REPRODUCTION AND ANNOTATION OF THE EMP SENSOR APPLICATION GUIDE

By W. Reed Edgel, PhD, PE

CHAPTER 1
PREFACE AND INTRODUCTION

The *EMP Sensor Application Guide* was originally written in 1970 by a group of scientists and engineers at the Albuquerque Division of EG&G, Inc, for the Safeguard Communications Agency. The author of this annotation knew personally and admired all of the original authors:

M. K. (Mike) Bumgardner
R. W. (Dick) Christiansen
D. L. (Dave) Endsley
J. L. (Jim) Harrison
W. J. (Bill) Motil
T. O. (Tom) Summers

These technologists were members of a group that developed many EMP sensors for the Air Force Weapons Laboratory and wrote the guide for the effective use of these sensors for the Safeguard Communications Agency. The author of this annotation joined the group after the guide was written.

The acknowledgements mention the excellent support and cooperation provided by E. L. (Ed) Breen and Capt. C. E. (Carl) Baum of the Air Force Weapons Laboratory, both of whom the author of this annotation knew personally and admired. Dr. Baum is still a driving force at what has become the Air force Research Laboratory.

Chapter 1 of the *EMP Sensor Application Guide* is an introduction including the background, purpose and scope of the original document. It is replaced by this introduction.

Chapter 2 of the *EMP Sensor Application Guide* is an excellent treatise on making valid measurements of electromagnetic field parameters. It is dated in its examples but classic in its approach. It is among the best documents of this nature that this technologist has encountered in the third of a century that has elapsed since the original document was written. Accordingly, the annotations are limited to explanations and minor typographic and grammatical errors. The annotations are inserted in square brackets [] in the body of the text.

Chapter 3 of the *EMP Sensor Application Guide* contains specific information about more than a dozen sensors. It is omitted from this reproduction and annotation, with the observation that many of the original sensors therein described have counterparts today.

The above having been said, we continue with Chapter 2 of the *EMP Sensor Application Guide.*

CHAPTER 2
SENSOR APPLICATION

2.1 General

The correct use of a transducer and its associated instrumentation to record field data of assured validity is an art normally acquired after extensive field experience. Numerous documents, covering the application of instrumentation systems and sensors to general field measurements, have been generated. By [and] large, these documents have been concerned with the principles of measurement in the low frequency region (<10 MHz). The measurement of EM fields having of frequency components extending up to 250 MHz requires careful attention to avoid the factors that contribute to errors.

Generally when working on any measurement program that utilizes electric and magnetic field probes, current sensors and voltage sensors, a first-order requirement is the establishment of the system measurement signal-to-noise ratio and the signal validity during the initial phase of the program. A few well analyzed and understood measurements, establishing the experiment and instrumentation quality, are preferred over an approach where numerous measurements are taken with little regard to their credibility. The latter approach generally yields data that must be questioned during later phases of the program, occupying significant analyst time.

Factors that can materially affect the validity of measurements are:

1. Feed cable losses (high and low frequency loss)
2. Connector leakage
3. Cable shield leakage
4. Probe orientation
5. Immunity of probe to other drive sources
6. Feed cable routing
7. Sensor arcing
8. Sensor saturation
9. Ground loops
10. Signal perturbation by nearby objects
11. Oscilloscope interference
12. Measurement system isolation
13. Recording system shielding

It should be pointed out that the following discussion on sensor application will treat only major issues important to their usage. To cover all of the details necessary to make a good measurement with a sensor would entail a volume several hundred pages in length. It is the intention of this chapter to point the reader in the general direction deemed most important as to the utilization of these sensors and systems. A lot of detail has therefore been deliberately avoided in preference to covering a large variety of general problem areas. The experimenter should be cautioned that the data presented in this chapter are neither complete nor definitive, but only a general guideline to stimulate the thinking experimenter in the inspection of areas that were possibly not considered when related to other types of measurements.

Four main areas discussed in this chapter are:

1. Measurement System/Sensor Calibration and Verification
2. Noise Sources
3. System/Sensor Installation
4. Recording Precautions

2.1.1 Measurement System/Sensor Calibration and Verification

The performance of a sensor is obviously only one of the variables that must be considered when making measurements of field intensities, currents and voltages. In addition to this, the transmission link and recording instrumentation characteristics must be evaluated before the system amplitude and bandwidth accuracies can be assessed. A typical system is diagrammed in Figure 1. It consists of three main elements whose characteristics should be determined separately and also as a complete system. The sensor should be tested in a simulator, the transmission link with dummy signals, and the recorder by conventional means.

Many of the current and voltage sensors supplied by the commercial firms are accompanied by calibration curves plotting transfer functions and transfer impedance as a function of frequency. This data can be incorporated with the characteristics of the transmission link and recording system and an overall system calibration obtained. However, this approach has basic drawbacks. In the case of ferrite core magnetic field probe, especially, one should be suspicious of the plot presented. In general, it will be smooth up to the upper 3 dB frequency point; however, measurements made in the EG&G current probe calibration facility *[PRODYN currently uses* several current probe calibration facilities, including one that essentially duplicates the EG&G *facility]* have shown that at high frequencies the curve sometimes oscillates badly. For example, in more than one probe with a constant input current, the output voltage amplitude exceeded the midrange response at one decade above the upper 3 dB point. Secondly, the assumption is made that the sensor's characteristics are stable with time. Factors such as humidity, dust, field handling, and excessively high currents and voltages can significantly alter the characteristics of a sensor. As a result, the calibration of any sensor must be verified periodically.

In addition to the commercially supplied sensors, home-built sensors are utilized in many programs. If accuracy and validity of data are desired, it is imperative that all sensors, regardless of their origin, receive periodic validation of their characteristics.

2.1.1.1 E and H-field Sensor Calibration Techniques

The fact that E and H-field sensors cannot presently be related to the National Bureau of Standards places the term “calibration” in an entirely new perspective. “Calibration”, when used with E and H sensors, means a measurement of the equivalent probe dimensions and subsequent comparison to that dimension predicted by one of Maxwell’s equations. For the H-field sensor, the governing Maxwell equation is:

$$\mathbf{x\ E = -\ \ B/\ \ t} \tag{1}$$

With manipulation, it can be shown that ep (probe voltage) = $A\ \ B/\ \ t$ where A is the effective probe area.

[The most significant technical annotation the author has to offer is a summary of the mathematics involved in getting from the differential forms of Maxwell’s equations cited in the subject document to the sensor transfer functions commonly cited today.

Equation (1) in the original document is the differential or point form of Faraday’s law. This vector equation states that the curl of the electric field equals the first partial derivative with respect to time of the magnetic field. Through some elegant and sophisticated operations involving vector algebra and intermediate electromagnetic theory, it can be transformed into the integral or field form of Faraday’s Law:

$$\mathbf{E}\cdot d\mathbf{l} = -d/dt\ \ \mathbf{B}\cdot d\mathbf{A}$$

This vector equation states that the line integral of the electric field around a loop equals the first time derivative of the flux of the magnetic field through the loop; it was the usual starting point for the derivation of the transfer function of the B-dot sensor. Faraday’s law applied to a loop in a plane perpendicular to the magnetic field vector and containing the electric field and propagation vectors yields the scalar transfer function of the B-dot sensor, as given in the original document:

$$e_p = -A\ \ B/\ \ t$$

This equation states that the voltage at a gap in the loop, which becomes the voltage output of the probe (e_p) equals the effective probe area (A) times the first partial derivative with respect to time of the magnetic field ($B/\ \ t$) through the loop. Since the EMP source and the sensor are in fixed locations relative to each other, $B/\ \ x = \ \ B/\ \ y = \ \ B/\ \ z = 0$ and B varies only with time. Thus $B/\ \ t$ becomes dB/dt. Changing the remaining notation yields the transfer function of the B-dot sensor, as given in most literature including the PRODYN catalogue:

$$V_o = A_{eq}\, dB/dt$$

This equation states that the voltage output of the sensor (V_o) equals the effective area of the sensor (A_{eq}) times the first time derivative of the magnetic field through the loop (dB/dt, called “B-dot”).]

As to the E-field sensor, two governing equations apply, depending on the type of sensor. For the sensor which measures dD/dt *[called D-dot, the first time derivative of the electric field displacement vector]* the following equation applies:

$$\mathbf{x\,H = J + \quad D/\ \ t} \qquad (2)$$

where $\mathbf{J} = 0$ in free space. The probe equation, derived from (2), is $ep = 50A\ \varepsilon_o\ \ E/\ t$, where 50Ω cable is utilized.

[An exposition similar to that for magnetic field sensors above explains how Equation (2) in the original document, the differential form of Ampere's law, yields the transfer function of the D-dot sensor, as given in most literature including the PRODYN catalogue:

$$V_o = A_{eq}\ dD/dt\ R$$

This equation states that the voltage output of the sensor (V_o) equals the effective area of the sensor (A_{eq}) times the first time derivative of the electric field displacement impinging on the sensing element (dD/dt, called "D-dot") times the impedance (R) of the output circuit. The electric field displacement, D, is the permittivity of free space, ε_o, times the electric field strength, E. in equation form, $D = \varepsilon_o E$.]

The parallel-plate sensor which measures E directly, rather than its derivative *[the derivative of its displacement], is governed by*

$$\mathbf{E} = \qquad \mathbf{V = V/h} \qquad (3)$$

where h is the effective height of the sensor and V = signal voltage.

[This vector equation states that the electric field in a parallel plate sensor is the gradient of the signal voltage. It is most commonly reduced to the scalar equation:

$$V_o = E\ h\ ]$$

The generation of "calibrating fields" can be accomplished by utilizing a small parallel-plate transmission line and strip-line principles. A typical probe checkout simulator is shown in Figure 2. [The original document included another figure that was a photograph of a large parallel plate EMP simulator. It was located immediately after figure 2, but there was no citation of the figure in the text of the original document. The photo is no longer available, so we made a sketch of the simulator and replaced Figure 3 with it, thus avoiding renumbering the figures.]

