Sensor and Simulation Notes

Note 311

Extrapolation of Ground-Alert Mode Data at Hybrid EMP Simulators

July 1988

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C.E. Baum, *Extrapolation Techniques for Interpreting the Results of Tests in EMP Simulators in Terms of EMP* ..., Sensor and Simulation Note 222, March 20, 1977.
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electromagnetic pulse simulation

Abstract

In this note, the methods of performing extrapolation on data taken at hybrid EMP simulators in ground-alert mode are discussed. Hybrid simulators require substantially different methods of extrapolation than other simulators because of the large reflected field that is inherent in their design. Although some extrapolation methods deal with the ground reflection better than others, all are approximations that could benefit from further research. One method that seems particularly ready for development requires the development of an "incident field" sensor. Although this sensor now exists only as a design on paper, it appears to offer a simple solution if existing designs for the sensor can be built and tested.

I. Introduction

When performing system-level EMP tests, the waveform provided by the simulator is often quite different from the desired threat waveform. In order to compensate for this difference, an extrapolation is performed. At most simulators, the extrapolation process is relatively straightforward, and it was first described by Carl Baum[1]. At hybrid simulators, however, relatively simple techniques break down because of a strong reflected field. This note discusses extrapolation techniques that might overcome this problem. A typical hybrid simulator is shown in Figure 1, and a general survey of hybrid EMP simulators is provided in Sensor and Simulation Note 277[2].

In general, it is possible to take data with an aircraft configured in either ground alert mode or in free space mode. Data are then normally extrapolated to the same mode from which

[1]C.E. Baum, *Extrapolation Techniques for Interpreting the Results of Tests in EMP Simulators in Terms of EMP Criteria*, Sensor and Simulation Note 222, March 20, 1977.
[2]C.E. Baum, *Review of Hybrid and Equivalent-Electric-Dipole EMP Simulators*, Sensor and Simulation Note 277, October 1982.

