Sensor and Simulation Notes

Note 246

26 December 1978

EMP Simulation and its Impact on EMP Testing

Carl E. Baum
Air Force Weapons Laboratory

CLEARED
FOR PUBLIC RELEASE
PL/PA 5/19/97

Abstract

In testing systems for their response to EMP it is necessary to consider the EMP criteria set. Then, having chosen some EMP simulation set, one must consider how closely each simulation approximates the respective criterion, correcting for this difference by extrapolation as necessary. This paper discusses these concepts in the context of currently used techniques.

I. INTRODUCTION

The interaction of the nuclear electromagnetic pulse (EMP) with a military or civilian electronic system is in general a very complicated process. It is this process which results in the system vulnerability or lack thereof to some EMP criterion or set of such criteria. If one had a perfect quantitative understanding of the EMP interaction process in all cases of interest, then one could presumably predict the system vulnerability or lack of same, i.e., one could perform an assessment by analysis. However, this utopia does not exist in practice.

The problem with the quantitative description of the EMP interaction process is its great complexity. There are typically such a large number of actual and/or potential items of significance to the EMP interaction process in a given system that it becomes impractical to adequately account for them all. This complexity manifests itself in at least two ways:

1. The number of individual items and combinations of items (wires, other conductor paths, impedances, propagation constants, cavities, apertures, conductive penetrations, antennas, interface circuits, filters, etc.) becomes large enough that even a small uncertainty in the analysis of the response of some individual process results in a large uncertainty in the analytically determined EMP response and hardness (or lack of vulnerability) of the system as a whole.

2. Even if the analysis in 1 were perfect (an unlikely circumstance) for a given specified system (say as specified by a "complete" set of blueprints), there is another practical difficulty. Experience has shown that the assumption that one is even <u>aware</u> of the <u>existence</u> of <u>all</u> relevant EMP

penetration paths is often errorneous. There are often items in the real system (for which the analysis is supposed to apply) which are not indicated on the drawings, and which represent important EMP interaction paths. This can be summarized as: the system is

1. too complicated, and
2. not sufficiently well defined.

The above observations of analysis uncertainty summarize the current state of affairs; this will not necessarily accurately reflect the future state of the art. It is clearly desirable to design new systems in a manner which significantly reduces the above problems. This is obtained in general by greater EMP hardening of the system. If the hardness margins for the individual signals reaching sensitive positions (failure ports) can be significantly increased across the board, then one expects that the probable number of cases with negative hardness margins will be significantly decreased, ideally decreasing to zero in the limit of sufficient individual-failure-port designed hardness. Whether or not (or how often) a practical system can be designed with sufficiently large hardness margins for individual signals such that the overall system hardness margin (smallest individual signal hardness margin) is positive (implying a hard system) is at present uncertain. Some promising concepts for improving the system hardening come under the general heading of electromagnetic topology, in which control is emphasized for all signals passing through defined principal surfaces which are closed surfaces (shields) bounding various volumes in the system [8]; this potentially applies a more structured approach to EMP hardening with various levels of control possible.

In any event, for high confidence that a system is EMP hard, one will have to resort to a full EMP system-level test as a demonstration, at a minimum. Complex systems are normally tested for their performance characteristics. Who commits, for example, a military or civilian aircraft to extensive production without a flight test program? As a reasonable engineering practice why then would one not perform a similar EMP test program on complex electronic systems which are supposed to function after exposure to EMP environments? As the technology evolves and better hardness control is presumably achieved, the extent of the "optimum" EMP test (duration and complexity) will likely also evolve with different parts receiving different emphases to best match the state of the art of EMP hardness understanding.

II. CRITERIA

Before one has an EMP test, he must know in some sense what EMP is. This paper does not go into a detailed discussion of EMP environments, such being available elsewhere [7]. However, the reader will need at least a simplified version of the EMP environment(s) of concern to be in a position to conduct a meaningful EMP test. A statement of an EMP environment in an appropriate form is referred to as an EMP criterion. Recalling a previous definition [3],

"A(n) (EMP) criterion is:

a quantitative statement of the physical parameters of the (EMP) environment relevant to the (EMP) response of a system of interest in a volume of space and region of time and/or frequency extended to contain all physical parameters having a non-negligible influence on any of the (EMP) response parameters (e.g., as in the case of EMP (plane wave) a particular direction of incidence and a particular polarization and proximity to other scatterers)."

