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Some Electromagnetic Considerations for a Rocket Platform for Electromagnetic Sensors

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Abstract

For measurements of EMP at high altitude one might use a rocket platform which can be approximated as a finite-length conducting circular cylinder. This distortion problem is particularly bad in the case of the electric field in conducting air where the problem is nonlinear. The magnetic field distortion problem can be reduced by judicious placement of the magnetic field sensors. To further reduce the distortion problem an inductive-resistive insert section is proposed for the platform which reduces the axial current on the cylinder for high frequencies. Finally a current sensor insert which can measure the axial current on the cylinder is discussed.

I. Introduction

For measurements of the nuclear electromagnetic pulse (EMP) at high altitudes above the earth one needs some sort of instrumentation system including sensors and supporting electronic and mechanical equipment. The sensors are then mounted on some platform containing various other equipment. This platform may significantly influence the electromagnetic fields in its vicinity as, for example, has been discussed for a sea-water-based platform[1]. The electromagnetic characteristics of the platform then need to be considered so that the electromagnetic field distortion can perhaps be made insignificant, or perhaps be taken into account as part of the sensor response to the incident field.

In this note we consider a rocket platform for electromagnetic sensors as roughly sketched in figure 1. The rocket platform, including sensors, is roughly approximated as a perfectly conducting circular cylinder of length, 2h, and radius, a, with the sensors comprising one end of the cylinder. This cylinder contains electronic equipment related to the measurements and may include parts of the rocket used to lift the package. This conducting cylinder, taken as parallel to the z axis, can significantly distort the incident electromagnetic fields. In non-conducting air the structure has a significant resonance at a frequency with a corresponding wavelength of approximately 4h. At low frequencies the electric field is significantly distorted, and in conducting air this distortion is nonlinear.

These distortion effects can be minimized to some extent for the magnetic field by optimum placement of the magnetic field sensors. Another improvement can be made by reducing the resonant scattering of the incident field. This can be done by the addition of an inductive-resistive (LR) section in the cylinder to dampen the resonant skin current. This section might be placed near the center of the cylinder as indicated in figure 1. This section could also be replaced by a current sensor to measure the skin current. In this note we consider some of the field distortion problems for negligible air conductivity and then for significant air conductivity. This is followed by a proposed inductive-resistive type of damping device. Finally we discuss a current sensor which can be interchanged with the LR damping device.

1. Capt. Carl E. Baum, Sensor and Simulation Note 39, Some Electromagnetic Considerations for a Sea-Water-Based Platform for Electromagnetic Sensors, March 1967.

