A Feasibility Study of RF Time-Domain Reflectometry as a Railgun Armature Tracking Technique

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A Feasibility Study of Radio Frequency Time-Domain Reflectometry as a Railgun Armature Tracking Technique

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Abstract—Since past investigations have shown that radio frequency (RF) signal transmission in the bore of a railgun can be practical, the feasibility of using time domain reflectometry and well-established transmission line theory is investigated as a means to determine armature position during launch. This report describes the transmission line model of the HEMCL and initial measurements suggesting that such an approach might be used to provide dynamic armature position profiles. However, subsequent continuous wave analyses of RF transmission line measurements shows that the electrical transmission line characteristics of the HEMCL railgun make it unfeasible to use RF time-domain reflectometry to characterize its dynamic behavior. The laminated containment structure enclosing copper rails of the HEMCL form a very lossy, poorly matched transmission line making it impractical to couple the RF signal into it; high RF attenuation diminishes that portion of the signal that it is coupled. Measurements showed that signals below 900 MHz are completely reflected at the 50-ohm/HEMCL-muzzle interface. A fraction of RF signals at higher frequencies (900–2400 MHz) can be coupled, but will attenuate by 20 dB or more after propagating only a few tens of centimeters.

1. Introduction

The current method for estimating the time-history of the armature position in the bore of the HEMCL railgun uses an array of etched-PCB axial B-dot detector coils inserted between the gaps of adjacent laminate stacks. The axial positions of the armature are determined by correlating the B-dot coil positions with the respective signals generated by the passing armature during launch. Velocity and acceleration profiles are estimated by numerical differentiation. By their very nature, however, B-dot probes are very sensitive to electromagnetic noise (EMI). A frequent cause of electromagnetic noise within the railgun is that caused by arcing at the armature–rail contact; consequently the data obtained from the B-dot detectors is often corrupted, especially during startup (due to startup-arcing) and near the end of the launch (due to transition-to-arcing). In addition, estimating the armature position with relatively low spatial resolution using a B-dot array requires a relatively high level of maintenance. Finally, it is only possible to incrementally improve the performance and reliability of the present B-dot technology.

Noting that the railgun has two parallel-plate conductors (rails) and a conducting short at an unknown location (the moving armature), radio frequency (RF), time-domain reflectometry (TDR) may potentially be used to obtain the position history of armature during launch. TDR is in widespread use in the cable television and telecommunications industries to locate cable faults and points of branching or termination in networks. The basic idea of TDR is simple: a temporally short EM pulse may be launched at a specific point (e.g., the muzzle) on a transmission line (e.g., the rails and surrounding containment), and the measured time required for the pulse to travel to and reflect back from the impedance discontinuity (e.g., the armature) will be proportional to the distance of the impedance discontinuity to the EM pulse application point within the transmission line. The TDR approach makes use of the linear relationship existing in most media between the distance *d* that an electrical or optical signal source has from a moving target with the associated, two-way time delay *t* that occurs for the reflected signal: $x=c\,t/2$, where *c* is the speed of light. The range resolution Δx of the TDR method can be similarly related to the time delay uncertainty Δt $\{\Delta x = c\Delta t/2\}$ or frequency resolution Δf $\{\Delta x = c/(2\Delta f)\}$ [1].

The success with prior works using UHF RF and microwave techniques motivated a study of TDR in a railgun. A simple experimental investigation of the quiescent MCL [2] determined that L band and S band microwave telemetry was feasible in a railgun. In that study, stationary measurements were made using a 1mW source placed just inside the breech at 100 MHz, 1.5 GHz, 2.0 GHz, and 2.3 GHz. Vertical dipole antennae connected to the receiver were tested at various locations within railgun bore as well as outside the containment. In was shown that the low-level UHF signals could be received even after propagation through the railgun containment structure with only a modest ~5–10 dB attenuation relative to that of free-space propagation over the same distance.

A subsequent investigation of a stationary magnetized railgun environment [3] verified that microwave signals were received with little attenuation after propagating either longitudinally or transversely through the laminated MCL barrel. The results of that static study indicated that telemetry would be successful in an EM launch, and a following work [4] measured acceleration measurements by conveying them from onboard an electromagnetic (EM) launched projectile using microwave telemetry techniques.