For simplicity and engineering utility this criterion is often expressed in some canonical form involving mathematical expressions (special functions, etc.). This canonical form is best chosen to contain the relevant features of the environment, but in an idealized, somewhat simplified, form. It is important that the simplifications do not remove features of the environment which can contribute to the system vulnerability. For this reason the criteria waveforms are taken to bound the environmental waveforms in relevant aspects such as rate of rise, peak amplitude, time integral (area under the curve), etc. However, to be useful such bounds should be reasonably tight. Such bounds should also be considered in terms of the magnitude of the Fourier transform, i.e., in frequency domain since system responses are typically frequency selective, or more generally complex-frequency selective in terms of poles of the Laplace transform [9].

While there are many kinds of EMP environments some are of more interest than others for present purposes. The nuclear-source-region EMP environments are rather complex in that they involve current density and conductivity as well as electric and magnetic fields in a non-linear and self-consistent combination [6]. On the other hand, if one goes away from the source region the EMP environment can often be approximated by a plane wave. This is especially the case for what is referred to as the high altitude EMP. In this case with the weapon detonation exoatmospheric, the γ rays interact with the atmosphere to produce compton electrons which spiral in the geomagnetic field in roughly the 20 km to 40 km altitude regime. The resulting fields below this source region (before reflecting from the earth's surface) are approximated as a plane wave with a rise time in the 10 ns regime, a peak for the electric field of the order of 10^5 V/m, and a pulse width in the 100 ns ball park.

For this important example of a high-altitude EMP environment canonical forms of the environment have been proposed and employed. Taking a general plane wave in free space as

$$\begin{aligned} \vec{E}(\vec{r},t) &= E_2 f_2\left(t-\frac{\vec{1}_1\cdot\vec{r}}{c}\right)\vec{1}_2 + E_3 f_3\left(t-\frac{\vec{1}_1\cdot\vec{r}}{c}\right)\vec{1}_3 \\ Z_o\vec{H}(\vec{r},t) &= -E_3 f_3\left(t-\frac{\vec{1}_1\cdot\vec{r}}{c}\right)\vec{1}_2 + E_2 f_2\left(t-\frac{\vec{1}_1\cdot\vec{r}}{c}\right)\vec{1}_3 \end{aligned} \qquad (1)$$

$$Z_o = \sqrt{\frac{\mu_o}{\varepsilon_o}} \quad \text{(wave impedance of free space)}$$

$$c = \frac{1}{\sqrt{\mu_o \varepsilon_o}} \quad \text{(light speed in free space)}$$

with orthogonal unit vectors

$$\begin{aligned} &\vec{1}_1 \equiv \text{direction of propagation} \\ &\vec{1}_2, \vec{1}_3 \equiv \text{orthogonal polarizations} \\ &\vec{1}_1 \times \vec{1}_2 = \vec{1}_3,\ \vec{1}_2 \times \vec{1}_3 = \vec{1}_1,\ \vec{1}_3 \times \vec{1}_1 = \vec{1}_2 \end{aligned} \tag{2}$$

Since the electric and magnetic fields are very simply related in (1), then in effect only one need be specified. The constants E_2 and E_3 are parameters with dimensions V/m, related to time-domain peaks. The waveforms are $f_2(t)$ and $f_3(t)$ shifted into retarded time. For present purposes only one such waveform $f(t)$ is considered, but in principle polarization can rotate.

The normalized waveform $f(t)$ is then taken in some convenient analytic form so that its properties in time domain $f(t)$, and complex frequency domain $\tilde{f}(s)$, appropriately approximate, or better bound (closely), a set of environmental waveforms. Here the two-sided Laplace transform is defined by

$$\begin{aligned} &\tilde{f}(s) \equiv \int_{-\infty}^{\infty} f(t) e^{-st} dt \\ &f(t) = \frac{1}{2\pi j} \int_{\Omega_0 - j\infty}^{\Omega_0 + j\infty} \tilde{f}(s) e^{st} ds \\ &s \equiv \Omega + j\omega \end{aligned} \tag{3}$$

