MODULAR, HIGH-POWER, WIDEBAND TRANSMITTERS FOR ELECTROMAGNETIC ENVIRONMENTAL EFFECTS (E3) TESTING

T. A. Holt[Ξ], M. B. Lara, C. Nunnally, C. W. Hatfield, J. R. Mayes
Applied Physical Electronics L C , PO Box 341149
Austin, TX, USA

Abstract

Applied Physical Electronics, L. C., (APELC) has developed a suite of high-power, wideband, dipole antennas targeted for use by the test and evaluation and the directed energy communities. Four dipoles spanning the frequency range of 50 to 500 MHz have been developed, manufactured, and used to support testing for various customers. The suite of dipoles was developed to address the new MIL-STD 464 C and all of the dipoles can be sourced by the APELC MG15-3C-940PF Marx generator. The dipoles feature corner reflectors to increase their directivity, which act to reduce side lobe levels. Additionally, a common, proprietary connector is implemented into the design of each dipole to facilitate the interchange of dipoles during deployment or testing scenarios. The dipoles manufactured to date vary in size from 20 cm in diameter and 245 cm in height to 17 cm in diameter and 37 cm in height for the 60-MHz and 400-MHz dipoles, respectively. The average amplitude of the peak electric field measured 110 kV/m and 200 kV/m for the 60-MHz and 400-MHz dipoles, respectively (electric field strengths normalized to 1 meter from source). Temporal and spectral data will be presented for each dipole offered and methods for obtaining higher peak electric field amplitudes will be discussed.

I. INTRODUCTION

APELC has been developing a number of high-power, Marx generator-driven, microwave sources over the past several years. Two impulse radiating antennas were developed and reported on in [1] and [2]. Several high-power helical antennas are reported on in these proceedings in [3], and this document discusses recent progress in developing high-power dipole transmitters backed by corner reflectors.

The wideband dipole antennas developed by APELC represent a continued effort to produce a product line of high-power, wideband transmitters capable of meeting the needs of the Electromagnetic and Environmental Effects (E3) testing community. Four dipoles have been developed to date with center frequencies of 60-MHz, 100-MHz, 250-MHz, and 400-MHz; the latter three are shown in Figure 1 along with the MG15-3C-940PF which serves as the common source for all four of the dipoles.

The results that follow are a continuation to previous efforts reported in [4] and [5]. Progress has been made in increasing the reliability and performance of the dipoles and a concentrated effort was made to reduce the total cost of the system by reducing complexity and using one common source to drive all of the dipoles.