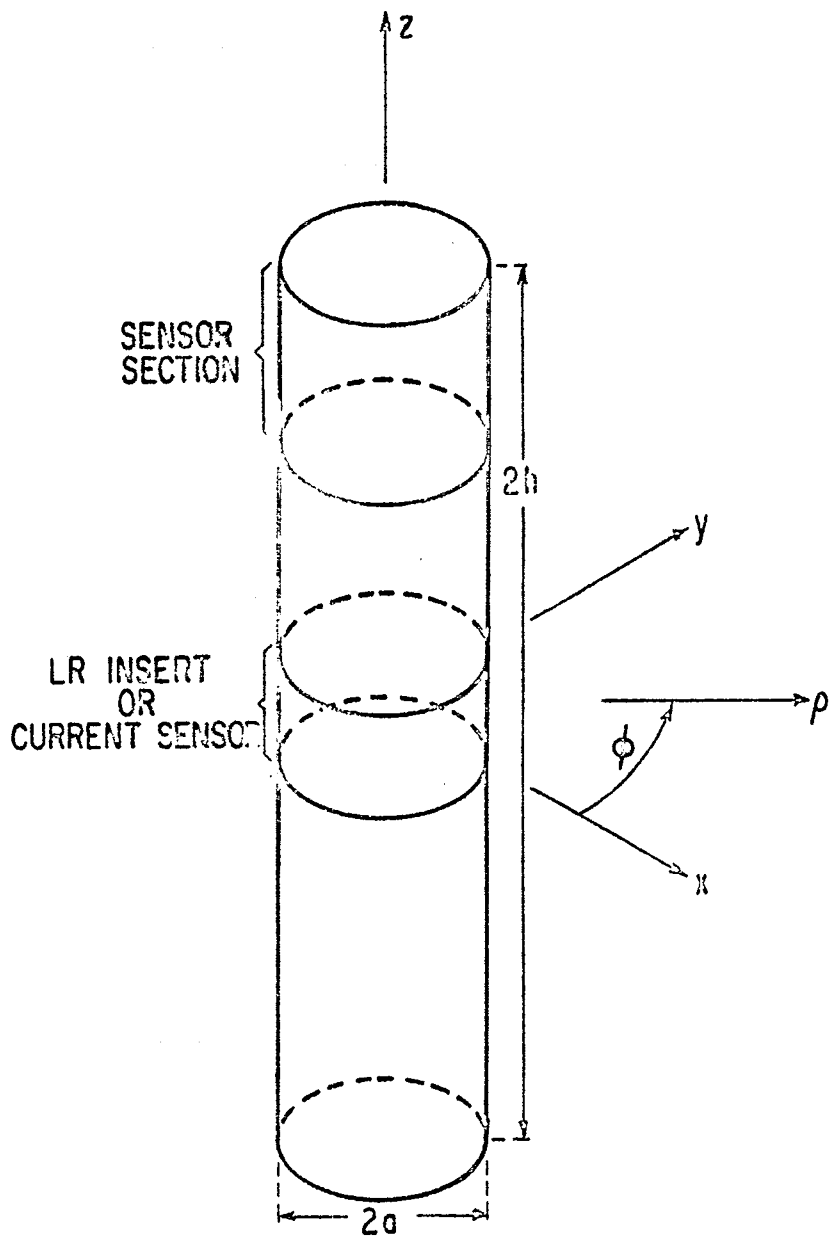

FIGURE I. ROCKET SENSOR PLATFORM IN FORM OF FINITE-LENGTH CIRCULAR CYLINDER

II. Negligible Air Conductivity

First consider the field distortion problem with the air assumed non-conducting. As is well known a perfectly conducting cylinder has a pronounced resonance at a radian frequency, ω_o , for which 2h is about half a wavelength[2,3]. There are also other higher frequency resonances but we only concern ourselves at present with the one at ω_o. This lowest order resonance will be excited by an incident electromagnetic pulse if it has significant radian frequency content near ω_o and does not have its polarization and direction of incidence in directions such that there is negligible coupling to this resonance. One might attempt to orient the cylinder such that the incident electric field has no z component, thereby having no coupling to this resonance. However, this may be rather difficult to accomplish with good accuracy.

The surface current density on the cylinder associated with this lowest order resonance is independent ϕ and has only a z component. The associated scattered electric field has z and ρ components; the scattered magnetic field has a ϕ component only. (See figure 1 for coordinates.) If the incident waveform has significant radian frequency content near ω_o and excites this resonance then these scattered field components will have a ringing waveform. Sensors located near the top of the cylinder, as in figure 1, will respond to these fields as well as to the incident fields. However, note that right on the z axis all components of the scattered magnetic field and the x and y components of the scattered electric field are zero. This applies not only to this first order resonant mode but to all scattering modes with only ρ and z electric field components and a ϕ magnetic field component which are all independent of ϕ. Thus we can ideally locate sensors on the z axis to measure B_x , B_y , B_z , E_x , and E_y and have such sensors insensitive to the principal resonant mode of the cylinder as well as some other scattering modes. The sensors would be centered on the z axis and would also be constructed symmetrically (since they have finite extent) to avoid coupling to the scattered fields associated with the principal resonant mode. In practice perfect symmetry will not be present and some unwanted coupling may still remain. A method of further reducing the magnitude of the scattered fields associated with the principal resonance is discussed in section IV.