Additional work with radar has also been performed in the IAT Light Gas Gun Range, and on the HEMCL, with mixed results. Circularly polarized, 35 GHz signals have been very successful in providing routine, high resolution velocity measurements on IAT's Light Gas gun [5]. However, such signals were found to be highly attenuated by the MCL bore [6]. Initial work using smaller wavelength 90 GHz, linearly polarized signals in the HEMCL had limited success but also suffered from signal loss a few milliseconds after the commencement of launch [7].

The objective of the investigation is to determine the feasibility of TDR as a projectile tracking technology in the HEMCL railgun environment. In Section 2, the railgun is described in a transmission line concept using continuous wave (CW) reflectometry analysis. Here, initial measurements are described suggesting that the TDR approach was feasible in a railgun if impedance matching and attenuation issues were successfully addressed. However, in Section 3, we describe more sophisticated CW reflectometry measurements that show conclusively that such issues will not be resolved in the HEMCL; even if RF signals are artificially coupled into the railgun TL, the attenuation remains detrimental. Conclusions and future work are described in Section 4.

2. Railgun as a Transmission Line

The railgun is considered to be a terminated, two-wire RF transmission line (TL) in this report. Figure 1 is a block diagram of a TDR system setup that might be used on a railgun launcher such as the HEMCL, showing the railgun as a transmission line to be probed. In general, a high frequency, pulsed signal source would be used to launch radio frequency (RF) signals into the railgun muzzle. The railgun TL is considered to be terminated by the conducting armature, which acts as a short-circuit. The reflected and transmitted waveforms are obtained from two of the ports of the bi-directional coupler, and digitally recorded for analyses. During active HEMCL launches, a passive, high-pass filter is used to isolate the high-frequency data acquisition equipment from the low frequency, high voltage applied at the breech of the railgun.

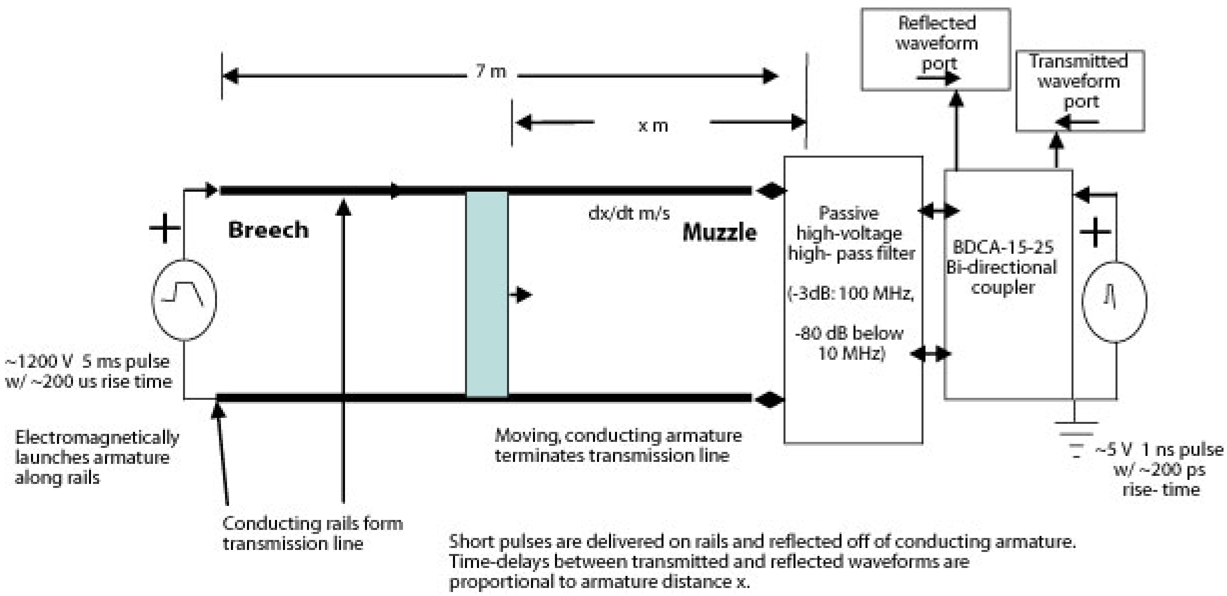

Figure 1. Block diagram to measure position and velocity using time-domain reflectometry in a railgun.