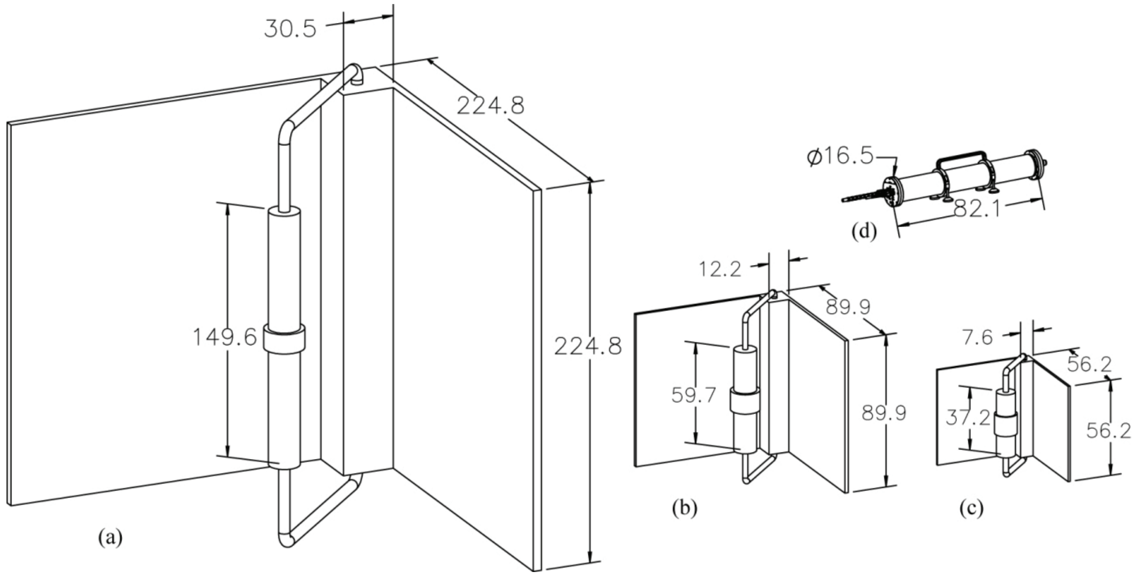

Figure 1. The APELC (a) 100-MHz, (b) 250-MHz, and (c) 400-MHz high-power, wideband, dipole antennas and the (d) Marx generator used as a common source for all the dipole antennas. All items are pictured on the same relative scale. Dimensions are approximate and are provided in centimeters.

[Ξ] email: tholt@apelc.com

II. THE WIDEBAND TEST SYSTEM

The basis technology of the APELC wideband test system (WBTS) is the MG15-3C-940PF Marx generator (MG15). A single MG15 can be used to drive all of the available dipoles independently to burst mode repetition rates determined by the MG15 support systems that comprise the remainder of the WBTS.

A. MG15-3C-940PF (MG15)

The MG15 is discussed in detail in several publications including [2] and [6]-[8], consequently only a brief summary of the generator is presented. Relevant specifications are provided in Table 1 for an MG15 equipped in standard configuration. Output metrics that can be achieved from an MG15 by using the support systems described in the subsequent section include between a 3 to 5-ns rise time and 150-Hz maximum pulse repetition frequency.

Table 1. MG15 specifications

Parameter	Value	Units
Number of stages	15	-
Peak erected voltage (matched load)	300	kV
Maximum charge voltage	40	kV
Maximum energy per pulse	33	J
Capacitance per stage	2.82	nF
Erected capacitance	188	pF
Series inductance	500	nH
Source impedance	52	Ohms
Housing maximum diameter	16.5	cm
Housing inner diameter	12.7	cm
Flange-to-flange length	82	cm

The MG15 can be operated at several different charge voltage levels, the lowest of which is 8 kV. Operating the MG15 at a charge voltage of 8 kV results in a peak erected voltage of 60 kV into a matched load. Any charge voltage between 8 kV and 40 kV can be selected as an operating point, the user only needs to adjust the MG15 vessel pressure and flow rate to ensure proper operation of the device. This charge voltage adjustment capability provides the user with 14 dB of dynamic range in peak MG15 output voltage.

B. WBTS Support Systems

Several support systems are required to operate the MG15 and the high-power dipole radiators. Dry breathable air is used as the insulating dielectric for the spark gaps in all of the dipoles as well as the MG15. Pressure settings are determined by the charge voltage of the MG15 and vary from 100 kPa to 1.14 MPa inside the volume of the MG15. Dipole pressure settings are dependent on the model dipole used and can range from 240 kPa to 2.45 MPa. Predetermined flow rates are required for burst mode operation of the WBTS. Given that the MG15, and the dipole driven by the MG15, operate at different pressures and flow rates, two independent gas flow control panels are required.

The MG15 is triggered with an APELC HRR-TU-18kV, which is a thyratron-based pulser. The unit employs a low-side switching topology and delivers a -18 kV pulse to the center pin of the first spark gap in the MG15.

The charge is supplied to the MG15 via a Lambda 802-L constant-current, high-voltage power supply. A burst rate of 150 Hz represents the maximum capability of the WBTS. This limitation is derived given the required dwell time between consecutive MG15 shots and the maximum power the Lambda 802-L can deliver.

System timing is controlled using a BNC model 575 delay generator. The delay generator is used to program the charge, dwell, and trigger times for the MG15 and the HRR-TU-18kV. The BNC model 575 also provides the versatility to change burst rates and burst types (continuous, duty cycle, predetermined number of pulses) quickly which allows for fast adaptation to changing test matrices.

Lambda 802-L and HRR-TU-18kV charge voltage waveforms can be monitored from the front panel of the HRR-TU-18kV. These events occur on the ms timescale and can therefore be monitored by lower bandwidth oscilloscopes.

