Sensor and Simulation Notes
Note 232

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Characterization of Errors in the Extrapolation of Data from an EMP Simulator to an EMP Criterion

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Abstract

In this note the extrapolation techniques previously described in Sensor and Simulation Note 222 are applied to exterior response measurements on the F-111 aircraft shape. The extrapolation functions and error estimates are examined and conclusions are drawn about the uncertainties in the extrapolation process caused by measurement noise, bandwidth limitations and angle of incidence effects.

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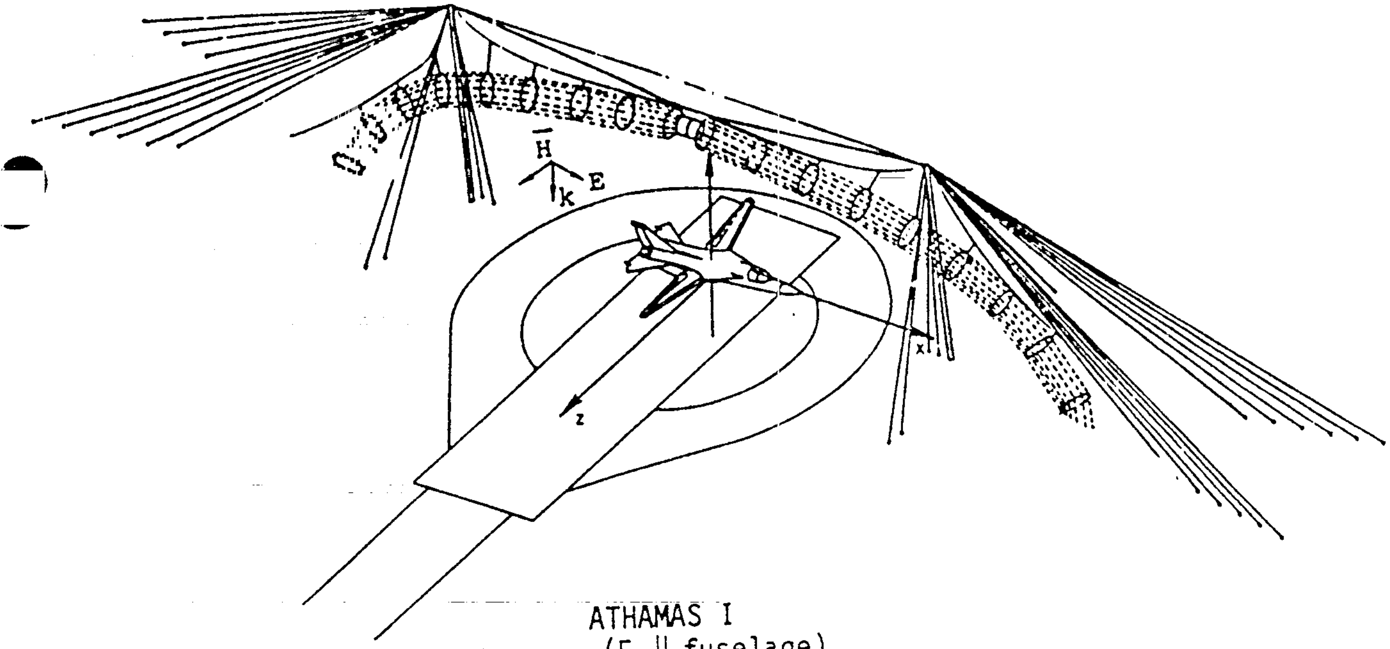
I. INTRODUCTION

The basic goal of an aircraft EMP response assessment is to determine how the aircraft would respond in an EMP threat criterion environment. Because testing in EMP simulators provides an inadequate simulation of the threat we must do the assessment in three steps: first, transient voltages and currents at interesting test points within the aircraft are measured in the simulator environment; second, these data are "extrapolated up" to the criterion environment mathematically; and finally, the susceptibility of the electronic circuits to these extrapolated voltages and currents is determined.

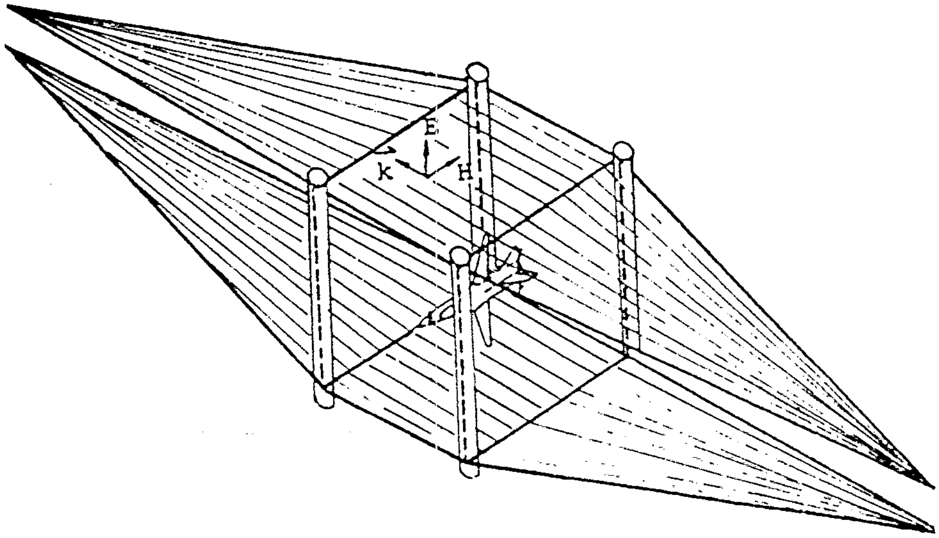
Ultimately our confidence in the EMP survivability of the aircraft is grounded in both the hardness margin demonstrated by the assessment program and the errors in that hardness margin. Some sources of error in the hardness margin are: 1) inadequate bandwidth of the response measurements caused by simulator or measurement limitations; 2) errors in extrapolating response data measured in a simulator to a criterion environment; 3) errors in determining the susceptibility of equipment to EMP transients; 4) errors in combining equipment response thresholds measured with one driven cable to obtain the threshold when all cables are simultaneously driven; 5) errors due to testing only one aircraft of the fleet in one short time interval.

In this note, examples of extrapolation error are provided following the format provided earlier in Sensor and Simulation Note 222 (ref. 1).

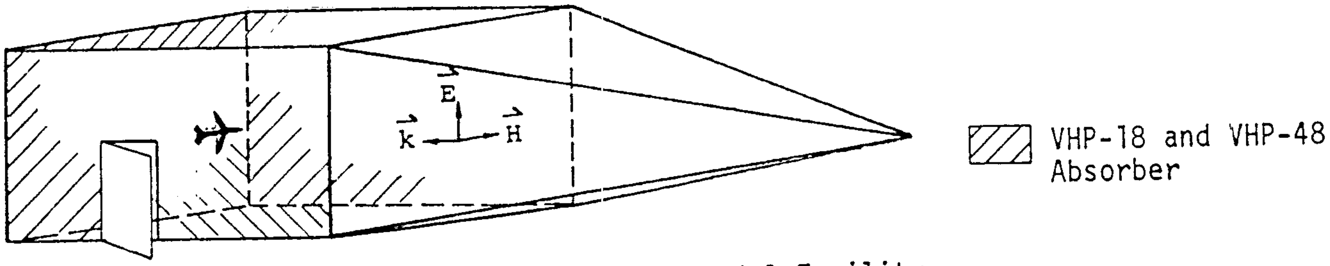
The principal sources of the measured data are surface current and charge density measurements made on the F-111 aircraft shape in the ATHAMAS I simulator (figure 1) (ref. 2) and a similar set of measurements made on scale models at the University of Michigan (ref. 3) in their surface



ATHAMAS I
(E || fuselage)



ARES
(E ⊥ fuselage)



University of Michigan Scale Model Facility
(E ⊥ fuselage)

Figure 1. The Three Simulation Facilities Used to Obtain F-111 Surface Response Measurements

field measurement facility. A secondary source of measured data was the ARES illumination of the F-111 shape (ref. 4). This source is considered secondary in that the data available are not of the same quality as that obtained in the other two facilities.