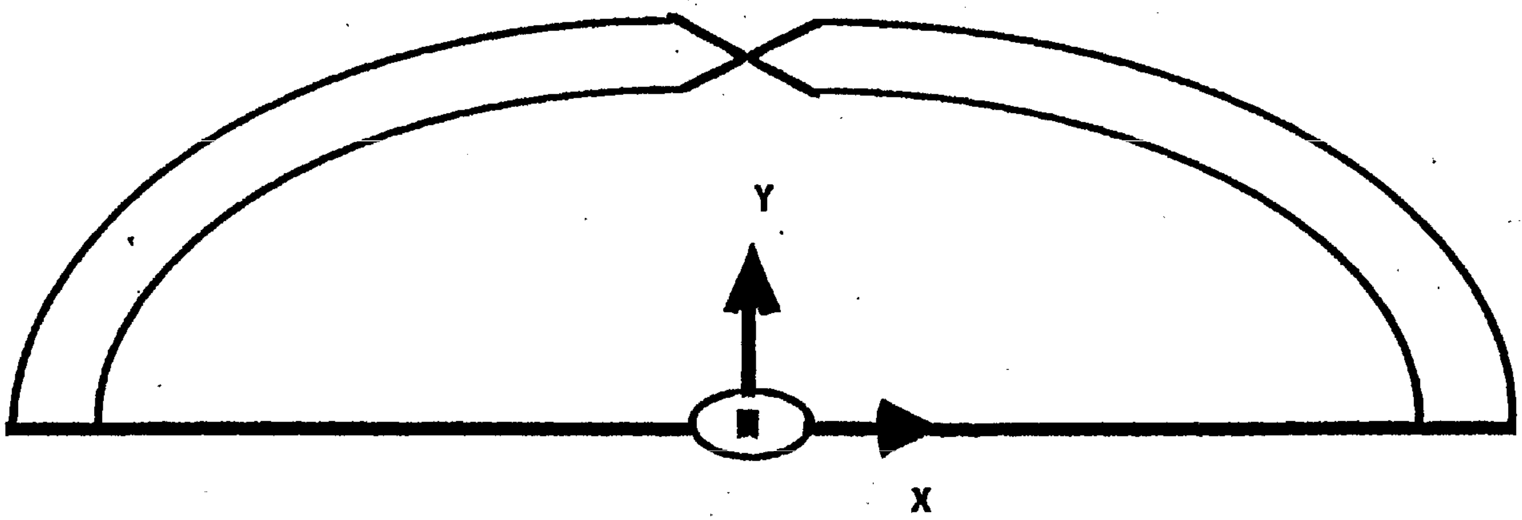

Figure 1. A Typical Hybrid EMP Simulator

they are taken; although it may in principle be possible to extrapolate to the other mode. The scope of this note is limited to extrapolations of data taken in ground alert mode to ground alert mode with a different incident field. Although it may be possible to consider extrapolations from ground alert mode to free flight mode, or to ground alert mode with a ground whose characteristics differ from those of the simulator, this is not treated here.

In this note, we begin with a brief review of the existing methods for performing extrapolations, and why simple approaches break down at hybrid simulators. Next, we suggest four alternative approaches for hybrid simulators. In addition, we attempt to evaluate the approaches to determine the usefulness of each in practical situations. Finally, and perhaps most importantly, we indicate where further work is needed to develop a particular technique.

II. Brief Review of Extrapolation

The most common method of implementing an extrapolation is to boost the measured currents by the ratio of the threat field to the simulator field. Thus, the extrapolated currents are

$$I^T(\omega) = \frac{E^T(\omega)}{E^S(\omega)}\, I^S(\omega) \tag{1}$$

where $E^T(\omega)$ is the threat field, $E^S(\omega)$ is the measured field of the simulator, and $I^S(\omega)$ is a measured current on the test object at the simulator. The ratio of electric fields is the extrapolation function. Note that one often uses a ratio of magnetic fields or skin currents to obtain the extrapolation function. Note also that the extrapolation function is often calculated as a geometric average over several measurement points.

In practice, the extrapolation function is calculated from the magnitude of the field or skin current ratios. Although it would be very useful to retain phase information in the extrapolation function, it is not usually done because of the difficulty of aligning two very different waveforms with each other on the time axis. The problem of how to retain phase in an extrapolation function undoubtedly requires further investigation, but it is not treated here.

Provided that problems with phase can be resolved, Equation (1) should work well when the simulator field has no or small reflections. At a hybrid simulator, however, there is a strong reflected field, which is described in detail in Theoretical Note 25[3]. Thus, the simple method breaks down because of the difficulty inherent in separating the incident field from the total field. When creating an extrapolation function, one must take the ratio of either incident threat to incident simulator fields, or total threat to total simulator fields. If one mixes incident and total fields, an incorrect result is obtained. There are four possibilities of resolving the problem, and these are now described.

[3] C.E. Baum, *The Reflection of Pulsed Waves From the Surface of a Conducting Dielectric,* Theoretical Note 25, February 18, 1967.

III. Type H1 Extrapolation: Measure Total E- & H-Fields and Extract Incident Waveform

The first of the methods for extrapolating ground alert mode data taken at hybrid simulators is at the moment somewhat cumbersome to implement. It may, however, turn out to be the method of choice, once it is developed further. It is a suggestion from Carl Baum[4]. To first order near the ground, one can think of a hybrid simulator with the pulser at the top of the arch as producing a plane wave incident from directly above, bouncing off the ground, and reflecting straight back up. If this is the case, one can represent the total electric field as

$$E^{TOT}(\omega) = E^{INC}(\omega)\,[1 + R(\omega)e^{-j2k_oh}] \tag{2}$$

where $E^{INC}(\omega)$ is the incident electric field directly under the pulser and h is the height above the ground. The direction of the field is in the $\hat{x}$-direction. In the above equations, $R(\omega)$ is the reflection coefficient of a plane wave incident onto a dielectric interface,

$$R(\omega) = \frac{Z_g - Z_o}{Z_g + Z_o} \tag{3}$$

where $Z_o = 377\ \Omega$, the characteristic impedance of free space, and Z_g is the characteristic impedance of the ground,

$$Z_g = \sqrt{\frac{j\omega\mu_o}{\sigma_g + j\omega\epsilon_g\epsilon_o}} \tag{4}$$

