TABLE OF CONTENTS

I. INTRODUCTION

In order to insure that an EMP-hardened aerospace system remains hard throughout its lifetime, it is desirable to make periodic inspections of the various hardening elements installed on the system. These include hatch gaskets, wire mesh aperture covers, ESAs and filters, waveguides beyond cutoff, etc. Presently, the most commonly used method for hardness surveillance is to visually inspect the hardening element for any flaws which would degrade the system hardness. For a simple system with only one or two such hardening elements, such a surveillance approach might be acceptable, but with a complex system such as an aircraft, a visual inspection of this sort is not only time consuming, but may be prone to errors. It is desirable, therefore, to develop an automated, electrical method for performing the EMP hardness surveillance of a complex system.

One possible approach to this problem is to develop an on-board excitation and monitoring subsystem which would periodically test the shielding integrity of the overall system and detect any flaws in the hardening elements. This concept has been discussed in reference to the EMP hardness of the B-52 aircraft [1] and a number of practical design considerations were outlined.

The basic conceptual design of the hardness assurance monitoring system (HAMS) requires that a number of electromagnetic field sources and sensors to be located on or within the aircraft, and measurements to be made periodically to verify that the system's response to these test sources is not varying over the lifetime of the aircraft. If the response at a sensor were to deviate from its nominal or "baseline" response, a fault isolation procedure would then be employed to identify the weakness in the hardening of the system and permit repairs to be made. The basic ideas involved in this EMP simulation concept have been developed originally by Baum in Ref. [2].

There are a number of considerations which must be taken into account in a practical HAMS design. First, we must use a reasonable number of sources for exciting the system. For exterior driving sources, a typical number might be on the order of 10, and for interior driving sources, such as current inducing probes around cables, a reasonable number of sources might be about 100. The location of these driving sources must be carefully determined, so as to optimally excite the exterior aircraft modes, as well as the interior cabling linking the subsystems within the aircraft. In this manner, the errors involved in such an on-board EMP simulation and test procedure can be minimized. Furthermore, the various driving sources must be physically realizable.

The second consideration is that the excitation provided by the HAMS, and the resulting response of the system, must be relatable to the criterion EMP excitation and response. This can be done by various methods having different degrees of accuracy, ranging from a simple scaling of the magnitude of the measured response through sophisticated extrapolation procedures.

A third important consideration is that the HAMS system and its associated electronics, cabling, etc., must not interfere with the shielding topology of the aircraft. That is, the HAMS should adhere to the same topological shielding constraints that are required of all other subsystems on the aircraft.

This note presents additional theoretical background material which pertains to the above important design considerations. Throughout this discussion, we will be discussing only the HAMS sources which excite the exterior of the aircraft (denoted as surface S_1). The omission of the interior sources (within V_2) is not because they are deemed unimportant, but due to lack of time in our relatively short design study.

II. RELATION BETWEEN PLANE WAVE EXCITATION AND SIMULATION

Figure 1 illustrates an in-flight aircraft subject to a high altitude EMP excitation. Transient surface currents $\overline{J}_s(\overline{r},t)$, are induced on the aircraft skin, and have a time history which depends not only on the incident EMP waveform, but also on the structure of the aircraft. These EMP induced currents will couple electromagnetic energy into the aircraft through apertures, antennas, etc. and excite the interior subsystems, possibly causing damage.

The HAMS concept for external sources is to locate several sources on the aircraft exterior, as shown in Figure 2, excite the aircraft, and induce a simulated surface current $\overline{J}'_s(\overline{r},t)$ which deviates from the EMP induced surface current by a known amount. Because it is often difficult to produce accurate, high energy, time domain waveforms which simulate the incident field, it is envisioned that this simulation will be performed using swept continuous wave (cw) excitation. Thus, in the remainder of this discussion, it is assumed that all measured or calculated quantities are in the frequency domain described by the variable s.

Considerable work has been performed in the past in attempting to calculate the EMP induced surface currents on the aircraft as shown in Figure 1. See Refs. [3,4]. This past theoretical work leads directly to the fundamental concepts used by HAMS for exterior excitation and simulation.

As discussed in [3,4] it is possible to derive an integral equation for the surface currents $\overline{J}(\overline{r})$, which involves a number of geometrical and frequency terms, as well as the tangential component of the incident electric field everywhere on the surface of the aircraft. This equation may be solved using the moment method [5] in conjunction with a computer.

The application of the moment method to solve for the induced surface current may be interpreted as dividing the aircraft surface into a large number of zones in which the current is assumed to be

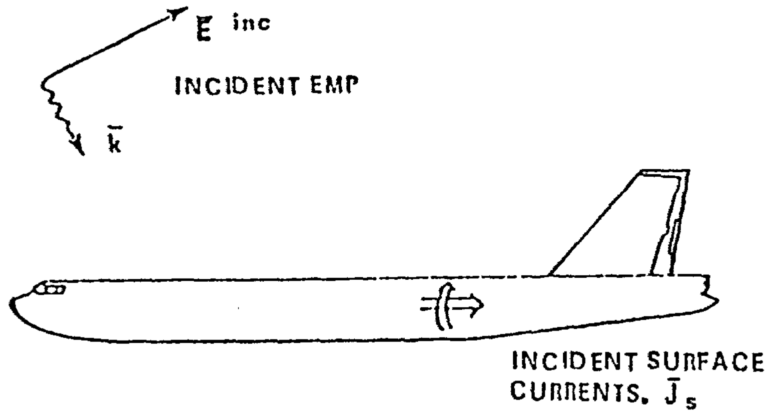

Figure 1. Surface currents $\bar{J}_s(r)$ on aircraft induced by incident EMP

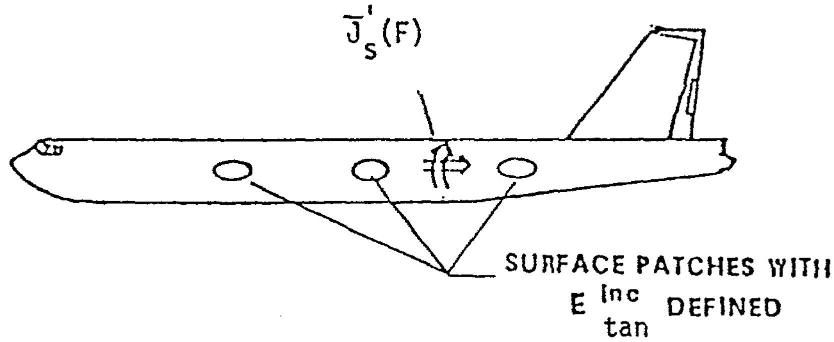

Figure 2. Simulated surface currents $\bar{J}_s'(r)$ on aircraft due to localized HAMS sources

constant. Likewise, the incident electric field can be taken to be constant in each zone. In this manner the integral equation can be transformed into a large matrix equation of the form

$$\left(\bar{\bar{Z}}(s)_{n,n}\right) \cdot \left((\bar{J}_s(r)_n\right) = \left((\bar{E}^{inc}_{tan}\,(r)_n\right) \tag{1}$$

where n represents the number of zones on the aircraft. The notation $\bar{J}_s$ refers to the spatial components of the surface currents and $(\bar{J}_s(r)_n)$ denotes an n-vector of surface currents at n different positions on the aircraft.