Next consider the electromagnetic field distribution around this cylinder at low frequencies. If the incident field includes an E_z component large E_z and E_ρ components will result near the ends of the cylinder. This effect will have to be included in calculating the response of electric field sensors near the end of the cylinder. Other incident electric field components are

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2. R. W. Sassman, R. W. Latham, and A. G. Berger, Sensor and Simulation Note 45, Electromagnetic Scattering From a Conducting Post, June 1967.
3. Richard W. Sassman, EMP Interaction Note 11, The Current Induced on a Finite, Perfectly Conducting, Solid Cylinder in Free Space by an Electromagnetic Pulse, July 1967.

distorted near the end of the cylinder, but not as drastically. Just below the sensor section begins the conducting cylindrical platform which we approximate as being perfectly conducting so that it excludes the magnetic field from the interior of the cylinder. This cylinder then distorts the magnetic field near the sensor section. This distortion is significant for distances of the order of several times the cylinder radius, a, from the cylinder. Thus we can space the magnetic field sensor a little away from the end of the conducting cylinder to avoid the distortion. Alternatively one might shape the conducting cap on the end of the cylinder to minimize the distortion and/or make the distortion more readily calculable so that it can be more easily taken into account in the sensor design.

III. Significant Air Conductivity

Now let the air have a significant conductivity, such as would be present in the source region from a high altitude nuclear explosion. As we have discussed in previous notes, the air conductivity is a function of the electric field making the electric field distortion problem a nonlinear one[4,5]. Then if there is a significant incident E_z the rocket platform will greatly distort it in a nonlinear fashion, thereby significantly perturbing a measurement of any electric field component. If the platform could be oriented such that there were no significant incident E_z one might then attempt to measure E_x and/or E_y with sensors centered on the z axis but removed several times the cylinder radius, a, from the end of the conducting cylinder. Again, however, orienting the platform in this direction such that there is no significant E_z may be rather difficult in practice. Electric field measurements in conducting air raise other problems as well[4,5]. In particular, the sensor should not distort the electric field. This requires the sensor conductors to be exposed to the conducting air. The air may be streaming by the sensor at high speeds if it is lifted to high altitudes by a rocket and the sensor may be to weak to withstand the forces and still have the required electrical characteristics. The problem of electric field measurement in conducting air on this rocket platform then looks difficult at best.

The problem of magnetic field measurements on this platform in conducting air is somewhat different. For frequencies low enough that the skin depth in the conducting air is much larger than the length of the platform, $2h$, then the magnetic field distortion associated with the local distortion of the air conductivity is small compared to the incident magnetic field. In a previous note we considered this problem for magnetic field loop sensors[6]. Now we have to compare the skin depth with $2h$ instead of the sensor dimensions which may be much smaller. The reader may refer to this previous note (ref. 6) for a lengthier discussion of this problem. Of course, one may wish to measure the magnetic field at higher frequencies for which the skin depth is of the order of $2h$, or even much less. For such frequencies the nonlinear air conductivity may be significant but its influence can perhaps be minimized to some extent. If there is a significant incident E_z then there will be a large surface current density flowing in the z direction on the conducting cylinder. The associated magnetic field should not couple very strongly to magnetic field sensors located at the end of the cylinder near the z axis. The sensors can be encapsulated in an insulating dielectric to impede any flow of current from the conducting cylinder through the sensor into the conducting air. Perhaps the conducting cylinder could itself be coated with

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4. Lt. Carl E. Baum, Sensor and Simulation Note 15, Radiation and Conductivity Constraints on the Design of a Dipole Electric Field Sensor, February 1965.
5. Lt. Carl E. Baum, Sensor and Simulation Note 26, The Influence of Finite Soil and Water Conductivity on Close-in Surface Electric Field Measurements, September 1966.
6. Lt. Carl E. Baum, Sensor and Simulation Note 29, The Influence of Radiation and Conductivity on $\dot{B}$ Loop Design, October 1966.

insulating dielectric to impede the flow of current between the cylinder and the conducting air. Another way to reduce the z component of the surface current density, at least for some of the high frequencies, is to use the technique discussed in section IV.

IV. Inductive-Resistive Reduction of Skin Current

We now consider a technique for reducing the z component of the surface current density, J_{s_z}, on the platform. Referring to figure 1 one thing one might imagine doing would consist of dividing the platform into two distinct cylinders, each with length roughly h. With no conductors at all running between the two parts then J_{s_z} would be zero at the division. However this type of splitting up of the platform may not be acceptable in many cases because one may want to run signal cables, power cables, etc. between the two parts of the platform.