The MG15 is equipped with a proprietary high voltage output cable connector that is equipped with a voltage and current diagnostic (d-dot and b-dot, respectively). The diagnostics are capable of resolving the rise time of the MG15 output pulse and consequently require a higher bandwidth scope for the measurement (> 100 MHz).

An emergency stop (e-stop) panel completes the WBTS support components. The e-stop panel is equipped with a low pressure interlock which will suspend operation if the main dry breathing air pressure drops below a predetermined value. An emergency stop panic button is also provided in the event the system must be immediately disabled. The e-stop panel also features a master system key allowing the end user to implement a lock-out, tag-out operating procedure.

C. Dipoles

The four high-power, wideband dipoles that APELC offers as the radiating elements of the WTBS are all based on the same design principle: an integrated resonator in the body of the dipole. The capacitance of the resonator is pulse-charged by the MG15 and a spark gap acts as a portion of the resonator inductance and closes after the capacitance reaches full charge. The spark gap is insulated with dry breathable air in all of the available dipoles. Additionally, all dipoles interface with the MG15 output high voltage cable using the same proprietary output cable connector that is used on the output of the MG15. The cable connector is a quick-disconnect style connector and its functionality facilitates the quick interchange from one dipole to another if required.

III. DIPOLE PERFORMANCE

Each of the four dipoles offered by APELC is equipped with a resonator integrated into the dipole body that is tuned to deliver maximum radiated electric field amplitude near the listed center frequency of the device. All dipoles are equipped with corner reflectors and the spacing of the dipole relative to the corner reflector is also tuned to deliver maximum radiated electric field amplitude.

An optional fiberglass stand is available and can support the 400 or 250-MHz dipoles in vertical or horizontal polarizations. The stand provides a total of 30 degrees of pitch adjustment (15 degrees above and below the horizontal plane), and is capable of elevating the transmitter to a height of 3 m from the center of the transmitter to ground. The stand is equipped with pneumatic-wheel casters for easy positioning and field testing. The 100 and 60-MHz dipoles require stands more capable of supporting heavier loads. The stand for the 60-MHz system is depicted in Figure 10.

The data acquisition setup is discussed first, followed by performance data for each of the dipoles presented in order from highest to lowest radiated frequency. All dipoles can be rotated on their stands for operation in either horizontal or vertical polarization. Data acquired from both polarizations is presented where possible.

A. Data Acquisition

All measurements presented in this document were obtained using a Prodyn Technologies model AD-55 free field d-dot sensor in conjunction with a model BIB-100F balun. A 30-m length of RG214 was used as a signal cable between the free field sensor and the Tektronix TDS6804B oscilloscope used to record the measurement. The signal cable and all attenuators used during data acquisition were calibrated on a vector network analyzer. The resulting signal chain calibration factor along with the probe and balun calibration factors were used to determine the radiated free field amplitude from the dipole. In all instances, the probe was at least 3 m above ground level. All measurements were made at a distance of 10 m from the dipole and normalized back to a 1-m distance.

B. 400-MHz Dipole

The 400-MHz dipole is the highest frequency dipole presently offered by APELC. The 400-MHz dipole and reflector feature lightweight construction with the dipole resonator body (which acts as a pressure vessel) representing a large fraction of the device's weight. Approximate device dimensions are listed in Figure 1 (c) and the overall weight of the device (dipole, reflector, and support structures) is 14.5 kg.

Data acquired with the 400-MHz dipole at the maximum operating point in vertical polarization are presented in Figure 2, which depicts an overlay of a total of 20 waveforms. An average peak electric field strength of 192 kV/m was observed and the transmitter is capable of a dynamic range of operation of approximately 14 dB.

