.8 ns, with a magnitude in excess of 50 kV/m, and a reversible polarity. The Full Width Half Maximum (FWHM) is to fall between 23 ns ± 5 ns.

Before testing the EUT, the test volume must be calibrated with a field probe. The diagram in Figure 1 defines the test points, and that no point may have more

[ξ] email: mayes@apelc.com

than a 6 dB variance from the maximum. Once calibrated, the input sensor, located between the pulse generator and the TEM cell is calibrated for reference during the test. A 500 MHz real-time oscilloscope is used to make the measurements.

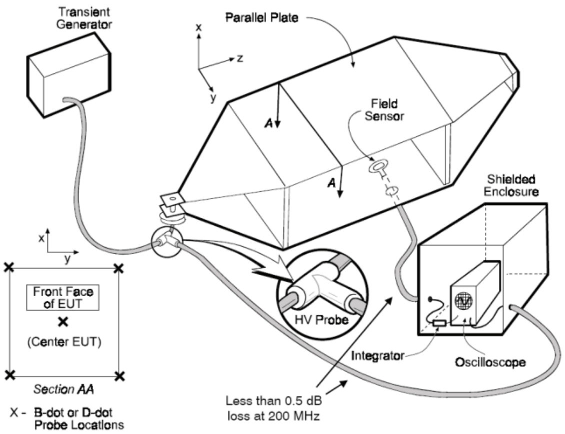

Figure 1. Suggested Hardware from the MIL STD 461 E/F (RS-105) Test Standard

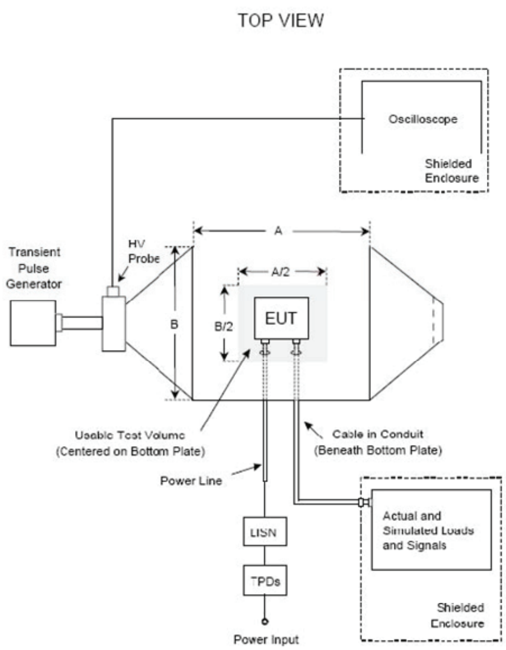

Figure 2. Top View of the Suggested Hardware from the MIL STD 461 E/F (RS-105) Test Standard, including Dimensional Definitions

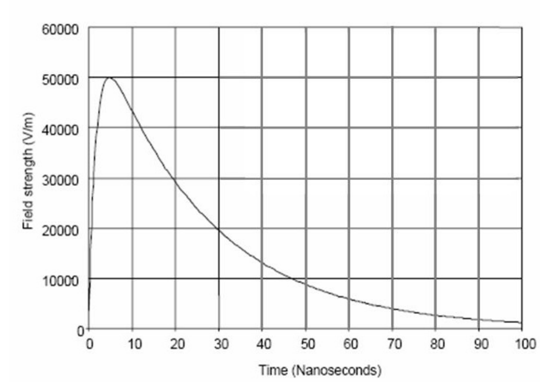

Figure 3. Defined Waveshape of the Electric Field within the Test Volume, as Defined by MIL STD 461 E/F (RS-105) Test Standard

III. INITIAL DESIGN AND RESULT

The design objective was to test a rackmount device, with a maximum volume defined as 24 in. x 24 in. x 16 in. From the test standard, the apparatus' volume can be derived, as illustrated in Figure 4. Using a parallel plate transmission line mode, as described by Figure 5, the relationship between the height and width can be derived from a defined characteristic impedance and the desired test volume definitions.

