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THE UNIVERSITY OF MICHIGAN

COLLEGE OF ENGINEERING

DEPARTMENT OF ELECTRICAL ENGINEERING

Radiation Laboratory

INVESTIGATION OF RE-ENTRY VEHICLE SURFACE FIELDS

QUARTERLY REPORT NO. 1

18 December 1965 - 18 March 1966

by
R. F. Goodrich, B. A. Harrison and E. F. Knott

1 April 1966

Contract AF 04(694)-834
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Ballistic Systems Division, USAF, AFSC

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ABSTRACT

This is the First Quarterly Report on Contract AF 04(694)-834 and covers the period 18 December 1965 to 18 March 1966. Work is discussed on the SURF program which has as its objective the determination of the radar cross section of cone-sphere shaped re-entry vehicles by means of a study of the fields induced on the surface of the vehicle models. In previous studies, the bare metallic body was investigated. In this quarter, work was begun on a determination of the effect of coating the re-entry shape with radar absorbing materials, the effects of perturbations due to flush mounted antennas and rocket nozzles and the effect of the plasma sheath on the radar cross section. **Considerable effort was** directed at developing probes to measure the tangential and normal electric field. The theoretical effort is being shaped by the limited results obtained so far.

I

INTRODUCTION

This is the First Quarterly Report on Contract AF04(694)-834 'Investigation of Re-entry Vehicle Surface Fields (SURF)". It covers the period from 18 December 1965 to 18 March 1966. The objective of the SURF program is the determination of the radar backscattering properties of re-entry vehicles with shapes generally similar to the cone sphere. The approach adopted in the investigation makes use of experimental measurements of the surface fields induced on various scale models of re-entry bodies and related shapes to aid in the construction of a theory to explain radar scattering behavior and in the formulation of mathematical expressions for the computation of radar cross section. In addition to the surface field measurements, backscatter measurements are relied on to furnish substantiation of the theory being developed or to guide the investigation in areas where surface field measurements alone do not provide adequate data. A digital computer program is being developed to study cases of oblique incidence on the target.

The basic metallic cone-sphere with tip and termination modifications was studied during the first year of this program. The results are summarized in the Final Report under AF 04(694)-683 "Radar Cross Section of the Metallic Cone-Sphere" (Report 7030-5-T). In this year, it is planned to complete the work on the 'clean' cone-sphere and study the effect of absorber coatings, rocket nozzles and flush-mounted antennas on the radar cross section.

During the earlier investigation of uncoated bodies, small probes were developed to measure the magnetic fields on the metallic models. An immediate goal for the study of coated bodies is the development of probes which can be used to measure the electric field on absorber clad models. This was studied during the first quarter and is proving to be a difficult task. To compensate for the experimental difficulties, attention is being given to adapting the computer program to provide data on coated objects as well as metallic ones.

The theoretical work of this quarter will be discussed under the headings: 1) coated clean shapes, 2) continuing basic problem, 3) perturbed perfectly conducting shapes, and 4) the plasma sheath.

None of this work has reached the point where any definitive results have been obtained. For this reason, we will describe the problems now under study with such preliminary results as have been obtained.

The experimental work of this past quarter is reported in Section VI.

II

COATED SHAPES

In the study of coated shapes we start with coatings which lead to an impedance boundary condition. We hope to parallel the work of the first year on perfectly conducting shapes in that we develop methods of predicting creeping waves, creeping wave enhancement, geometric reflection, and the extension to the resonance region for surface fields on impedance boundaries. Our initial plan was to use surface field experimental measurements to assist in formulating the theoretical description of these phenomena as well as to check the theoretical predictions. However, due to the experimental difficulty of measuring the tangential electric fields (see Section VI) in the directly illuminated region we need to rely more on theoretical analysis, back scattering measurements and digital computer programming while experimental problems are being solved.

We have underway the preliminary analysis leading to the calculation of the surface fields on an impedance sphere. From these calculations compared with surface field measurements in the shadow region and far field measurements we will explore the accuracy of the creeping wave formalism on approaching the resonance region, $ka \sim 1$, where $k = 2\pi/\lambda$, λ is the wavelength and a is the sphere radius. This analysis will enable us to determine the range of validity of the application of the creeping wave formalism to the impedance cone-sphere.

The enhancement problem is considerably more difficult than in the perfectly conducting case. The difficulty arises in that neither the impedance cone nor impedance wedge solutions are easily obtained. We are now approaching the problem using a generalization of the method of Hong and Weston+ applied to the two-dimensional impedance surface consisting of a semi-infinite plane smoothly joined to a parabolic cylinder as shown in Fig. 1.