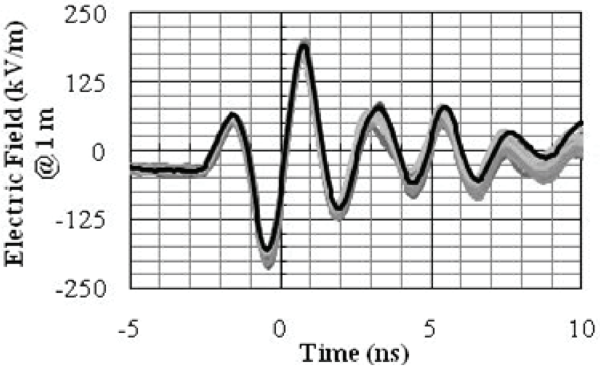

Figure 2. An overlay of 20 measured radiated impulses from the 400-MHz dipole. The measurements were performed at a distance of 10 m from the device and normalized to 1 m.

The spectral density corresponding to the data presented in Figure 2 is shown in Figure 3. The transmitter has a 3-dB bandwidth ranging from 380 to 465 MHz and a center frequency near 440 MHz.

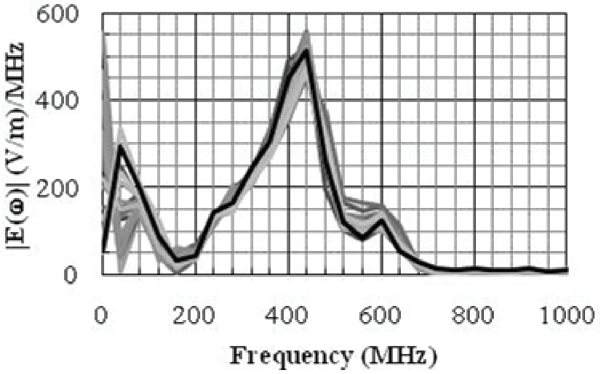

Figure 3. An overlay of spectral density derived from the data presented in Figure 2.

An H-plane map was derived by measuring the electric field intensity at nominal increments around the transmitter and is shown in Figure 4. The angular resolution of the H-plane map varied with angular position. The area of highest resolution was the 40° region between 340° and 20° which was measured in 5° increments. The remainder of the map was performed in 10° or 15° angular increments around the dipole. Each data point of the map is an average of five peak radiated electric field amplitude measurements performed at that angular location. The 3-dB beamwidth in the H-plane of the transmitter was found to be 43 degrees nearly centered along the bore sight of the transmitter. Additional testing demonstrated an MG15 to transmitter jitter of 48 ps, proving the feasibility of an array of transmitters to achieve higher radiated electric field levels.

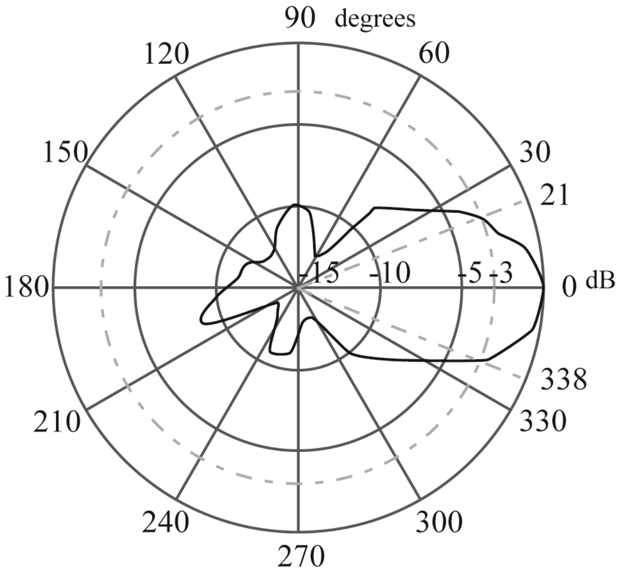

Figure 4. The H-plane antenna pattern of the 400-MHz dipole antenna.

C. 250-MHz and 100-MHz Dipoles

The 250 and 100-MHz dipoles have seen less use than the 400 and 60-MHz versions, but have been field tested and had their peak electric field amplitude measured by a third party. The data acquired by the third party is shown in Figure 5 and demonstrates capability to achieve a peak electric field amplitude of nearly 180 kV/m at a distance of 1 m from the source. The first generation 100-MHz dipole recorded a peak electric field amplitude of nearly 70 kV/m at a distance of 1 m from the source. APELC's design methodology has matured since the fielding of the first generation 100-MHz dipole, and APELC firmly believes a peak radiated electric field strength greater than 100 kV/m at a distance of 1 m from the source can be achieved, as is indicated by the 60-MHz dipole which meets or exceeds the 100-kV/m metric.