with Ω_0 in the strip of convergence. Examples of waveform functions which have been used [5] include

$$f^{(1)}(t) = \left[-e^{-at} + e^{-bt} \right] u(t) \quad , \quad a>b>0$$

$$\tilde{f}^{(t)}(s) = \frac{a-b}{(s+a)(s+b)}$$

$$f^{(2)}(t) = \left[e^{-at} + e^{bt} \right]^{-1} \quad , \quad a>0, \; b>0 \tag{4}$$

$$\tilde{f}^{(2)}(s) = \frac{\pi}{a+b} \csc\left(\pi \frac{a-s}{a+b}\right)$$

In both of these cases a is chosen to give the desired rise characteristics in time domain and high-frequency characteristics of $\tilde{f}(j\omega)$. Typically

$$a \gg b \tag{5}$$

in both examples, corresponding to rise time small compared to decay time. Detailed properties of these canonical waveform functions are discussed in [5].

The plane-wave criterion form in (1) is appropriate for the case of a system in flight below the high-altitude nuclear source region, but at an altitude appreciably above the earth surface, so that the pulse reflected from the earth surface arrives sufficiently later in time that it may be considered a separate event. For a system operating on or near the earth surface such a high-altitude criterion must include the earth reflection, at least implicitly. Furthermore, the proximity of the earth to the system must also be included in the criterion because of the earth effect on the system Green's function (including natural frequencies, etc.).

Having an EMP criterion, such as in (1) we cannot stop there. Such canonical environments still have several parameters to be specified. In (1) the direction of incidence $\vec{1}_1$ must be specified; actual EMP environments can have a range of realistic values for $\vec{1}_1$, so one must specify some range or set of $\vec{1}_1$. Similar comments apply to the polarization $\vec{1}_2$ and $\vec{1}_3$.

Let us define a statement of a criterion as in (1) and (4), together with a range of the associated parameters (such as the unit vectors $\vec{1}_1$, etc.) as being a criteria set. It is this criteria set which the system is supposed to survive in some defined sense.

III. SIMULATION

Having some defined EMP criteria set we next must have some kind of EMP simulation set which tests the system of interest in some way which approximates or is quantitatively and experimentally related to the criteria set. As previously defined [1] (EMP) simulation (an individual simulation normally related to a single criterion) is:

"an experiment in which the postulated (EMP) exposure situation is replaced by a physical situation in which:

1. the (EMP) sources are replaced by a set of equivalent sources which to a good approximation produce the same excitation (including reconstruction by superposition to the extent feasible) to the total system under test or some portion thereof as would exist in the postulated nuclear environment, and

2. the system under test is configured so that it reacts to sources (has the same Green's function) in very nearly the same way and to the same degree as it would in the postulated nuclear environment."

"A(n) (EMP) simulator is a device which provides the excitation used for (EMP) simulation without significantly altering the response of the system under test by the simulator presence."

For a given individual criterion and system of interest (including its operational situation to be simulated) one may select an appropriate (EMP) simulator and design the simulation (test); this defines a criterion-simulation pair, abbreviated as a CS pair. A "complete" EMP test program may involve different configurations (including orientations) of the system in a given simulator, and perhaps even several different simulators;

this set is referred to as a simulation set. Now in determining the system response in a simulation test the failure-port response is a most relevant parameter. A failure port [3] "might be some pin on a connector into some black box. This position is of interest because one uses it for referencing signals associated with permanent damage or temporary functional disruption (upset)." This gives two ways to consider a CS pair. First there is a failure-port CS pair concerned with the criterion vs. simulation response at a particular failure port; the best simulation in this sense minimizes the difference between these two at the selected failure port. More interesting is the CS-pair system set which encompasses the failure-port CS pairs throughout the system for a given CS pair.

Now the CS-pair system set defines an individual criterion assessment which is a statement of the system vulnerability or lack thereof to the individual criterion of interest. However, since an EMP criterion set encompasses a range of excitation parameters, and for each selected individual criterion there is in general a separate simulation, then it is the collection of CS-pair system sets, varied over the same set of parameters that determines the criteria set, which determines the assessment of the system to the criteria set of interest; this defines the criteria-set assessment, or system assessment for short. Later there is discussed the use of extrapolated (E) response as an approximation to criterion (C) response. For that case the substitution of extrapolated for criterion, and extrapolated system response set for criteria system response set is appropriate.