II. DATA SUMMARY

One of the principal outputs of the measurements made at the ATHAMAS facility in 1976 was an extensive data base of surface current and charge measurements on the F-111 aircraft shape.

There were sixteen locations on the aircraft skin where surface current and charge density measurements were made (figure 2). Although not all the measurements were made for every configuration of the aircraft in every simulator, there does exist a sufficient data base for the computations desired.

With the available data it is possible to calculate both an "incident field" extrapolation function (type 3A):

$$\tilde{f}_e^{(A)}(s) = \frac{\tilde{\hat{E}}^{(C)}_{inc}(r_o,s)\cdot\hat{1}_o}{\tilde{\hat{E}}^{(S)}_{inc}(r_o,s)\cdot\hat{1}_o} \qquad \left(\begin{matrix}\text{INCIDENT FIELD}\\ \text{EXTRAPOLATION}\\ \text{FUNCTION}\end{matrix}\right) \tag{1}$$

and a "surface response" extrapolation function (type 3B) which in its simplest form is

$$\tilde{f}_e^{(B)}(s) = \left\{\prod_{i=1}^{N} \frac{F_{si}^{(C)}(s)}{F_{si}^{(S)}(s)}\right\}^{1/N} \qquad \left(\begin{matrix}\text{SURFACE RESPONSE}\\ \text{EXTRAPOLATION}\\ \text{FUNCTION}\end{matrix}\right) \tag{2}$$

Here $\tilde{\vec{E}}_{inc}(r_o,s)$ is the principal electric field component of the exciting field at the center of the aircraft in the Laplace transform domain. $F_{si}(s)$ is a surface response measurement (J_{s_a}, J_{s_c}, ρ_s) at the i^{th} sensor location (among N total locations). The superscript C or S refers to a measurement made or expected in the criterion or simulator environment.

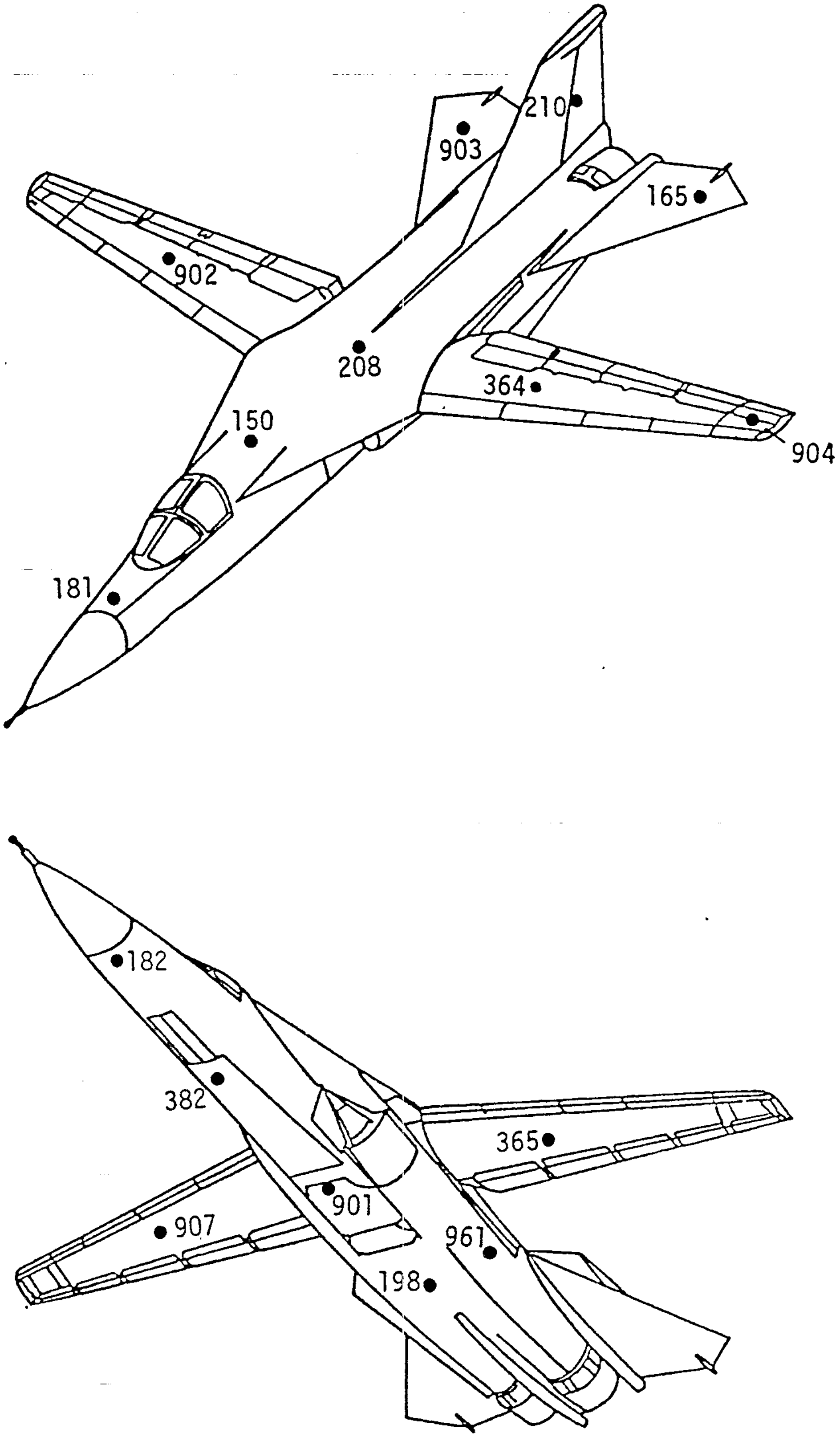


Figure 2. F-111 Test Locations Used to Measure Surface Responses for Extrapolation

Note that the interior responses can be "extrapolated up" by simple multiplication

$$I_{cable}^{(C)}(s) = \tilde{f}_e^{(A \text{ or } B)}(s) \times I_{cable}^{(S)}(s) \quad . \qquad (3)$$

The "surface response extrapolation" procedure requires the measurement of criterion relatable surface response measurements with a scale model. However, it overcomes the principal shortcoming of the incident field extrapolation, which is the ambiguous choice of E^{inc} or H^{inc} as the incident field reference.

An estimate of the error made in either extrapolation process is obtained by comparing the individual criterion responses to the extrapolated quantity

$$\tilde{R}_{s\ell}(s) = \tilde{f}_e(s) \frac{F_{s\ell}^{(S)}(s)}{F_{s\ell}^{(C)}(s)} \qquad \ell \in [1,N] \quad . \qquad (4)$$

The incident field (A) or surface response extrapolation (B), when accompanied by an error estimate, is called the type 3C extrapolation process.