For the case of plane wave excitation of the aircraft by an EMP (often referred to as a "criterion" excitation) the n-vector $(\bar{E}^{inc}_{tan}\,(r)_n)$ is full (i.e., each of the n components of the vector is non-zero). It is well known that the system of equations in Eq. (1) are similar to those defining the v-i relationship for an n-port linear current [5], as illustrated in Figure 3a, where v_1, v_2, ... are related to the incident electric field over each patch.

Using the n-port circuit analogy, the case of a discrete number of HAMS sources on the aircraft exterior can be represented by the n-port circuit with only a few ports excited and with all others short circuited. This is shown in Figure 3b. In both cases, it is possible to calculate the n-vector current flowing in the input ports. The difference between the two, therefore, gives a measure of the error involved in simulating the incident $\bar{E}$ field with a small number of local sources.

There is one additional fact that has some importance on the concept of HAMS escitation of the aircraft. For these tests in which non-linear component effects will be neglected, it is possible to superimpose the results obtained by using only one HAMS source in various locations, so as to obtain the total response for all of the HAMS sources. This is of particular interest if it is desirable to simulate the effect of different

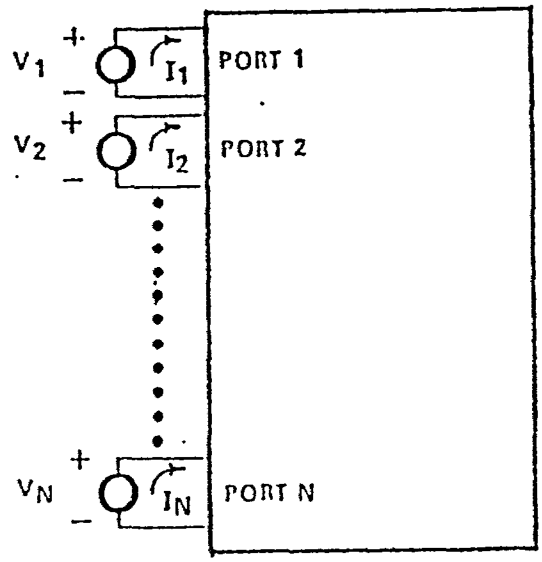

Figure 3a. Equivalence of descretized field problem to an n-port circuit problem

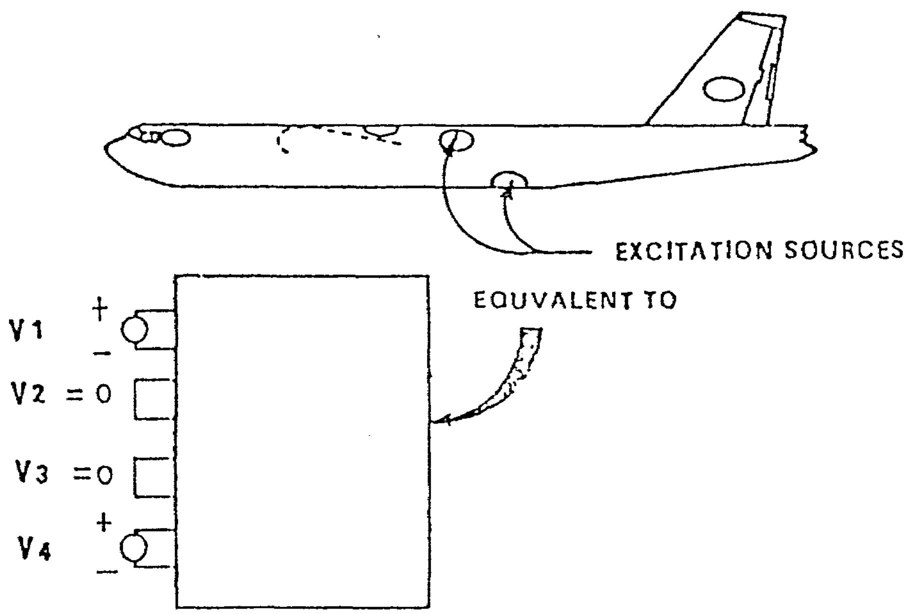

Figure 3b. Small number of HAMS sources is equivalent to n-port with sparse excitation

angles of incidence on the EMP response of the aircraft currents. Figure 4 illustrates this concept.

The idea of using a few discrete sources as the aircraft surface to simulate the EMP response has been discussed by Baum[1,6] and is referred to as the "PARTES" concept. In doing this, there are a number of important considerations. First, the errors due to having a finite number of discrete sources must be determined. Second, all measured results must be extrapolated to criterion conditions so as to obtain the true system response. It is also important to consider the design details of the sources which produce the incident simulated field. Finally, the data processing schemes for using all of the HAMS data must be thoroughly studied and optimized so as to make maximum use of the information content of the data. These considerations will be discussed in the following sections.