For high-altitude EMP simulation various types of EMP simulators are appropriate, the common ones including guided-wave simulators (such as parallel-plate transmission lines) for simulating in-flight conditions (with the system not actually in-flight), equivalent-electric-dipole simulators (vertically polarized) for testing systems in actual flight, and hybrid simulators for testing systems which are supposed to be on the ground (buildings, parked aircraft, etc.). For other types of EMP, there are other types of simulators. For an extensive discussion of the various types of EMP simulators see [1].

IV. EXTRAPOLATION

Simulation is not in general perfect; this should not be a surprise to anyone, considering that simulation is an experiment which is not the "real thing". One would like to have a near perfect simulator, but this is not always possible or practical; it is also generally expensive. Given some particular simulation test, is it possible to quantify the errors and/or correct the results in order to have a more accurate estimate of the system response under criterion conditions? This is the subject of extrapolation as defined and discussed in [3], with the definition:

"Simulator extrapolation is:

an extension of the simulator in which the system undergoing a simulation test is corrected to some degree for differences of its response from those under criterion conditions associated with

1. differences in the simulator environment from the criterion environment, and

2. proximity of the simulator to the system changing its response characteristics (Green's function) from those existing under criterion conditions. (Note that local earth, water, etc., in the context of an EMP simulator is part of the simulator.)"

This can be generalized to simulation extrapolation if one includes

"3. differences in the system configuration changing its response characteristics from those existing under criterion (operational) conditions."

For present purposes only the first two points are considered.

Figure 1 diagrams the various types of extrapolation discussed in [3] which are summarized here. This extrapolation sequence diagram is a topo-