Assume that we want the sensor platform to have one continuous conducting shield for a single enclosed volume containing the electronic equipment. At the same time we would like to effectively segment this shield to block exterior currents, at least to some degree. We propose an inductive-resistive (LR) insert section, such as the one illustrated in figure 2, as one way to achieve this partial exterior segmentation. This would be inserted somewhere near the middle of the platform as shown in figure 1. The interior shielded volume is a circular cylinder of radius, a, both above and below the insert; the radius shrinks to b in the insert. This central passageway in the insert allows cables to pass between the top and bottom sections of the platform without leaving the shielded volume. The insert section has a height w in the z direction. Note that the top and bottom sheets of the insert section form part of the conducting shield for the shielded volume. Around the central conducting tube there is a doughnut-shaped magnetic core with permeability $\mu = \mu_r\mu_o$, inner radius b', outer radius a', and height w'; its conductivity is assumed negligible. The remainder of the volume between $\rho = b$ and $\rho = a$ is filled with insulating dielectric of permeability μ_o. Around the outside there is a resistive sheet of uniform surface resistance R_s which connects to the conducting shield on both sides of the insert.

Now consider frequencies low enough that wavelengths or skin depths, as appropriate, in the magnetic core, insulating dielectric, and air are all much larger than both a and w. Current in the z direction on the shield passes through the insert by passing either through the resistive sheet or on the central tube of radius, b (via the top and bottom conducting sheets on the insert). Associated with these two current paths there are two impedances which act in parallel to give the equivalent circuit in figure 3. The resistance associated with the resistive sheet is given by[7]