The experimental check on the enhancement for an impedance cone-sphere must come from comparing the shadow values of the creeping waves for the cone-sphere and the sphere, and from the back scattering comparison of the cone-sphere and sphere returns.

The surface fields on other than spherical terminations to the cone for an impedance boundary condition are predictable only asymptotically in frequency using the first order creeping wave formalism. The approach to resonance in this case awaits the resolution of the same problem in the perfectly conducting case (see Section III), however, the solution can be attempted numerically. The numerical solution of this problem is now being worked on.

+Hong, S. and V. H. Weston "A Modified Fock Function," The University of Michigan Radiation Laboratory Report 7030-2-T, November 1965, 22pp.

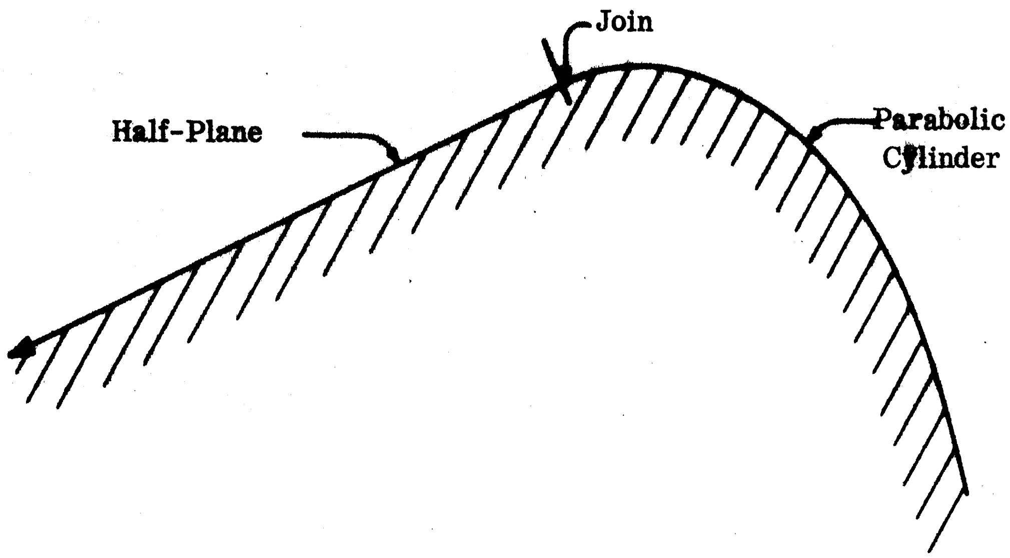

FIGURE 1: SURFACE REPRESENTATION

III

CONTINUING BASIC PROBLEMS

The problem of diffraction by re-entry shapes in the resonance region remains the central continuing basic problem. We are approaching this problem in two ways.

First, we are studying the higher order creeping wave terms from an analysis of the integral equations defining the surface field. Here we are attempting to bring out the dependence of the field on the change in curvature along the geodesic path of the creeping waves and the dependence on the curvature in the direction transverse to the creeping wave paths.

Second, we are using the diffraction by a prolate spheroid which is nearly spherical in order to determine the coupling between the various multipole terms of the incident wave and those of the diffracted wave. We hope to discover the form and magnitude of the coupling and relate it to the geometric properties of the spheroid and thence to more general shapes.

The integral equation analysis is underway but has not reached a point of any definitive results. The analysis turns about a local description of the surface in terms of the two curvatures and a **two-dimensional** stationary phase evaluation of the integral. Due to the difficulty of the analysis we can make no estimate as to the time of completion of this work.

The spheroid problem has just been started.

A third continuing problem is that of diffraction in the interior of a paraboloid. The work on the paraboloid itself was essentially completed in the first year. We will discuss the present work in Section IV.

IV

PERTURBED PERFECTLY CONDUCTING SHAPES

The two classes of problems we are studying in which the surface is perturbed from the clean re-entry shapes are the small perturbations such as slots on rocket nozzles and concavities in the rear. In the small perturbation case we believe the effect on the surface fields of the comparable clean shape will be small and that the slots, etc. can be treated independently. The confirmation of this awaits our experimental results; both scattering and surface field measurements. Until the experimental results are available we plan no theoretical analysis.

The analysis of the effect of concavities is proceeding from the paraboloid results of the first year. We have in hand a representation of the paraboloid solution which consists of a finite series of terms which we interpret as arising from geometric reflections and an infinite residue series which we are now in the process of interpreting. The residue series is very like the concave analog of creeping waves. We are now determining the phase origin of these terms so that we can interpret the physical origin of them for general concave surfaces in order to devise a 'geometric theory of diffraction' for concave surfaces.