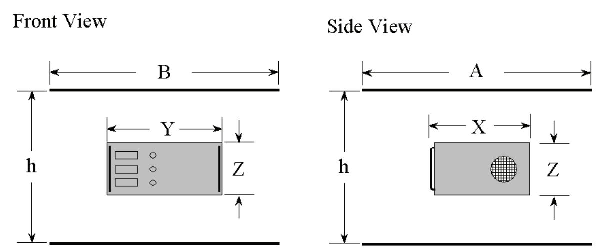

Figure 4. Test Volume Definitions Derived From the Test Standard

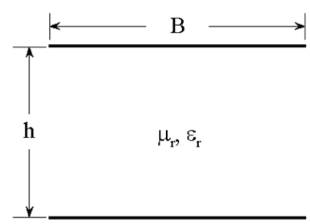

Figure 5. Definitions for a Simple Parallel Plate Transmission Line

The equation for the characteristic impedance of a parallel plate transmission line is given by:

$$Z_o = 377 \frac{h}{B} \sqrt{\frac{\mu_r}{\varepsilon_r}} \qquad (1)$$

Solving for the width, B, and assuming an air insulated volume:

$$B = 377 \frac{h}{Z_o} \quad (2)$$

The test standard suggests a characteristic impedance of 50 Ω; however, with a structure 48 in. in height, a width of 340 in. results, which is hardly portable. By increasing the impedance to 200 Ω, the line's width becomes more manageable, with a width of 96 in. The final transmission line volume is h = 48 in., B = 90 in., and Z = 48 in (linear length of the line).

The input and output sections to the transmission line were implemented with asymmetric tapered transmission lines. The input side includes a coaxial cable-to-parallel plate transition, illustrated in Figure 6, which then opens to the aperture defined by the test volume, and in a length of 96 in.

Figure 6. Input Transition

The output section is nearly a mirror image of the input section, tapering down from the test volume aperature to a 50 Ω geometry. A carbon composition resistor array terminates the line.

The line is sourced by a 6 stage Marx generator, connected via a short section of RG-220. An ancillary module supplies the Marx generator with high voltage (polarity selectable), pressurized dry air and a high voltage trigger pulse.

System Testing and Diagnosis

A sample test electric field waveform measured inside the test volume is provided in Figure 7. The waveform suggests a number of problems with the line: The initial portion of the pulse is characterized by excessive ringing. Approximately 20 ns into the pulse, reflections from the load begin to appear, and approximately 60 seconds into the pulse, more load reflections are observed. The multiple reflections from the load are problematic since they can force the system to fall out of specification.

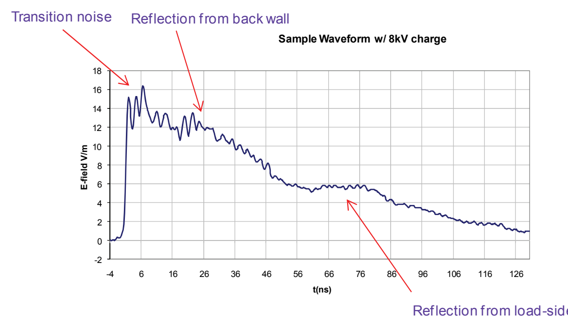

Figure 7. Sample Measured Electric Field Waveform Made Inside the Test Volume

Figure 8 is provided to illustrate the wave dynamics on the transmission line, and is used to diagnose the problems with the measured waveform. As the high voltage pulse is launched onto the TEM structure, two waves are generated in section **D**: a free wave that is generated as a consequence of the input appearing much like a linear half TEM horn antenna **1,** and a bounded wave that propagates the line **2**. The bounded wave **1** continues through the transmission line and is mostly terminated by the load resistor. Reflected energy **3** from

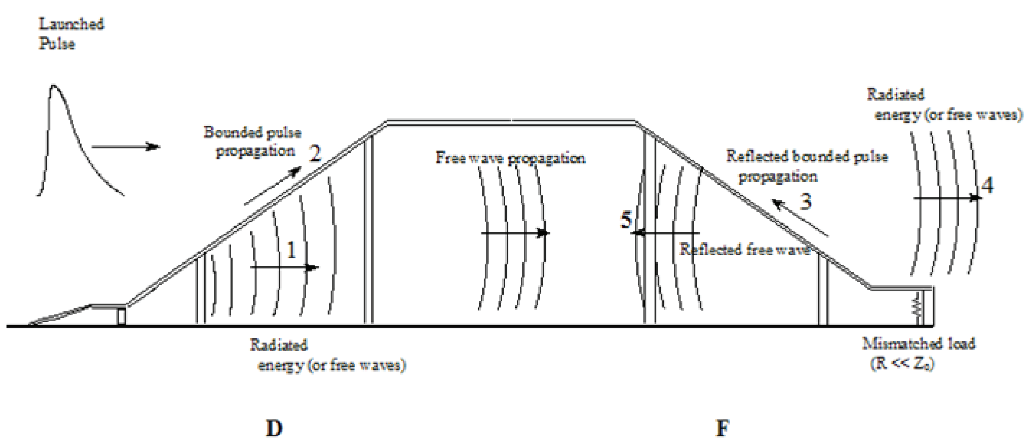

Figure 8. Illustration of the Waves Propagating the TEM Structure

the load, due to impedance mismatches between the line and the load, propagates back into the test volume.