Although conceivably 39 to 48 measurements could be input to the computation, usually only one-third of the measurements were used. This occurred either because the data sets were both incomplete and dissimilar or, because the data were bad.* At best, 18 measurements were used and in the worst case only four measurements were used.

a. Incident Field Extrapolation Function

Figure 3 shows the magnitude of the "incident field extrapolation functions", which extrapolates measurements made in ATHAMAS I to measurements made in ARES.

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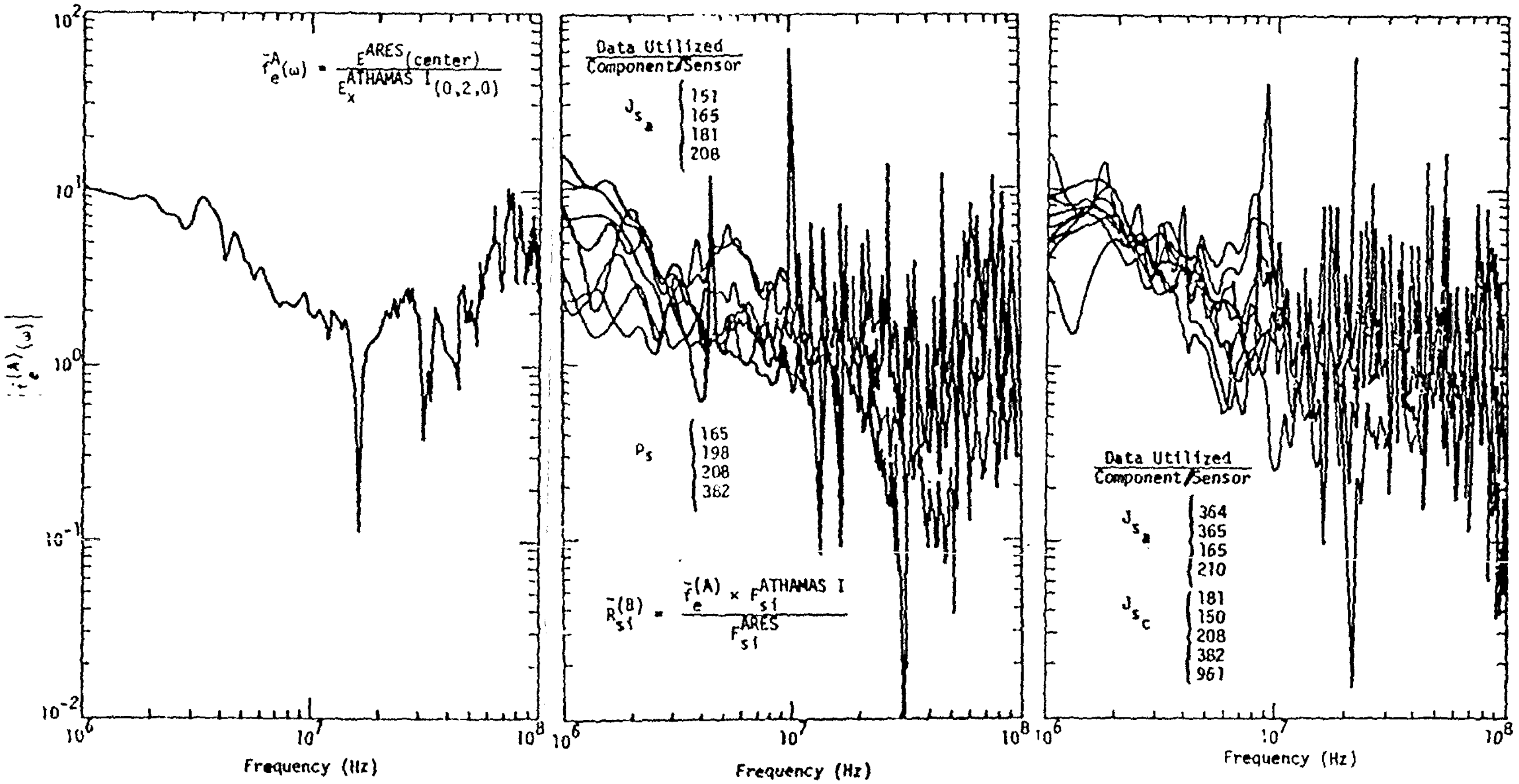
*For example, some pictures were mislabeled, and some charge density measurements made at ARES were evidently erroneous, perhaps caused by sensor grounding. (Procedures have been improved since 1974.)



Amplitude of the Incident Field Extrapolation Function (Type 3A)

Overlay of $|\tilde{R}^{(A)}_{s_{\ell'}}(\omega)|$ for Symmetric Excitation ($\vec{E} \parallel$ Fuselage).

Overlay of $|\tilde{R}^{(A)}_{s_{\ell'}}(\omega)|$ for Antisymmetric Excitation ($\vec{E} \perp$ Fuselage).

Figure 3. Incident field extrapolation function with error estimates for the extrapolation of ATHAMAS I simulator data to ARES data (as the criterion field).

As expected the extrapolation function shows that the ATHAMAS I field has lower spectral content than ARES on both the high and the low end of the spectra. In the midband it differs by a factor of 2 which is about the same as the difference in the peak amplitudes of the time domain waveforms.

Also provided in figure 3 are the "extrapolation error functions" for both the principal aircraft orientations. It is interesting to note that

1) the incident field extrapolation function "over-extrapolates" the midband data - that is, the average response near resonance observed on the aircraft in ARES was a factor of 2 less than you would have predicted by extrapolating ATHAMAS I data;

2) the spread in data among the sensors in the midband range (2 to 17 MHz is about 5 (as discussed later this is an expected result). Above the "ARES notch" at 17 MHz there are other deep nulls in the ARES environment that cannot be easily recorded by normal instrumentation. The complexity of the spectral description, coupled with data processing errors in the manually digitized ARES data, is probably the reason for the wide departures of the extrapolation error functions.

B. Surface Response Extrapolation

One way to overcome the type 3A over-extrapolation problem is to use the exterior response of the body itself as in the surface response extrapolation process. For this process we need a set of criterion relatable exterior response measurements. The University of Michigan data fill this need.