The amount of plate separation on the parallel-plate transmission line should be at least an order of magnitude times the maximum vertical dimension of the sensor to achieve a calibration accuracy of five to ten percent.

The sensor should be mounted between the parallel plates in such a manner as to generate maximum signals from the sensor. In addition, the feed line cables and measurement recording system should have bandwidths twice as great as the suspected sensor bandwidth. A Tektronix 109 mercury wetted reed switch generator is commonly used to drive the input of the parallel-plate line. *[One-third of a century of innovation in pulse generation technology has not yielded a better pulse generator than the "Tek 109", because solid state switches are no faster and not as strong or reliable as mercury-wetted reed relays. If PRODYN could get parts for theirs, they would use it in preference to the more modern pulse generators they have.]* Pulse widths on the order of 50 to 100 nanoseconds should be used and voltages on the order of 100 volts are generally adequate to test the characteristics of sensors having low sensitivities. A sampling oscilloscope, preferably one capable of 28 to 70 picosecond risetime, should be used with short cabling from the sensor to the oscilloscope head.

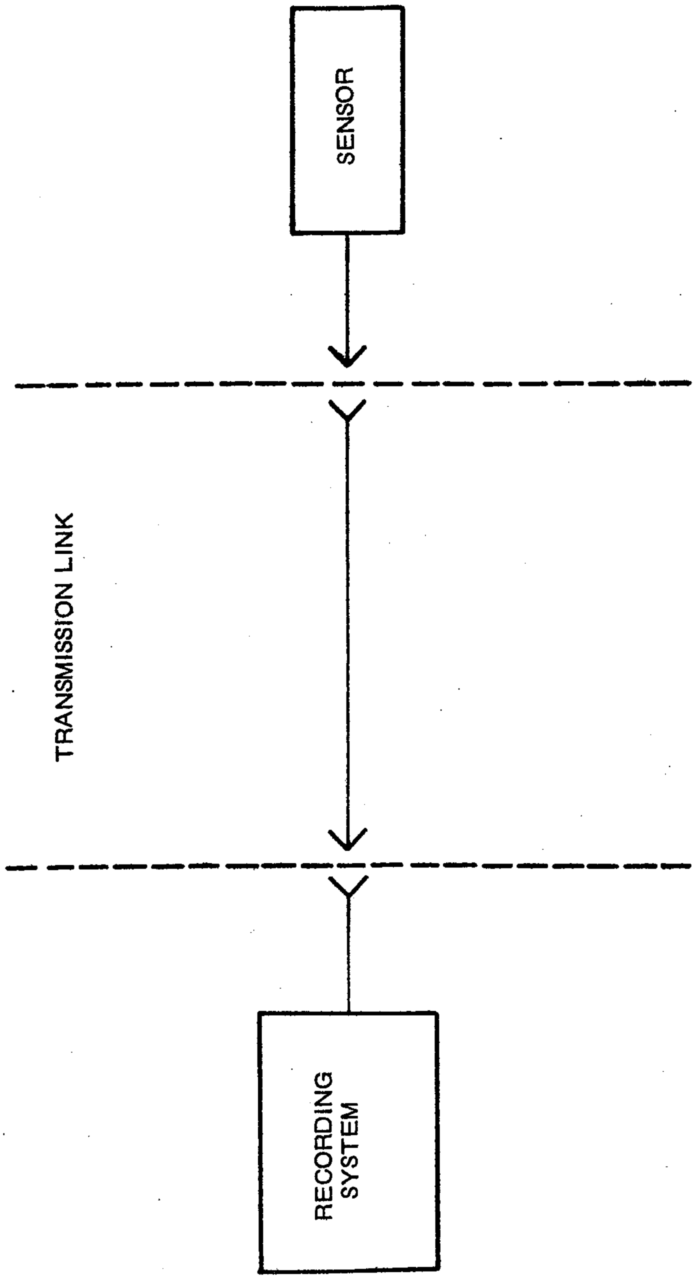

Figure 1 – Typical Measurement System

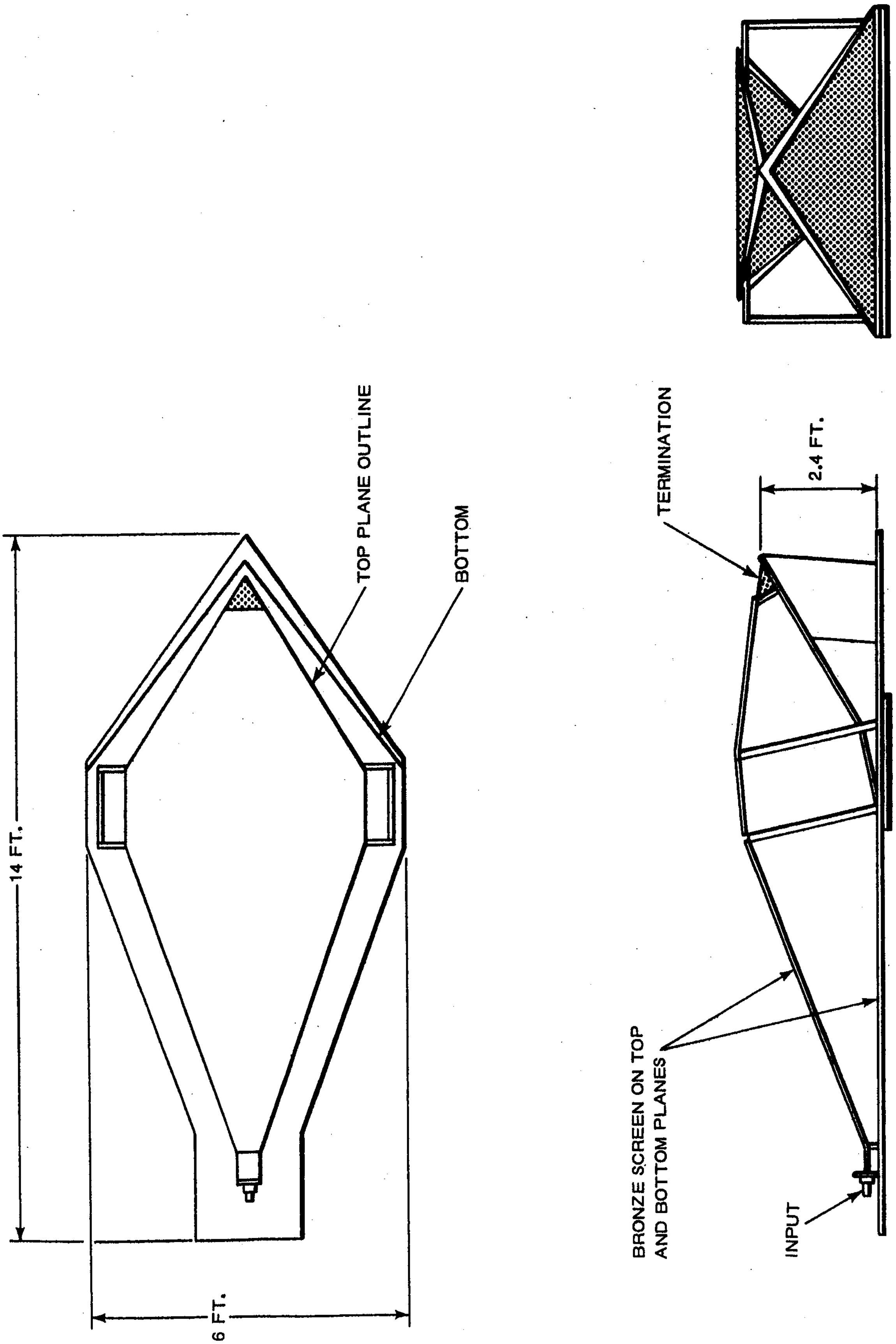

Figure 2 – ARES Probe Checkout Simulator

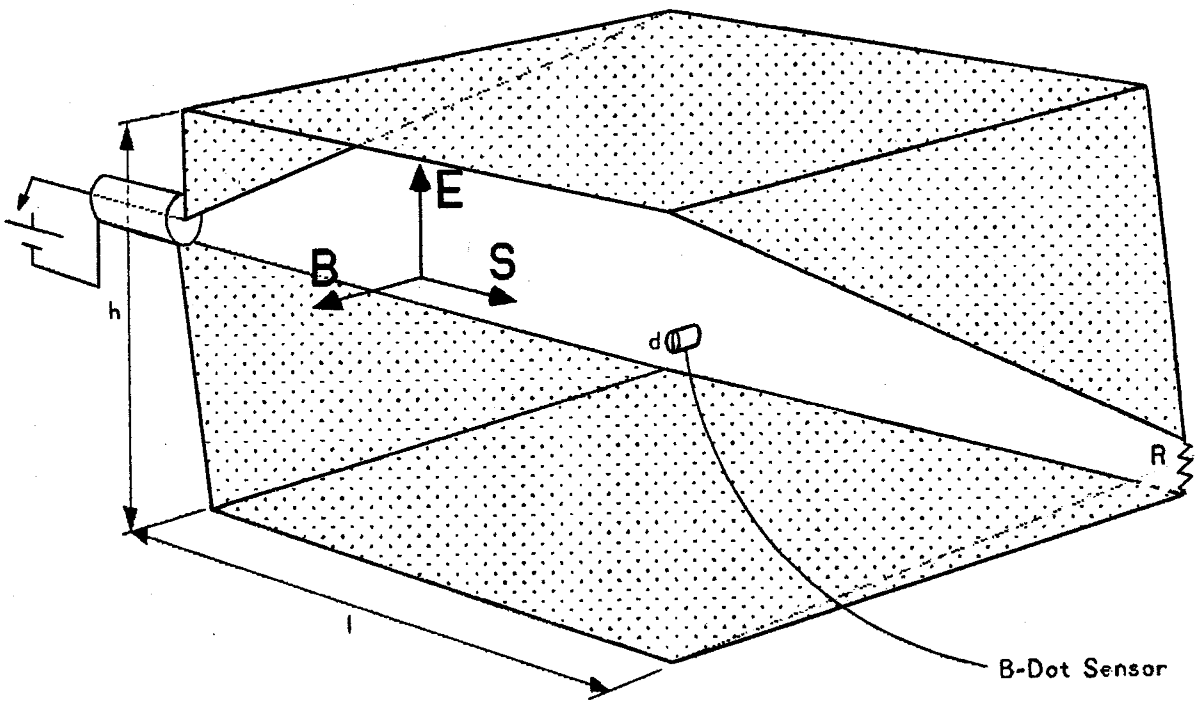

Figure 3–Large Parallel Plate EMP Simulator

It is important that the risetime limitation be due primarily to the sensor rather than to the measurement instrumentation and feed cables. Using this approach, the bandwidth capability of the sensor is indeed measured. The driving waveform present on the plates of the parallel *[plate]* simulator should be measured with a probe directly at the parallel-plate line input. The field intensity that the sensor is subjected to is then calculated by dividing the voltage amplitude by the plate separation at the sensor position. The calculated field intensity, however, still requires correction.[1]

The recorded waveforms from B-dot and D-dot probes are derivatives of the applied waveform. To cross-check the measured probe area versus the area calculated from a voltage measurement by Maxwell's equation, this derivative voltage spike area must be measured.