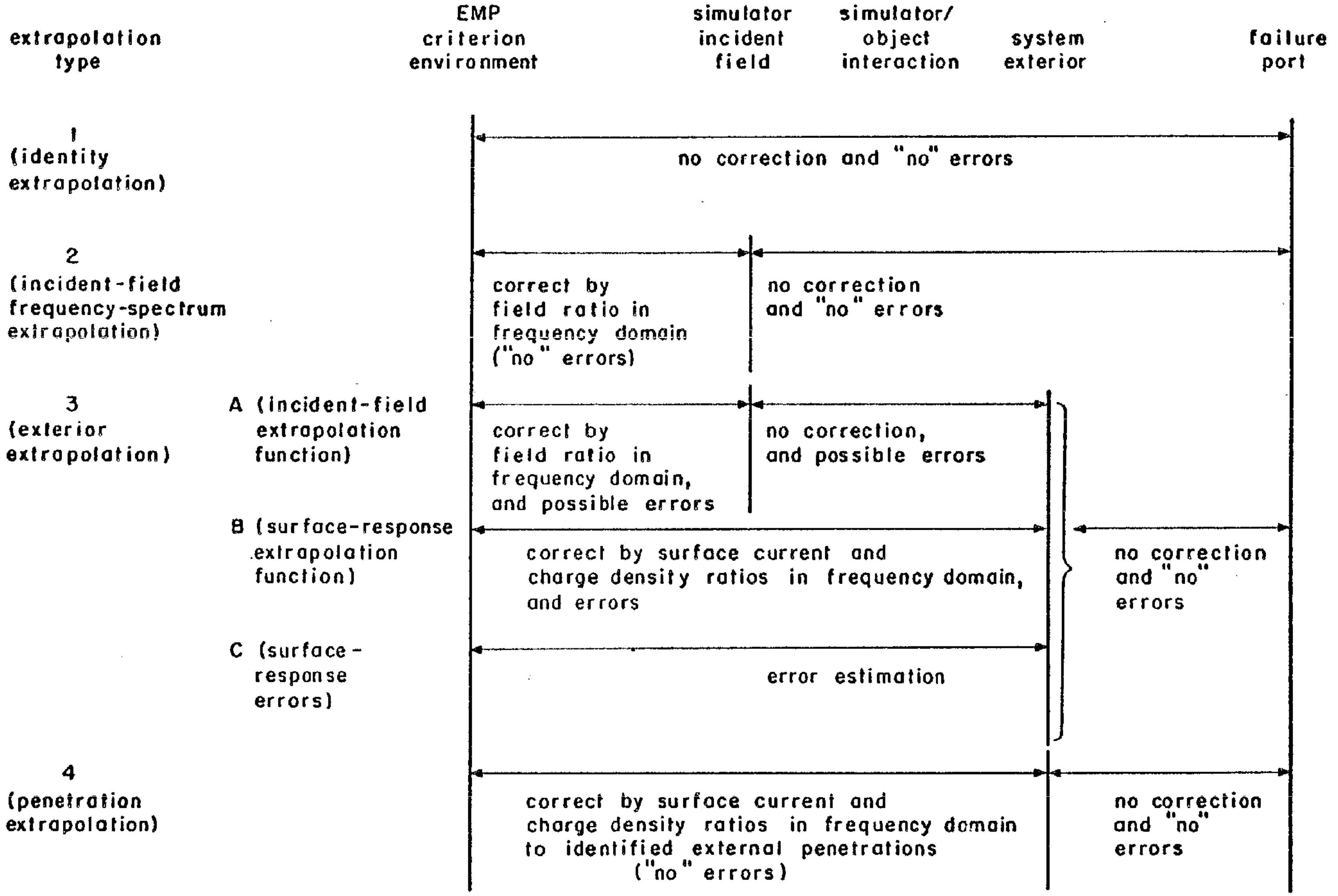

Figure 1 Extrapolation Sequence Diagram

logical diagram similar to the interaction sequence diagram [8] in that it is based on signal flow from the incident wave to the system exterior, through the system exterior, and on to some failure port (such as the input to one of the "black boxes") in the system. Note the inclusion of the simulator/object interaction as a step which can influence the signal flow between the incident field and system in criterion conditions as well as in the simulator. This assumption is often valid but not always; it does, however, significantly simplify the extrapolation problem.

For the extrapolation there is introduced the concept of an extrapolation function, designated in complex frequency domain by $\tilde{f}_e(s)$. This function is defined such that it multiplies a response function somewhere to give a corresponding extrapolated response which in some sense approximates the response under criterion conditions. For this purpose we introduce superscripts

$$\begin{aligned} C &\equiv \text{criterion} \\ S &\equiv \text{simulation} \\ E &\equiv \text{extrapolated} \end{aligned} \tag{6}$$

so that we can write

$$\tilde{F}^{(E)}(s) \equiv \tilde{f}_e(s)\, \tilde{F}^{(S)}(s) \tag{7}$$

where $\tilde{F}$ refers to some response function of interest with $\tilde{F}^{(E)}$ approximating (perhaps in a very crude way) $\tilde{F}^{(C)}$.

Type 1 extrapolation is (for completeness) identity extrapolation with

$$\tilde{f}_e(s) \equiv 1 \tag{8}$$

i.e., nothing is done to results from the simulation test. Of course this is accurate only in the limit of the simulation perfectly matching the particular criterion in all relevant aspects.

Type 2 extrapolation corrects for waveform differences, but not different spatial variations of the incident fields or simulator/object interaction, by defining

$$\tilde{f}_e(s) \equiv \frac{\tilde{F}^{(C)}_{inc}(s)}{\tilde{F}^{(S)}_{inc}(s)} \qquad (9)$$

with the incident-field function defined in a variety of ways, such as

$$\tilde{F}_{inc}(s) \equiv \tilde{\vec{E}}_{inc}(\vec{r}_o,s) \cdot \vec{1}_o \qquad (10)$$

where $\vec{r}_o$ is some selected position in space and $\vec{1}_o$ a particular direction (polarization) there. This type 2 extrapolation is then an <u>incident-field frequency-spectrum extrapolation</u>. It is particularly appropriate for cases that the simulator spatial distribution of the fields closely matches that of the criterion (e.g., (1)) with a different waveform and field amplitude. An example of such a case is an aircraft flying by an EMP simulator at sufficient range to well simulate in-flight conditions (for perhaps limited choices of direction of incidence and polarization).