To accelerate the armature in an actual railgun launch, the applied excitation at the breech is typically of order 1 kV, resulting in a ~1 MA scale, ~100 μs rise-time current at the breech and armature. Such an excitation can interfere with the TDR excitation pulses and equipment connected to the muzzle. Fortunately, the shorting-effect of the armature reduces the muzzle voltage to only 10s of volts (at least before transition). Still, a high-pass filter must be used at the muzzle in active launches to further isolate the high-frequency (100–100 MHz) TDR signals and equipment connected at the muzzle from the not-insignificant, lower frequency (~0.01 MHz) railgun excitation pulse applied at the breech. Since active HEMCL launches were not necessary in this investigation, a high-pass isolation filter was not needed or used.

2.1 Initial CW Reflectivity Analyses for an *Impedance-matched* Railgun

We investigated the transmission line characteristics of the HEMCL by using CW reflectivity analyses. Initial measurements were carried out in a simplified railgun environment using a 12 foot pair of copper rails (each ¼ in x 1 ¼ in) without a magnetic containment. The rails were spaced 5 mm apart so that they also presented a nearly matched (~50 Ω) transmission-line impedance. The setup for this analysis differs from that shown in Figure 1 in that no railgun excitation was applied at the breech, no filter was present at the muzzle and a ten-dBm, CW signal (IFR 2024 Signal generator) was the RF source applied at the muzzle.

This setup minimized potential matching issues associated with the 50-ohm coax cable, 50-ohm signal generator and 1 GHz, LeCroy Wavepro 950 oscilloscope (with each channel set to 50 Ω). The forward and reverse propagating voltage waveforms were sampled with the Bidirectional coupler (BDCA-15–25 from MiniCircuits, valid for 500 MHz $< f <$ 2500 MHz). A moveable short was placed between the rails at many different longitudinal positions. Continuous wave reflectivity analyses confirmed that the basic rail geometry acted as a transmission line. CW Signals at different frequencies (500 MHz, 650 MHz, 800 MHz and 950 MHz) at 10 dBm were applied to the muzzle, and the reflected voltage component was recorded with the oscilloscope. For 650 MHz CW signals, the measured half wavelength (spacing between adjacent reflected voltage minima) was observed to be 21 cm throughout the length, revealing that its propagation velocity in the TL was 91% of the speed of light in a vacuum.

2.2 Initial CW Reflectivity Analyses of HEMCL Environment

Next, the transmission line characteristics of a *tabletop* HEMCL were examined by arranging four-meter lengths of 1.75 in x 0.75 in copper rails, held 3 inches apart by sections of G10 insulators. Additionally, pieces of the laminated stainless steel HEMCL containment structure surrounded the rail/insulator assembly. However, moveable-short measurements similar to those described in Section 2.1 did not result in identifiable minima and maxima if the short was moved more than a few cm away from the source, suggesting that a combination of a poor CW signal coupling and high attenuation of the railgun TL was responsible. Attempts using a tapered balun were unsuccessful to improve the broadband impedance match between the 50-ohm instrumentation and cable impedance with that of the tabletop HEMCL and containment structure. A 133-ohm load resistor resulted in the smallest (though still large) SWR = ~5, which was used for the remaining measurements. Signal measurements obtained with an isolated, differential probe were necessary to distinguish the signal matching and attenuation issues.

3. CW Transmission and Reflectivity Analyses with an Isolated Differential Probe

A brief opportunity arose allowing us to evaluate precision, 3-GHz data acquisition equipment from LeCroy Corporation, which included a high bandwidth 7300A Oscilloscope and WL300, two-point differential probe. In order to distinguish the RF signal matching and attenuation issues in the HEMCL transmission line, the axial length of the tabletop HEMCL shown in Figure 2 was shortened to 1 meter and examined in more detail. The block diagram in Figure 3 shows the setup used for these CW transmission and reflectometry measurements.