The simplest technique for determining this area is to record the derivative waveform on a chart recorder allowing the waveform amplitude to occupy approximately full scale on an 8 ½ x 11 sheet of graph paper. A planimeter can then be used to traverse the entire boundary of the waveform with some reasonable degree of accuracy. Many considerations should be kept in mind with this method of measurement. One important factor to consider is that enough time must be allowed for the waveform to rise to its peak value. This means, when evaluating the derivative waveform area, the total time selected for the planimeter measurement must be long enough to allow the integrated pulse to achieve its final value.

The trade-off for this measurement is the fact that any reflections that may occur in a calibration simulator will occur on the waveform at some later time. If the amplitude calculation is not made before the reflection is registered, significant errors will occur in the amplitude calibration.

Other techniques are available to take the integral of the derivative waveforms electronically using the output of the sampling oscilloscope. This particular technique was utilized in the mapping of the ALECS Facility in 1966. [2]

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[1] The S&S Notes are publications put out by the DASA Information and Analysis Center and are entitled "Electromagnetic Pulse Sensor and Simulation Notes". The initial publication (Volume 1) is dated April 1967 and contains Notes I-XXVI.

Partridge, Ralph E., S&S Note I, LASL, February 1964
Partridge, Ralph E., S&S Note XI, LASL, February 1965
Latham, R.W., S&S Note LV, Northrop Corporate Laboratories, May 1968

[The notes (Sensor and Simulation Notes (EMP 1) 1 through 422, Sept '99 Version) are now available from the Air Force Research Laboratory Directed Energy Directorate, Dr Carl E. Baum, Editor. Contact Magdalena Lopez, AFRL/DEHP, 3550 Aberdeen Ave SE, Kirtland AFB, NM 87117-5776. Telephone: 505-846-4101, e-mail: magdalena@kirtland.af.mil]

[2] Endsley, D.L., "Special Report on Field Measurements" EG&G Publication No. AL-186, 28 December 1967

2.1.1.2 Current Sensor Calibration

Calibration of a current sensor can be accomplished with conventional CW drive techniques over the majority of the sensor's frequency spectrum. The transfer impedance of the sensor can be easily measured from low frequencies (1 to 10 kHz) up to approximately 10 MHz with conventional measurement techniques. A low inductance fixture, capable of delivering current through the center of the probe is used. Above 10 MHz, the conventional CW measurement technique becomes inaccurate due to the inductance of the fixture. This inductance creates large reactive impedance when coupled with the purely resistive load, causing a reduction in the effective current through the center of the sensor. This effect, however, can be calculated and corrections applied to the curve, resulting in extending the upper frequency calibration capability to about 150 MHz. Above 150 MHz, the measurements become extremely difficult, requiring precision instruments and low leakage connectors and cables. A typical current calibration system is shown in Figure 4.

In addition to the conventional CW technique and calibration of the transfer impedance, the peak current capability of this type of sensor should be determined. Since current probes of this type utilize a ferrite core, it is expected that saturation effects will occur at very high currents. This saturation is related to a current/time product applicable to a given probe. The saturation current level will be lower for wide pulse widths compared to narrow pulse widths. This characteristic can be checked by using a single-shot high peak current calibrator as shown in Figure 5.

The calibration system is basically a charge line pulser feeding a low inductance section around which the sensor is located. The signal is normally terminated by a copper sulfate resistor capable of terminating high peak currents.

[The High Current Pulse Calibration System provides another check of a current probe's condition in] addition to the saturation characteristic check. The shunt resistors that are a part of the current sensor may be damaged due to excessive currents, temperatures, and basic handling. Pulsed calibration will quickly show any changes in the characteristics of these resistors.

2.1.1.3 Voltage Probe Calibration

This class of sensor has as yet not become popular in measuring signals that reside on components within systems. The main reason for this is the difficulty in making measurements over a reasonable frequency range with them. Any reasonable technique for making voltage measurements must be done on a differential basis since appreciable common mode rejection must be present in order to reject any high frequency noise. If this is not possible, any unbalance in the measurement legs of this differential measurement will result in an error signal being measured rather than the true signal developed across a particular component.

Several voltage probes, the differential voltage probe particularly, are made by different manufacturers, principally Tektronix. The calibration of this type of probe is rather straightforward. A simple compensated RC network could be used for the calibration of a voltage probe of this type.

Another limitation of this differential type measurement is that the probe's common mode voltage capability is limited to 25 or 30 volts. If, inadvertently, several hundreds of volts are accidentally placed between the probe and its ground return point, damage to the probe could result. Typically, the best method of avoiding such destruction is to operate any oscilloscope or recorder using a battery system. Even this technique does not guarantee that large common mode voltages between the tip of the probe and the return line of the system would not develop.