Here, $\mu_o = 4\pi \times 10^{-7}$ H/m is the permeability of free space, σ_g is the conductivity of the ground plane, $\epsilon_o = 8.85 \times 10^{-12}$ F/m is the permittivity of free space, and ϵ_g is the relative permittivity of the ground plane. With the above approximation, the magnetic field is

$$H^{TOT}(\omega) = H^{INC}(\omega)\,[1 - R(\omega)e^{-j2k_oh}] \tag{5}$$

where the H-field is in the $\hat{z}$-direction under the pulser. Since we are assuming the incident field is a plane wave, this can also be expressed as

$$H^{TOT}(\omega) = \frac{E^{INC}(\omega)}{Z_o}\,[1 - R(\omega)e^{-j2k_oh}] \tag{6}$$

If we now sum the electric and magnetic fields, we find

$$E^{INC}(\omega) = \frac{1}{2}\,[E^{TOT}(\omega) + Z_oH^{TOT}(\omega)] \tag{7}$$

Thus, we find that we can reconstruct the incident electric field from a measurement of the total electric field and total magnetic field. Furthermore, since the reflected electric field is just

$$E^{REF}(\omega) = E^{INC}(\omega)R(\omega)e^{-2jk_oh} \tag{8}$$

we can obtain the reflected field from the total field

$$E^{REF}(\omega) = \frac{1}{2}\,[E^{TOT}(\omega) - Z_oH^{TOT}(\omega)] \tag{9}$$

[4]C.E. Baum, Personal communication.

Note that the only difference between the incident and reflected electric fields is a change of sign.

There are several ways one might implement Equation (7) to obtain the incident field. The simplest way would be to make measurements with a sensor that measures both E- and H-fields at the same time, and performs the summation automatically. Although two possible designs for such an "incident field" sensor appear in a note by Yu, Chen, and Baum[5], they have yet to be built and tested. Alternatively, it may be possible to measure the electric and magnetic fields with two separate sensors near the same location, but then one would have to be concerned about reflections between sensors. The best one could do in this case would be to place one of the sensors so that it is in the null of the radiation pattern of the other sensor. It would then be necessary to test experimentally to what degree the interaction between sensors contaminated the signal. Finally, one might make measurements of the E- and H-fields on separate shots; but since there is a certain amount of shot-to-shot variability, it is not clear how valid the approach would be. Since field mapping measurements are usually averaged over several shots anyway, it would be worth looking into. In any case, if the "incident field" sensor can be developed, this method will probably become the method of choice.

IV. Type H2 Extrapolation: Divide Measurements by One Plus the Delayed Reflection Coefficient

A second approach to extrapolation at hybrid simulators is to calculate the incident field from the total field by dividing by one plus the delayed reflection coefficient. Recall that, to first order near the ground, one can think of a hybrid simulator as generating a plane wave incident from directly above, bouncing off the ground, and reflecting straight back up. If this is the case, one can represent the total electric field as

$$E^{TOT}(\omega) = E^{INC}(\omega)[1 + R(\omega)e^{-j2k_o h}] \tag{10}$$

where $E^{INC}(\omega)$ is the incident electric field directly under the pulser and h is the height above the ground. The direction of the field is in the $\hat{x}$-direction. The reflection coefficient, $R(\omega)$, is uniquely determined by the ground dielectric constant and conductivity. Thus, one can get the incident field just by dividing the expression $[1 + R(\omega)e^{-j2k_o h}]$ from the total waveform.

In the past, this method has not been used because there has been a reluctance to commit to a certain ground dielectric constant and conductivity. This is because these characteristics were thought to vary with the time of day and moisture content of the ground. It is normally possible, however, to find data on the ground that one could use[6]. Although the concern about variability is justified, it is not clear how much difference it makes. This is certainly an area where more work is needed. In any case, this is one of the simpler methods of performing the extrapolation, and possibly the most accurate with presently available methods.

[5] J.S. Yu et.al., *Multipole Radiations: Formulation and Evaluation for Small EMP Simulators*, Sensor and Simulation Note 243, July 19, 1978.

[6] J.P. Castillo and B.K. Singaraju, Personal communication.