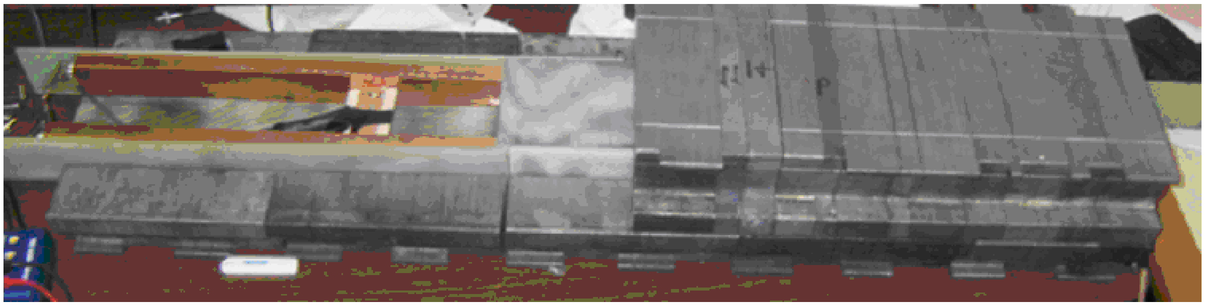

Figure 2 is a picture of the rail and parts of the containment structure used to analyze the TL characteristics of the HEMCL. During measurements, the containment structure and G10 insulators fully enclosed the rail environment between the CW source at the muzzle to 6 cm past the differential probe at the load on the left.

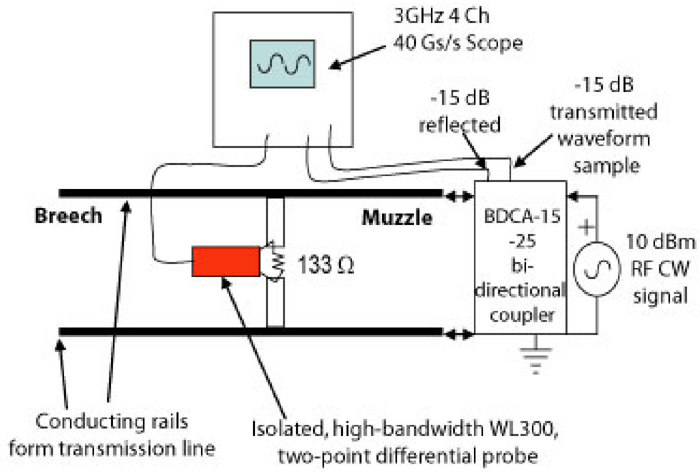

Figure 3. Block diagram of experimental setup for isolated, differentially probed CW transmission and reflectometry measurements. A ten-dBm CW signal was applied to the rails (muzzle) at the right, and a high impedance, differential probe measured the transmitted voltage between the rails at different frequencies and axial locations. A containment structure fully enclosed the rail environment between the CW source at the muzzle to 6 cm past the differential probe at the load on the left.

The received signal was measured across the rails (which were terminated with a 133-ohm resistor) using the calibrated two-point differential probe and the LeCroy 7300A to record signals up to the 2400 MHz frequency limit of the signal generator. CW source levels at 10 dBm were applied to the input port of the directional coupler. The "main" (output) port was connected directly to the muzzle. Samples of the forward and reverse components (reduced by ~15 dB) were provided by respective ports of the bi-directional coupler.

CW Signal measurements of the tabletop HEMCL and containment structure conducted with the differential probe confirmed that the coupling of the CW signal to the HEMCL TL was poor. Only small CW signal levels were detectable in this structure when received at a one-meter axial distance from the ten-dBm source at frequencies ranging from 500–2400 MHz. Clearly much of the signal loss was due to poor RF signal coupling at the muzzle due to impedance mismatch; however, an accurate calibration procedure described in Appendix A. allowed us to characterize the signal attenuation over a smaller (70 cm) axial distance with the fraction of the RF signal that was coupled.

Figure 4 shows the power levels received 70 cm uprange of the source at the muzzle. Nearly the entire signal was reflected at frequencies 500–900 MHz—as indicated by nearly equal magnitudes of C1 (the forward or incident component) versus C2 (the reverse or reflected component). Moreover, the corresponding, received output signals (C3) are about 40 dB smaller than source level at the muzzle at these frequencies.