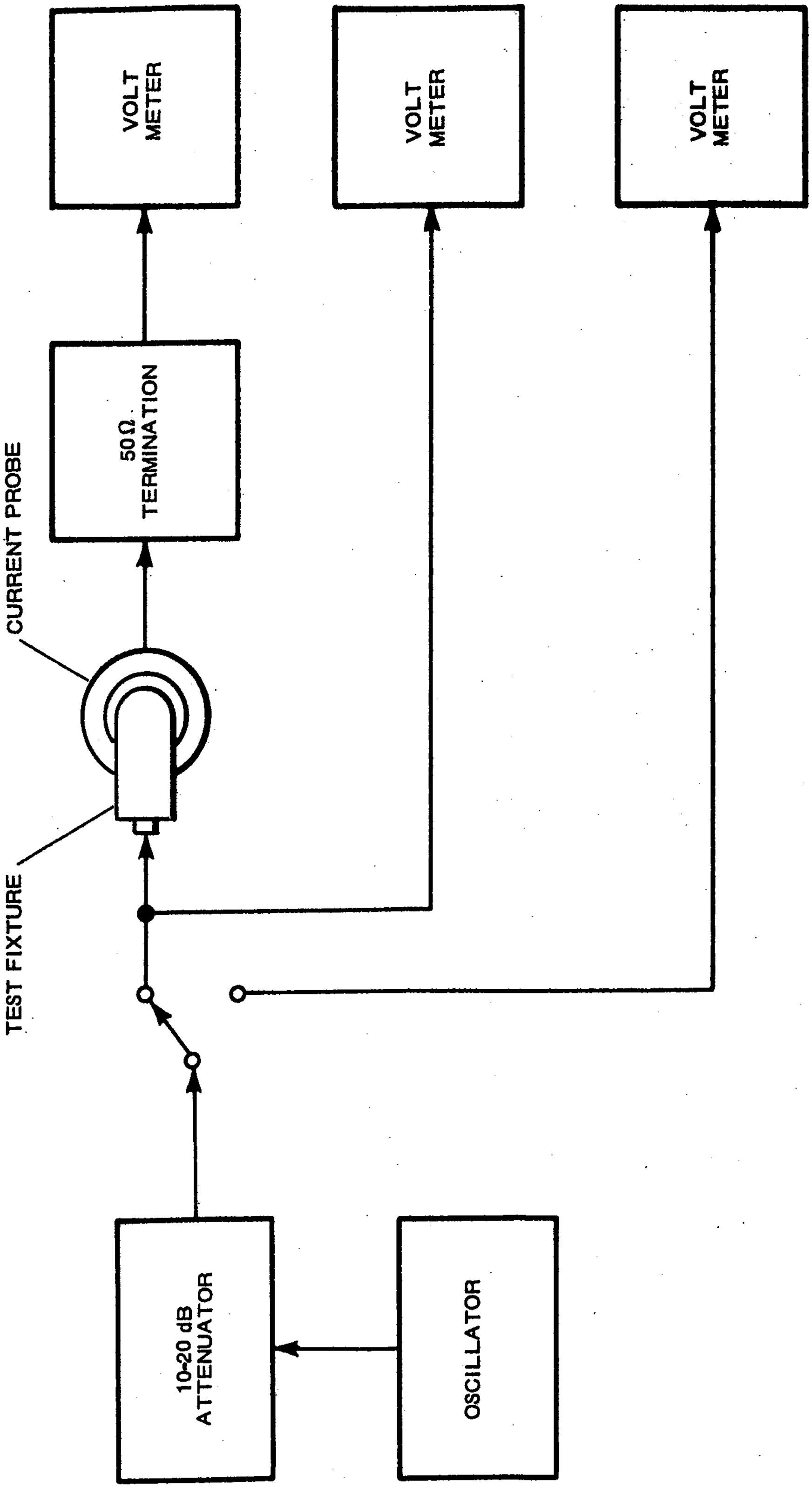

Figure 4 – Current Probe Transfer Impedance Measuring System

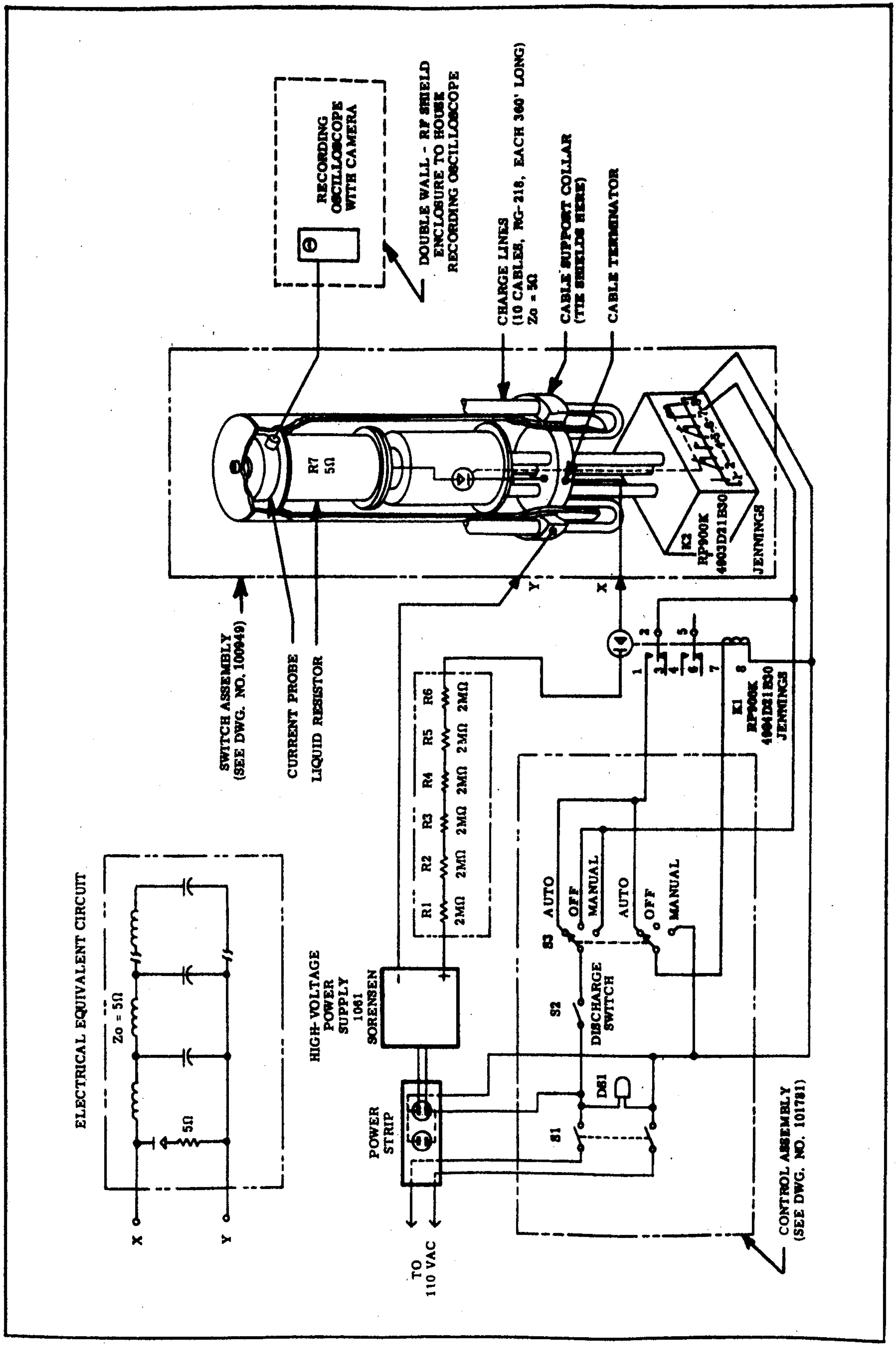

Figure 5 – High Current Pulse Calibration System (schematic)

2.1.1.4 System Calibration

The final value *[of an EMP parameter]* recorded by the *[measurement]* system will be influenced not only by the sensitivity of the sensor, but also by the losses and sensitivity of the cables that feed the signal to an oscilloscope and the amplitude and sweep time characteristics of the recording oscilloscope. In addition, the connectors interfacing the probe with the transmission line and the transmission line with a scope can appreciably affect the amplitude of fast risetime signals.

Cable Loss

Each cable used in measurement setup should be carefully measured (and labeled for future reference) as to its high frequency performance and loss characteristics. It is well known[3] that the losses incurred by feed cables are primarily of the high frequency type. This varies with the type of cable used. RG-58, which is rather inexpensive cable, will cause significant high frequency loss for long runs of 50 feet or more. The high frequency loss characteristics are minimized with high quality cable of Styrofoam, foam-flex, or spyroflex variety. One of the basic *[tests of]* cable characteristics is a waveform with *[a]* gradual rising or sloping tail on a step function applied at the input of a long section of coaxial cable. If the high frequency (>100 MHz) characteristic of a cable is rather poor, the output waveform from a step function input appears like that shown in Figure 6. The *[output]* waveform jumps immediately to a 50 percent *[amplitude]* point, with a risetime *[that]* is very close to the risetime of the input pulse. Thereafter, the waveform slopes up to a final value with a complementary *[decaying]* error function variation. As can be seen, the problem of determining a 10 to 90 percent risetime is difficult and causes the analyst many problems in calculating signal response times and resolution. It is fairly well known that a 10 to 15 percent variation in the peak values for the first five to ten nanoseconds can exist in cables of equal of equal length and type. In addition to the initial cable characteristic measurement, verification measurements of these cables should be made periodically to determine *[whether]* normal field handling has altered their characteristics. Moisture inside coaxial cables creates another high frequency loss mechanism.

Oscilloscopes

The amplitude and sweep calibration of an oscilloscope is something that is often taken for granted. Normal calibration cycles call for a six-month periodical recalibration. The bulk of the commercially supplied oscilloscopes, whether they are sampling oscilloscopes or the single-shot oscilloscopes of the Tektronix 454 variety, may experience changes in their vertical sensitivity and sweep linearity. This is especially true when they are used in field applications. Here, they are normally confined in small-shielded enclosures where heat buildup can be significant.

In addition to the normal daily field handling of the oscilloscope, which can cause potential changes in the amplitude and the sweep, a majority of the oscilloscopes of the HP183 and Tektronix 454 variety will suffer a loss in high frequency response characteristic when maximum

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[3] Nahman, N.S., "A Discussion on the Transient Analysis of Coaxial Cables Considering High Frequency Losses," IRE Transactions on Circuit Theory, Vol. CT-9, No. 2 pp. 144-152, June 1962

sensitivity is used. Thirty to fifty percent pulse amplitude errors during the initial step could occur when measured by an oscilloscope with an abbreviated high frequency response.