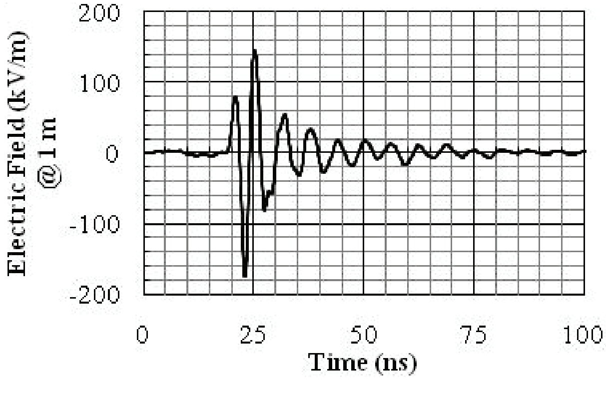

Figure 5. A measured radiated impulse from the 250-MHz dipole antenna as measured by a third party.

D. 60-MHz Dipole

The 60-MHz transmitter is the lowest frequency transmitter offered by APELC. The system is housed inside a 40-ft (12-m) trailer during periods of storage and transportation.

The 60-MHz dipole and corner reflector are mounted to a vertical cart that travels up and down a vertical mast for total height adjustment capability of up to 4.6 m above the ground as measured from the center of the transmitter. The base of the vertical mast is hinged and can adjust continuously from horizontal to 8° beyond vertical. The vertical cart is lowered to the bottom of the vertical mast, the corner reflector flaps (which are hinged in the center) are folded, and the vertical mast is lowered to its horizontal position during storage. The base of the vertical mast is fixed to a horizontal cart via a slewing bearing which allows for the transmitter to be steered by a total of 36°. During deployment of the transmitter, the horizontal cart is extracted from the rear of the trailer to provide sufficient clearance for the vertical mast to rise without interfering with the trailer ceiling. The vertical mast is raised into position using a linear actuator. When the vertical mast is in the desired position, the horizontal cart is retracted back into the body of the trailer and the antenna is then raised into position. A slewing bearing on the vertical cart provides capability for adjusting the polarization of the radiated signal by physically rotating the entire dipole and corner reflector assembly to the orientation that produces the desired polarization. The transmitter and reflector were fabricated from light weight materials such as aluminum where possible. The vertical mast and horizontal cart were fabricated from steel. The entire system is depicted in Figure 10.

A superposition of 21 time-domain waveforms acquired in vertical polarization is shown in Figure 6 and the corresponding spectral density is shown in Figure 7. In the vertical orientation, the system has a 3-dB bandwidth ranging from 56 to 71 MHz. An average peak radiated electric field amplitude of 96 ± 5 kV/m was observed in this polarization.

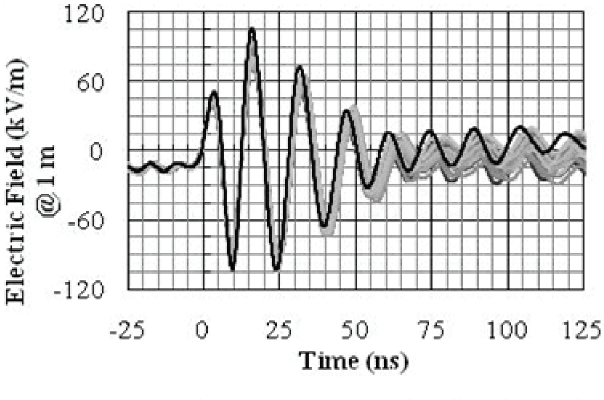

Figure 6. An overlay of 21 measured radiated impulses from the 60-MHz dipole in vertical polarization. The measurements were performed at a distance of 10 m from the device and normalized to 1 m.