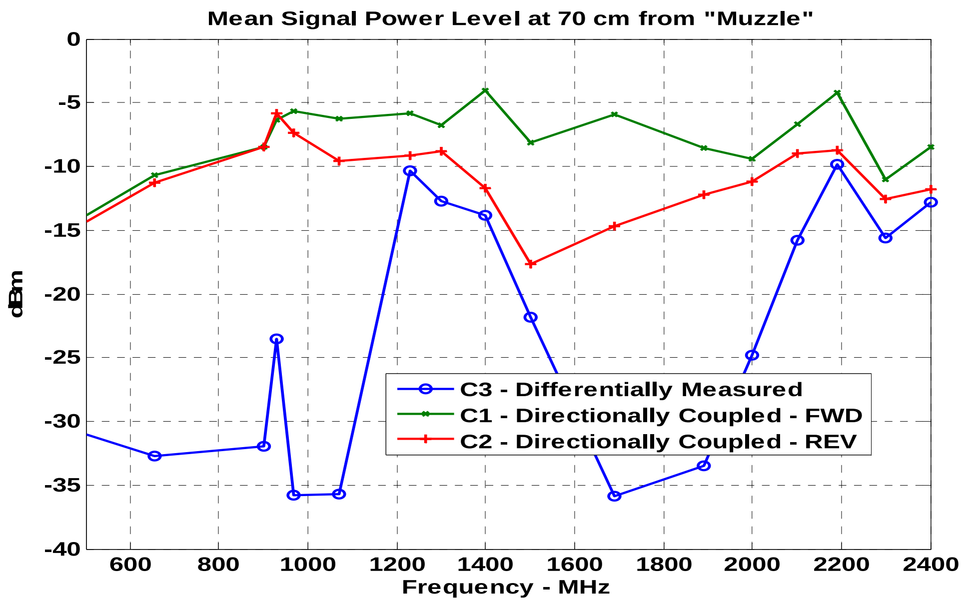

Figure 4. Mean received CW signal levels vs. frequency from a ten-dBm source at 70 cm source/receiver range. Corresponding standard deviation estimates are smaller by at 20 dB or more.

Signal measurements shown in Figure 5 were also carried out as a function of axial distance from a 900-MHz (ten-dBm) source at the muzzle. The magnitudes of the corresponding incident (C1) versus reflected (C2) components differed by less than 1 % at all distances (3–70 cm) measured, confirming that very little signal is coupled into the railgun at 900 MHz. Least-square fitting to Figure 5 shows that the portion that was coupled suffered 87 dB/meter of attenuation.