V

THE PLASMA SHEATH

5.1 Background

The initial work done on the plasma sheath problem arose from a critical survey of the literature on this problem. On the basis of this we present the approach we are now taking.

Various attempts to predict the radar cross section of a re-entry vehicle surrounded by a plasma sheath are reported in the literature. Most of the theoretical work is based on a geometrical optics approach. This method gives a good solution as long as the conditions for its validity are met. These conditions are not met if the thickness of the plasma sheath is less than one-half the wavelength of the radar wave and/or if the plasma properties vary appreciably within a wavelength. Since, according to data provided by the Aerospace Corporation plasma sheaths exhibiting the above two properties of interest, another method for obtaining a solution is needed.

The objective of the present work is to provide both analytical and numerical solutions of canonical problems which will be applied to predict the radar cross section of cone-sphere-like bodies surrounded by a plasma sheath.

An initial theoretical model postulates arbitrarily polarized plane electromagnetic waves impinging on an inhomogeneous plasms slab backed by a perfectly conducting plane. This analysis will show how various properties of the plasma sheath, polarization of the incident wave and the incident angle affect the amplitude and phase of reflected waves.

Particularly, from this, the following information will be obtained.

a) The amount of energy penetrating the sheath, which will be important to determine when and if the properties of the material backing the sheath will be crucial, and

b) the total tangential electric and magnetic fields generated on the surface.

Thus, using an equivalent physical principle, the scattered field produced by a conical sheath may be obtained.

5.2 Physical Optics Approach

The method of physical optics is used to estimate the radar cross section. In this method one assumes that the induced surface field at a point in the illuminated region is the same as would be induced on an infinite plane occupying the position of the tangent plane, and that the surface field in the shadow region is identically zero. Thus, the scattered fields can be expressed in terms of the two reflection coefficients of the infinite tangent plane for vertical ($R_{\perp}$) and horizontal ($R_{\parallel}$) polarization. In particular, when the scattering body is

symmetric with respect to the propagation direction of the incident radar wave, the radar cross section is given in a simple form:

$$\sigma = \frac{4\pi^3}{\lambda^2} \left| \int_{\substack{\text{illuminated}\\ \text{region}}} \left[R_{//}(\rho) - R_{\perp}(\rho) \right] e^{i2kz(\rho)} \rho d\rho \right|^2 ,$$

where z is the axis of symmetry when the surface is conical, $z(\rho) = \rho \cot \alpha$, where $\rho = \sqrt{x^2 + y^2}$ and the angle α is the cone half-angle.

The reflection coefficient $R_{\perp}$ is found by first obtaining the solution of the following equation

$$\frac{d^2 u}{dx^2} + k^2 \left[\epsilon(x) - \sin^2 \theta \right] u = 0 \quad ,$$

subject to the boundary conditions

$$u + \frac{1}{ik \cos \theta} \frac{du}{dx} = 2 \qquad \text{at } x = 0$$

and

$$u = 0 \qquad \text{at } x = -h \ .$$

Here $\epsilon(x)$ is the effective dielectric constant of the plasma sheath, and h the local thickness of the plasma sheath and θ the angle of incidence. $R_{\perp}$ is then directly obtained from the following relation

$$R_{\perp} = u(x = 0) - 1 \ .$$

The reflection coefficient $R_{//}$ is found by first obtaining the solution of the equation

$$\frac{d^2 v}{dx^2} - \frac{1}{\epsilon} \frac{d\epsilon}{dx} \frac{dv}{dx} + k^2 \left[\epsilon(x) - \sin^2 \theta \right] v = 0$$

subject to the boundary conditions

$$v + \frac{1}{ik\epsilon \cos \theta} \frac{dv}{dx} = 2 \qquad \text{at } x = 0$$

and

$$\frac{dv}{dx} = 0 \qquad \text{at } x = -h.$$

It is then derived from the solution

$$R_{\perp} = v\ (x = 0) - 1.$$

In order to evaluate $R_{//}$ and $R_{\perp}$ for an arbitrary distribution of ϵ (x), an organization of the computer program is in progress.

VI

EXPERIMENTAL RESULTS

6.1 Coated Clean Shapes

Phase A

Our capability to measure phase is adequately developed to meet anticipated needs. To prove the capability, we have measured the phase of both the radial electric and tangential magnetic field around a sphere with an estimated accuracy of $\pm 10^{o}$ at S-band. We feel this is sufficiently accurate for any data analysis that will be undertaken.