$$R = \frac{w}{2\pi a} R_s \qquad (1)$$

Associated with the current, I_b, in the +z direction on the central tube

7. All units are rationalized MKSA.

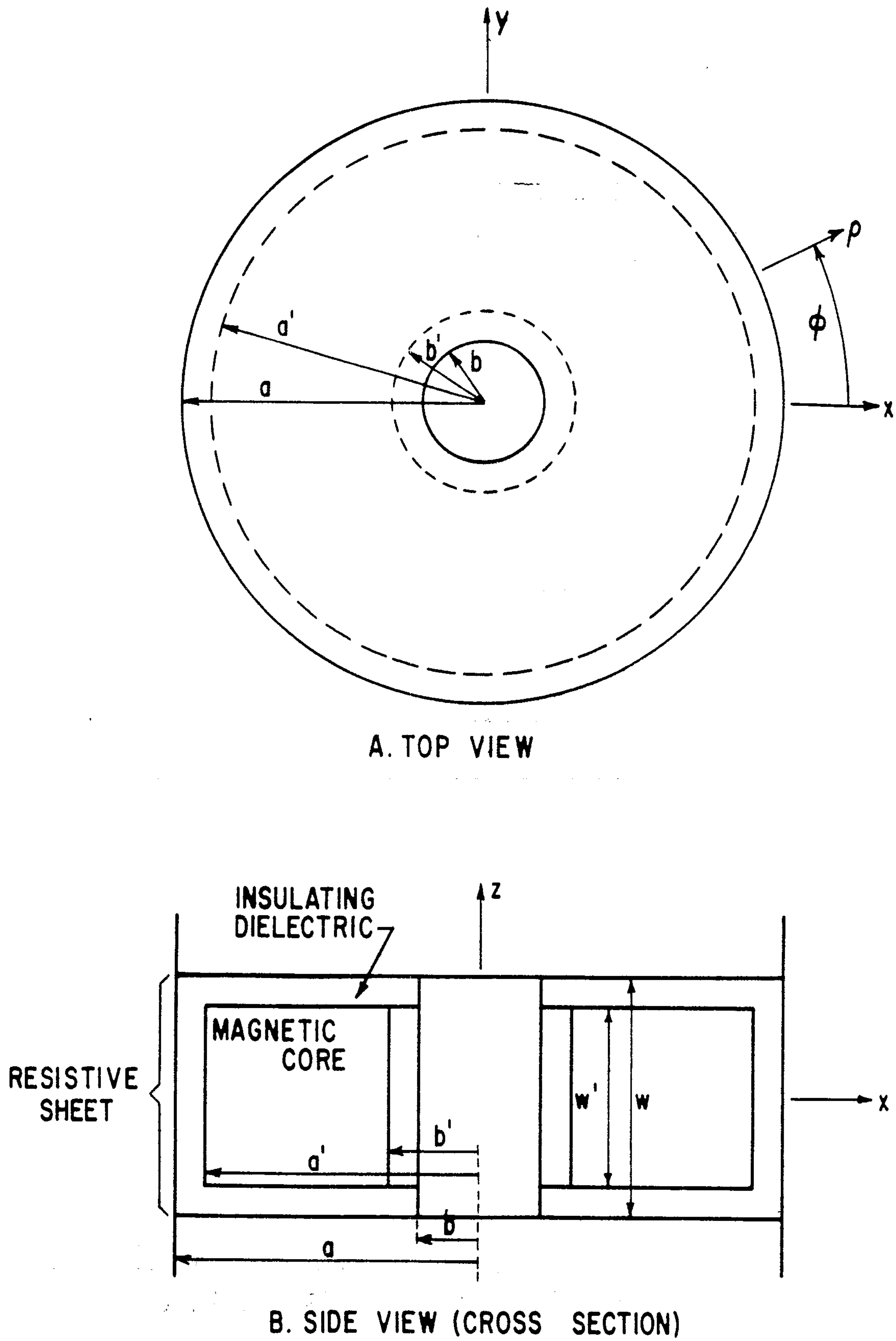


FIGURE 2. INDUCTIVE - RESISTIVE INSERT SECTION

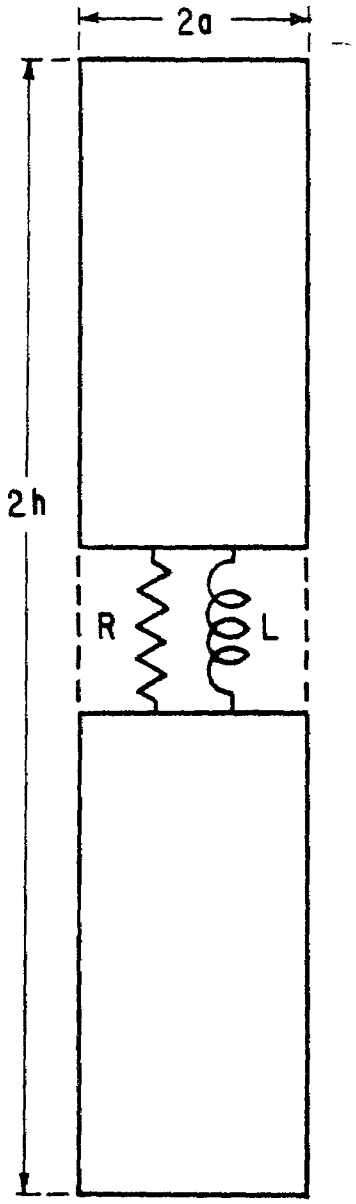


FIGURE 3. EQUIVALENT CIRCUIT OF INDUCTIVE-RESISTIVE INSERT SECTION OR CURRENT SENSOR INSERT SECTION IN PLATFORM

there is a magnetic field in the ϕ direction for $b < \rho < a$ given by

$$H_\phi = \frac{I_b}{2\pi\rho} \tag{2}$$

This gives an inductance associated with this volume in the insert for $b < \rho < a$ as

$$L = \frac{\mu_o}{2\pi}\left[w\ln\left(\frac{a}{b}\right) + (\mu_r - 1)w'\ln\left(\frac{a'}{b'}\right)\right] \tag{3}$$

We then characterize the insert by L and R or as an inductive-resistive insert. For sufficiently high frequency, of course, the impedance characteristics of this insert deviate from the simple parallel R and L in equations (1) and (3) respectively.

In the presence of negligible air conductivity and without this LR insert the platform has a resonance at a radian frequency, ω_o, with a corresponding wavelength approximately $4h$. The associated current, I, is parallel to the z axis. Now add the insert, but first consider $R = \infty$. Then the current is forced to flow through the inductance, L. Combining L with the source impedance of the platform would still give an oscillatory configuration with a lowered resonant frequency. Note, however, with the introduction of L there is a voltage drop across it. Now adding R in parallel with L, current is made to flow through R thereby introducing some loss into the system and damping I and the associated resonant fields.