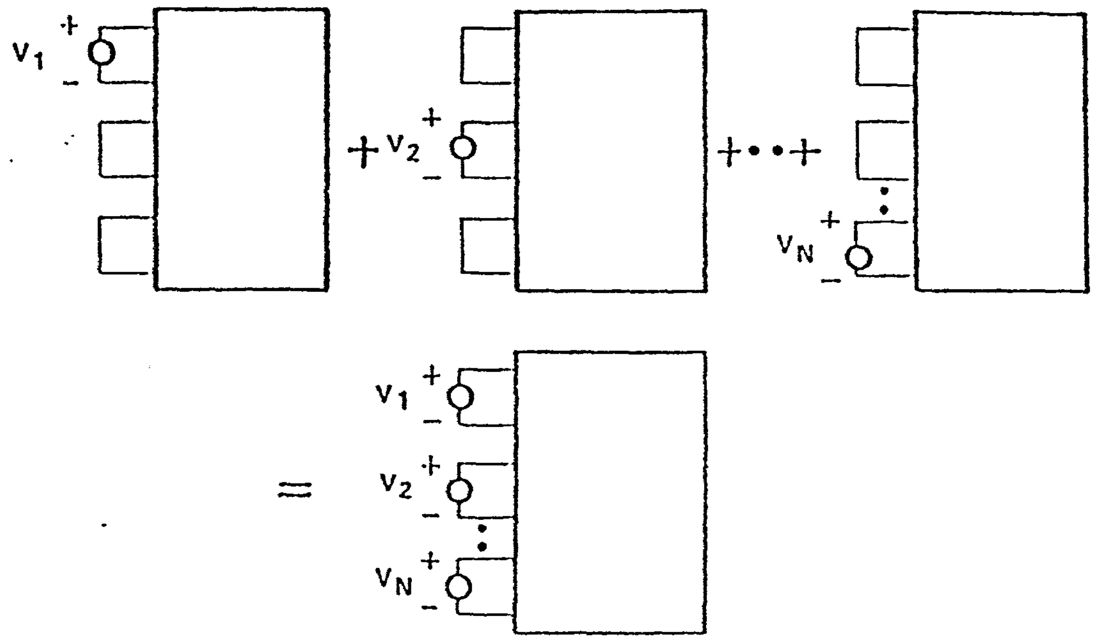

Figure 4. The solution to a number of HAMS Sources can be constructed using the concepts of superposition, if the system is linear.

III. ERRORS IN SIMULATION

There are a number of sources of error in the HAMS concept of testing. One relatively large source of error lies in the fact that we are using a small number of discrete sources to simulate a continuous incident field. One way to estimate errors induced in this way is to use the natural resonance (SEM) analysis [7] of cylindrical bodies and investigate the coupling coefficient for various numbers of HAMS sources. Although the example presented here is for a simple cylinder, it may be applied to a crossed wire aircraft model for more accurate calculation of the errors, if desired.

Consider the problem illustrated in Figure 5, where a plane wave strikes a cylinder of some finite length. It is desired to simulate this criterion excitation by a few discrete sources. In both cases, the SEM expansion of the current at a point x on the cylinder can be expressed as

$$I(x) = \sum_{\alpha} \frac{\eta_\alpha \nu_\alpha(x)}{s - s_\alpha} \tag{2}$$

where α refers to the index of the complex natural resonances s_α, s is the generalized frequency variable $(s = \sigma + j\omega)$, ν_α is the natural current mode and η_α is the coupling coefficient which is related to the incident or exciting electric field on the surface of the cylinder. Specifically, for the case of the cylinder, the coupling coefficient may be evaluated as

$$\eta_\alpha = \beta_\alpha \int_0^L E_{tan}^{inc}(x)\nu_\alpha(x)\, dx \tag{3}$$

where β_α is a constant and E_{tan}^{inc} is the indicent electric field tangential to the wire surface due to either the plane wave of the HAMS sources. L is the length of the cylinder.

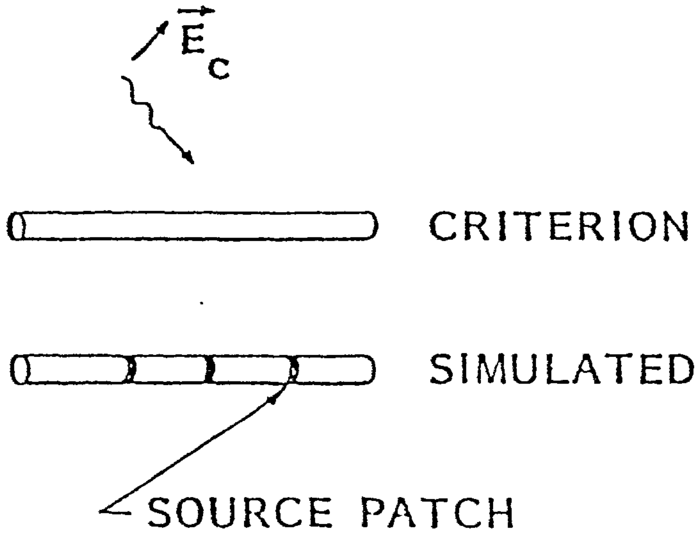

Figure 5. Thin Cylinder Excited by Incident Plane Wave (Top) and Discrete HAMS Sources (Bottom) for Determining Simulation Errors

By defining η_{α_c} to be the coupling coefficient for the plane wave (criterion excitation) and η_{α_s} for the simulated calculation, a convenient measure of simulation error is thus given by the quantity $|\eta_{\alpha_c} - \eta_{\alpha_s}| / |\eta_{\alpha_c}|$. For the cylinder, the natural modes $\nu_\alpha(x)$ are approximately given by $\sin(\alpha\pi x/L)$, so that η_α can be evaluated easily. Figure 6 shows this resulting error measure for various numbers of HAMS sources, denoted by N_s. These sources are uniformly distributed along the wire. Note that this error is given for an assumed broadside incidence of the criterion field. Thus, the coupling coefficient for even values of α are zero. Errors for $\alpha = 1, 3, 5, 7$, and 9 are indicated in Figure 6.

As mentioned earlier, this same calculation may be performed for a more realistic aircraft model using crossed cylinders. Taylor [8] has studied this problem to some extent, and the first four natural current modes (magnitudes) for a crossed wire model are shown in Figure 7. To date, however, the above error calculation has not been performed.