Our capability to measure electric fields, however, is not as secure as this. Several electric field probes have been constructed and evaluated; some of these are shown in Fig. 2. In an attempt to prevent the currents induced on the outer conductor from interfering, baluns and chokes have been installed but without much success. Most of the probes behave well in the absence of an obstacle but when the obstacle (usually a sphere for these preliminary tests) is installed, most of the probes do not give the correct indication.

If one is content to measure radial electric fields near the surfaces of conducting objects, probes C and D can be used with some measure of success. We have found that the probes work best if the outer conductor contacts the surface being probed and if the inner conductor forming the pick-up arm is directed radially from the surface. In fact, to enhance the contact, probe D was constructed with a small metallic disk soldered to the outer conductor. Typical results obtained with probe D are shown in Fig. 3 for a sphere 2.0 λ in circumference. The agreement between theory and experiment is quite good and may be attributed to the fact that the electric field is entirely normal to the surface. We regard the data as a demonstration of our present capability to measure the radial electric field at the surface of a perfect conductor.

The problems attending the measurement of a radial field, now having been solved, we must address that of measuring E_θ, the tangential electric field. Measurement of this component is best performed by the use of the balanced dipole shown in Fig. 2. The probe has dual output leads and if the two arms of the dipole are colinear, the outputs are phased 180^{o} apart, with respect to the outer conductor. The two signals are added in a hybrid tee after one of them has been shifted in phase by the proper amount. The required phase shift demands that the probe be tuned for each frequency used, but once it has been adjusted it need not be balanced again unless the frequency is changed.

The first balanced probe was made of coaxial line 0.085" in dia., but the size of the line prevented the dipole arms from coming near enough the surface of the sphere. If they could, of course, there should ideally be no signal, for E_θ vanishes at the surface. Instead, a relatively large signal was being detected when the probe was nearest the surface. The large coaxial line was replaced with