In order that the insert be effective in damping I it is necessary that L be large enough to allow the dissipation of the stored energy in the unwanted oscillatory fields by R in times comparable to one oscillation period. Roughly speaking, this requires L to be about as large as what one might term as the platform inductance which is of the order of $\mu_o h$ (provided h/a is not too large or too small). Assuming that w' is almost as large as w, then from equation (3) we see that L is of the order of $\mu_r \mu_o w$. Assuming that $w \ll h$ this then requires μ_r to be of the order of $\frac{h}{w} \gg 1$. In case a high-frequency relative permeability of this magnitude is difficult to obtain then the design of the insert will have to be changed. For example, the central tube passing between the two sections of the platform could be bent to wind around a magnetic core several times to increase the inductance. There is no significant problem in realizing the required resistance since R can be varied over an extremely large range in practice. To accurately determine the effect on I due to varying L and R one can calculate I from the solution of an electromagnetic boundary value problem. One note has been written about this approach and a second, including numerical calculations, is being prepared[8].

8. R. W. Latham and K. S. H. Lee, Sensor and Simulation Note 51, Minimization of Induced Currents by Impedance Loading, April 1968.

In the presence of sufficiently high air conductivity the platform (without the LR insert) does not exhibit the resonant behavior discussed above. In this case there is no resonance to dampen. However this LR insert may still be useful in that it can reduce the current flowing in the $\pm z$ direction on the platform for high frequencies and thereby perhaps reduce some of the magnetic field distortion at high frequencies.

While we have discussed the insertion of one LR section in the platform, it may be desirable to insert more than one, if practical. For the case of negligible air conductivity one might try to dampen some of the higher order resonances, as well as the principal one, by appropriate positioning of several LR inserts.

V. Measurement of Skin Current

Instead of reducing the axial skin current one might want to measure it for various reasons. One way to do this is by the insertion of a current sensor, such as the one illustrated in figure 4, in the rocket platform instead of the LR insert. Again there is a conducting tube of radius b to allow passage of cables between the two sections of the platform. There is a vertical conducting sheet at $\rho = a'$ with a circumferential gap of width w'. A current, I, in the $+z$ direction then produces a magnetic field as in equation (2), giving a magnetic flux, Φ, between $\rho = b$ and $\rho = a'$ as

$$\Phi = \frac{\mu_o}{2\pi} w \ln\left(\frac{a'}{b}\right) I \tag{4}$$

where w is the height of the sensor volume in the z direction. Note the presence of insulating dielectric of permeability μ_o in the sensor volume as well as outside the sensor gap. If now we place signal cables to pick up the voltage across the circumferential loop gap we will have a signal voltage (for negligible signal-cable load) given by