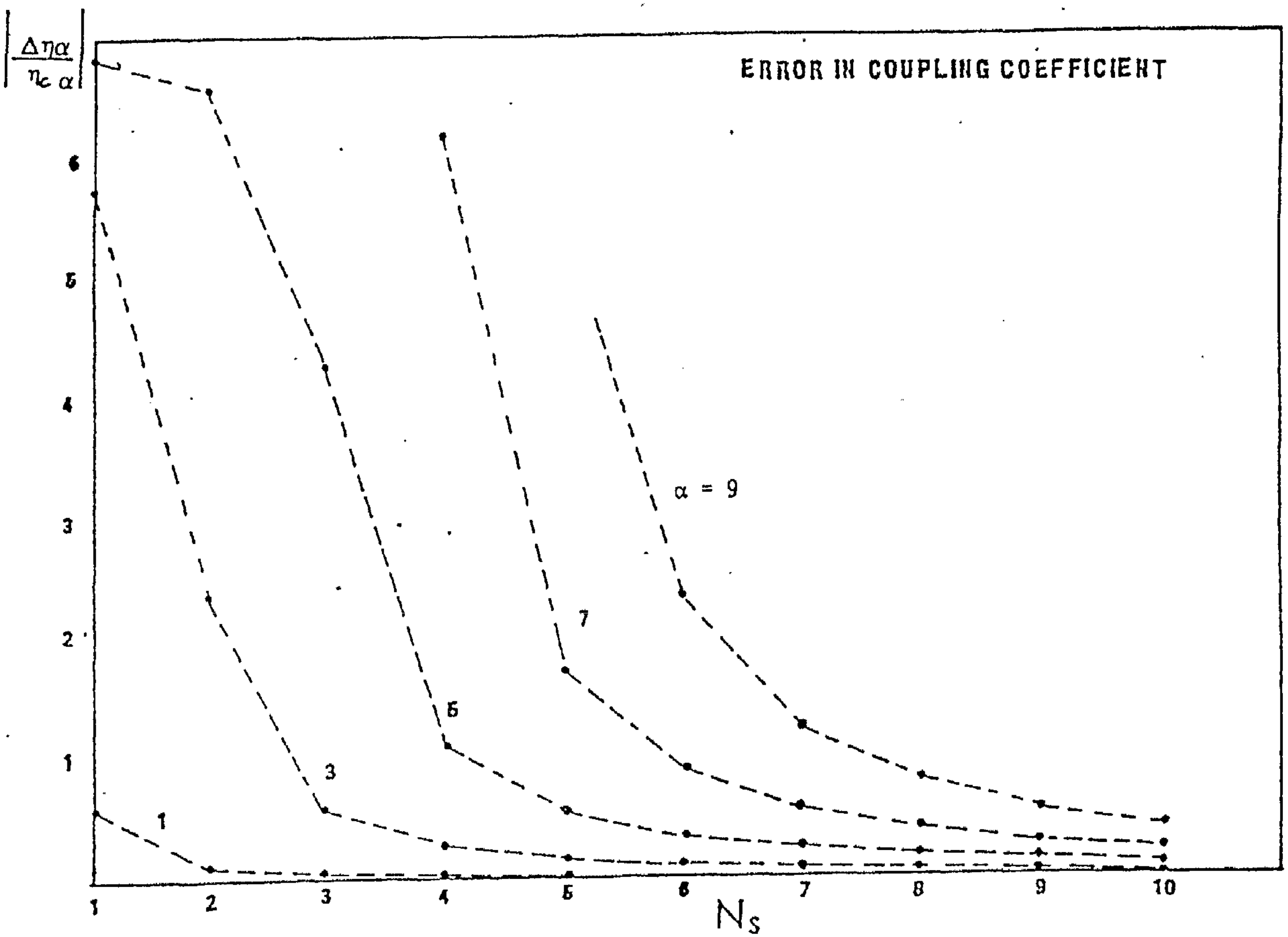

Figure 6. Relative errors in coupling coefficients for α = 1,3,5,7,9 as a function of the number of sources, N_s, on a thin cylinder.

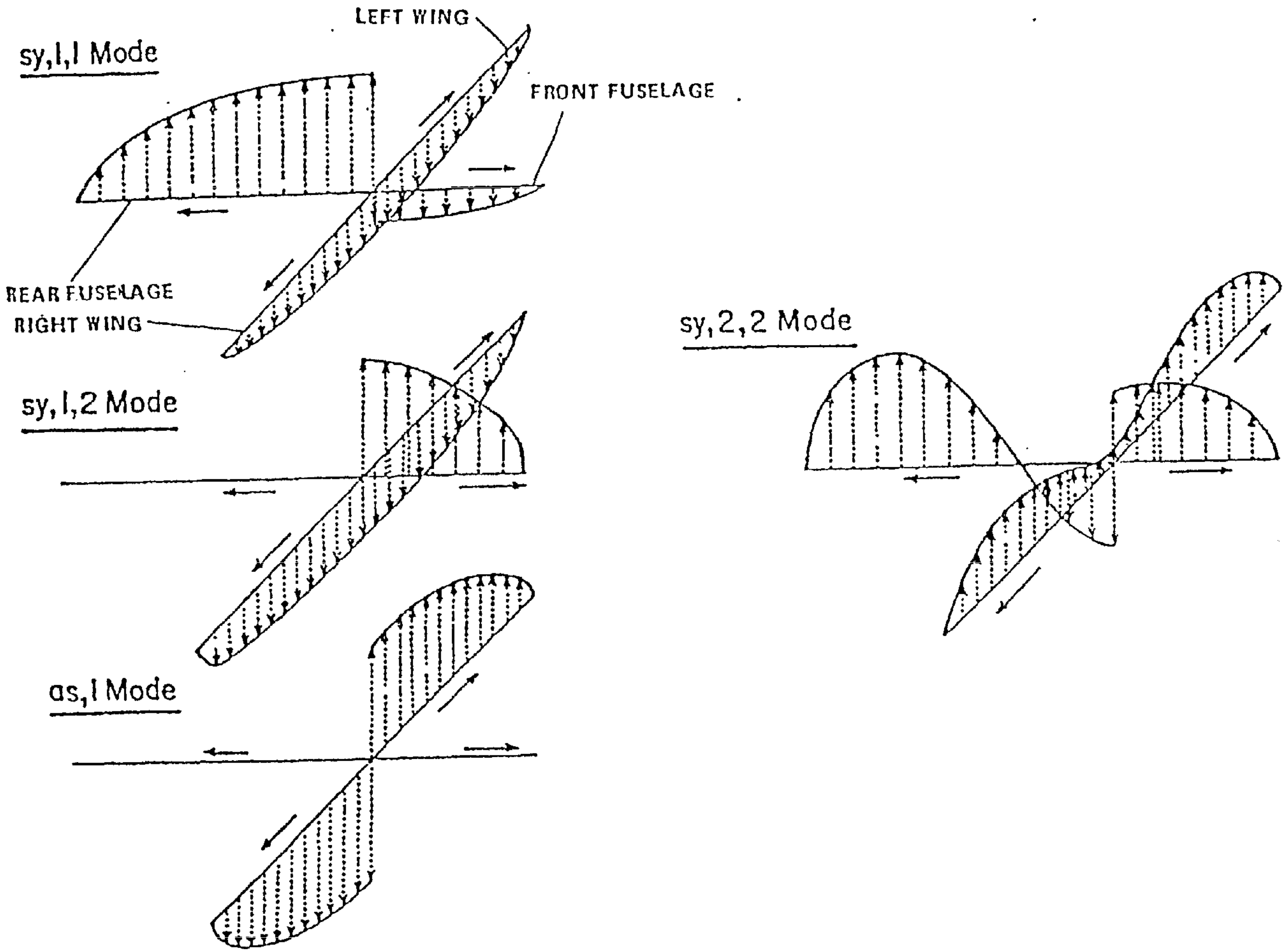

Figure 7. First four natural current modes on a crossed cylinder model of an aircraft.