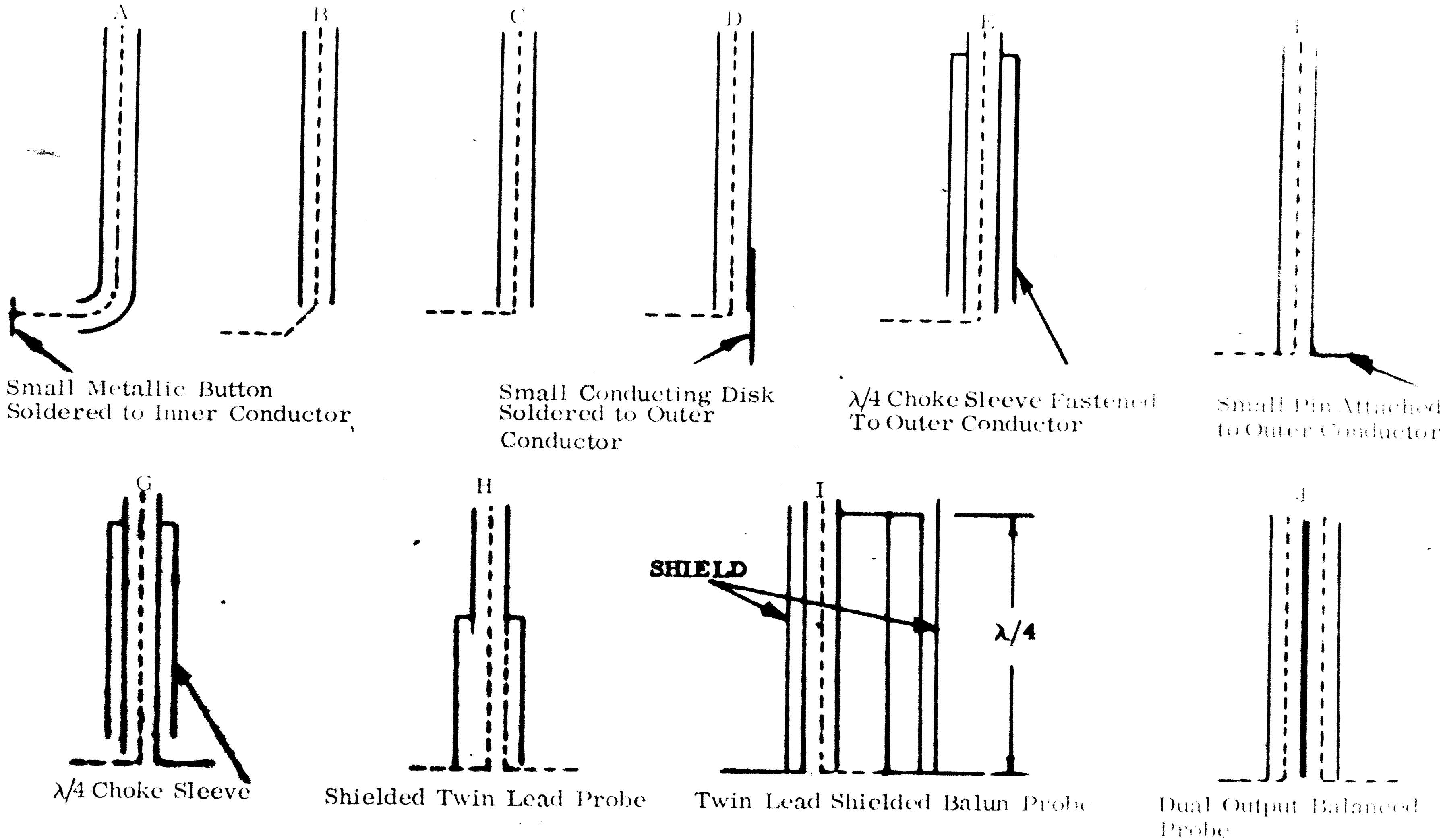

FIG. 2: SOME OF THE ELECTRIC PROBES WHICH HAVE BEEN CONSTRUCTED. (The First Five are Monopoles; the Last Five, Dipoles).