At the University of Michigan scale model facility the response is normalized to a constant one volt per meter field intensity. To directly compare the data to simulator responses the data are multiplied by the Laplace transform of the EMP criterion pulse, here taken to be

$$\mathrm{EMP}(t) = 5.4\times10^4[\exp(-4\times10^6 * t) - \exp(-4.76\times10^8 t)]U(t). \qquad (5)$$

The surface response extrapolation function is then computed from

$$f_e^{(B)}(j\omega) = \left(\prod_{i=1}^{N} \frac{\mathrm{EMP}(j\omega) * F_{si}^{UM}(j\omega)}{F_{si}^{\mathrm{simulator}}(j\omega)} \right)^{1/N} \qquad (6)$$

and the extrapolation error function is

$$R_{si}^{(B)}(j\omega) = \left(\frac{f_e^{(B)}(j\omega) * F_{si}^{\text{simulator}}(j\omega)}{\text{EMP}\ (j\omega) * F_{si}^{UM}(j\omega)} \right) \qquad i \in [1,N] \qquad . \qquad (7)$$

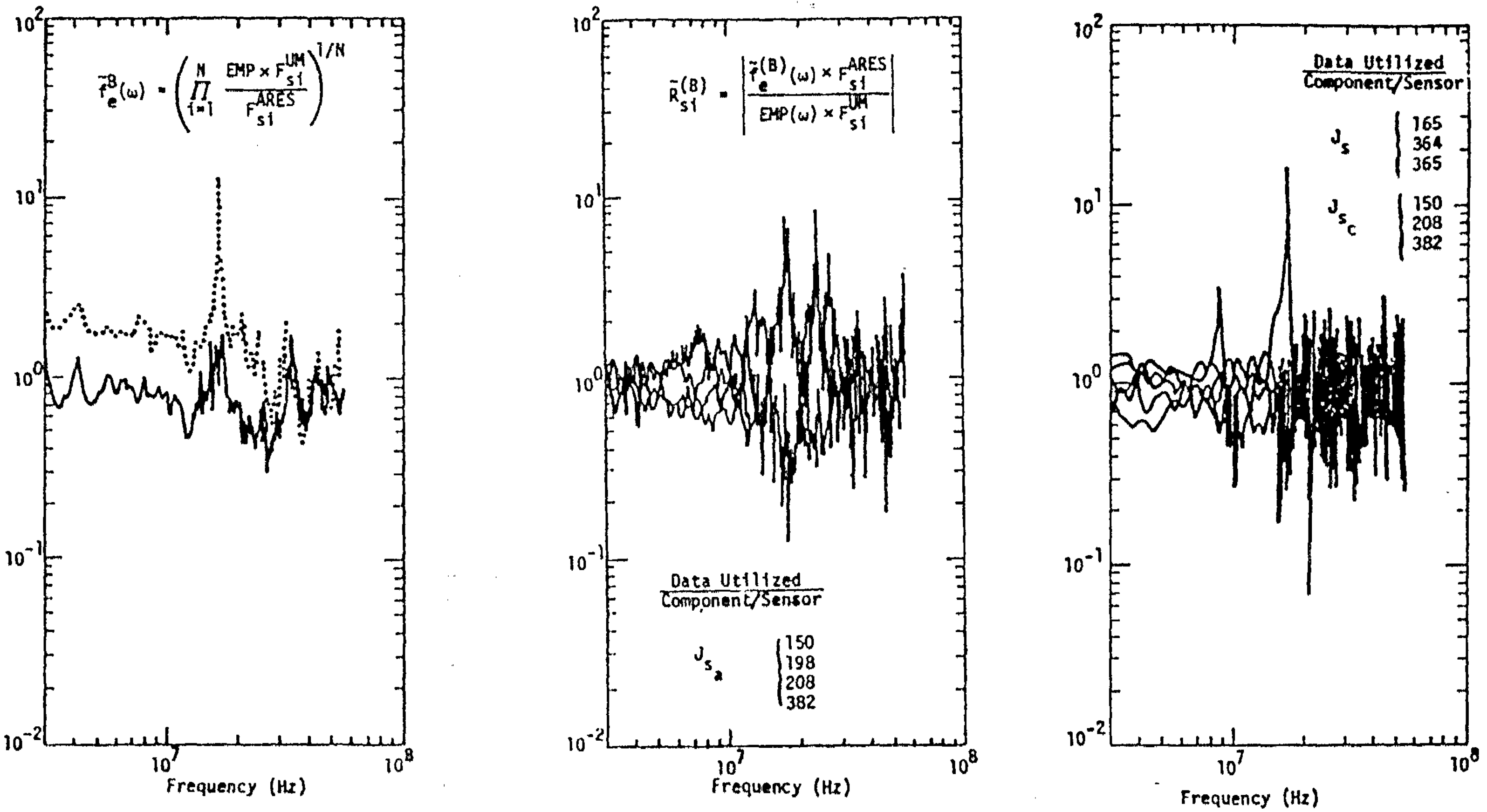
The ARES measurements should also be threat relatable since the field in ARES is a plane wave field and the measurements are made with the aircraft supported in a vertical plane, where imaging effects are small. Figure 4 shows the surface response extrapolation process applied to extrapolate the ARES simulator data to the University of Michigan data as the criterion. Here the extrapolation function is nearly one across the band and the distribution of errors in the response is probably related to more noisy measurements in ARES than to any basic difference in the response function.

Figure 5 shows the result of extrapolating ATHAMAS I simulator data to the University of Michigan data. This calculation is done with the best available data, hence the data are expected to be usable from 3 to 50 MHz. The reader will note the similarity of these data and that of figure 6 where the ATHAMAS I data are extrapolated to the ARES data. Over the frequency range where comparison is possible (3 to 17 MHz), there is little difference in the extrapolation functions and essentially no difference in the spread of the extrapolated response data. The variation is about a factor of 5 in both cases, which is the spread caused by the ATHAMAS I ground bounce fields illuminating the aircraft.

III. MEASUREMENT NOISE SOURCES IN THE DATA

A. Effect of Noise on Error Estimates

At first it would seem that the envelope of the extrapolation error function overlays shown in figures 3 through 6 would represent the composite error due to instrumentation problems and data handling problems as well as incomplete simulation. While it is true that all the errors are represented, a simple example reveals that the errors in the extrapolation function could be underestimated by the extrapolation error function so that the (3C) process is neither a "worst case" or a "best case" error estimator.