$$V = M \frac{dI}{dt} \tag{5}$$

where M is the mutual inductance given by

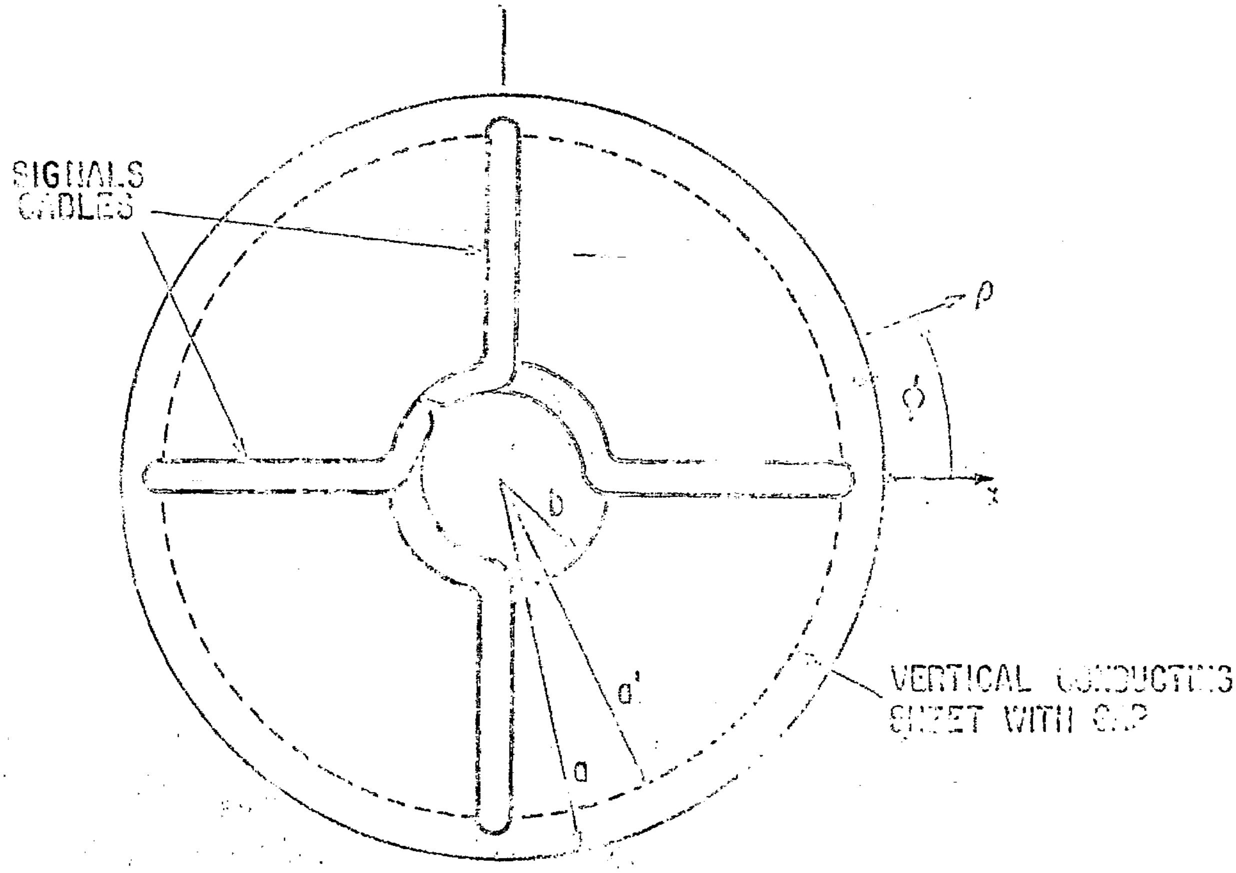
$$M = \frac{\mu_o}{2\pi} N w \ln\left(\frac{a'}{b}\right) \tag{6}$$

and where N is the effective number of loop turns linking Φ. This number, N, depends on the way the signal cables are hooked up.

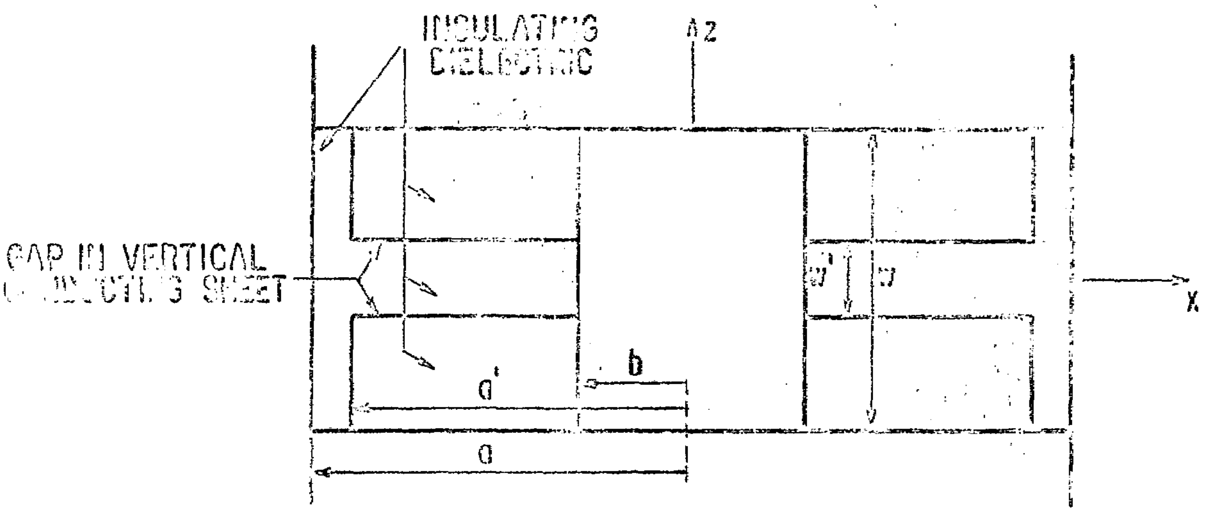
Ideally the inputs to the signal cables are uniformly distributed around the circumferential gap so that the resulting signal comes only from the magnetic field associated with I, the net platform current in the z direction. Figure 4A shows a case of 4 signal cables removing the signal from the gap, passing through the top conducting sheet, and coming together at some common collection point. All the cables should have the same transit time from the loop gap. The cables are assumed to be properly terminated so as to give a net resistance R as a load across the gap. The inductance of the current sensor structure, as presented to the platform, is