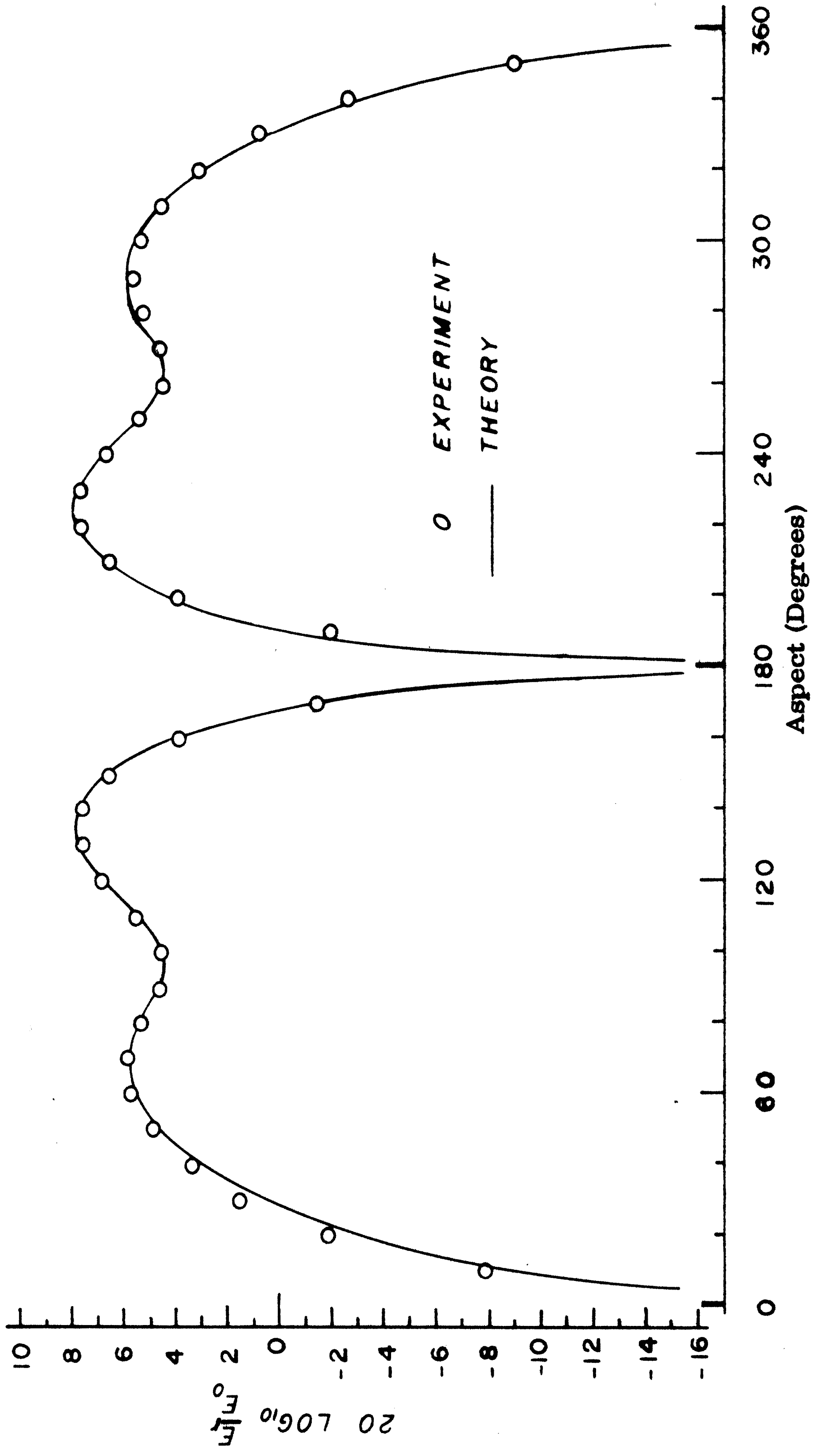

FIG. 3: RADIAL ELECTRIC FIELD AT SURFACE OF SPHERE FOR ka = 2.0.

smaller lines with improved results (smaller signals) but some anomalous behavior. has been observed. Figure 4 is a plot of $|E_\theta|^2$ at the specular point on the sphere as a function of the distance from the surface. It can be seen that on the surface there is a finite signal which drops to a minimum a very short distance from the sphere and beyond this minimum the field builds up extremely fast. One-tenth inch from the surface, it has risen 22 db after which it appears to be leveling off. It can be shown that in the region of a null $|E_\theta|^2$ is proportional to $(x/\lambda)^4$ where x is the distance from the null to the point at which $|E_\theta|^2$ is measured. Based upon this result $|E_\theta|^2$ should increase by 19.1 db in passing from x = .01 inch to x = .03 inch and, indeed, inspection of Fig. 4 shows the measured variation to be 20 db. At the time of this writing, the presence of the null just off the surface cannot be explained, but we feel it is deep enough and close enough to the surface to substantially represent zero field at the surface. We note in passing that the radial field vanishes at the specular point.

At any other point on the sphere E_θ theoretically vanishes and all testing has shown the probe has a strong response even when oriented parallel to the surface. It appears that the probe responds to the radial electric field even when oriented 90^o with respect to it. Measurements of E_θ around the sphere show that the probe output rises and falls in unison with the radial field. Attempts to evaluate the coupling of the probe with this component came to nil; it was hoped the coupling coefficient was a constant but in fact it changes from place to place on the sphere. The probe output contains radial field component signals which are approximately 15 db below the incident field at most. It appears we will not be able to measure tangential electric fields with any accuracy greater than this.

For Phase A of Coated Clean Shapes we conclude that:

1) Radial electric fields can be measured at perfectly conducting surfaces.

2) Probe response to tangential electric field near perfectly conducting surfaces is good if the radial electric field is zero.

3) Probe response to tangential electric fields near perfectly conducting surfaces is no greater than -15 db relative to the incident field if there is a radial electric field.

Phase B

Preliminary measurements have been made upon conducting cylinders coated with absorbing materials. Electrically, two cylinder sizes have been used, corresponding to ka = 2.7 and 8.1 and three materials have been used. The materials run