The free wave **2** continues toward the load, although non uniform as the wave is aimed slightly off the horizontal. Some of the free wave energy reflects off the solid load-side waveguide and returns to the test volume **5**.

The reflected free wave signal proves to be the greatest problem in the measured waveform, since the reflected bounded wave energy is negligible. As illustrated in Figure 9, the expected double exponential pulse is followed by the added reflection of the free wave, causing the pulse to fall out of the standard's FWHM requirement.

RF absorbing material does help quench the effects of the reflected free wave; however, more drastic measures were required. As illustrated in Figure 10, a forward moving wave is comprised of the free and bounded waves, and a rearward moving wave is comprised of the reflected free and bounded waves. In the original measured waveform, the reflected free wave dominates, pulling the measurement out of specification. By intentionally under-damping the load, and causing an inverted bounded wave to synchronize with the reflected free wave, the measured waveform can be forced into specification, as illustrated in Figure 11.

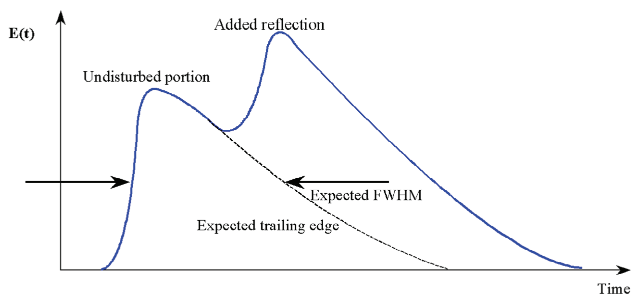

Figure 9 Illustration of the Effects of the Reflection on the Measured Field Inside the Test Volume

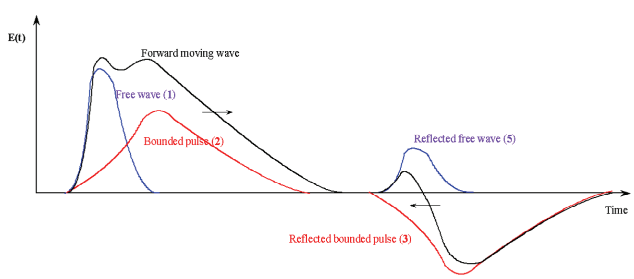

Figure 10. Illustration of the Forward and Rearward Moving Waves and the Respective Components

IV. FINAL DESIGN AND RESULT

A second design was made to mitigate many of the problems found with the first system. The second system was proposed for a light weight, ultra-portable solution, with improved wave dynamics and integrated pulse power systems. Many of the problems in the first design were caused by the solid plate material used for the TEM structure. The cost in these plates were realized by excessive weight, non-uniform wave propagation and a solid surface by which free waves may reflect. The transition, from the coaxial cable to the parallel plate geometry also proved to be problematic, and often failed.

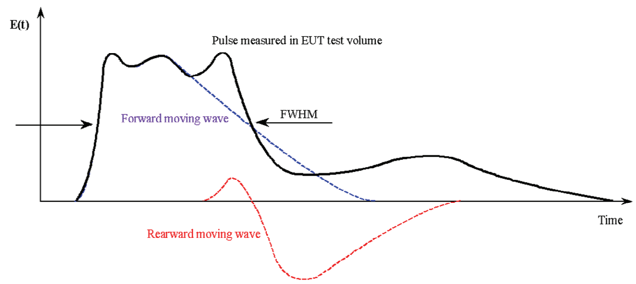

Figure 11. Illustration of a "Tuned" Rearward Moving Wave Pulling the Measured Waveform into Specification

The parallel plate geometry also led to a secondary problem by forcing the current toward the outside edges of the plate. This characteristic was observed in the measurements, as the electric field strength was higher on either side of the test volume and lower in the center.

Simulations were made with CST Microwave Studio to study a rod geometry to replace the solid plates of the TEM structure. The results of Figure 11 indicate that the rod geometry is preferred. By launching a pulse down the rod structure, the current remains uniform on each of the rods, instead of migrating toward the edges. Furthermore, the electric field in the test region is much more homogeneous.