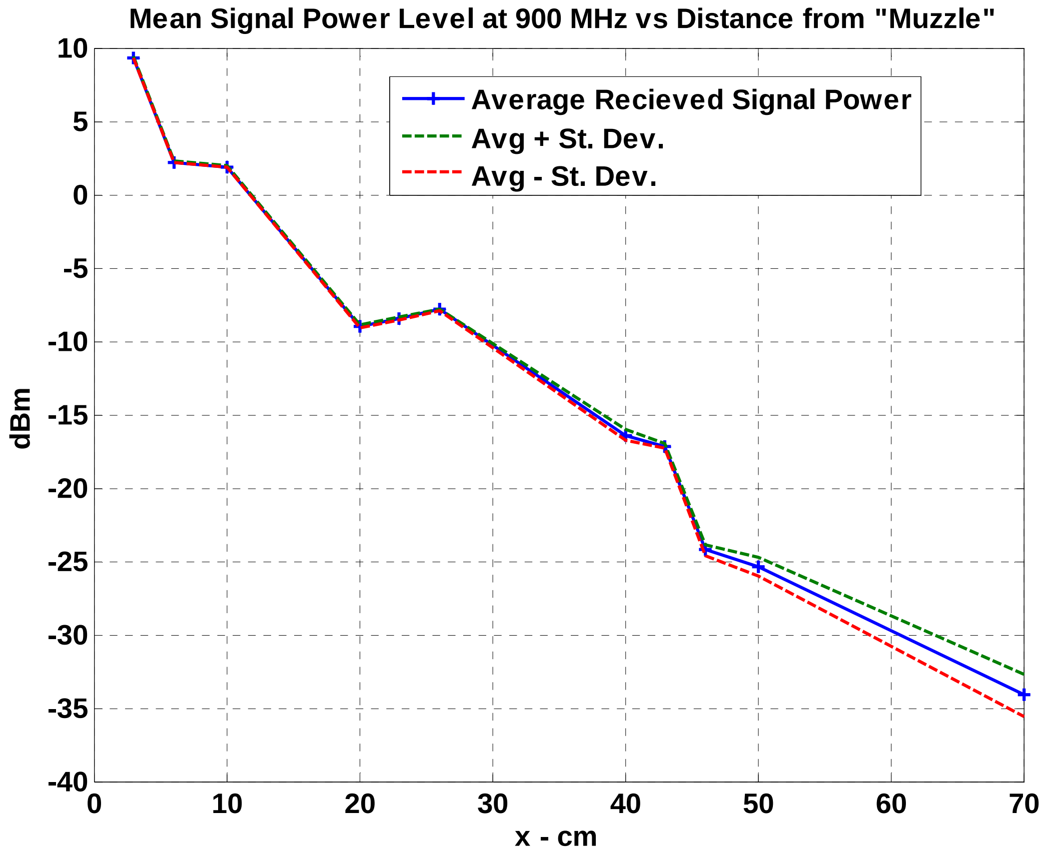

Figure 5. Received CW signal levels and estimated standard deviations vs. source/receiver range from a 900 MHz, ten-dBm source at the muzzle.

At frequencies higher than 900 MHz, Figure 4 shows the incident components were significantly greater than the reflected components, and a fraction of these signals *were* coupled into the HEMCL TL. But because broadband impedance matching could not be achieved, the magnitude of the received signal C3 is the result of both attenuation and frequency dependent (constructive or destructive) interference. At those frequencies where interference plays constructive role, reductions in the received signal level from the ten-dBm source level is the result of an attenuation mechanism. In Figure 4, the maximum measured output signal—10 dBm—occurs at 1200 MHz and 2200 MHz, indicating the HECML transmission line attenuation at 70 cm is approximately 20 dBm or more at these frequencies. Signal attenuation of this magnitude cause RF TDR to be impractical in a railgun.

4. Conclusions

Although RF signal propagation though the a railgun containment structure was found to be feasible in [2–4], this study has shown that the electrical transmission line characteristics of the HEMCL railgun cannot be exploited using RF time-domain reflectometry to characterize its dynamic behavior. Attempts to achieve a broadband impedance match between the 50-ohm instrumentation and cable impedance with that of the HEMCL and containment structure were unsuccessful. From these works, we believe the railgun is a poor RF transmission line and that the EM features of the railgun structure that allow propagation *through* it also contribute to signal losses during axial propagation *inside* it. Careful signal analyses showed even when 500–2400 MHz RF signals are artificially launched in that environment that they will be attenuated by 20 dB or more after axially propagating only a few tens of centimeters.

Noting that coherent transmission of 850 nm optical signals [8] has been successfully demonstrated at high velocity in the light gas gun, we recommend the consideration of optical methods, such as optical TDR and optical heterodyne velocimetry [9] for characterizing railgun dynamics. They are non-perturbing and may offer significantly higher temporal and spatial resolution.

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Appendix A. Calibration/characterization of bidirectional coupler and differential probe

Calibration of the equipment used in the CW reflectivity analysis was performed by measuring the amplitude and phase for each of several forward-going and reflected or reverse-going CW signals spanning 43–2400 MHz. Figure A1 shows the calibration setup used for the high-frequency, differential measurements. As in Figure 2, the IFR CW signal source was set to deliver 1 dBm output (707 mV RMS), and connected directly to the input port of the BDCA-15-25 bi-directional coupler. However, the output port of the coupler was attached to the input port of a 50-ohm micro-strip-line shown in Figure A2a. This provided clean access to both conductors (ground and center) with the WL300 bi-directional probe (see Figure A2b) while maintaining impedance matching. Short sections (< 1m) of RG-58 cable connected the ports and the7300A oscilloscope. Phase differences measured between respective signals in the calibration were used to compensate for cable length differences.