V. Type H3 Extrapolation: Measure H-Field on a Large Conducting Ground Plane

One of the simplest methods of extrapolating at a hybrid simulator is to measure the total B-field with a B-dot sensor on a large conducting ground plane. The boundary conditions for a perfect electric conductor are such that the incident magnetic field is just half of the total field.

Although this appears to solve the problem simply, in practice it is quite difficult to implement. This is because the method requires a very large ground plane which is difficult to install. To get a feel for the size of the ground plane needed, consider the diagram in Figure 2. One can trace a ray from the pulser directly to the sensor; and a second ray from the pulser to the edge of the plate, and from there to the sensor. The difference in time of arrival between the two rays is the only time for which the technique is rigorously correct. After this time, the signal is affected by the finite size of the ground plane. Typically, it is impossible to make this delay time large enough. For example, for a square ground plane 3 m on a side, the signal is affected after only 5 ns. We are normally interested in times out to at least 1 μs.

This situation is analogous to the problem of measuring the magnetic field near the surface of sea water, a problem that was considered by Carl Baum in Sensor and Simulation Note 39[7]. In this note, Dr. Baum considers the size of a conducting ground plane required to measure EMP near the surface of sea water. He demonstrates that unless the ground plane is very large, the magnetic field is disturbed significantly. In particular, the size of the conductor must be large compared to the depth of penetration of the wave into the dielectric material. This penetration depth is estimated to be

$$d = \sqrt{\frac{4}{\pi}\frac{t}{\mu_o \sigma}} \tag{11}$$

where σ is the conductivity of the ground and t is the time length of the signal. Typically, the ground conductivity is 0.01 mhos/m, and we are interested in time out to 1 μs. This gives a depth of penetration of about 10 m. Thus, it is impractical to have a conducting ground plane whose dimensions are large compared to the 10 m penetration depth. It is quite difficult to predict the effect of using a small ground plane. The problem is complicated enough so that one would prefer to avoid it altogether.

VI. Type H4 Extrapolation: Skin Current Comparison

The last approach to extrapolating ground alert mode data at a hybrid simulator is a comparison of skin currents between those measured at the simulator and what they would be at threat. Thus, the extrapolated currents are

$$I^T(\omega) = \frac{I^T_{skin}(\omega)}{I^S_{skin}(\omega)}\, I^S(\omega) \tag{12}$$

where $I^T_{skin}(\omega)$ is the skin current at threat in the presence of a ground plane, $I^S_{skin}(\omega)$ is the skin current measured at the simulator, and $I^S(\omega)$ is a cable current measured at the simulator. The ratio of skin currents is the extrapolation function. The threat skin currents could be determined with either scale model measurements or theoretical calculations. One would usually want to

[7] C.E. Baum, *Some Electromagnetic Considerations for a Sea-Water-Based Platform for Electromagnetic Sensors*, Sensor and Simulation Note 39, March 27, 1967.