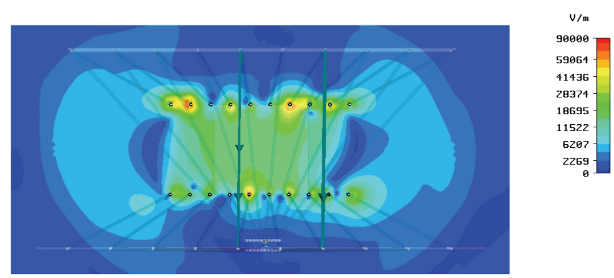

Figure 12. Simulation Results Illustrating a Homogeneous Electric Field Pattern Inside the Test Volume with Rods Used as the Conductors

The load-side was largely left similar to the original design, with a tapered linear half TEM geometry. However, the load was replaced with a water resistor, to allow for tuning of the resistance. It is also anticipated that the water resistor will have a longer lifetime than the array of carbon composition 2W resistors, which are also becoming difficult to obtain.

The source-side section of the transmission line was altered from the linear half TEM geometry to a symmetrically tapered TEM geometry, so that the radiated wave would evenly illuminate the test volume. The lateral length was maintained at 96 in.

The RG-220 coaxial cable and the balun, used in the first design, were removed from the design. Instead, the Marx generator was attached directly, and orthogonally, to the TEM structure. Furthermore, the power electronics and control components were co-located with the Marx generator, alleviating the cabling necessary to connect the two components. A fiber optically connected, hand held control box was added to "charge" and "fire" the Marx generator remotely.

In order to achieve the high voltages necessary for the standard, a Marx generator is utilized. This method of voltage multiplication is preferential over cascade voltage multipliers in that the total erected voltage is only present for a few hundred nanoseconds, as opposed to existing during the entire DC charging cycle. This greatly reduces the insulation requirements for the system.

The Marx generator utilized in this system is comprised of five 500 nF stages, resistively charged and triggered electronically. While sufficiently fast rise-times are possible with the APELC family of generators; stability, accuracy, and repeatability are key concerns when conducting MIL-standard testing. Therefore, a proprietary pulse-forming section independent of the Marx generator was implemented. The energy of the generator is transferred into this circuit, and then discharged through an adjustable low-inductance switch into the TEM cell. So, while the generator itself can fall out of tolerance over time and lose its waveform characteristics, the pulse-forming section is easily externally adjusted by the operator and ensures that the system test-bed meets the MIL-standard specifications with every shot, while requiring little to no down time for routine maintenance of the pulsed-power.

Both the Marx generator and the pulse-forming section require an insulation medium to provide voltage hold-off at the higher operating voltages of the system. In traditional pulsed-power systems this is accomplished using an insulating oil, or "transformer oil". Transformer oil, while a perfectly good insulator, adds considerable weight to the system and eventually needs to be changed due to carbon deposits which build-up over time. The pulsed-power used in this system utilizes easily obtainable, compressed, dry breathing air. The power-electronics module contains an electronic pressure regulator, allowing the user to make incremental increases in the system pressure with each increase in charge voltage. This sufficiently insulates the system in a manner that does not add to system weight, and is easily purged every few shots ensuring an uncontaminated operating environment for the system with each round of testing.

The power electronics module, described by the block diagram in Figure 13, includes a front panel and fiber-optic remote control. The module includes a positive and negative HVPS, a compact mechanical high-voltage relay to change polarity, an electrical pressure regulator and a solid-state trigger generator. All components in the power electronics module were hardened for reliability and long-lifetime in a high-level EMI environment. In typical operation, the user chooses a charge voltage and pressure that corresponds to the desired EUT electric field amplitude. Then the user commands charge and fire using the fiber-optic remote control. This allows electrical isolation and operation from a remote location. A photograph of the front end module is provided in Figure 14.