Type 3 extrapolation is referred to as <u>exterior extrapolation</u>. As the name implies the electromagnetic response of the system exterior (surface current and charge densities) enters into the extrapolation formulas in the definition of the extrapolation function and/or the estimation of the remaining errors. For this purpose the system is assumed to have an approximately perfectly conducting outer envelope. Of course there are electrical penetrations through this envelope. For present purposes these penetrations are assumed to be sufficiently small (both electrically and physically) and of not too large a number. Then the transfer function from the incident field (criterion and simulation) to a failure port can be factored into a sum of products with each product having as a factor $\tilde{F}_{s_m}(\tilde{r}_s,s)$ where

$$\tilde{F}_{s_m}(\tilde{r}_s,s) = \begin{cases} Z_o\,\tilde{\vec{J}}_s(\vec{r}_s,s)\cdot\vec{1}_{u_m} & \text{for } m = 1,2 \\ \frac{1}{\varepsilon_o}\,\tilde{\rho}_s(\vec{r}_s,s) & \text{for } m = 3 \end{cases}$$

$$\vec{r}_s \equiv \text{coordinate on surface (envelope)} \qquad (11)$$

corresponding to the two components of surface current density and one of the surface charge density. The $\vec{1}_{u_m}$ are a right-handed set of unit vectors corresponding to an orthogonal u_m coordinate system with u_3 = (some constant) corresponding to our system envelope. Furthermore, for developing the error formulas it will be assumed that for a given failure port only one value of m and one of $\vec{r}_s$ is dominant, i.e., only one penetration and penetration mode is important for any frequency (or at least most frequencies) of interest, although different frequencies may have different dominant penetrations and/or penetration modes.

As a first step define an extrapolation function. One way (type 3A) is defined as in (9) based on the incident field giving

$$\tilde{f}_e^{(A)}(s) \equiv \frac{\tilde{F}^{(C)}_{inc}(s)}{\tilde{F}^{(S)}_{inc}(s)} \qquad (12)$$

Noting from (10) that there is some choice of measurement position $\vec{r}_o$ and orientation $\vec{1}_o$ for this type of incident-field extrapolation function, one might even average the above ratio over various choices of $\vec{r}_o$ and $\vec{1}_o$. Another way (type 3B) is defined from the surface response quantities as in (11) as

$$\tilde{f}_e^{(B)}(s) \equiv \frac{\tilde{F}_{s_m}^{(C)}(\vec{r}_{s_o},s)}{\tilde{F}_{s_m}^{(S)}(\vec{r}_{s_o},s)} \tag{13}$$

for some particular $\vec{r}_s = \vec{r}_{s_o}$ and choice of m. Better, an average over the surface and m is made. Various averages are possible; the one in most common use is a logarithmic average or geometrical mean as

$$\begin{aligned} \tilde{f}_e^{(B)}(s) &= \exp\left\{\sum_{\ell=1}^{N_p'} \ell n \left[\frac{\tilde{F}_{s_\ell}^{(C)}(s)}{\tilde{F}_{s_\ell}^{(S)}(s)}\right] \frac{1}{N_p'}\right\} \\ &= \left\{\prod_{\ell=1}^{N_p'} \frac{\tilde{F}_{s_\ell}^{(C)}(s)}{\tilde{F}_{s_\ell}^{(S)}(s)}\right\}^{1/N_p'} \end{aligned} \tag{14}$$

where $\ell = 1,2,\ldots,N_p'$ is an index corresponding to pairs of selected positions ($\vec{r}_{s_n}$ on the envelope) and orientations ($\vec{1}_{u_m}$), perhaps randomly chosen. This latter choice has the property of minimizing the errors (in a ratio sense) which follow.

Now take the surface response quantities to define a set of ratios as

$$\tilde{R}_{s_\ell}(s) \equiv \frac{\tilde{F}_{s_\ell}^{(E)}(s)}{\tilde{F}_{s_\ell}^{(C)}(s)} \equiv \frac{\tilde{f}_e(s)\tilde{F}_{s_\ell}^{(S)}(s)}{\tilde{F}_{s_\ell}^{(C)}(s)} \equiv \tilde{E}_{s_\ell}^{-1}(s) \tag{15}$$