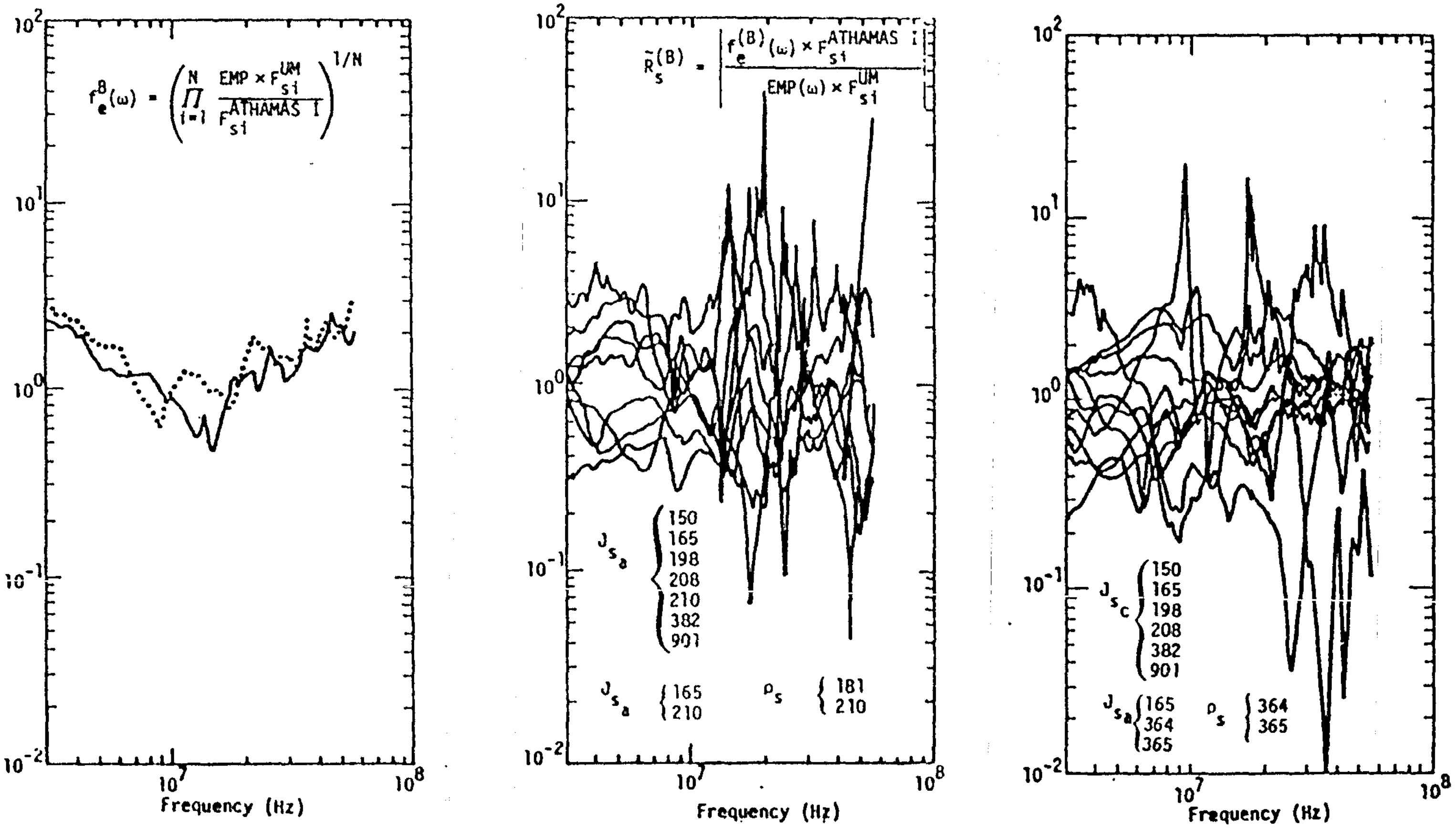


UM/ARES Type 3B Extrapolation Function Amplitudes, $\vec{E} \parallel$ Fuselage (——), $\vec{E} \perp$ Fuselage (...).

Overlay of $\left|\tilde{R}^{(B)}_{s_{\ell}}(\omega)\right|$ for Symmetric Excitation ($\vec{E} \parallel$ Fuselage).

Overlay of $\left|\tilde{R}^{(B)}_{s_{\ell}}(\omega)\right|$ for Antisymmetric Excitation ($\vec{E} \perp$ Fuselage).

Figure 4. "Surface response extrapolation" function with error estimates for extrapolating ARES simulator data to the University of Michigan scale model data (as the criterion response).

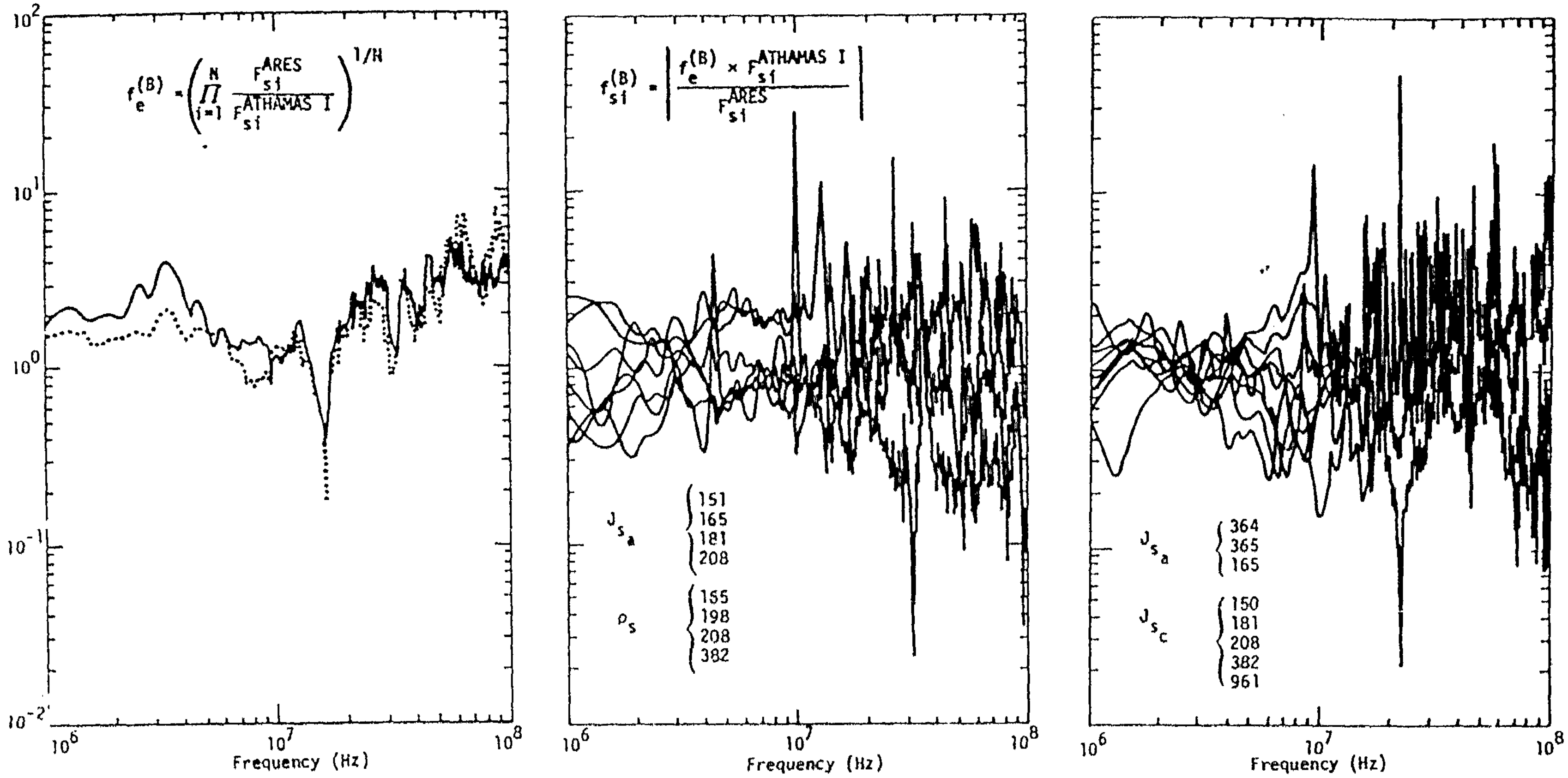


UM/ATHAMAS I Type 3B Extrapolation Function Amplitudes, $\vec{E} \parallel$ Fuselage (——), $\vec{E} \perp$ Fuselage (...).

Overlay of $\left|\tilde{R}_{s_{\ell'}}^{(B)}(\omega)\right|$ for Symmetric Excitation ($\vec{E} \parallel$ Fuselage).

Overlay of $\left|R_{s_{\ell'}}^{(B)}(\omega)\right|$ for Antisymmetric Excitation ($\vec{E} \perp$ Fuselage).

Figure 5. "Surface response extrapolation" function with error estimates for extrapolating ATHAMAS I simulator data to University of Michigan scale model data (as the criterion response).