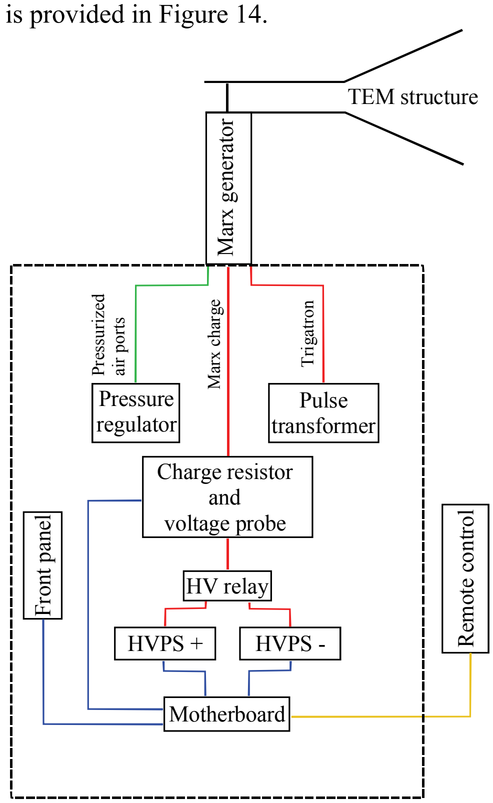

Figure 13. Schematic of Frontend

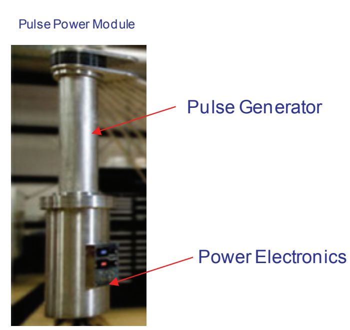

Figure 14. Photograph of the Frontend Module

A CAD rendered drawing of the final structure is shown in Figure 15, providing dimensioned side and end views. The final structure is approximately 18 ft. in length, and 7 ½ ft in height. The structure was lifted 48 in. from the ground to maintain the parallel plate characteristic, instead of a stripline characteristic, should the test stand be used over a conductive surface. By implementing the TEM structure with aluminum rods, the overall weight of the system was reduced from approximately 1,200 lbs to less than 200 lbs. Furthermore, the complete structure can be compactly crated, and is two-man portable and assembled in less than one hour. Moreover, the front-end module is designed to be completely self-contained, and easily replaceable. In the spirit of better supporting the test community, this system has been designed for use with a wide variety of source modules – each module offering a unique RF signature, such as damped sinusoids or variable pulse length microwave.

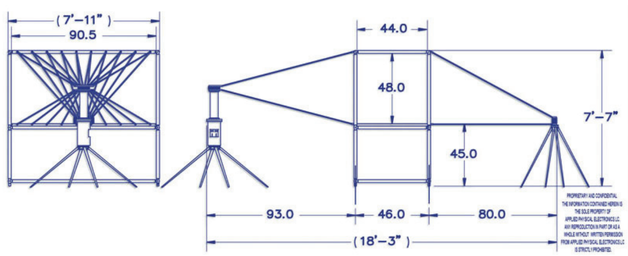

Figure 15. Illustration of the Final RS-105 Test Structure

The basic characteristics of the system are provided in Table 1. The electric specifications are met, with a risetime of 2 ns and a FWHM of 23 ns. The source is reversible in its polarity, and electric field strength inside the test volume is variable from 10 kV/m to 60 kV/m. Figure 16 provides a sample measured waveform.

Table 1. Characteristics of the APELC MIL STD 461 E/F RS-105 Test Stand

Symbol	Parameter	Value	Units
T_r	Pulse rise time	2	ns
PW	Pulse width (FWHM)	23	ns
R_{Load}	Load impedance	100	Ohms
PRF	Pulse repetition frequency	1	ppm
V_{charge}	Maximum charge voltage	20	kV
$V_{erected}$	Maximum erected voltage	100	kV
POL	Available polarity	±	-
	Precision of indicated charge voltage	± 2	%
	Input power voltage	110	VAC
	Input peak power rating	40	Watts
D	Pulse generator diameter	8	in
H	pulse generator hieght	37	in
W	Pulse generator weigth	20	lbs

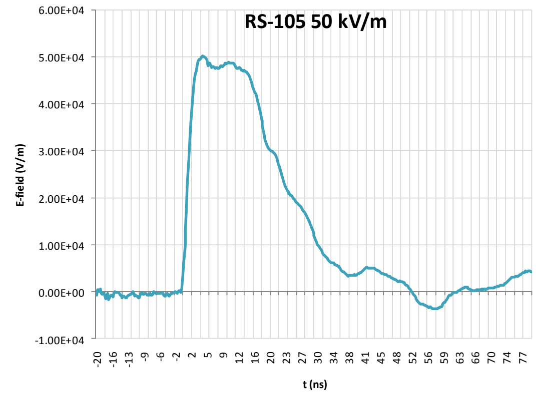

Figure 16. Sample Waveform Measuring the Electric Field Inside the Test Volume

V. CONCLUSION

A test stand was designed and tested to meet the MIL-STD 461 E/F, RS-105. Two iterations were made and reported in the paper. The first iteration developed a working prototype, and was used to understand the nuances of the design, including the wave dynamics. A second iteration was made to better the performance and mitigate many of the problems found with the first design. The completed system met all of the MIL standards specifications, while realizing a very compact and easy to use and deploy system.

Future work will tend toward developing a variety of front-end modules to help researchers understand the effects on electronics with a wider variety of field characteristics, such as variable duration sinusoidal signals.