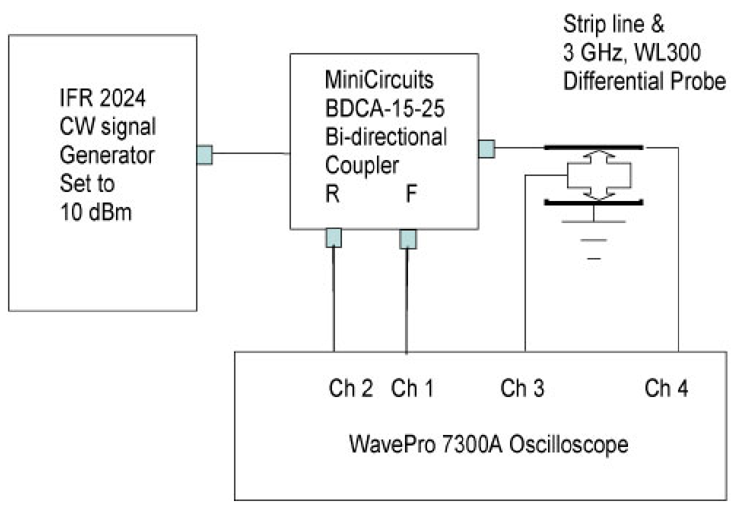
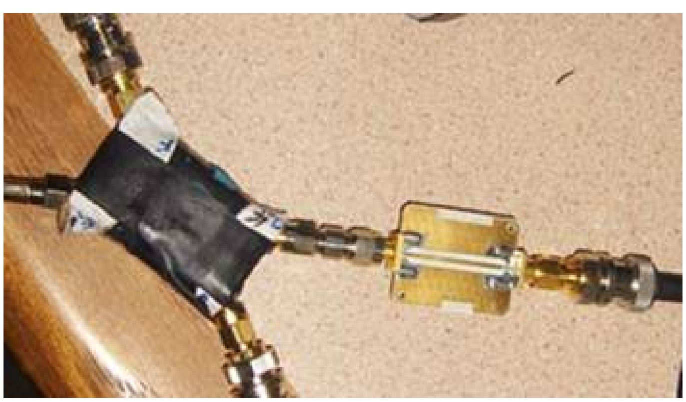


Figure A1. Set-up to calibrate bi-directional and high-frequency probes.



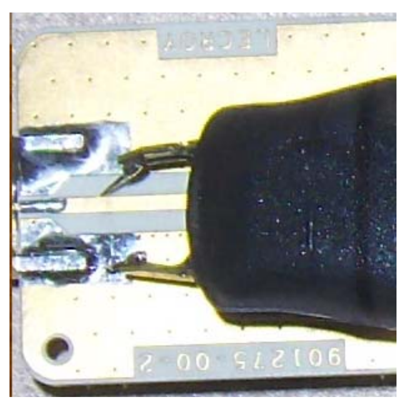


Figure A2a. Bi-directional coupler, 50-ohm strip-line, RG-58 coaxial cable connections.
Figure A2b. A close-up of the strip-line and differential probe connection.

Figure A3 shows the mean and relative standard deviations of the power level for each of the signals collected as part of the calibration procedure; Figure A4 shows phase differences of these same signals. Note that the signal measured by the differential probe on the sampling micro-strip-line did not suffer any significant reflection or phase distortion for frequencies used in the calibration procedure. Above 500 MHz, the directional coupler provides an approximately -15 db coupling factor for forward (C1) propagating signal (i.e., the forward-going signal-pickoff "sees" only -15 dB of the signal). Signals reflecting downstream of the coupler (C2) were smaller by an additional 8–25 db. Below 500 MHz, is outside of the manufacturers' specification of lower design frequency, and the coupling factor fell rapidly as the frequency decreased.