IV. HAMS SOURCE CONSIDERATIONS

The HAMS simulation concept requires the production of an incident tangential electric field over a small "source" patch on the aircraft. In order to do this, we may consider one or more kinds of fundamental sources, so as to understand the field distributions on the surface of the source patch. These are small electric and magnetic dipole sources. In addition, it is certainly possible to consider using combinations of electric and magnetic dipole sources, or even arrays of sources, based upon design requirements. The final choice of the HAMS source configuration is, of course, heavily influenced by the physical realizability of the sources. In this section, we briefly examine the behavior of a few candidate sources for HAMS.

One of the possible sources is an electric dipole of moment, $\overline{P}$, located in the $\hat{x}$ direction at a height h above the ground plane, as shown in Figure 8. Of special interest is the incident electric field at the surface of the ground plane at $z = 0$. The electric field at a point $\overline{r}$ due to this dipole is given by [7]

$$\overline{E}(\overline{r}) = \frac{e^{-\gamma r}}{4\pi}\left\{\left[\frac{1}{\varepsilon_o r^3} + \frac{Z_o s}{r^2}\right]\left[-\overline{\overline{1}} + 3\,\hat{r}\,\hat{r}\right] + \frac{\mu_o s^2}{r}\left[-\overline{\overline{1}} + \hat{r}\,\hat{r}\right]\right\}\cdot\overline{P}(s) \qquad (4)$$

where $s = \sigma + j\omega$ is the generalized complex frequency variable, Z_o = free space impedance, ε_o and μ_o are the free space constitutive parameters and $\overline{\overline{1}}$ is the unit dyadic. The term $\gamma = s/c$ is the propagation constant in free space.

As an example of the field distribution on the ground plane, Figure 9 shows contour plots of the normalized tangential electric field on the gound plane. This quantity has been normalized with respect to the quantity $IL/4\pi$ where L is the length of the dipole source. For this plot, the frequency was such that $kh = \omega h/c = 1$.

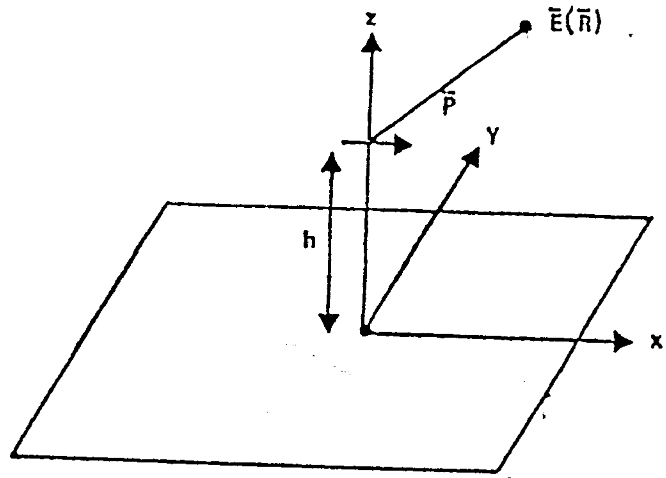

Figure 8. Point electric dipole above ground plane.

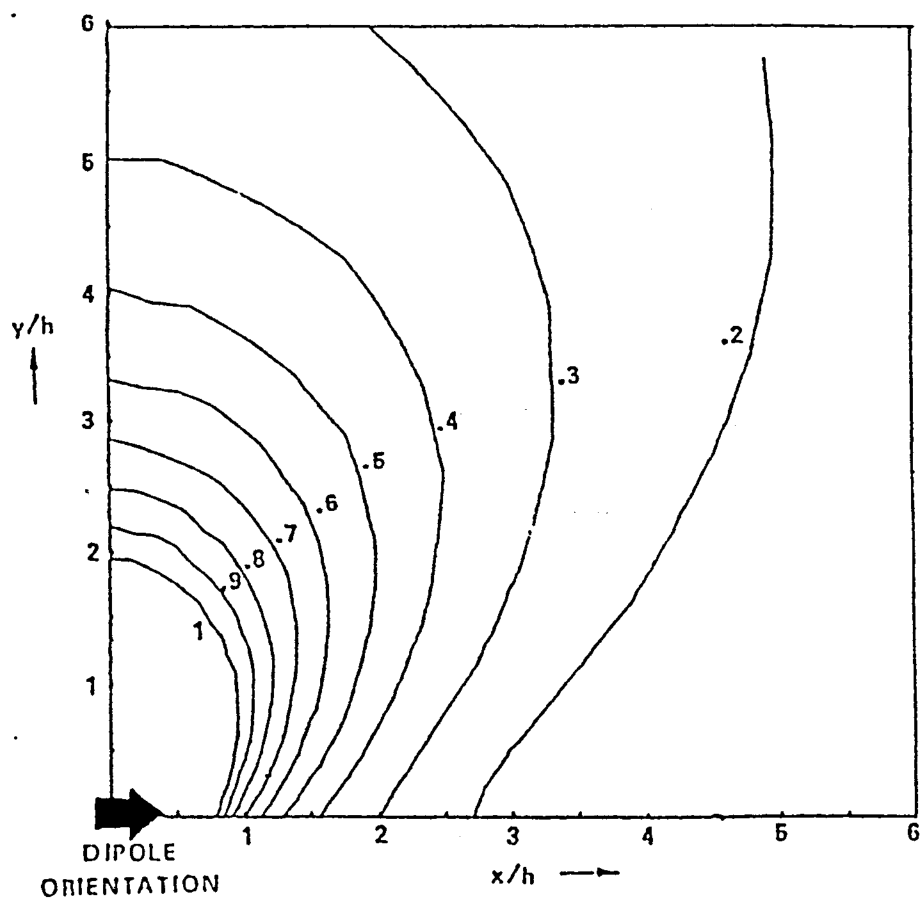

Figure 9. Contour plot of the normalized tangential electric field on a plane of distance h below an electric dipole. For this plot, $kh = \omega h/c = 1$.

Note that a similar plot could be obtained for the normal component of the electric field for this particular case, but this has not been done due to the difficulties in easily obtaining a physically realizable design for this type source which should be flush mounted on the aircraft surface for aerodynamic reasons.