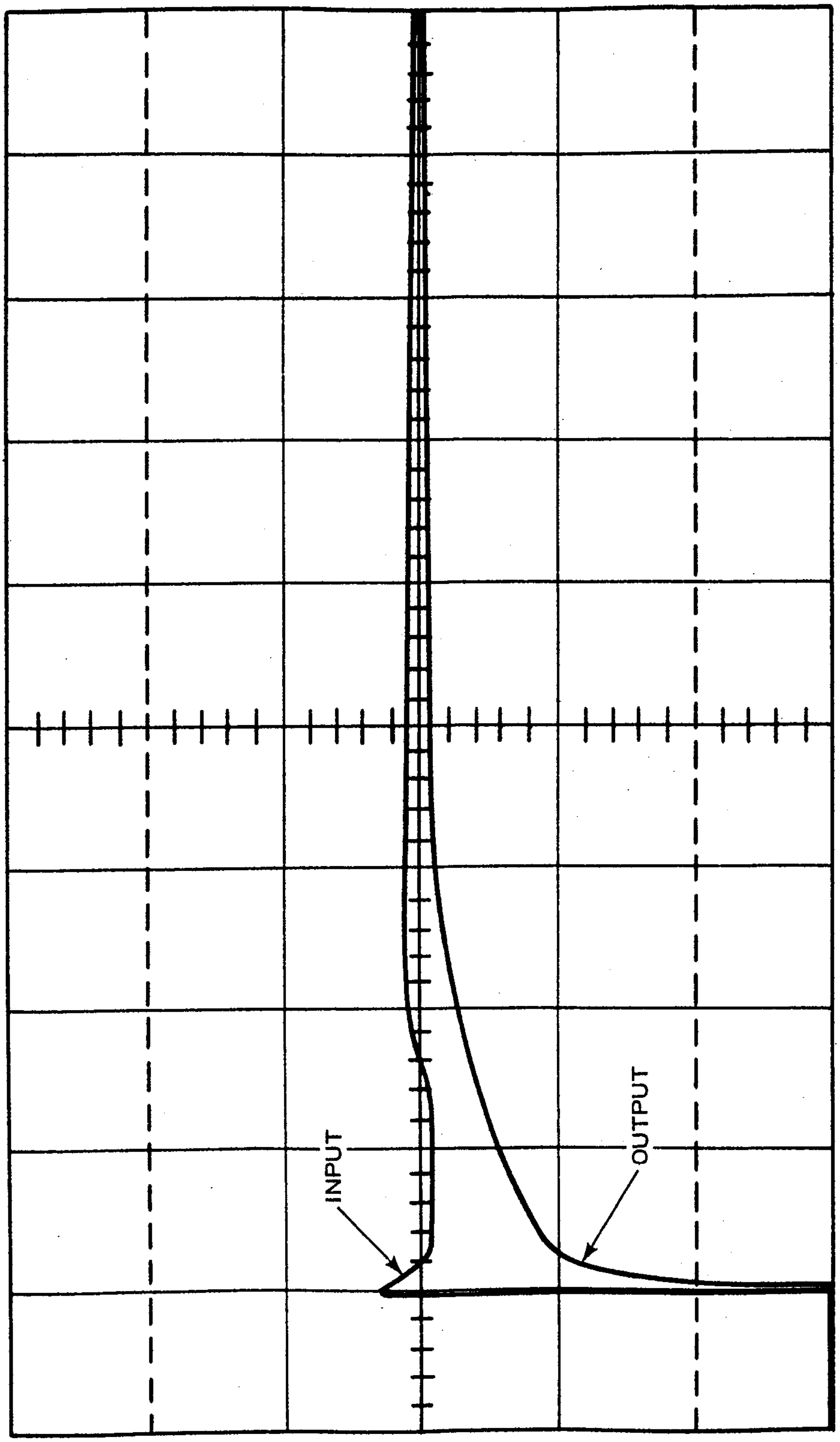

Figure 6 – Waveform Distortion Due to cable Effects

Connectors

One of the weak elements in the measurement system is the connector(s) at the probe-transmission-line interface and the transmission-line-scope interface. Due to their repeated usage and exposure to dust and basic field hazards, losses in signal amplitude and major changes in the signature of the waveform can result. GR type connectors are particularly susceptible to field damage. The tendency during field usage is to mechanically stress the GR connector beyond its design limits causing the center pins to break and the ground connections to be faulty. The GR connector and the normal twist-on bayonet type connector are both susceptible to high frequency leakage since they rely on pressure fitting for connection of the cable shields and the center conductor.

2.1.1.5 System/Sensor Verification

Whether the system and sensor combination is measuring E or H-fields, currents or voltages, a periodic verification of its recording characteristics is a must for any measurement program where overall system accuracy is claimed. The economics of an extensive field measurement program requires that a standard amplitude and known pulse or waveform be applied to the overall system prior to a major test run.

Periodic standard amplitude and time verification of the system's operating characteristics could potentially save significant operating costs during an extended measurement program. In addition to the periodic verification system in the field, prior to its deployment, the measurement system should receive exhaustive initial characteristic testing. The ability of the analyst to arrive at meaningful conclusions is directly dependent upon the systems resolution and recording accuracy.

Resolution

The minimum time required for two separate signals to be recognized as separate is a measure of the resolution of the measurement system. Obviously, the resolution is directly dependent upon the response time of the system. The ability to distinguish reflections occurring in particular measurement geometry is obviously dependent upon the resolution ability of a system. It would be absurd to ask or expect to resolve a one-nanosecond reflection when the measurement system has a resolution of five nanoseconds. However, many experimenters have asked and concluded more from the data then they have any right to by virtue of the unknown characteristics and specifications of the recording system.

Accuracy

The question of measurement accuracy is one that always occurs and must be answered in any final report in which the results of any measurement program are described. Extensive effort should be expended initially on any measurement system to qualify its accuracy capability. The measurements performed to determine this accuracy should conclude with a percentage number, which will allow the experimenter to attach error bars to his measurement points. Many considerations must be made while assessing this accuracy figure. Some of these are the ability of the particular oscilloscope to record the data, the ability of the operator to read that data off a photograph, the trace width of the recording lines, the size of the photograph, and the calibration status of the oscilloscope and the noise level of the measurement. To demonstrate the system's accuracy, a very carefully known amplitude and risetime pulse should be used to exercises the system from sensor through oscilloscope recorder over its dynamic range. This process should be repeated many times by several people to determine the scatter or spread in measurement points.

2.1.2 Interference

Due to the complicated nature and characteristics of real signals resulting from an EMP drive source, it is difficult to recognize the difference between a real signal and an interference of some kind since damped oscillation type signals and damped oscillation containing the sums and differences of many signals are rather standard. To properly recognize a noise signal and distinguish it from an actual system response signal requires several tests and the basic measurement setup. In addition to a noise signal masking or interfering with the signal of interest, there could also be time delays or time differences between a noise and an actual signal. It is often very easy to lock your window time recorder onto the noise signal and completely miss or ignore the signal of interest.

2.1.2.1 Interference Indication

Noise or interference is often times diagnosed due to nothing more than a very educated feel for what a signal should look like. As an example of this, a signal recorded with almost classical characteristics or waveshapes, such as a damped oscillation with only one frequency present, would be highly suspect unless you are measuring the type of physical element that could generate that type of signal. If one is making a measurement on a device or geometric element that is obviously rather complicated, one should expect a reasonably complicated signal. When a clean oscillation occurs, of the form e^{-at} sin wt, one immediately suspects that either a cable ground has been opened or a direct exposure of the coaxial center conductor to an E or B-field driving source has occurred. This type of waveform is illustrated in Figure 7. As is shown in Figure 8, a signal that might be driven primarily by magnetic field rather than electric field will have an offset rather than an oscillation about some zero axis. Typically, these waveforms occur when a leaky shield is driven by a surrounding magnetic field. One of the simplest methods for verifying whether or not the sensor and measurement system is subject to interference sources is to reverse the sensor in direction as to its driving sources. If it is a real signal, it should invert and appear 180 degrees out of phase with the previously recorded signal. If the signal is not a true one, but rather interference, one should not expect a reversal in the phase of the signal.

In addition to rotating the sensors 180 degrees to check signal phase reversal, there are several other simple techniques that can be used to find if extraneous leakage is occurring. One technique is to terminate the cable. This is done by removing the sensor and terminating the cable at that point with a 50-ohm terminator that is not susceptible to external drive. The cable can also be shorted at that particular point where the sensor was connected and measurements can be continued to see if there are any appreciable signals there after the sensor has been removed. If there are significant signals, a leakage or an interference source has been detected and must be discovered before any meaningful measurements can be made. Noise signals will always exist; however, the question is how much can be tolerated. Most certainly, a 20dB signal-to-noise ratio can be tolerated and no extensive effort should be expended if the measurements accuracy, or the accuracy desired, could tolerate this signal-to-noise ratio. Another technique to determine if noise sources are present is to alter the transmission line routing and check for noise entry. Often this technique is advantageous if one cannot find a cable termination or cable short that could restrict the high frequency currents from penetrating to the inner conductor of the cable.

Generally, GR and Tektronix make the type of terminations and shorts where this will not occur; however, a "home-brew" short, where one places a wire from the outer conductor to the inner conductor without adequate shielding, allows leakage signals to enter the cable at the short.

2.1.2.2 High Frequency Interference

Whenever the spacing or mesh of a metallic object is approximately the wavelength of the impinging frequency, the material appears rather porous to this energy, which in turn will penetrate to drive other cables and systems. One of the reasons that high quality braided cable will suffer in shielding characteristics at high frequencies is due to the penetration of the high frequency energy through the cable braid to the inner conductor. This is why solid jacketed coaxial cable is always recommended for measurements where high frequency energy is present. Connectors also suffer from leakage, particularly the type of connector that does not utilize a screw-on connection. This high frequency interference manifests itself as a leading edge oscillation, which is replaced by the slow changing characteristics or slower changing segments of the real signal waveform. The majority of the high frequency interference can be blocked with thin layers of a high conductivity substance. High frequency currents, as is well known, will reside on the first few microns of the metal surface.

2.1.2.3 Low Frequency Interference

A recorded waveform showing initial transient variation followed by a long time low frequency, large amplitude excursion from the baseline is a case where low-frequency interference is occurring. Solid jacketed coaxial cable is susceptible to this type of noise, which resides primarily in the low kilocycle frequency region. These frequencies are generally induced on the coax shield by an E or B-field driving source and are eventually fed through to be registered by the inner conductor. In addition, 60-cycle pickup can easily be registered by a measurement system of the type discussed in this chapter. If the feed cable ground loops are not avoided, this type of noise will appear in a repetitive sweep on the oscilloscope as a widening or increase of the baseline width. Normally, the sweep speed of the oscilloscope is such that the sweep is so fast that only a portion of the low frequency waveform is intercepted. This, coupled with the fact that it is not in sync with the high frequency recording, makes it appear as an increase in the baseline width.

2.1.3 System/Sensor Installation Considerations

Improper installation of a sensing probe, feed cables, or a recording device can cause serious errors in amplitude and the fine structure of the recorded data even though the system verification has shown it to be more than adequate in characteristics to make the measurement. The undesired effects of inadequate cable routing, instrumentation package distorting of the currents and field, and probe position, can negate all other precautionary steps taken to make good measurements.

2.1.3.1 Cable Routing and Probe Positioning Electromagnetic Field Measurement

The recording of the time history of an EM field on a ground plane or on one of the boundary plates where its polarization is known, is probably the easiest measurement to make since the feed cables and recording equipment can be located underneath the ground plane or routed externally, exiting with minimal cable and equipment drive by the exciting fields. The major consideration related to these measurements is that the probe has been positioned to maximize the signal to be measured.

The physical makeup of B-dot sensors will allow for some E-field drive if the gap across which the B signal is developed is aligned parallel with the E-field direction. Figure 10 illustrates the correct and incorrect positioning of a single ended B-dot sensor in the exciting field.

The Multiple Gap Loops (MGL), which are discussed in detail later, are designed to minimize the E-field drive so the sensor's position need not be a concern.