The effect of ground bounce on the 60-MHz system is difficult to mitigate due to the physical size of the system. Separation from ground is limited to the height of the trailer above the ground in addition to the length of travel on the vertical mast. Burst mode repetition rates of 150 Hz are possible with this system. Additionally, the system is capable of a dynamic range of operation of 10.4 dB through charge voltage adjustment or 15.5 dB by adjusting the transmitter to reflector spacing. The dynamic range through charge voltage adjustment appears limited when compared to numbers mentioned in a previous section of this document, and this is due to the fact that the dipole does not operate below a 15-kV charge voltage level on the MG15.

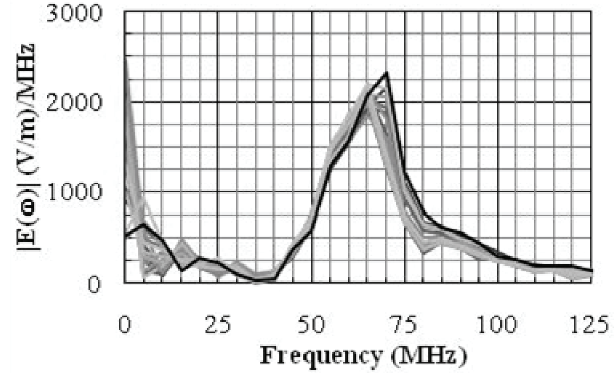

Figure 7. An overlay of spectral density derived from the data presented in Figure 6.

The performance data summarized for the 60-MHz dipole were not acquired in the far field of the transmitter but are near 10% of the far field values as determined from subsequent testing. In the horizontal orientation the system has a 3-dB bandwidth ranging from 52 to 68 MHz and data acquired in the horizontal orientation is presented in Figure 8 and Figure 9. An average peak radiated electric field amplitude of 106 ± 4 kV/m was observed in this polarization.

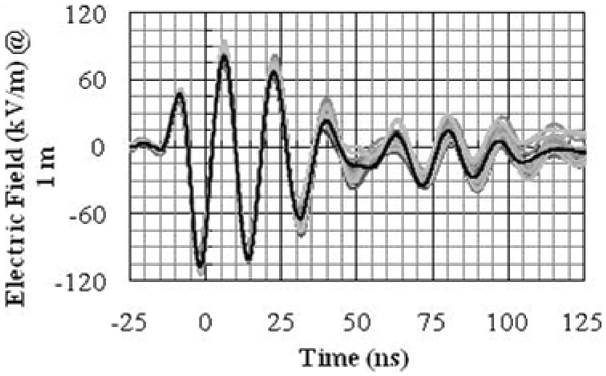

Figure 8. An overlay of 21 measured radiated impulses from the 60-MHz dipole in horizontal polarization. The measurements were performed at a distance of 10 m from the device and normalized to 1 m.

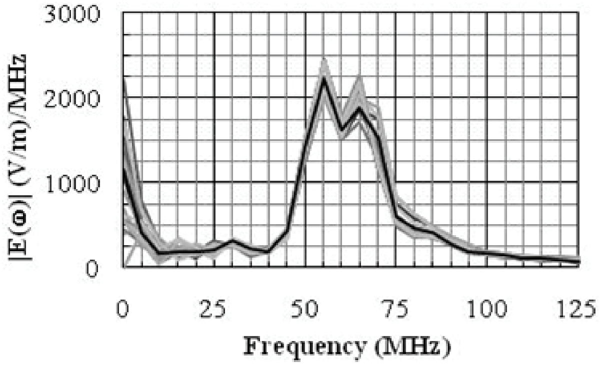

Figure 9. An overlay of spectral density derived from the data presented in Figure 9.