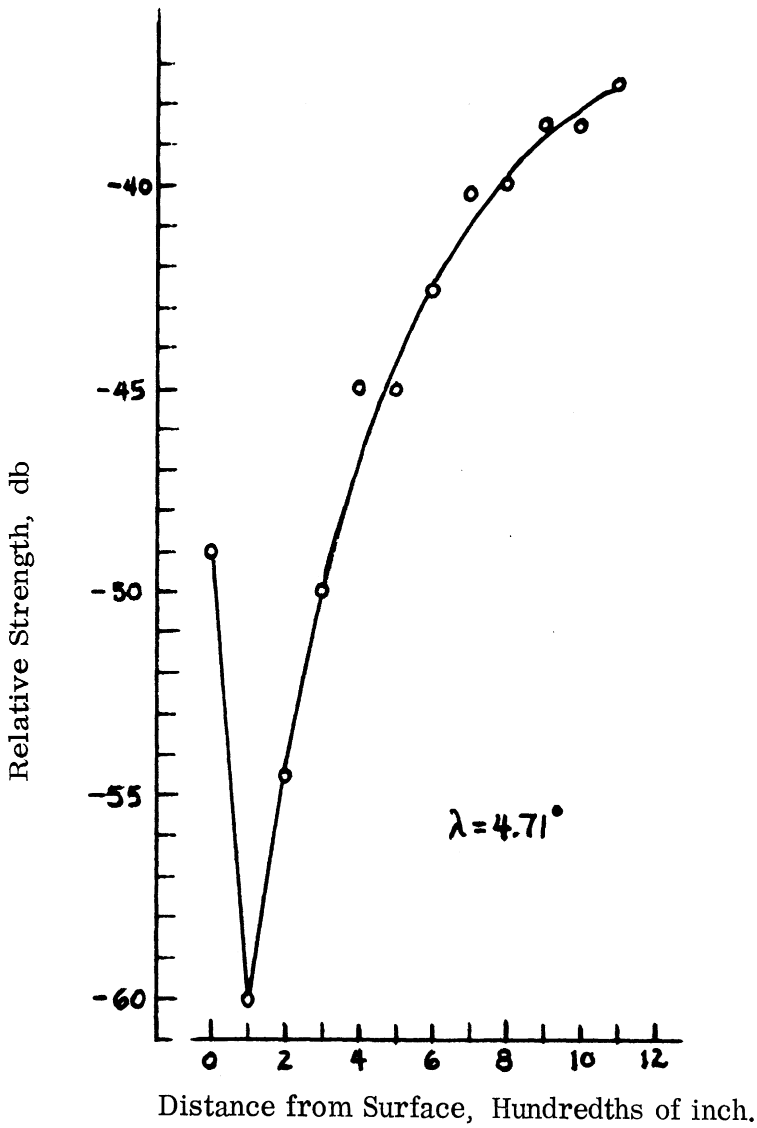

FIG. 4: VARIATION OF $|E_\theta|^2$ AT FRONT OF SPHERE AS PROBE IS WITHDRAWN FROM SURFACE.

from poor (power reflection coefficient greater than -7db) to good (less than -20 db). The data have not been analyzed, but suggest that an impedance boundary condition **holds on the illuminated side only.**

The data were obtained by the measurement of E_θ and H_z as shown in Fig. 5.

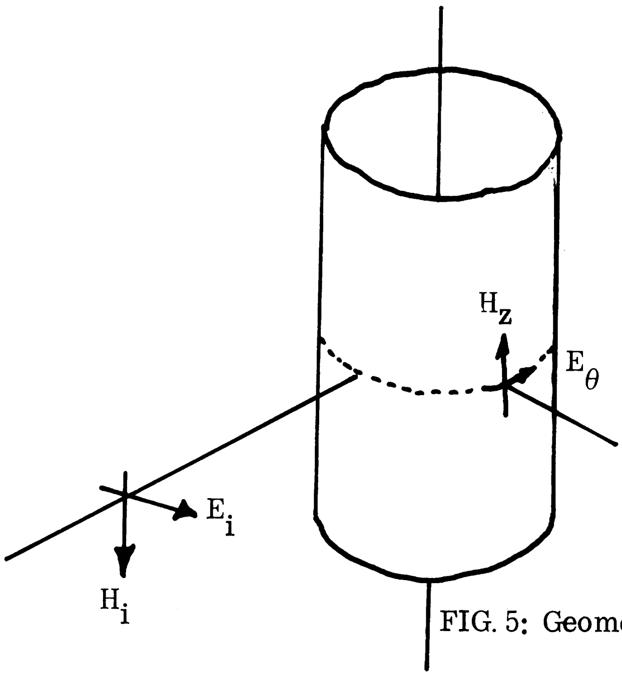

FIG. 5: Geometry for Cylinder Measurements.

These fields are orthogonal at the surface of the coating and are both tangential to the surface. If an impedance boundary condition holds, then E_θ and H_z are related by a constant for any position around the cylinder circumference and for fixed frequency. The data however, show that this is not true on the lit side but is approximately true in the shadow region. **The materials** used were flat sheets wrapped about the cylinder and the resulting seams were found to influence the local fields.

The choice of materials was largely dictated by that which was currently on hand in the laboratory and included broadband multi-layer absorber as well as a single layer resonant material. Samples of broadband, single layer materials are on order, but these are relatively poor materials. Also on order is a pour-in-place absorber which we hope will **eradicate** the seam problem found with flat sheet materials.

The latter material may prove useful in our quest to obtain uniformly thick absorber coatings on re-entry shapes, but we should not rule out piecing together segments of plane sheets to form a coating on a typical object. Indeed, when we examine the effects of fairing an absorber into the surface, the piecemeal application of flat sheet absorbers may be the quickest way to obtain coatings for preliminary measurements.

For Phase B of Coated Clean Shapes we summarize that

1) Measurements made so far indicate that the impedance boundary condition holds approximately on the shadowed side and not at all on the lit side.

2) Materials are being acquired which can be applied to re-entry shapes.