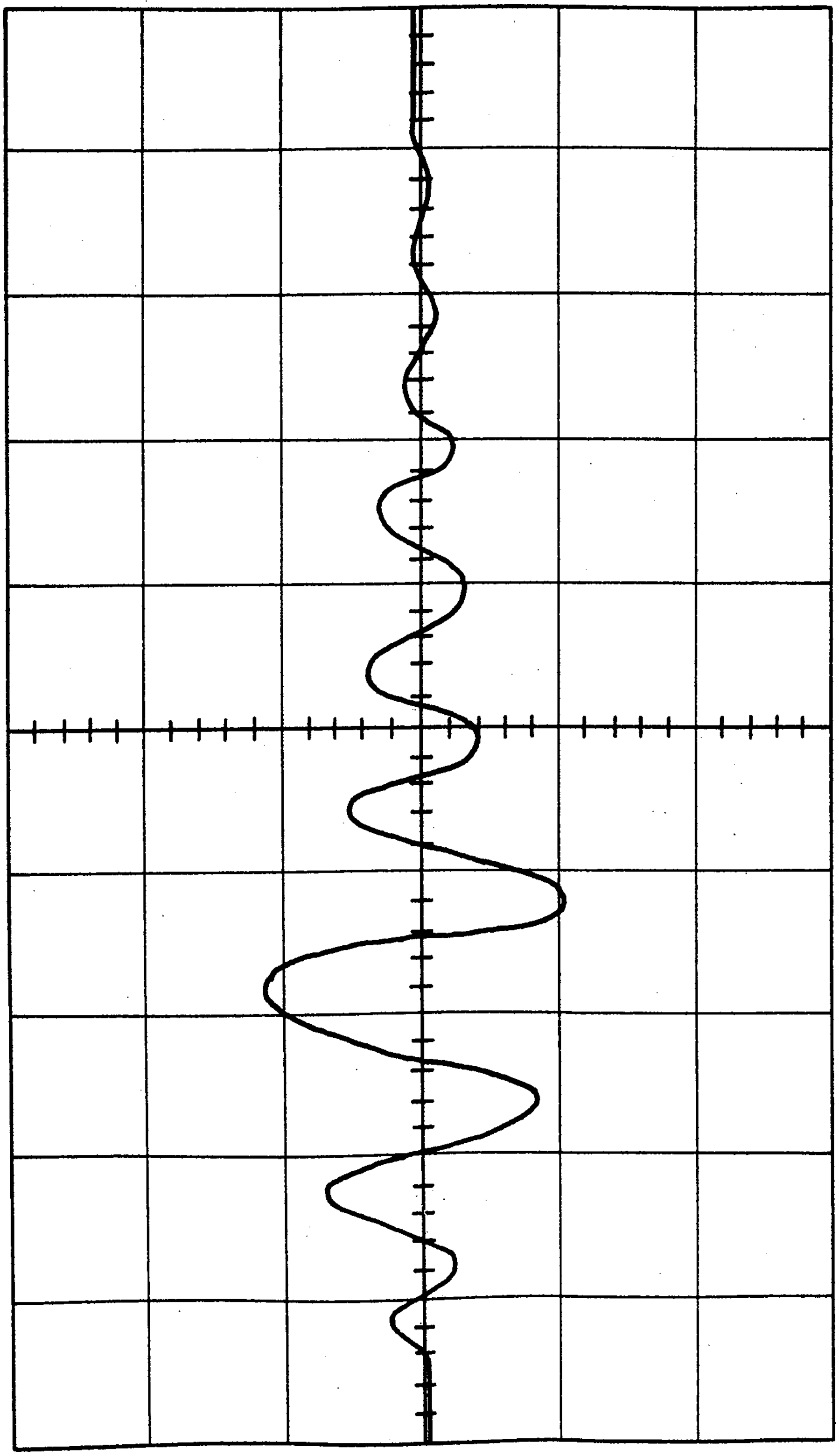

Figure 7 – Idealized Waveform Illustrating Possible Open Ground

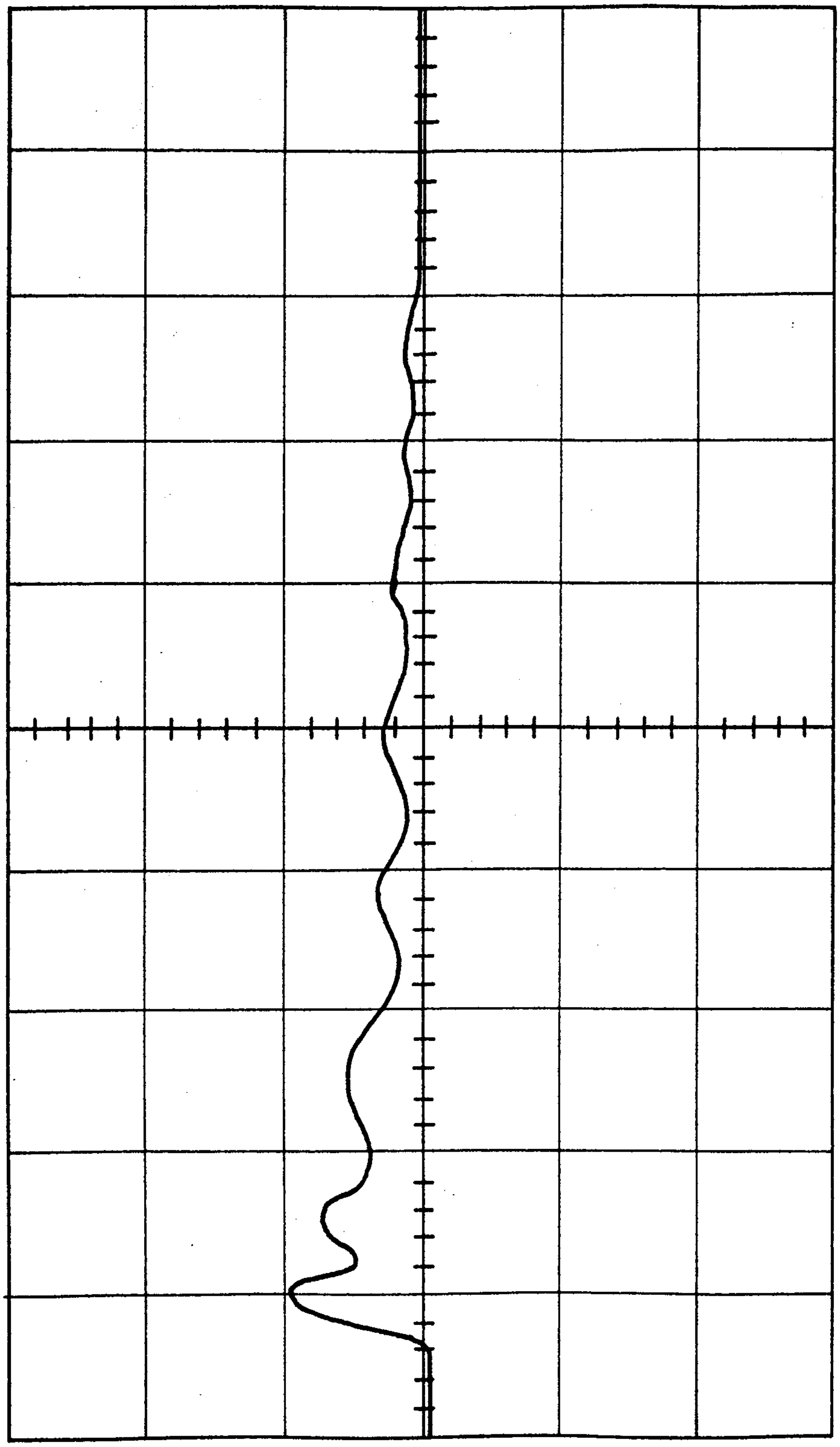

Figure 8 – Waveform Illustrating B-field Drive Offset from Baseline

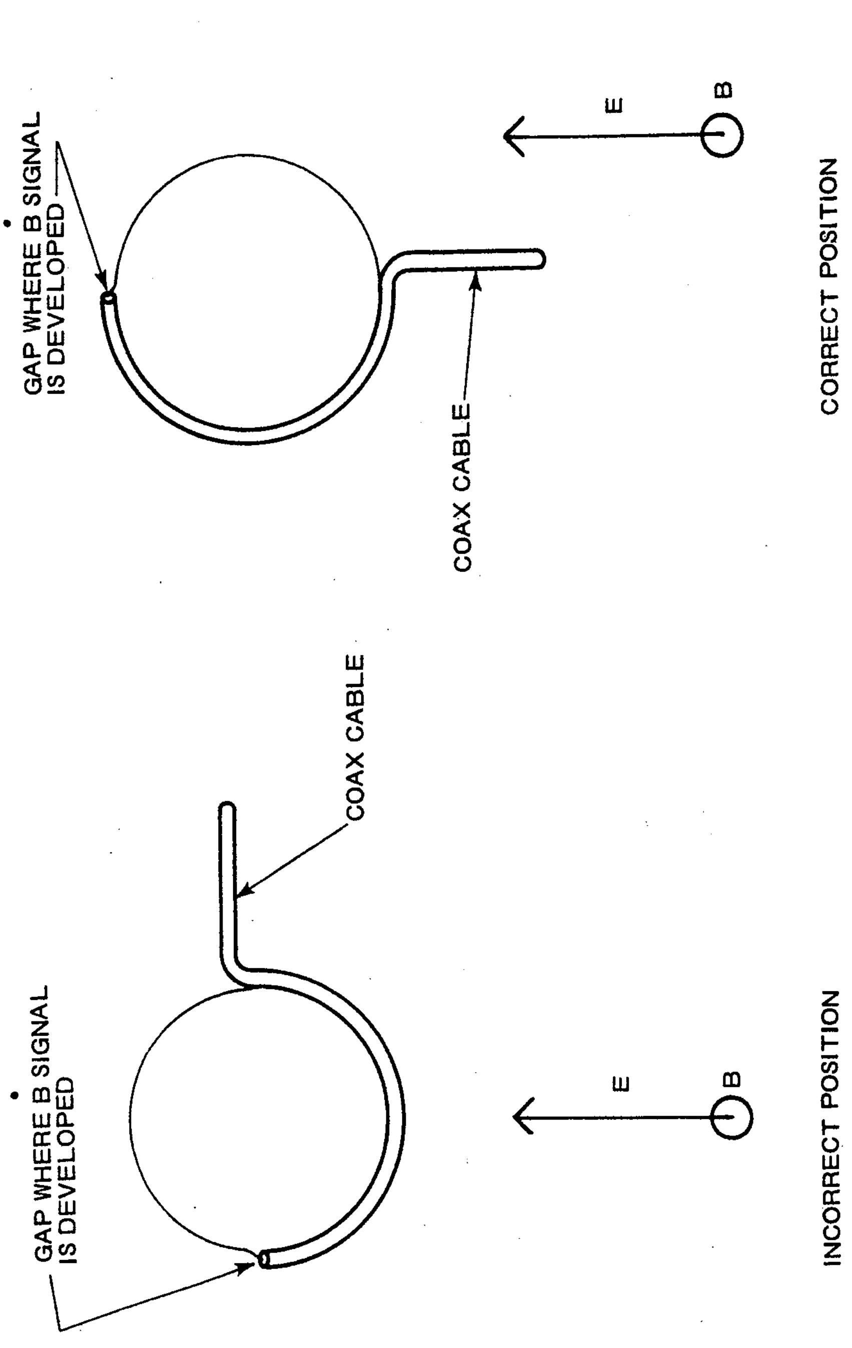

Figure 9 – Single Ended B Sensor Positioned in Propagating Field

Measuring electric and magnetic fields above a ground plane or at points within a large volume where fields also reside, requires careful isolation of the sensor from potential noise sources. Two techniques, used to transmit the signals from the sensor to a remote recording point, are as follows:

1. Modulate a light or RF source and radiate a modulated carrier.
2. Coaxial transmission line.

The first approach provides adequate isolation since a system of this type is battery operated and floats at the position potential. Systems of this type have been successfully used on missile test programs in the past.[4] The major limitation of this first solution is the cost of the system, delivery times to supply such equipment, and the size of the transmitting package compared to the sensor.

The second technique of routing cables for the sensor is the most expedient method. Although the isolation suffers due to the metallic tie between sensors and recording point, there is a temporary isolation established for short times due to the L/R time constant associated with cable length, size, and shield construction. For late times and consequently the low frequency components, there is virtually no isolation of the sensor from the ground or recording point and late time date are not valid. Early time data, occurring at times much less than the L/R cable shield time constant, can be accurate.

Two cable routing methods used with successful results are illustrated in Figure 10.

Figure 10a shows the feed cable on a vertical and radial line from the sensor. Due to the inductive isolation, early time measurements can be made with this approach. Care must be exercised to preserve the radial geometry and symmetry of both probe and cable. The rationale for the ability of this routing not to alter the real signal with noise is basically that of symmetry. The currents created on the shield will divide equally at the intersection of the cable and probe and drive the loop gap with equal and opposite amplitudes. In addition, the magnetic field generated from the cable shield current will cancel over the symmetrically divided probe area.

Figure 10b shows the feed cable on an equipotential line. This technique should be used when the symmetrical properties of the probe and cable are in question. The vertical drop should be made at a point where the clear time (2D) is long enough that the measurement of interest will be undisturbed by the reflected energy from the vertical section.

The disadvantages of this second approach are the supports required to position the horizontal cable run.

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[4] Harrison, J.L. and Ingro, J., "ALECS G Single-Channel Microwave Telemetry System, "EG&G Publication No. AL-319, 4 June 1969.

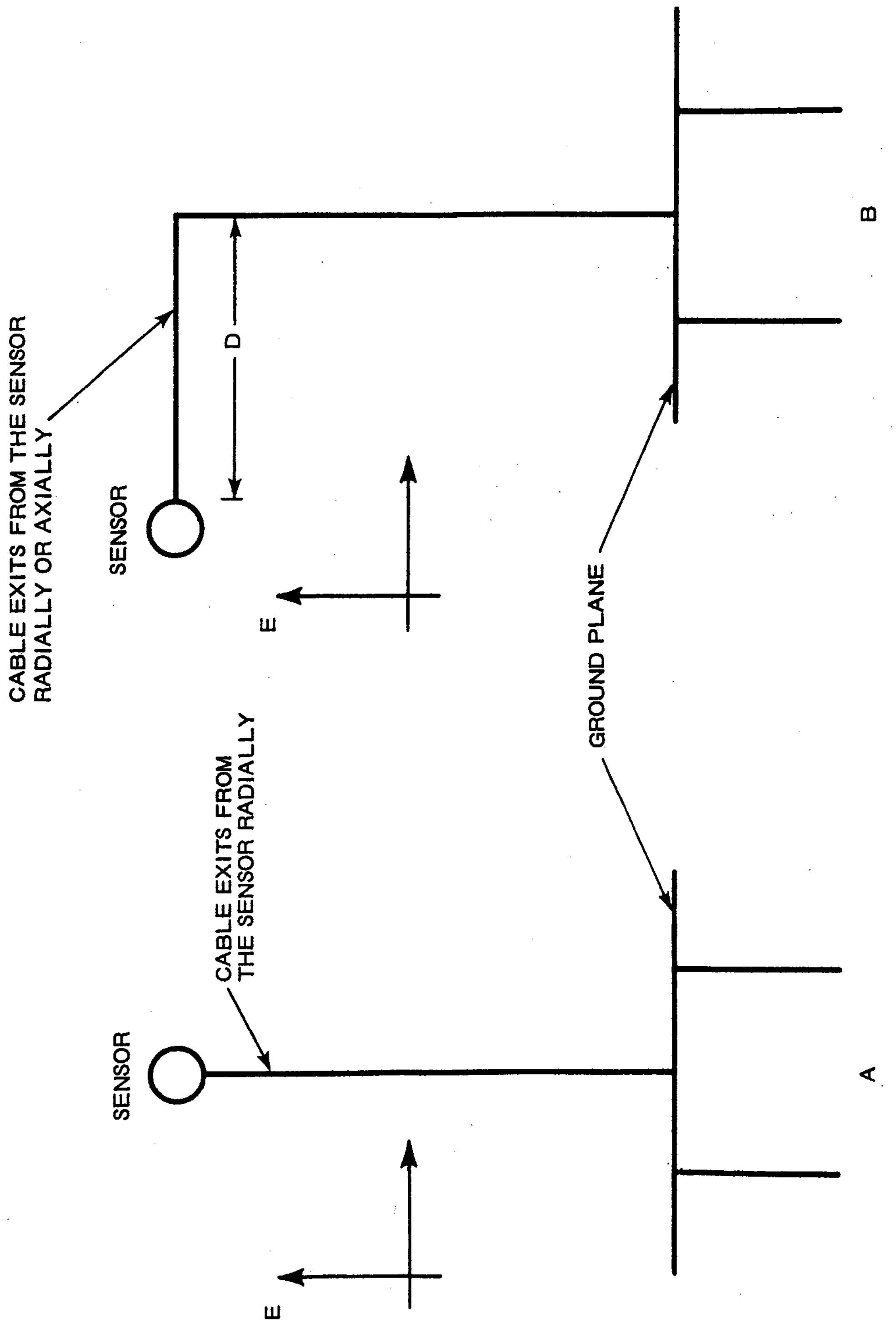

Figure 10 – Cable Routing from Sensor

Current and Voltage Measurements

The measurement of currents and voltages residing on the cabling and components of a system under test presents unique problems that are generally different for each geometrical configuration being tested. Some of the important considerations to be made are:

1. Insulate the current probe's metallic case from other cable shield and metal structures. This reduces noise signals on the probe and minimizes other current paths.
2. To determine the critical functions, minimize the number of measurement points (and thus feed cables) by careful study of the system under test. This particular issue is important since the test program could result in determining the effect of the measurement system on the system under test. This particular issue is important since the test program could result in determining the effect of the measurement system on the system under test rather than the response of the tested system to the excitation fields.
3. Bulkhead and box penetration should tie cable shields to metal surfaces rather than allowing them to float. The predominant noise sources are due to induced currents penetrating into the system through points of entries.

Shielded Enclosures

When systems are located in the vicinity of intense electromagnetic fields, valid data recording and timing requires excellent RF shielding. The consequences of improper shielding of control and diagnostic systems will result in erroneous trigger times for oscilloscopes, apparent negative sweeps on oscilloscopes, and transient oscillation signals on the diagnostic oscilloscopes.

These problems occur because the induced noise signals will couple-in through the points of entry that are normally present on any non-RF shielded enclosure. These signals will then interact with the system components and appear as genuine signals.

At present, the shielding trend in EMP testing is the utilization of double shielded rooms consisting of steel plates welded continuously to form an unbroken metal shell. The attenuation characteristics of this type of shielded enclosure are extremely good from low frequencies (approximately 1 kHz) to over 1000 MHz. For frequencies above 100 kHz, the realized attenuation is approximately 120 dB. This attenuation holds true for the high impedance electric fields, low impedance magnetic fields, and plane wave fields. In many cases, the 120 dB enclosure (double-walled) may not be needed. However, the risk of using less shielding capability generally cannot be taken when extensive field measurement validity is at stake.

In the situation where oscilloscopes are operated with a dc to ac converter and batteries and floated at the particular height potential, double-walled screen boxes are also recommended. The main consideration when coupling the diagnostic oscilloscope through a transmission line to a sensor which is sampling a particular system reaction current, is to attempt to keep all of the generated surface currents on the outside of the shielded box. Allowing current penetration to the inside of the box induces noise signals. This is even more important than ground loop generated signals which are often second and possibly third order effects.

2.1.3.2 TDR Measurements

TDR verification of *[the condition of]* sensors and feed cables is strongly recommended not only for field verification checking, but also for troubleshooting during times off questionable data. The TDR verification of cables should be a standard troubleshooting method whenever the signal characteristics are suspect. In addition, close examination of a TDR waveform of an electric or magnetic field probe can be used to determine if the probe's electrical characteristics have changed. A TDR waveform of a B-dot sensor is shown in Figure 11. An important consideration is not that TDR waveforms conform to an absolute standard, but rather that initially in the measurement program the sensors used receive a baseline check and the fine structure waveform is recorded for later reference. Comparison between earlier TDR waveforms and waveforms obtained later in the test program could identify any probe whose characteristics may be changing. KEEP A LOGBOOK!