ARES/ATHAMAS I Type 3B Extrapolation Function Amplitudes, $\vec{E} \parallel$ Fuselage (——), $\vec{E} \perp$ Fuselage (...).

Overlay of $\left|\tilde{R}_{s_{\ell}}^{(B)}(\omega)\right|$ for Symmetric Excitation ($\vec{E} \parallel$ Fuselage).

Overlay of $\left|\tilde{R}_{s_{\ell}}^{(B)}(\omega)\right|$ for Antisymmetric Excitation ($\vec{E} \perp$ Fuselage).

Figure 6. "Surface response extrapolation" function with error estimates for extrapolating ATHAMAS I simulator data to ARES data (as the criterion response).

Consider a given criterion surface response, say an axial current density, with a constant value in the frequency domain of 10^3 amp/sec/meter up to 50 MHz, and falling off rapidly to zero above 50 MHz. Consider also a corresponding simulation response of a constant 10^2 amp-sec/meter up to 100 MHz, falling off rapidly to zero above this frequency. Assume also that measurements of these responses have a noise background on the criterion response measurement of 10 amp-sec/meter, and on the simulator response measurement of 1 amp-sec/meter. Plots of these two responses are illustrated in figure 7. Now consider the ratio of the criterion to the simulation response measurements, shown in figure 8. Below 50 MHz this has a constant value of 10, between 50 MHz and 100 MHz a value of 0.1, and a value of 10 above 100 MHz. Knowing what the "true" responses are like we can state that their ratio is actually 10 up to 50 MHz. However, between 50 MHz and 100 MHz, the "true" ratio value is zero, so that when the criterion measurement has dropped in the noise, the ratio obtained from measured data is only an upper bound. Above 100 MHz the "true" ratio is indeterminate, so that when both measurements have dropped into the noise, the ratio obtained from measured data is not a good upper or lower bound.

This example illustrates the need for interpretation of extrapolation functions using a knowledge of the measurement and processing errors in the constituent signals. Reasonable looking extrapolation functions can be created from the ratios of pure noise.

B. What is the Noise in the Data Used Here?

The F-111 surface response measurements made at the ATHAMAS I facility were carefully monitored to assure that the measurements were of high quality. Additionally, studies of the residual error in these measurements were made. Because the Tektronix 7912 transient digitizers were used here, the principal source of error is the dynamic range limitation on the microwave telemetry system. The error is expected to be 10% over the bandwidth from 2 to 50 MHz (ref. 5).

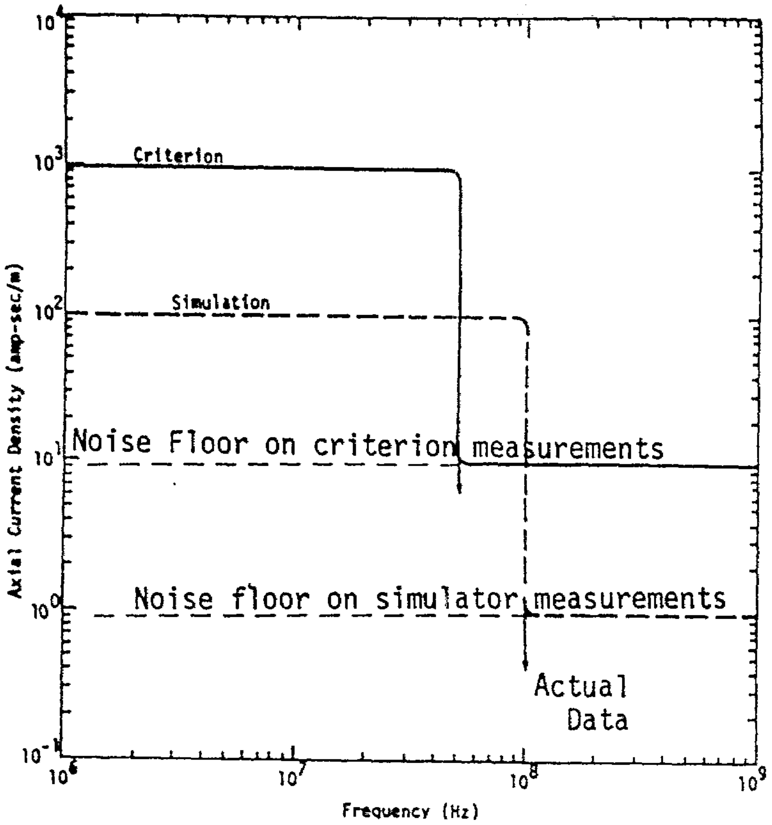


Figure 7. Idealized Criterion and Simulation Responses with Noise

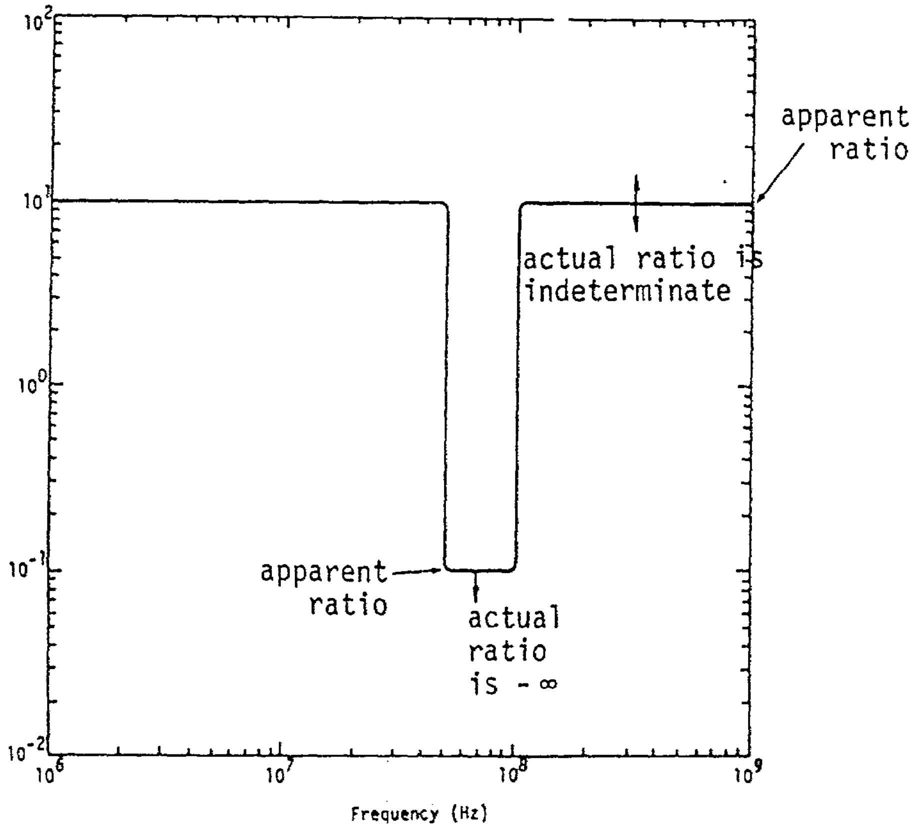


Figure 8. Ratio of Idealized Criterion and Simulation Responses with Noise Included

The ARES data were recorded by oscilloscope cameras and manually digitized without the benefit of stringent quality control procedures. Accordingly much of the data observed faithfully records the peak and the general features of the data but it suffers from base line shift and truncation errors often as much as 10% to 15% of peak. Further the manual digitization is apparent in most of the data which adds further noise. Our estimate of data quality is that the dynamic range of the data is only 10:1 and that 50% to 100% error might be present in a usable bandwidth of 1 to 30 MHz.