Another kind of elemental source which could be considered for the HAMS is the magnetic dipole source. As shown in Figure 10, this consists of a magnetic dipole moment (i.e., small current loop) of moment $\overline{M}$ oriented in the $\hat{y}$ direction and located at a distance h above a ground plane. It is well known [9] that the electric field at a point $\overline{r}$ is given in this case by

$$\overline{E}(\overline{r}) = \frac{e^{-\gamma r}}{4\pi} \left[\frac{\mu_o s}{r^2} + \frac{\mu_o s^2}{rc} \right] \hat{r} \times \overline{M}(s) \tag{5}$$

As in the case of the electric dipole source, it is possible to plot the tangential field components on the ground plane to obtain an indication of the field behavior at any frequency. For the special case of low frequency (i.e., $s \to 0$), Eq. (5) above simplifies considerably to yield the tangential field in relatively simple terms as

$$\overline{E}_{tan}(\overline{r}_s) = \frac{1}{2} \mu_o s \, M(s) \, \frac{\xi}{h^2} \, \hat{x} \tag{6}$$

where $\overline{r}_s$ lies on the ground plane and the function ξ is plotted in Figure 11. In Figure 11, the parameter ψ is given by

$$\psi = \frac{\Psi}{h} = \frac{(x^2 + y^2)^{1/2}}{h} = \frac{\text{cylindrical radius}}{\text{distance of dipole from plane}} \tag{7}$$

For both this case (low frequency) and the more general high frequency case, it should be noted that the tangential field is in the $\hat{x}$ direction on the ground plane.

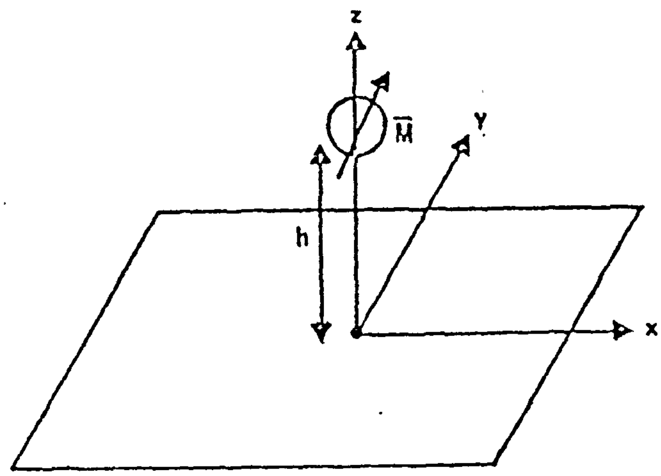

Figure 10. Elemental Magnetic Dipole Source Located a Distance h above a Ground Plane

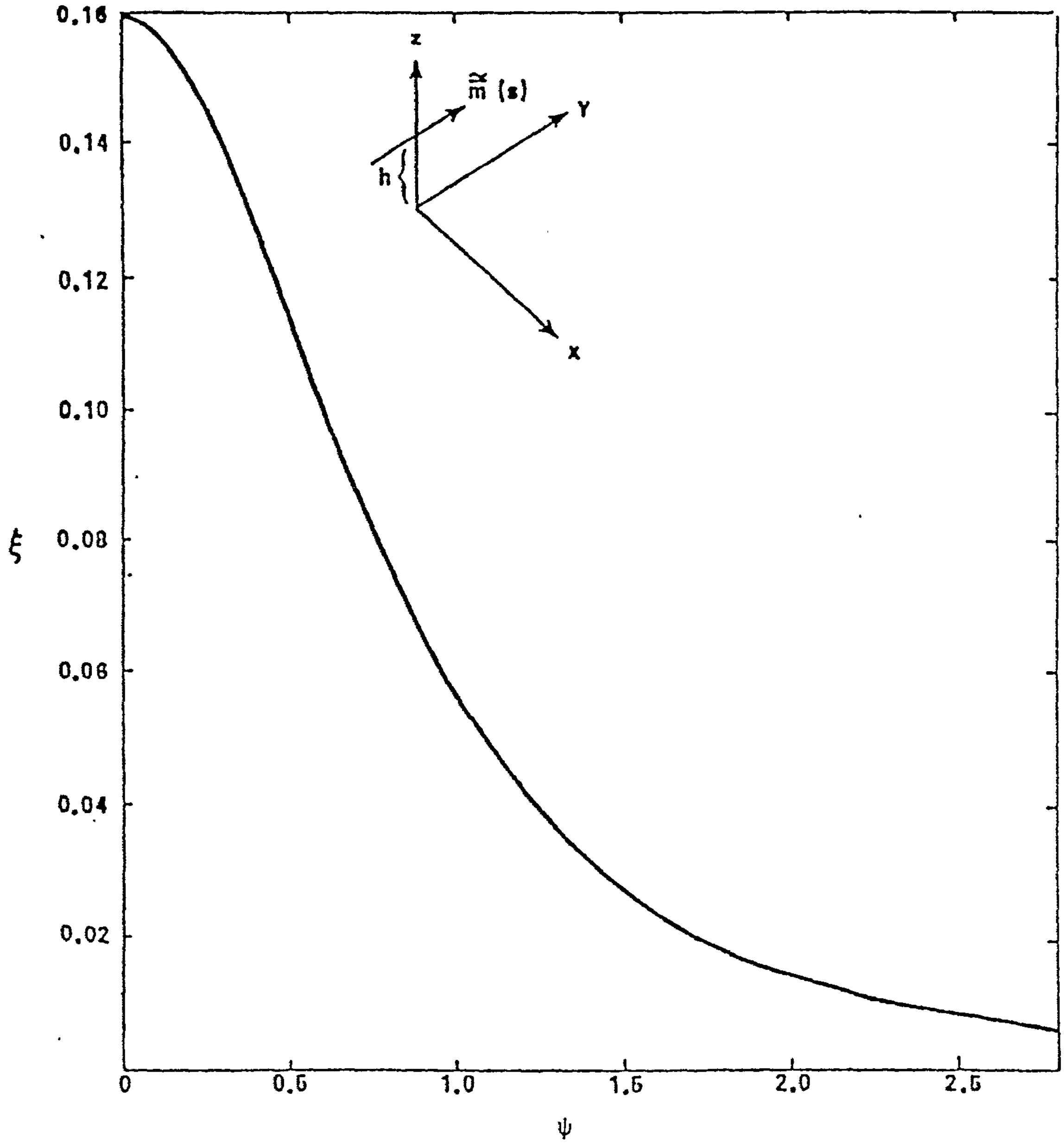

Figure 11. Plot of function ξ for determining low frequency tangential field due to magnetic dipole.