2.1.3.3 Measurement Perturbation Due to Instrumentation and Sensor Location

Significant changes in geometrical configuration can easily occur with indiscriminative positioning of the measurement system in and around the subsystem to be examined. This statement holds true both for the measurement of electromagnetic fields in free space or the measurement of currents and voltages internal to a system. This may be particularly bothersome when numerous channels are in the same immediate area. When this issue is in question, it is recommended that a small single channel system be used to make measurements at a particular reference point and this data recorded. The multiple channels recording system should then be reinstalled and that same point measured with the full complement of instrumentation in place.

Interaction effects occurring due to the multiplicity of measurement systems can readily be seen by changes in amplitude and significant changes in the fine structure of the recorded data. If this effect is indeed occurring, the experimenter must make trade-offs in the number of channels versus his interaction level.

2.1.4 Data Recording Considerations

The data recorder still enjoying the greatest popularity in the measuring of EMP signals is the oscilloscope. Although this device has many disadvantages in this type of data recording, they are outweighed by its reliability and versatility. Data recorded on 35 mm film or Polaroid, are normally processed by the data analysis people using a quick check mode or computer.

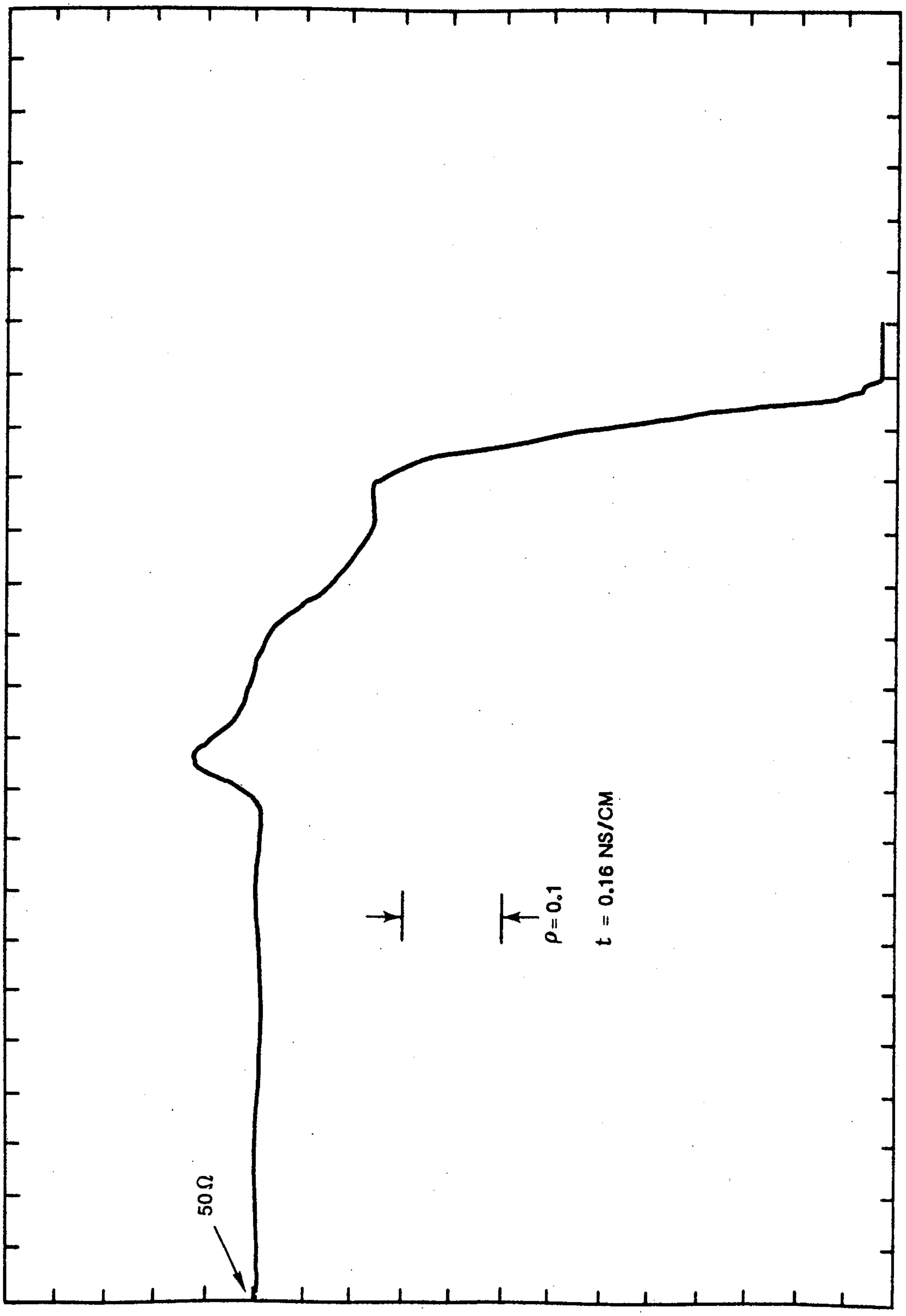

Figure 11 – TDR Waveform of the MGL-4A (A or R) B-Loop Sensor

Several modified system approaches, which make use of the oscilloscope, can be utilized to improve the data bandwidths and dynamic ranges required in an in-depth analysis program.

2.1.4.1 Time Synchronization

Since the oscilloscopes can only record data in a very narrow time window (i.e., time window dependent upon the total sweep length), care must be exercised to position the sweep start before the signal occurs. The use of an oscilloscope internal trigger is very undesirable and is not recommended where rapid and unquestionable data recording is required. It is obvious that as the amplitude of the measured signal changes, the triggering characteristics of the oscilloscope also change when internal triggering is utilized.

Whether the oscilloscope is a sampling or single shot type, external triggering of oscilloscopes from a signal generated by the pulsing source is recommended. External time synchronization, with appropriate delays to position the real data on the oscilloscope trace, is the only sure way the experimenter *[can be sure that he]* will not miss any useful data.

2.1.4.2 Parallel Scope Channels

The risetime and waveform duration of the majority of the signals recorded, either as environment or diagnostic reaction data, cannot be recorded on one single oscilloscope trace. It is inconvenient and often unwise to perform two separate experiments with a corresponding change in the sweep speed of the oscilloscope since pulse amplitude and spectral content repeatability is difficult to obtain utilizing a pulser having high peak energies and high voltages. One technique offering a solution to this problem is the operation of two scopes or numerous scopes off one single channel, thus recording simultaneous data on one signal with different sweep speeds on the oscilloscopes. In this way, one could adjust one oscilloscope to examine the fast risetime of the wave front while the other oscilloscope sweep speed could be set low enough to examine the long time waveform duration. This cab be accomplished utilizing the configuration shown in Figure 12. Careful attention must be given to signal splitting and preserving the characteristic impedance of the feed transmission line at the termination point of the oscilloscope in order to prevent reflections occurring and accompanying data distortion.

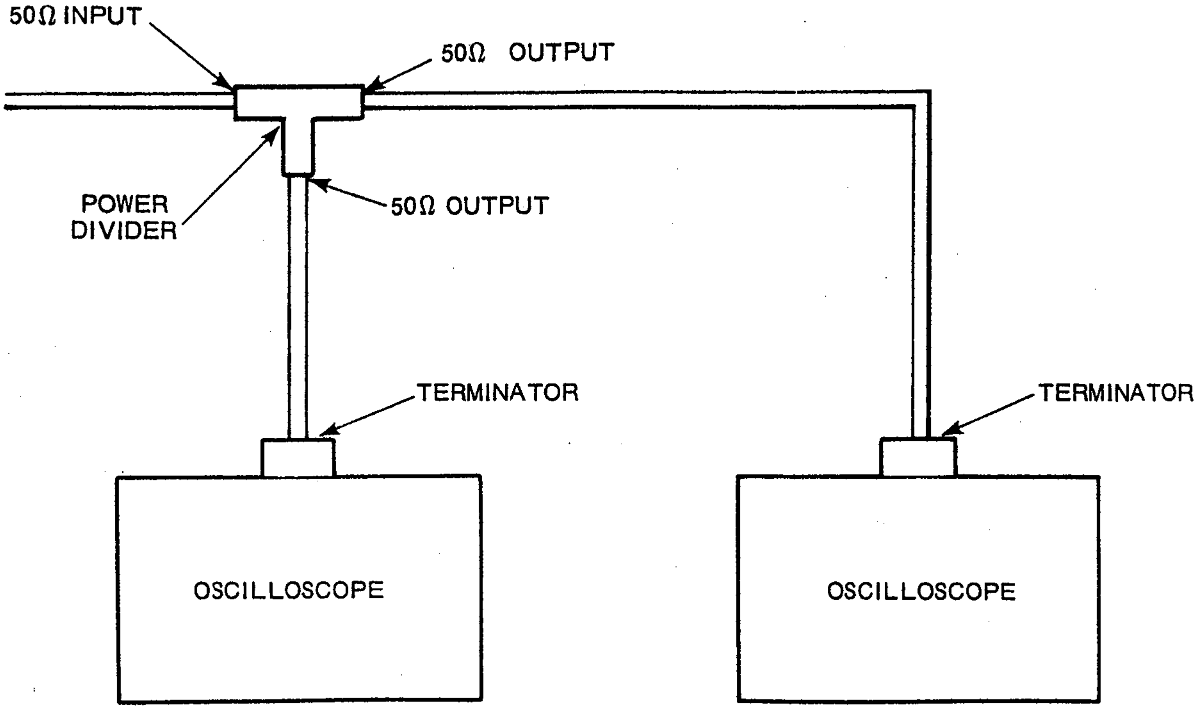

Figure 12 – Parallel Scope System