The University of Michigan data are frequency domain measurements taken in a laboratory environment and consequently one would expect better accuracy in the data than available at the EMP facility. However, some problems like sensor placement and sensor lead coupling are aggravated in scale model testing. Figure 9 shows measurements made at the University of Michigan (after extrapolation up to threat). Here one component of the surface current density should have been zero. A measurement of this nonexistent component shows a dynamic range limitation of about 20:1 near resonance and less elsewhere. The reader will also note that this is not totally alignment error (in which the response function of the small component is just a constant fraction of the response function of the principal component).

In summary we have concluded that excrusions of more than a factor of 10 in the error estimating ratio are probably due to poor dynamic range of the response measurements. Further re-examination of the error estimating ratios in figures 3 through 6 will reveal that the errors evidently are maximised in the 10 to 20 MHz range and then *diminish* above that. We now conclude that the apparent reduction is probably due to dynamic range limitations on both measurements.

IV. ANGLE OF INCIDENCE EFFECTS

As noted earlier the extrapolation of the ATHAMAS I data to either the ARES data or the University of Michigan data (figs. 5 and 6) shows a spread in the error estimating ratios of about a factor or 5.

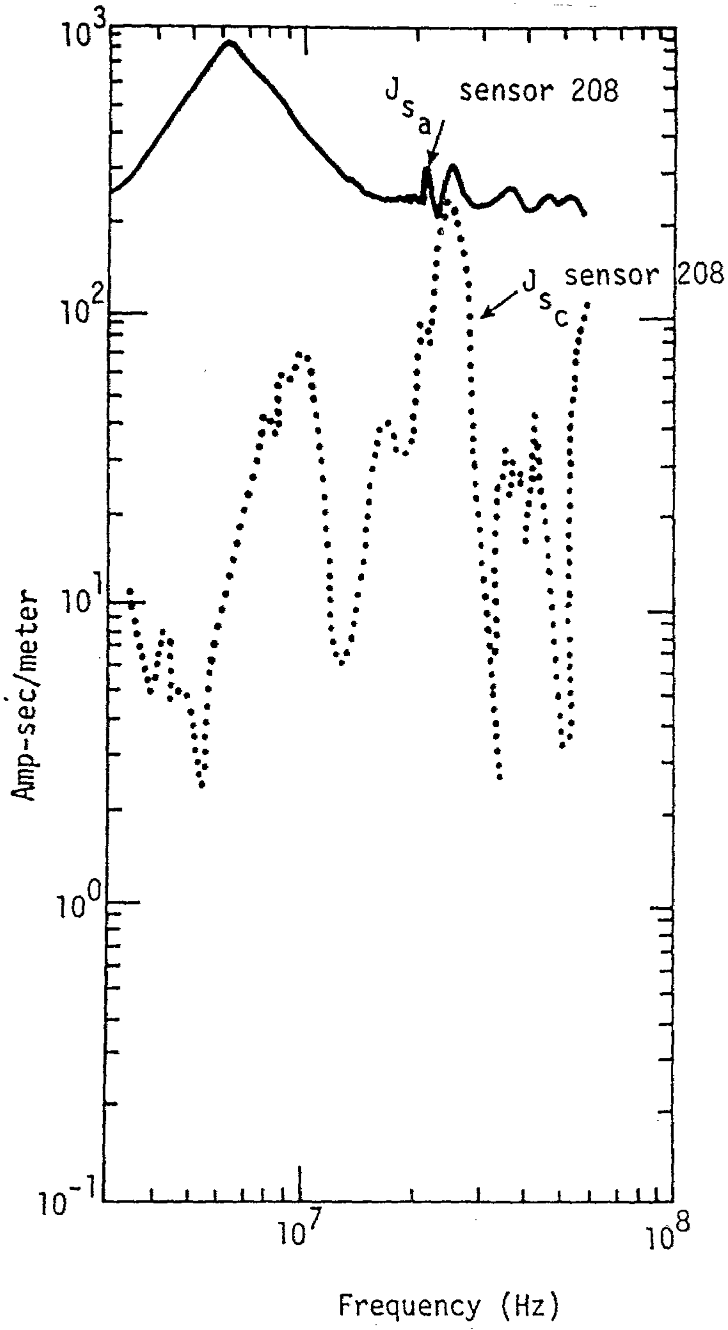


Figure 9. Measurements of principal surface current density components and "zero" current density component (as required by aircraft symmetry) in the University of Michigan facility, E || fuselage.

Using analytical data for infinite cylinders and numerical data for finite cylinders, Lee was able to show that this difference is to be expected (ref. 6). Figure 10 shows the numerically desired ratio R_s for four sensors located at the center of a 10-meter long pipe where the comparison now assumes that the field incident on the pipe in free space and that which illuminates the pipe one meter above the ground plane are identical, so that the difference is just the ground reflected source field and the pipe image.

Lee also examined the simpler problem of just how well illuminating an object with one angle of incidence represents illuminating it at any angle of incidence. Again taking the pipe as a model and using numerical data provided by Sancer (ref. 7) and by Holland (ref. 8), he showed that the difference is at least as severe as that observed in extrapolating ATHAMAS I data to a plane wave field (figure 11).

The result of Lee's work casts a different light on the data before us. We now see that

1) selecting a criterion pulse incident at one angle of incidence can cause errors of 2 to 10 in the surface responses that would have been observed with *any* angle of incidence;

2) even if the concrete pad were transparent and the pulser were perfect, testing an aircraft by exposure to one angle of incidence would not be a high quality test program.

V. CONCLUSIONS

Since the over-extrapolation of "incident field extrapolation" is only a factor of 2 around first resonance in a test program where angle of incidence effects are factors of 2 to 10, it appears that significant improvements in test quality for this frequency range are not obtained by just changing the extrapolation function from type 3A to type 3B. Far better improvement can be made by using penetration extrapolation (type 4 extrapolation) in which the excitation of individual penetrations is extrapolated separately. With this procedure, angle of incidence effects can be studied