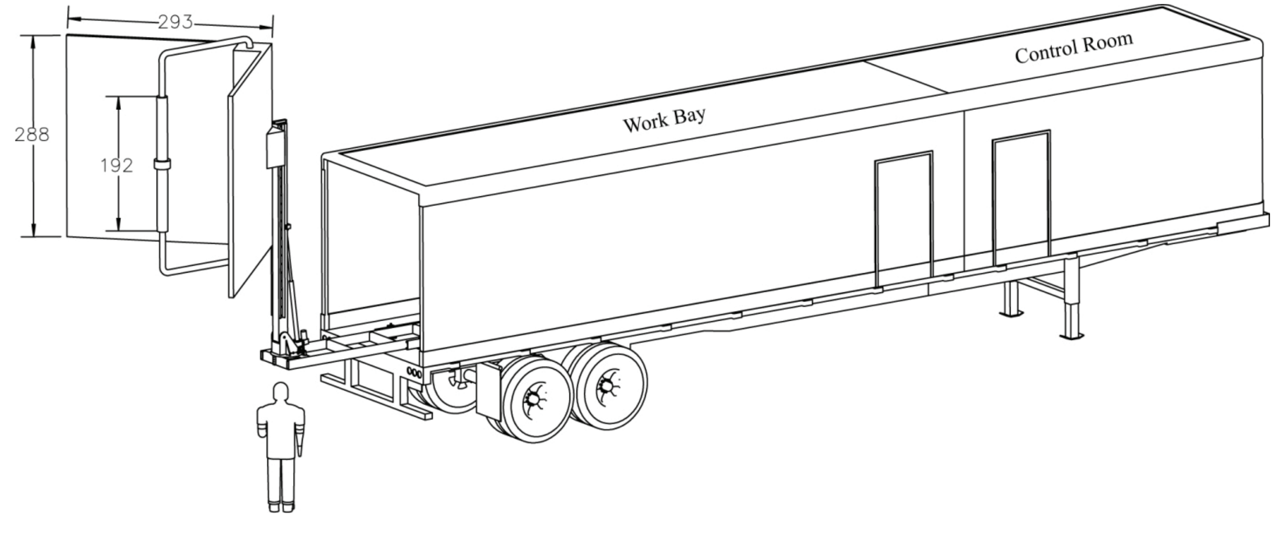

Figure 10. The APELC 60-MHz high-power, wideband, dipole antenna and the trailer that houses the unit during storage and transportation. The units mechanical control systems are stored in the work bay and the electrical control systems are kept in the control room. All items are pictured on the same relative scale. Dimensions are approximate and are provided in centimeters.

IV. CONCLUSIONS

APELC has designed, developed, and fabricated a suite of wideband transmitters driven by a common source, the MG15. The transmitters have demonstrated a dynamic operating range of at least 10 dB. Peak electric fields exceed 70 kV/m normalized to 1 m in all instances. The output connector common to all transmitters facilitates interchange and enables the user to quickly cover the 50 to 500-MHz band for MIL-STD-464C testing.

APELCs future efforts will concentrate on developing a dual-polarity driven dipole backed by a corner reflector to increase the maximum radiated electric field from a single dipole. Additional research will focus on developing an array of dipole radiators to achieve the standoff distances required for directed energy applications.

V. REFERENCES

[1] T. A. Holt, et al., “A Marx Generator Driven Impulse Radiating Antenna,” in proceedings of the 17th IEEE International Pulsed Power Conference, Washington, DC, 2009, pp. 489 - 494.

[2] T. A. Holt, et al., “Marx Generators for High-Power RF and Microwave Applications,” in proceedings of the IEEE Power Modulator and High Voltage Conference, Atlanta, GA, 2010.

[3] M. B. Lara, et al., “Modular Interchangeable High Power Helical Antennas,” these proceedings.

[4] J. R. Mayes, C. W. Hatfield, and J. D. Dowden, “Development of a Dual-Polarity Marx Generator Designed for Pulse Charging a Dipole Antenna,” in proceedings of the IEEE Power Modulator and High Voltage Conference, Atlanta, GA, 2010.

[5] J. R. Mayes, et al., “A Compact High Power Wideband System,” in proceedings of the IEEE Power Modulator and High Voltage Conference, Atlanta, GA, 2010.

[6] T. A. Holt, et al., “A Versatile Marx Generator for use in Directed Energy and Effects Testing Applications,” these proceedings.

[7] J. R. Mayes, et al., “Sub-Nanosecond Jitter Operation of Marx Generators,” in proceedings of the 13th International Pulsed Power Conference, Las Vegas, NV, 2001, pp. 471 - 474.

[8] C. Nunnally, et al., "Compact 200-Hz Pulse Repetition GW Marx Generator System," in proceedings of the 17th IEEE International Pulsed Power Conference, Washington, DC, 2009, pp. 1309 - 1311.