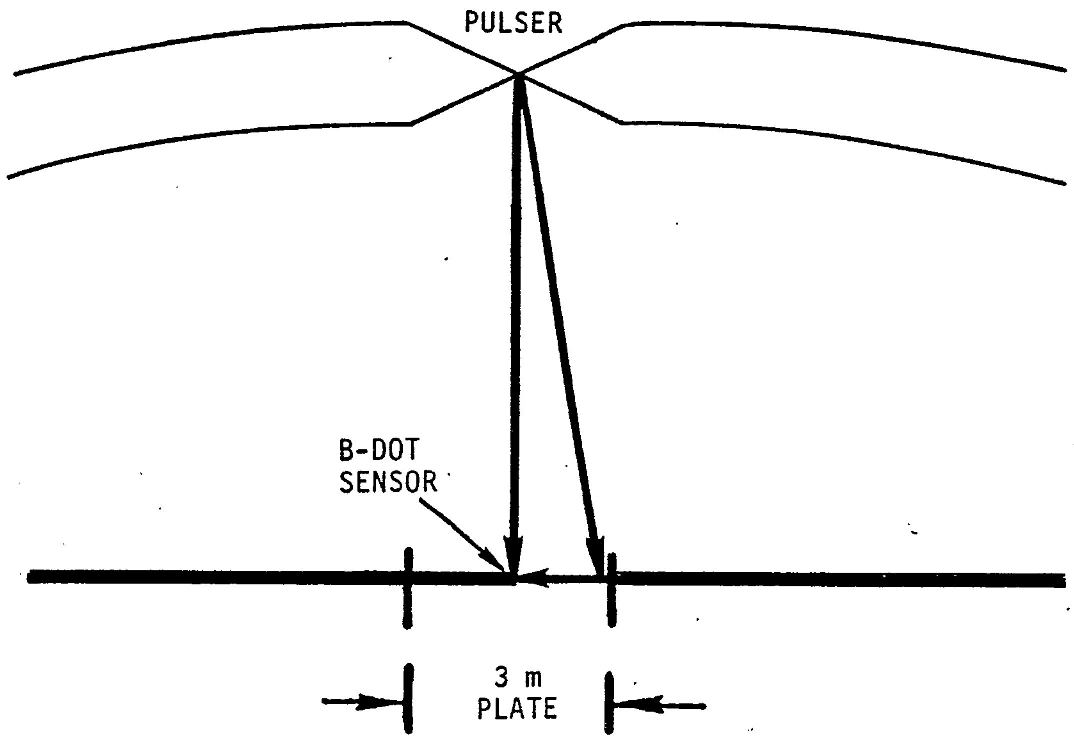

Figure 2. Ray Tracing to Determine the Time of Validity of B-dot Measurements of a Ground Plane

average the extrapolation function over several locations. Note that one would need to make skin current measurements on the device under test with this method, which might be a problem for aircraft whose skin has been treated to reduce its radar cross section.

This approach is a form of Carl Baum's Type 3B extrapolation[8]. The difference is that the threat skin currents are determined in the presence of a ground plane. Thus, if scale model measurements are used to determine the threat-level skin currents, it would be necessary to place the device under test on a plane that simulated the ground characteristics of the simulator. It is not clear yet if this can be done, since the finite conductivity of the ground is somewhat difficult to scale with frequency. Alternatively, if a theoretical model were used to determine the threat-level skin currents, the device would have to be in the presence of a simulated ground plane. This usually complicates matters because a free-space Green's function can no longer be used in the calculations. We conclude, therefore, that although this technique holds promise, it requires extensive further development.

VII. Conclusions

The problem of extrapolating ground alert mode data at a hybrid simulator is not a simple one. Four methods of performing ground alert mode extrapolations at such a simulator have been discussed, and their relative merits have been evaluated.

The first approach, the H1 extrapolation, involves measuring the total E- and H-fields and extracting the incident waveform. It is expected that this should ultimately give the most accurate results most simply. There are three ways of implementing this approach. The first way requires an "incident field" sensor that has not yet been developed, although it appears to be feasible. The second and third ways, which involve using separate sensors for the E- and H-fields, may also work but may be less accurate.

The second approach, the H2 extrapolation, involves dividing out the effect of the reflection coefficient directly. It appears to have the best chance of working without further development, although there remain some concerns about the constancy of the ground parameters, and the validity of the plane-wave approximation.

The third approach, the H3 extrapolation, involves measuring the B-field against a conducting ground plane. It appears to have difficulties arising from the small size of the ground plane. This affects the signal at a very early time in a manner that is difficult to predict. It is not clear how one might compensate for this problem.

Finally, the H4 extrapolation involves a comparison of skin current data measured at the simulator and skin current data at threat. The skin current at threat is obtained either from scale model measurements or theoretical calculations. In either case, a ground plane must be retained as an integral part of the model. Although this is probably one of the more accurate methods, it can be inconvenient for a number of reasons. First, it is difficult to simulate a ground plane with finite conductivity when making scale model measurements. Second, it is always more difficult to make calculations of the skin currents of an object when it is near an imperfect ground than when it is in free space. Finally, one often does not want to place skin current sensors on an aircraft if it

[8] C.E. Baum, Sensor and Simulation Note 222.

has been treated to reduce its radar cross section.

We conclude this note with the thought that there is still a great deal of work left to be done in the extrapolation of EMP data taken at hybrid simulators. It is hoped that this note will spur further research in the area.

Acknowledgement

We wish to thank Carl Baum for his many helpful discussions on this topic.