6.2 Perturbed Bare Shapes

Phase B

No work has been performed in this phase of the experimental program, mainly because of the lack of a model. A tentative model design has been submitted and the model will be constructed as soon as the design is approved.

The planned dimension of the object is shown in Fig. 6. Some of the dimensions there are redundant but they are included so that the accuracy of the model may be checked by its building and its ultimate user. The front of the model is separate from the rear so that several terminations may be constructed with varying degrees of indentation, as required. For the sake of simplicity, only two circles have been used (as opposed to three on full-scale objects) to provide the indented rear.

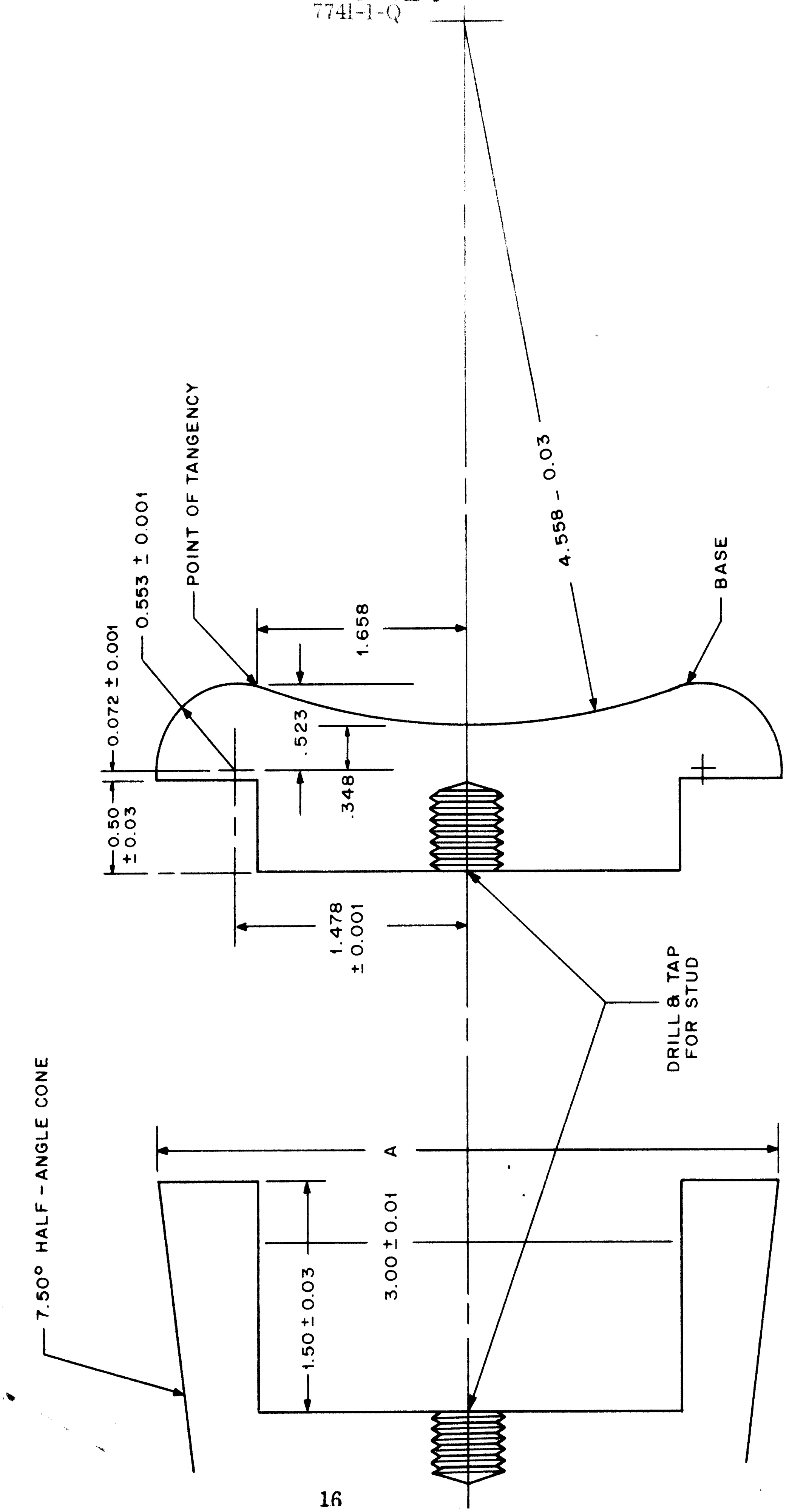

FIG. 6: PROPOSED MODEL TO BE CONSTRUCTED

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13. ABSTRACT

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