Another type of source configuration that is worth considering is an array. Consider a doubly infinite array of magnetic dipoles each of moment $\overline{M} = M\hat{x}$, separated a distance L apart and at a height h above the ground plane. After a considerable amount of algebraic manipulation, the two existing components of the electric field on the ground plane can be written as

$$E_y = \frac{\mu_0 sM}{L^2}\left\{\frac{e^{-\gamma h}}{2} + \left[\cos\frac{2\pi x}{L} + \cos\frac{2\pi y}{L}\right] e^{-\frac{2\pi h}{L}}\right\} \tag{8}$$

and

$$E_z = \left[\frac{2\mu_0 sM}{L^2} \sin\frac{2\pi y}{L}\right] e^{-2\pi h/L} \tag{9}$$

Note that E_y is the tangential component of the field, and E_z is the normal component on the ground plane.

It is possible to develop an estimate of the error involved in attempting to simulate an incident plane wave striking the ground plane. Consider an incident electric field propagating in the $-\hat{z}$ direction and oriented in the y direction, denoted by

$$\overline{E}^{inc} = E_o e^{\gamma z}\,\hat{y} \tag{10}$$

By choosing the dipole moment, M, to satisfy the relation

$$M = \frac{2L^2 E_o}{\mu_o s} \tag{11}$$

it may be noted that the propagating term of Eq. (8) will provide the same incident electric field at a distance far from the array (i.e., for large h/L).

One measure of the error in the simulated field is given by

$$\varepsilon = \frac{|E_y - E_y^{inc}| + |E_z - E_z^{inc}|}{|E_y^{inc}| + |E_z^{inc}|} \tag{12}$$

Using Eqs. (8, 9, and 10), it is possible to express the error as

$$\varepsilon = 2\varepsilon' \; e^{-2\pi h/L} \tag{13}$$

where the normalized error term ε' is independent of, h, the distance of the array from the ground plane. Figure 12 shows this normalized error plotted both in a 3-D fashion and as a contour plot in one of the unit cells formed by the dipoles. The dipoles are located at the corners of the rectangle (0,0), (0,1), (0,1), and (1,1).

Note that because of the exponentially decaying term in Eq. (13), the farther away from the ground plane is the source array, the smaller is the error in the simulated field. The maximum error occurs with the array directly on the surface $(h = 0)$ and Figure 12 indicates that roughly a maximum factor of 4 error is to be expected. Detailed calculations on the currents induced on the surface below the source array have not been carried out, but are completely feasible.

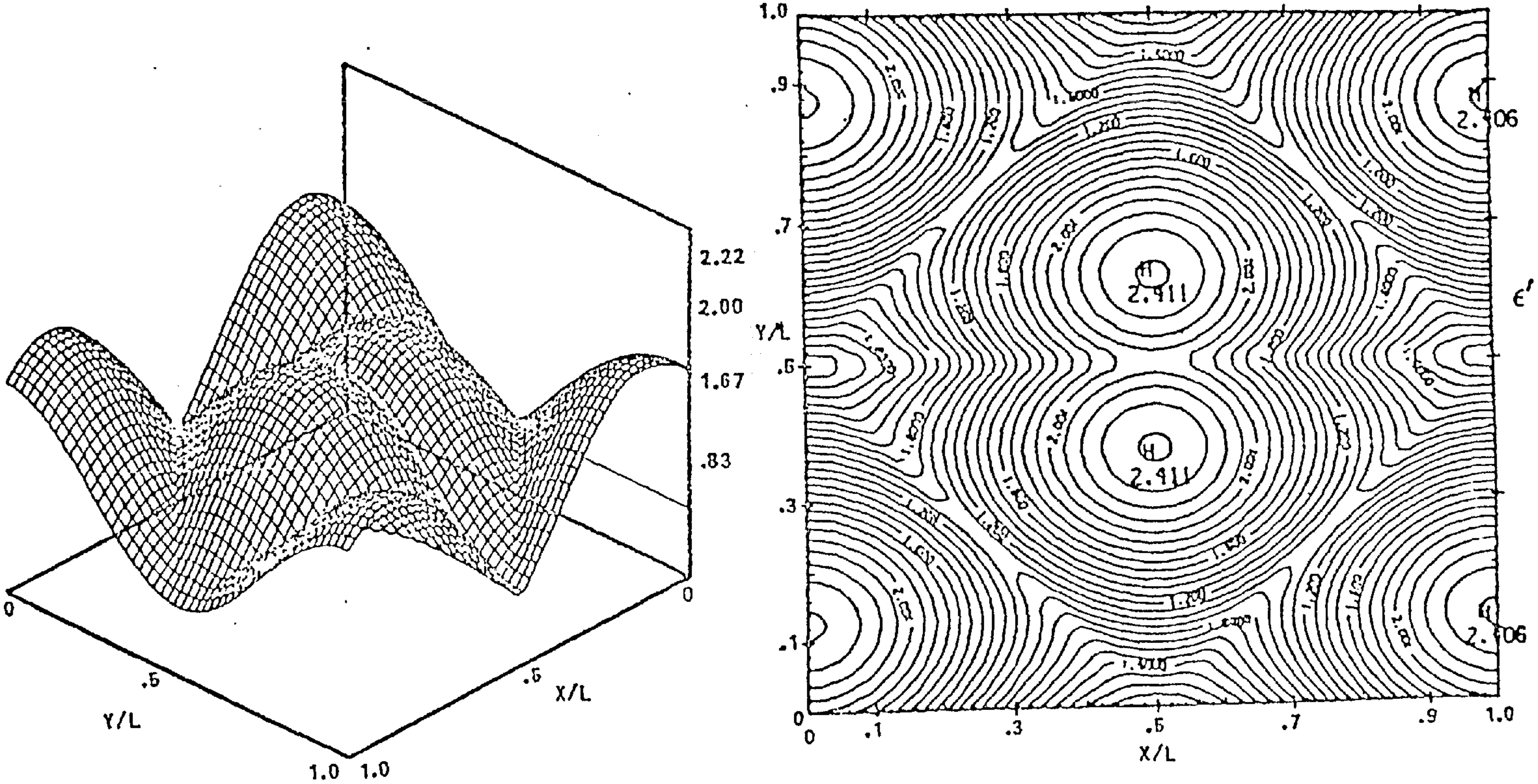

Figure 12. Plots of normalized error function ε' for infinite array of magnetic dipole sources.

V. USE OF HAMS DATA

As previously indicated, the HAMS will provide a way of verifying the hardness of the aircraft to an EMP environment. This may be done by performing an on-board HAMS test and comparing the measured response (say at a particular pin or cable) with the response when the aircraft was known to be EMP hard.

Another possible method for using the HAMS data is to simulate the response of the aircraft to an incident, plane EMP wave (i.e., to the criterion excitation) by exciting all of the HAMS sources with the proper phases and magnitudes, and then extrapolate the simulated response to the criterion response. This is indicated in Figure 13, where the response of the aircraft skin current at some point is labeled as $\bar{J}_c$ for the criterion excitation, and by $\bar{J}_s$ for the simulated excitation. Some form of data processing is necessary to relate $\bar{J}_c$ to $\bar{J}_s$, or for that matter, any other pair of observables within the aircraft. Theoretical foundations of this extrapolation process have been developed by Baum [10] and will not be discussed here further.