where either (A) or (B) can be applied as a superscript on the extrapolation function. If one graphs $|\tilde{R}_{s_\ell}(j\omega)|$ as a function of ω (or $f = \omega/(2\pi)$) for $\ell = 1,2,\ldots,N_p'$, deviation of the magnitudes of the ratios from unity can be taken as a measure of the (linear) errors remaining after correction of the system response at the failure ports by the extrapolation function. These errors can also be considered in time domain by using individual ratios as in (13) to construct N'_p different extrapolation functions with multiplication as in (7) and inverse Laplace transformation; the spread of the resulting time-domain failure-port waveforms from that using (12) or (14) gives the time-domain errors. Note that as the spatial part of the fields in the simulator is made to match the criterion, and the simulator/object interaction tends to criterion conditions, then all the ratios in (15) become the same. Furthermore if the surface extrapolation function in (13) or (14) is used, then the above ratios all become 1.0. This general kind of error is referred to as type 3C in this extrapolation development.

In order to obtain the surface response quantities above one needs the surface response set under criterion conditions. This can be obtained in various ways. The real system can be used to experimentally determine the criterion surface responses, provided for this purpose a sufficiently pure simulation which requires no-more severe than type 2 extrapolation is used. Typically measurements on scale models (of the system exterior envelope, including large antennas) have been used to obtain the criterion surface responses [2, 4].

Finally, type 4 extrapolation attempts to avoid the 3C errors. It does this by experimentally associating the signal at a failure port with the surface response quantities (11) appropriate to the penetrations driving that particular failure port. While this avoids the uncertainty as in (14), it introduces the significant complexity of determining which penetrations and penetration modes are associated with each failure port. In effect, extrapolation functions must be determined for each failure port.

V. CONCLUSION

This paper has outlined the basics in the process of EMP *assessment*. Some *particular system* is designed or defined to operate under exposure to some EMP *criteria set*. For each particular case under the EMP criteria set (or an appropriate sample of such cases) an *individual criterion assessment* can be performed. This requires the definition of an appropriate EMP *simulation set*, an individual simulation corresponding to an individual criterion. However, an individual simulation is in general not perfect, i.e., it has errors. These errors are in general different at each *failure port*.

The failure-port CS pair concerns the survivability of the individual failure port to the individual criterion. The *CS-pair system set* extends this consideration to the entire system, and forms the basis for an individual criterion assessment. Extending this to the criteria set with its associated *simulation set* one can determine the *criteria-set assessment* or *system assessment* as a statement (ideally quantitative) of the system vulnerability or lack thereof to the criteria set.

However, simulation is in general imperfect. So one defines a process of *extrapolation* to correct the signals at *failure ports* under simulation conditions to a more accurate representation of *criterion conditions*, i.e., *extrapolated conditions*. With an appropriate *definition of an extrapolation function* and associated *errors*, one can begin to approximate (replace) criterion responses by extrapolated responses. Then simulation (S) in the previous paragraph can be replaced by extrapolated (E). This defines the *failure-port CE pair*, and the *CE-pair system set* to give an *individual extrapolation assessment*. Extending this to the *criteria set* one has the system assessment in terms of the extrapolation set as an approximation to the criteria set.

The comparison between criteria-set response and extrapolation-set response is a measure of simulation quality. The best simulation (corresponding to some individual criterion) is that which involves in some sense the least extrapolation. The differences of simulation response from criterion response fall into two categories. The first difference concerns the required extrapolation function or functions; the closer this function is to 1.0 for all frequencies the better is the simulation. The second difference concerns the errors after extrapolation; the smaller the errors (or the closer the "exact" individual extrapolation functions approach to some common (or universal) extrapolation function) the better is the simulation.

This comparison of simulation quality to criterion can be turned into an economic question. How much is high-quality simulation worth? One should consider the alternatives. One can have poor simulation (extrapolation functions far from unity and/or large residual errors) with corresponding large uncertainties in system assessment. This can alternately be interpreted as requiring large hardness margins at failure ports (ratios of signals for vunlerability to extrapolated signals, including implications of probabilistic distributions of such ratios). While this may be cheap in terms of simulators it requires large hardness margins with appropriate constraints on their distributions. Alternatively one can have better simulation (at greater expense) and tollerate smaller hardness margins (with appropriate attention to distributions). This is perhaps an oversimplified view, but still realistic. There are still state-of-the-art limitations on the technology for determining what the best trade-off is. Note that such trade-offs are still in the context of linear extrapolation; nonlinear effects still require high quality simulation.

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