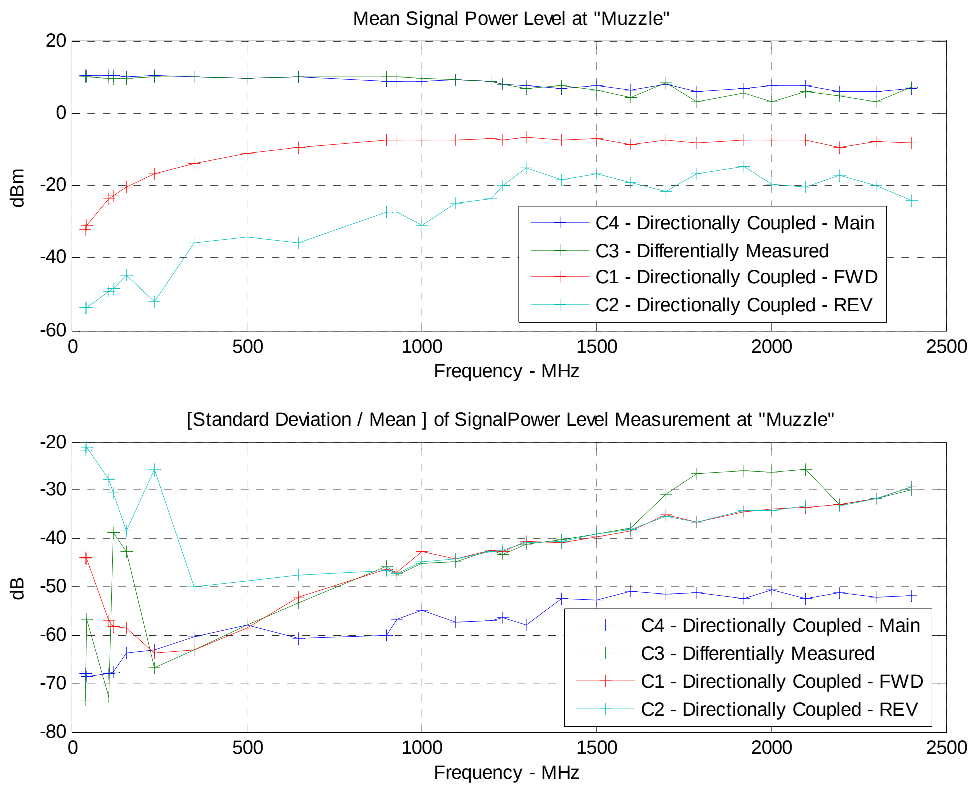


Figure A3. Calibrated CW Signal Levels at Muzzle.

The differences in signal phase $\Delta\theta$ (Figure A4) between the forward-going signal and the differentially measured output signal (C1-C3) was nearly 0 degrees for all signals (39–2300 MHz). The signal phase difference $\Delta\theta = \Delta x \cdot f/c$ between the transmitted and differentially measured (C3-C4) varied linearly with frequency due to the increased cable length Δx of the differential probe; the linearity is clearly visible when it is appropriately *unwrapped*–at closely spaced frequencies in Figure A4. On the other hand, the phase difference between the forward and reverse signal components (C1-C2) at all frequencies show no regular pattern–probably because the reverse component was mostly low level noise due to the very good impedance match between the cable and 50-ohm scope input load.

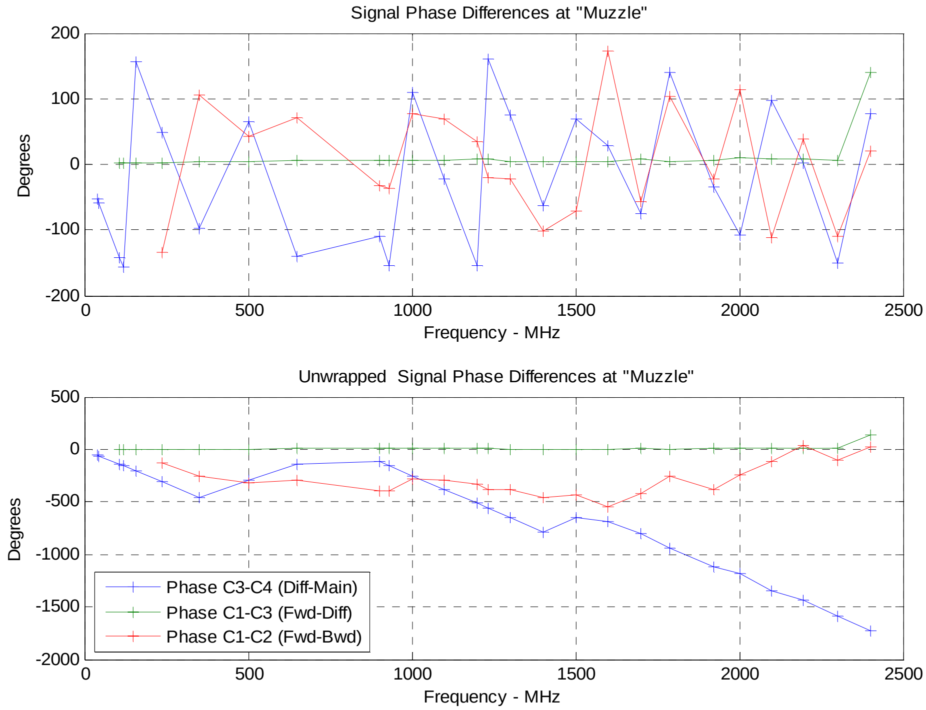


Figure A4: CW Signal phase differences at the muzzle.