One aspect of the HAMS data processing that must be considered is that it is desired to be able to bound the response of the system for variations of the polarization and angle of incidence of the incident EMP. In other words, we are often interested only in the worst case response of the system. If a set of n responses (say voltages of selected pins) is represented by the n-vector (R_n), it is postulated that these may be related to the incident tangential electromagnetic field, (E_m^{inc}), at m different points on the aircraft, through a $m \times n$ transfer function as

$$(R_n) = (T_{n,m}) \cdot (E_m^{inc}) \tag{14}$$

In order to estimate the maximum possible value for any of the n responses R_n, it is possible to bound the response using appropriate norms [11] as

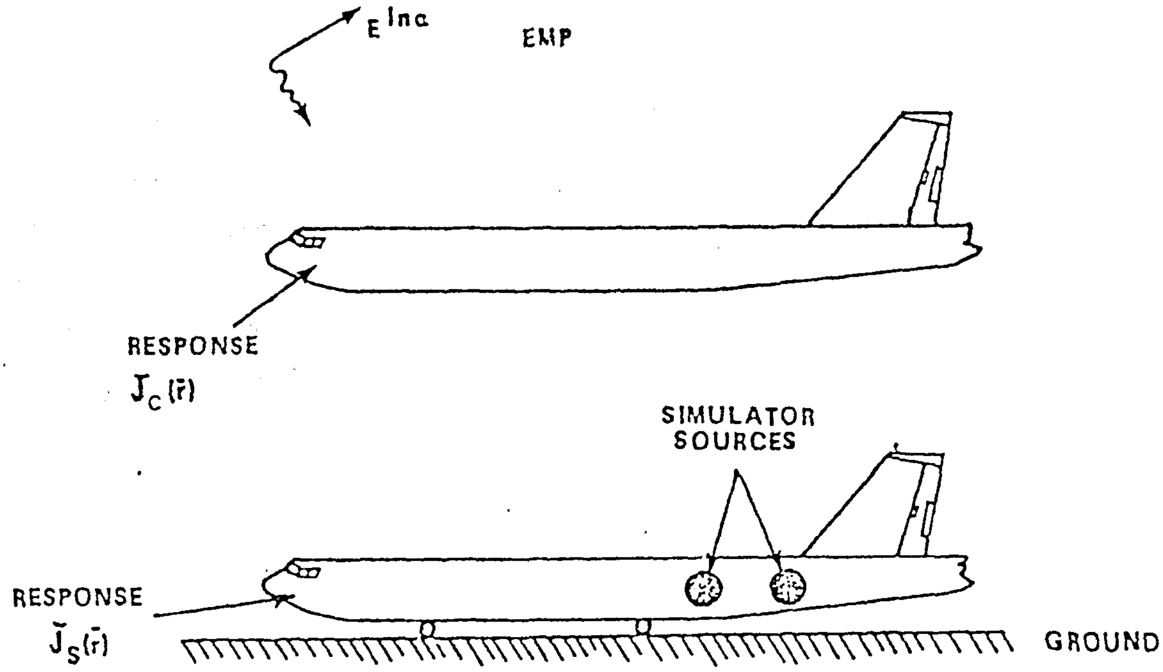

Figure 13. The criterion response $J_c(\bar{r})$ must be related to the simulated response $J_s(\bar{r})$ through an extrapolation procedure.

$$\| (R_n) \| \leq \| (T_{n,m}) \| \; \| E_m^{inc} \| \tag{15}$$

where the $\| \;\; \|$ symbol represents a norm of the vector or matrix in Eq. (14). At the present time, this concept has not been developed fully and applied to the present HAMS design.

A final potential use for the HAMS data is for fault isolation, once the system has degraded. This would entail making measurements with all n HAMS sources, one at a time, and then performing on-board or off-board data processing to obtain knowledge of the fault location. As in the last case, there remains a considerable amount of work to be done to design and implement this concept.

VI. SUMMARY AND CONCLUSIONS

This note has attempted to describe a number of the important considerations for the design of a hardness assurance maintenance system. Due to the rather short duration of this study, only a limited number of features of the HAMS have been considered. Of prime concern has been the inherent error involved in performing the simulation, and methods of estimating this error. Future calculations should be oriented towards the specific aircraft on which the HAMS is to be implemented, so as to obtain a better idea of the estimated errors.

One important theoretical aspect of the HAMS is the design of the interior sources and sensors. Many of the same theoretical questions can be posed for the interior sources, so as to minimize the simulation error and optimize the information content in the measured data. Future design studies for HAMS should undoubtedly include these features.

References

1. "B-52 survivability as a standoff cruise missile carrier,' Report prepared by Computer Science Corporation, 15 Jan. 1980.

2. Baum, C.E., "The PARTES concept in EMP simulation," Sensor and Simulation Notes, Note 260, Dec. 9, 1979.

3. Taylor, C.D., "External interaction of the nuclear EMP with aircraft and missiles," IEEE Trans. EMC, Vol. EMC-20, No. 1, Feb. 1978.

4. Sancer, M.I., et al., "Formulation of EMP external interaction above a lossy earth/comparison of numerical results with experimental data for the special cases of free fluid interaction and interaction above a perfectly conducting ground," AFWL-TR-78-1-73, Air Force Weapons Laboratory, Kirtland AFB, NM.

5. Harrington, R.F., Field Computation by Moment Methods, reprinted by the author, 1978.

6. Baum, C.E., "Some types of small EMP simulators," Misc. Simulator Memos, Memo 9, Dec. 22, 1976.

7. Tesche, F.M., "On the analysis of scattering and antenna problems using the singularity expansion technique," IEEE Trans. A.P., Jan. 1973.

8. Taylor, C.D., et al., "Singularity expansion method applied to perpendicular crossed wires over a perfectly conducting ground plane," Sensor & Simulation Notes, Note 258, June 1979.

9. Baum, C.E., "Some characteristics of electric and magnetic dipole antennas for radiating transient pulses," Sensor and Simulation Notes, Note 125, Jan. 1971.

10. Baum, C.E., "Extrapolation techniques for interpreting the results of tests in EMP simulators in terms of EMP criteria," Sensor and Simulation Notes, Note 222, Air Force Weapons Laboratory, March 1977.

11. Baum, C.E., "Norms and eigenvector norms," Mathematics Note 63, Nov. 1979.