$$L = \frac{\mu_o}{2\pi} w \ln\left(\frac{a'}{b}\right) \tag{7}$$

This L and R give the elements for the equivalent circuit of the current sensor in the platform as illustrated in figure 3. Note that for this equivalent circuit to apply we need $a' = a$. If $a' < a$ then we could include another



A. TOP VIEW



B. SIDE VIEW (CROSS SECTION)

FIGURE 4. CURRENT SENSOR INSERT SECTION

inductance for the volume of height w between $\rho = a'$ and $\rho = a$.

To have this sensor respond to $\dot{I}$ as in equation (5) we need L/R much less than times of interest. Assuming this to be the case then L is the dominant element in the equivalent circuit of figure 3. For the case of negligible air conductivity and frequencies of the order of ω_o (principal resonance) or less the platform inductance as considered before is of the order of $\mu_o h$. Since typically we have $w << h$ then L is much less than the platform inductance and produces only a small perturbation in the platform current, I. For a more general air conductivity if we have radian wavelengths or skin depths much larger than the largest linear dimension of the sensor and also $h >> a,w$, then we can think of the sensor as a small perturbation in the geometry giving only a small perturbation in I.

There are other designs of inductive-resistive current sensors one might also consider which are symmetric about the z axis and maintain the continuity of the platform shield through the sensor. For example, one might wish to make the inductance much larger than the resistive load to have a signal proportional to I instead of $\dot{I}$. For each case, however, one should assure himself that the impedance introduced by the sensor into the platform only perturbs I insignificantly.

VI. Summary

A rocket platform used for EMP measurements at high altitude can introduce significant distortion of the incident electromagnetic fields in the vicinity of the electromagnetic sensors. In the presence of negligible air conductivity the platform has its lowest frequency resonance with large axial currents for the cylinder length approximately a half wavelength. This resonance may introduce a ringing waveform in the sensor outputs, superimposed on the incident waveform of interest. By adding an inductive-resistive insert to the platform this resonance can be damped. Also some of sensors can be located to minimize coupling to the scattered fields associated with this resonance.

In the presence of significant air conductivity the field distortion problem is nonlinear. Then if there is any significant distortion of the incident electric field any electric field measurements are questionable. The effects of the electric field distortion and accompanying air conductivity distortion are not as detrimental to the magnetic field measurements. For skin depths in the conducting air much larger than the platform length the distorted air conductivity should not have a very significant effect on the magnetic field measurements. For smaller skin depths or higher frequencies the effect of the field distortion on the magnetic field measurements can be reduced by several techniques. The sensors can be located to reduce coupling to the scattered magnetic field; the inductive-resistive insert can be used to reduce the high frequency axial currents; insulators can be used to cover the sensors and platform, thereby reducing the flow of current between the medium and the platform - sensor combination.

Instead of reducing the field-distortion problem by using an inductive-resistive insert, one can measure the axial platform current. Note that the current sensor can be made to be interchangeable with the inductive-resistive insert at the same position in the rocket platform, thereby increasing the flexibility of the measurement system. Also note that both the inductive-resistive and current sensor inserts can be made so as to preserve the continuity of the platform electromagnetic shield for the internal equipment.

The problems associated with measurement of the EMP fields are rather complex. This is especially the case in the conducting air in the source region. It would be highly desirable to subject such a platform with sensors to a realistic simulation of the environment to obtain confidence that the various problems have been solved and to estimate the accuracy of such a measurement system. From a theoretical viewpoint there are various electromagnetic design problems for such a platform and its sensors which may be treated in detail in some future notes.