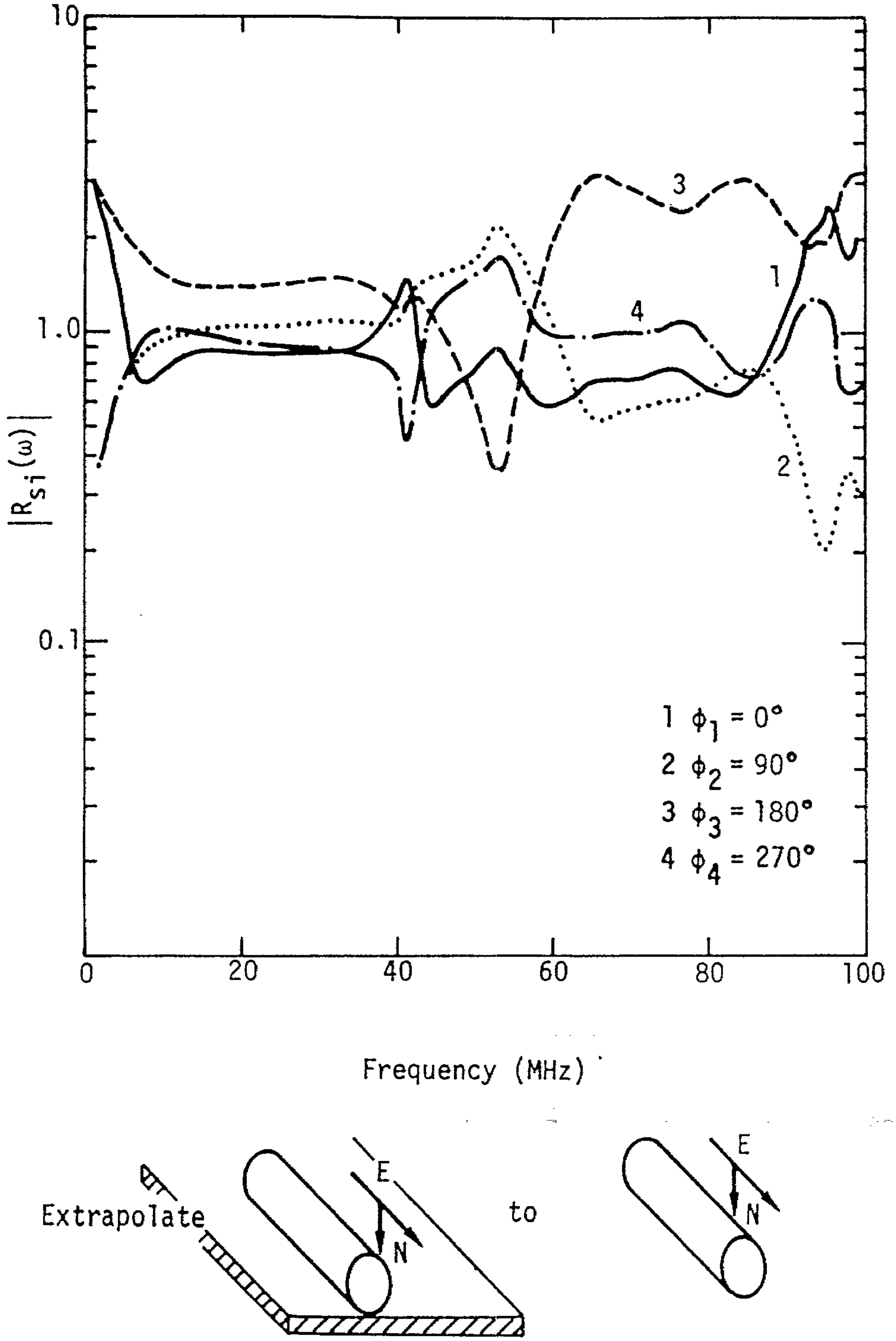


Figure 10. The predicted error estimating ratios $|R_{si}(\omega)|$ for extrapolating exterior response data expected on a cylinder above a ground plane to data expected on a cylinder in free space. Total length = 10 meters, radius 0.5 meter, height of cylinder axis 1 meter, ϕ is measured from the bottom of the cylinder.

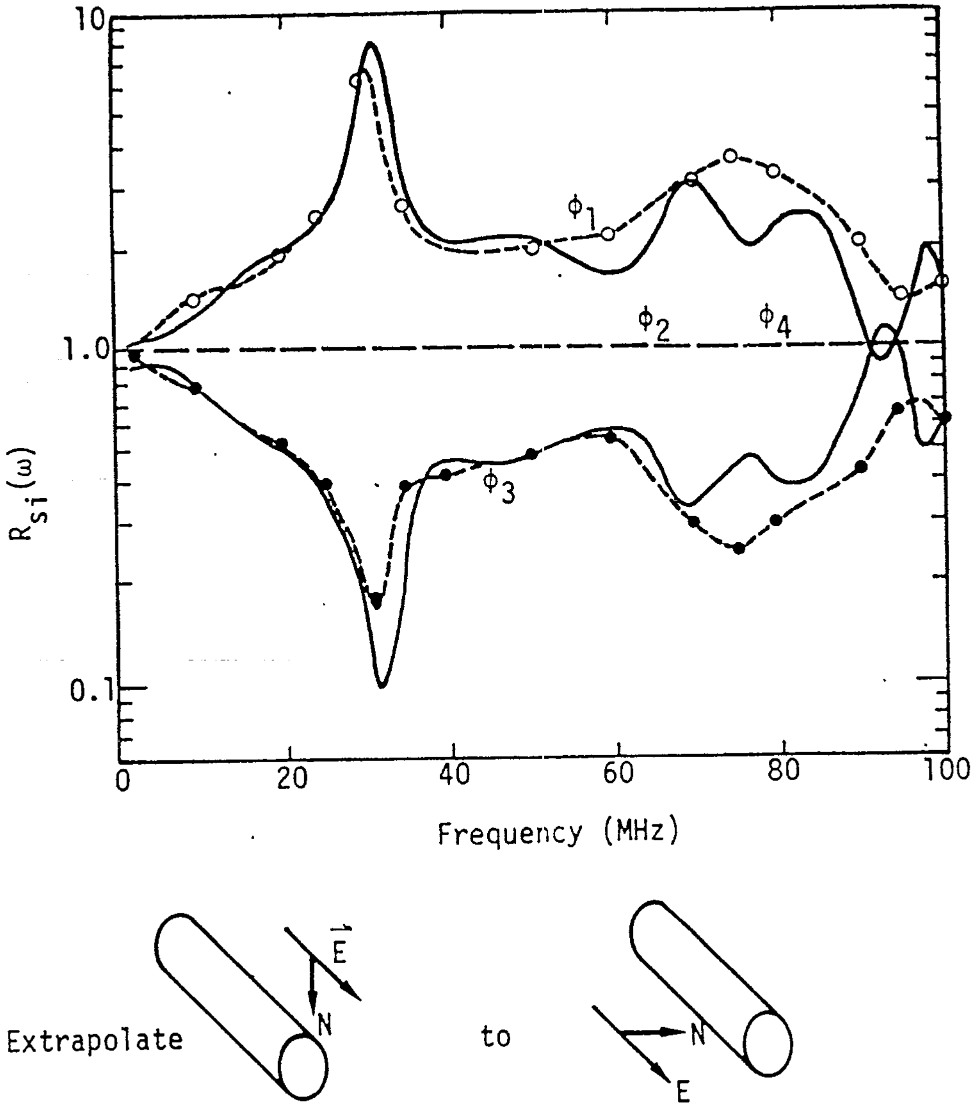


Figure 11. The ratio $|R_{si}(\omega)|$ for extrapolating the exterior responses on an end-capped cylinder in free space from one angle of incident wave to another with incident angle different by 90°.

——— calculated using 3-D code

--o--
--●-- calculated using Sancer's code

with ϕ_1 = 0°, ϕ_2 = 90°, ϕ_3 = 180°, ϕ_4 = 270°

Length = 10 meters, diameter = 1 meter

in both the system level test program and the model illumination program. The overall accuracy of the test program can then be 20% to 30% over the frequency range where the driving fields have sufficient spectral content.

We have noted that the use of the error estimating ratios of the 3C extrapolation process can help the analyst understand the size and causes of the uncertainties in this process. However, the interpretation of these ratios cannot be done blindly, since they produce valid error estimates only when valid data are used in the calculation.

In any event these ratios do show that there are errors present to various degrees in real EMP simulation programs.

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